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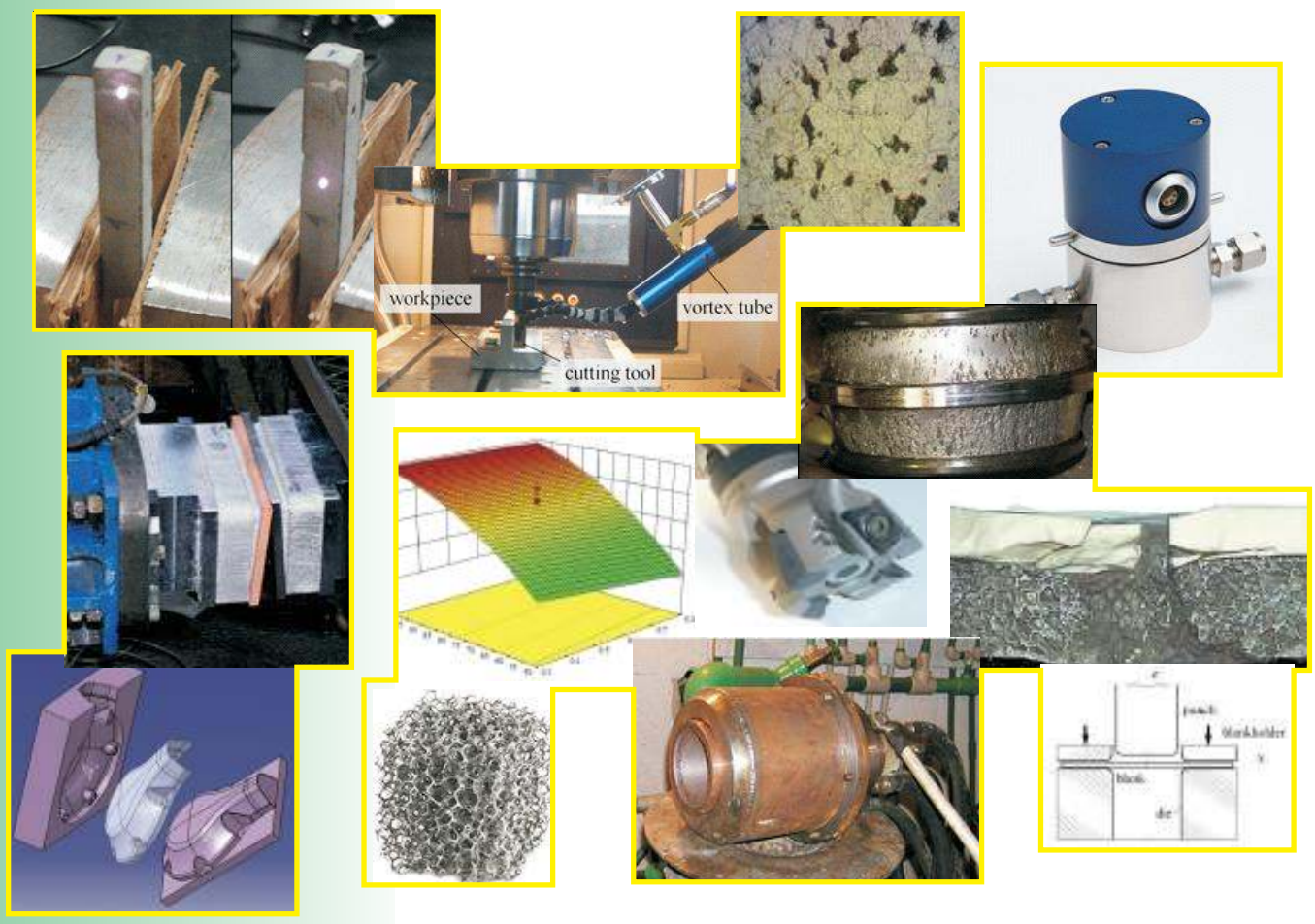

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Projekt plinofikacije Dalmacije

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Pregledni rad
Sažetak: U ovom radu je prikazan projekt uvođenja prirodnog plina kao novog energenta na područje triju dalmatinskih županija. Kao dio hrvatske energetske strategije projekt plinofikacije je u potpunosti privatno financiran od tvrtke EVN Croatia Plin, tvrtke kćeri međunarodnog energetskog koncerna EVN AG.
Pored prikaza općih i tehničkih karakteristika projekta plinofikacije, u radu su prikazana i osnovni pokazatelji korisnosti plinofikacije za poboljšanje standarda života na području Dalmacije kao i mogućnosti unapređenja gospodarstva kroz upotrebu zemnog plina kao energenta.

Dalmatia Gasification Project

Review article
Abstract:
This paper gives short overview of on-going project introducing natural gas as a new energy source in Dalmatia. As a part of national energetic strategy, gasification of Dalmatia is green field project fully private funded by EVN Croatia Plin, subsidiary of Austrian based international energy group EVN AG.
Additionally to general project description focusing on opportunities and challenges of project in development and operational phase of distribution system, paper presents gas grid development plans and construction technologies used in execution of pipelines and possible applications and advantages of using natural gas as energy source. Possible applications and advantages will be explained using actual examples from our customer's experience.

1. Uvod

Strategijom energetskog razvoja Republike Hrvatske u dijelu koji se odnosi na razvoj transportnog i distributivnog sustava RH predviđa se *"...izgradnja transportnog sustava na svim područjima gdje je to gospodarski opravdano u odnosu na opskrbu ukapljenim naftnim plinom…"*. Nacionalni operater transportnog sustava tvrtka Plinacro je u prethodnom razdoblju vođena ciljevima Strategije dovršila izgradnju transportnog sustava Dalmacije (visokotlačni plinovod 75bara od Bosiljeva do Dugopolja) i time omogućila izgradnju distributivnog sustava za potrebe triju dalmatinskih županija. Koncesijskim ugovorima potpisanim 2009. i 2010. Zadarska, Šibensko-kninska i Splitsko županija su projekt razvoja distributivnih mreža povjerile austrijskom energetskom koncernu EVN AG. EVN AG je energetski koncern iz Donje Austrije sa sjedištem u Maria Enzersdorfu s preko 9.000 zaposlenih i ukupnim godišnjim prometom oko 2.5 milijarde eura. Za potrebe realizacije projekta u Hrvatskoj osnovana je tvrtka EVN Croatia plin sa sjedištem u Zagrebu i poslovnicama u Zadru i Splitu. Ukupno ulaganje u izgradnju i upravljanje distributivnom mrežom procijenjeno je na 100 milijuna eura.

2. Projekt izgradnje distribucijskog sustava

Projekt izgradnje distribucijskog sustava odvija se paralelno u sve tri dalmatinske županije i ovisno o vremenu potpisivanja koncesijskog ugovora i pripremnim radovima na ishođenju potrebnih dozvola nalazi se u različitim fazama razvoja.

1.1. Zadarska županija

Ugovor o koncesiji između Zadarske županije i EVN-a potpisan je u lipnju 2009. Područja obuhvaćena koncesijskim ugovorom su gradovi Zadar, Biograd na Moru i Benkovac (Slika 1.). Procijenjeni broj potencijalnih potrošača prema studiji iz koncesijskog ugovora je 26.000. Ukupna duljina plinovodne mreže za punu pokrivenost iznosi 390 km uz ukupnu investiciju u vrijednosti 160 mil. HRK.

Slika 1. Prikaz plinovoda u Zadarskoj županiji

U Zadru je trenutačno u pogonu prvih 10-tak km distributivne mreže na koju je priključeno 160 korisnika dok je za tehnički pregled te zatim i upotrebu pripremljeno dodatnih 7 km.

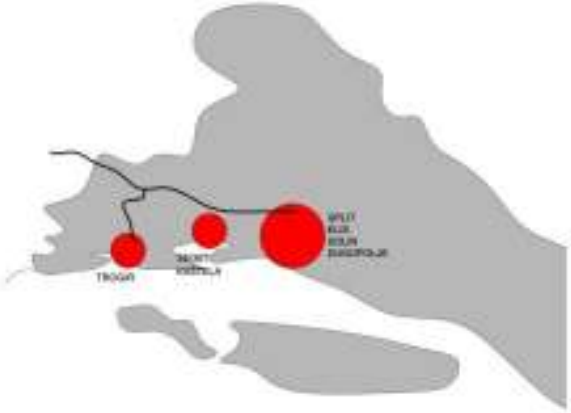
1.2. Šibensko- kninska županija

Ugovor o koncesiji između Šibensko-kninske županije i EVN-a je potpisan u svibnju 2010. Područja opskrbe plinom prostire se na području gradova i općina Šibenik, Drniš, Knin, Vodice, Bilice, Tribunj, Pirovac, Tisno i Murter-Kornati (Slika 2.). Broj potencijalnih potrošača je 23.000, ukupna duljina plinovoda je 435 km i predviđena vrijednost investicije 210 mil. HRK.

Slika 2. Prikaza plinovoda u Šibensko- kninskoj županiji

1.3. Splitsko-dalmatinska županija

Ugovor o koncesiji između Splitsko-dalmatinske županije i EVN-a je potpisan u prosincu 2009. Područja opskrbe plinom: Split, Solin, Kaštela, Trogir, Dugopolje, Klis i Seget (Slika 3.). Broj potencijalnih potrošača je 81.000 dok je ukupna duljina plinovoda potrebna za punu pokrivenost 625 km. Ukupna vrijednost investicije iznosi 380 mil. HRK.



Slika 3. Prikaza plinovoda u splitsko-dalmatinskoj županiji

Trenutačno je na području Splitsko-dalmatinske županije u tijeku projektiranje i ishođenje dozvola za građenje kroz šest različitih projekata kojim će biti omogućena distribucija zemnog plina i opskrba budućih korisnika. Navedeni projekti predviđaju izgradnju dviju mjerno regulacijskih stanica (MRS Klis i Split I), dviju odorizacijskih stanica za potrebe odorizacije zemnog plina (OS Dugopolje i Trogir) kao i izgradnju visokotlačnog plinovoda Dugopolje-Klis, Klis-Split I i Klis-Kaštela kao i izgradnju pripadajuće srednjetlačne mreže za gradove i općine pokrivene koncesijskim ugovorom. Na slici 4. prikazana je dio plinsko distribucijskog sustava Splitsko-dalmatinske županije odnosno pregledna situacija plinsko-distribucijskog sustava grada Splita.

Slika 4. Prikaza plinovoda u splitsko-dalmatinskoj županiji

3. Karakteristike PDS-a

EVN Croatia Plin d.o.o., kao operator distribucijskog sustava, preuzima zemni plin od operatora transportnog sustava tvrtke Plinacro d.o.o. Točke preuzimanja su mjerno redukcijske stanice. U mjerno redukcijskim stanicama se tlak prirodnog plina koji vlada u transportnom sustavu 50 bar ili 75 bar, reducira za potrebe distribucije na razine odgovarajućih tlačnih razreda i to do 5 bar (srednjetlačni razred) ili 5-16 bar (visokotlačni razred).

Budući je prirodni plin bez mirisa (kao i boje i okusa), obveza je svakog operatora distribucijskog sustava izvršiti dodavanje karakterističnog sredstva za miris tzv. odoranta. Za tu svrhu se koristi tetrahidrotiofen (THT) i etilmerkaptan. Ovaj postupak se obavlja u odorizaciskim stanicama ubrizgavanjem odorizacijskog sredstva u tok prirodnog plina pomoću odorizacijskog uređaja (spremnik, pumpa, injektirajuća sapnica). Odorizacijske stanice predstavljanju početnu točku svakog distribucijskog sustava.

Od materijala za izradu distribucijskih plinovoda koristi se polietilenen visoke gustoće (PEHD) za tlakove do 10 bar (koeficijent sigurnosti 2,0 za PE 100), te čelik odgovarajuće kvalitete za visokotlačne plinovode. Više je razloga za korištenje polietilena kao što su:mala specifična masa, velika udarna žilavost, elastičnost, kemijska postojanost, dobra električna otpornost, brzo spajanje i polaganje, izuzetno čvrsti (pouzdani) spojevi u usporedbi s drugim materijalima. Spajanje PE cijevi međusobno kao i PE spojnih elementa (lukovi, redukcije, T-komadi), vrši se s elektro spojnicama (grijaća zavojnica) i sučeonim zavarivanjem. U oba slučaja potrebno je osigurati toplinsku energiju kako bi se dobila talina s odgovarajućom temperaturom i tlakom (temperature oko 200°C i tlak do 25 bar za promjer d 225 mm i PN6). Radi se o fuzijskom zavarivanju bez dodavanja dodatnog materijala. Različiti promjeri i različite debljine stijenke PE cijevi traže različito vrijeme zagrijavanja i hlađenja.

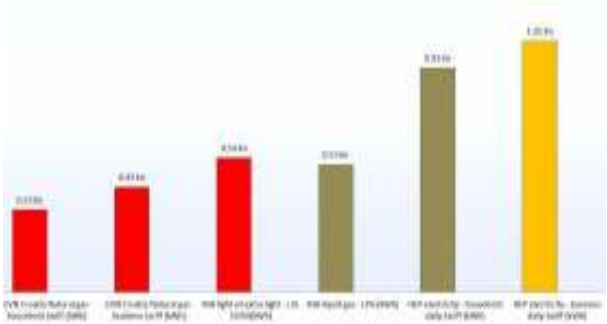
Gradnja i ispitivanje novoizvedenih kao i postojećih plinovoda provodi se s naročitom pažnjom i u skladu s važećom regulativom (HRN EN norme, DVGW i ÖVGW pravilnici).

Krajnji korisnici za svoje potrebe preuzimaju prirodni plin od operatora distribucijskog sustava putem mjerno-redukcijskih stanica koje predstavljaju dio interne plinske instalacije korisnika.

4. Zemni plin – energent budućnosti

Potencijalni korisnici zemnog plina iz distribucijske mreže EVN Croatia plina su javne institucije, male tvrtke, industrijski pogoni i domaćinstva. Gotovo je nemoguće zamisliti granu industrije ili uslužni sektor koji ne bi imao višestruke koristi od zemnog plina. Kemijski sastav i ekološki prihvatljiv produkt izgaranja zemnog plina čine ga idealnim izvorom energije za mnogobrojna područja života i poslovanja. Postoji vrlo malo toga što se ne može postići sa zemnim plinom. Zamislite koliko bi lakše i jeftinije bilo osigurati toplu vodu za hotel pun gostiju u jeku turističke sezone ili rashladiti urede ili trgovine tijekom vreloga dalmatinskog ljeta. Također kada zimi

zapuše bura, ništa ne može ugrijati prostorije tako učinkovito, lako i financijski najpovoljnije kao zemni plin. Primjena zemnog plina pored industrije,grijanja, kuhanja i pripreme tople vode sve više postaje značajna u transportu kao energent za vozila gradskog prijevoza, komunalnih i dostavnih službi. Zemni plin ima sve karakteristike idealnog poslovnog partnera. Pouzdan je fleksibilan, uvijek je na raspolaganju i daje izvrsne rezultate uz najniže troškove eksploatacije u usporedbi s drugim izvorima energije (Slika 5.).



Slika 5. Usporedba cijena energenata u RH

Financijska ušteda korištenjem zemnog plina u odnosu na druge energente ovisi o vrsti potrošača i namjeni upotrebe u može donijeti uštede do čak 40%. „Maraska d.d." je prvi priključeni industrijski pogon u regiji gdje je napravljena konverzija energenta. Odustajanjem od korištenja lož ulja, primjenom prirodnog plina uz korištenje modernih rješenja i primjenom nove termoenergetske opreme ostvarili su smanjenje potrošnje energije preko 30%, smanjena je emisija CO2 za 54% tj. 485 tona, te je gotovo nestala emisija SO2 koja je smanjena za 99%. Interesantno je ukazati na Istraživanje uštede u stambenim jedinicama koja su pokazala da četveročlana obitelj u stanovima prosječne veličine 75 m2 koji su koristili električnu energiju za grijanje, kuhanje i pripremu tople vode na godišnjoj razini troškovi bi iznosi 6.354,90 kn, dok uporabom zemnog plina uz nepromijenjene uvjete troškovi bi iznosili 2.348,55 kn što jednoj obitelji donosi uštedu od čak 64%.

Zemni plin ima izvrsna svojstva izgaranja i može se pretvoriti u toplinu bez daljnje obrade. Niski troškovi održavanja plinskih sustava i način opskrbe koji ne zahtjeva skladištenje dodatna su prednost. Zemni plin je ekološki najprihvatljivije fosilno gorivo jer prilikom njegova sagorijevanja nastaje uglavnom vodena para te vrlo male količine ugljičnog dioksida i to zahvaljujući kemijskom sastavu metana. Korištenjem plina smanjuje se emisija ugljičnog dioksida te doprinosimo zaštiti okoliša.

5. Zaključak

Izgradnjom transportnog sustava Like i Dalmacije postignuta je potencijalna dostupnost zemnog plina na 95 % teritorija Republike Hrvatske. Kako bi se ovaj potencijal realizirao potrebno je napraviti dodatni korak na izgradnji distribucijskog sustava. Ovog izazovnofg zadatka kroz koncesijske ugovore prihvatila se tvrtka EVN Croatia plin. Uz sve izazove razvoja ovakvog infrastrukturnog projekta njegova potreba i opravdanost je neupitna.

Pružanje mogućnosti korištenja zemnog plina širokom spektru korisnika na području Dalmacije predstavlja veliki potencijal za unapređenje kvalitete života, gospodarstva i energetske neovisnosti Dalmacije.

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Burning Coal by Using Plasma

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Plasma burner

Ključne riječi
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Sustav plazma-gorivo
Plazma plamenik

Early information

Abstract: Despite increasing environmental concerns, the utilisation of pulverised coal in power generation is likely to retain its important role in the near future. Although widely used and well established, the combustion of pulverised coal in utility boilers of thermal power plants still embraces a variety of difficulties. Thus, potential remains for improving and optimising the performance of this technology. This paper deals with the application of electric arc plasma systems in pulverised coal combustion technology. The overview of plasma system is given, followed by the presentation of numerical results, the experimental and to some extent the industrial measurements. Finally, the potential of applying plasma systems in other technologies is discussed.

Izgaranje ugljena pomoću plazme

Predhodno priopćenje

Sažetak: Usprkos općoj zabrinutosti za klimatskim promjenama i očuvanjem okoliša, za očekivati je da će ugljen i u bliskoj budućnosti zadržati svoju važnu ulogu u proizvodnji električne energije. Iako je od davno razvijena i u širokoj upotrebi, tehnologija izgaranja ugljena u pećima termoelektrana još uvijek uključuje i mnogobrojne probleme. Dakle, potencijal za poboljšanje i optimiziranje ove tehnologije postoji. U ovom članku prikazane su mogućnosti primjene elektrolučne plazme u okviru tehnologija izgaranja ugljena. Nakon opisa i prikaza plazma sustava, prikazani su numerički i eksperimentalni rezultati rada plazma sustava i njegovog utjecaja na proces plinificiranja i izgaranja ugljena. Konačno, naveden je i potencijal primjene plazma sustava u okviru drugih tehnologija.

1. Introduction

Today, coal is the second largest source of energy, generating some 41% of the world's electricity [1], while during the last decade coal has been the world's fastest growing energy source [1]. Apart from power generation, coal is used to produce 68% of the world's steel [1], while close to 90% of the world's cement is produced with the use of coal [2]. Others include production of aluminium, lime, brick, and so on.
The utilisation of coal in power generation is widespread around the world, where for example countries like Denmark, USA and Germany still produce more than 40% of their electricity from coal, while Poland some 85% [3]. Finally, all scenarios on future energy demands estimate the increase in coal consumption.

Compared with other fuels, the advantages of coal are proven and widely available reserves, coal price, and costs of generated electricity. The disadvantages are primarily related to CO_2 emissions released during the coal combustion.

The utilisation of coal is directly related to pollution since coal combustion generates emissions of different gases and particulates. The operation of power plants commonly necessitates the utilisation of other auxiliary fuels, such as heavy oil or natural gas. These are necessary for starting-up a cold boiler, while their environmental and economic contributions have to be taken into account as well.

The development of coal combustion technology has relatively long history. Among the existing coal combustion technologies, pulverised coal combustion (PCC) is the most widely used and generally accepted as a referent technology [4]. In order to increase the economics and the environmental performance of coal-fired plants, a range of technologies have been developed. They are applied at different stages of coal life cycle, and they all referred to as 'Clean Coal Technologies' (CCT).

They may be separated into two groups, where technologies within the first group are mainly concerned with the pre-combustion treatment of coal (e.g. 'washing' of coal), and the reduction of pollutants generated by existing pulverised coal combustion systems (e.g. flue gas desulphurisation, electrostatic precipitators, low-NO_x burners, selective catalytic reduction, etc.). Second group of CCTs includes the variety of advanced coal technologies, such as Supercritical (SC), Ultra Supercritical (USC) and Integrated Gasification Combined Cycle (IGCC) plants, and Carbon Capture and Storage (CCS) technology. A detailed account of these technologies is beyond the scope of this paper.

Although well established and deployed worldwide, the utilisation of coal in power generation still embraces a variety of difficulties. Thus, a lot of potential remains for improving and optimising the performance of this technology. Nonetheless, amongst the existing difficulties two specific problems may be also identified. The first being high sensitivity of the combustion process on the quality of utilised coal, which affects the stability of the flame. The second being a necessity to warm up a cold boiler, in order to attain its operational temperature.
Both problems require the consumption of appreciable amount of the auxiliary fuels. Based on existing estimations some 50 million tonnes of heavy oil per year are consumed for supporting the coal flame and for starting up of a cold boiler [5]. As a possible solution a plasma technology has been proposed and already applied in number of coal-fired power plants [6].

2. Plasma Technology for Coal Combustion

2.1. General description

Conventional pulverised coal systems utilise auxiliary fuels for initial warming up of a cold boiler and for supporting the unstable combustion of low rank coals. Taking into account the availability and the prices of heavy oil and natural gas, their consumption in pulverised coal-fired power plants as auxiliary fuels could be barely justified. As technologically and economically effective substitution to auxiliary fuels, plasma systems have been proposed [7, 8].

Plasma technology for combustion of pulverised coals may be summarised as heavy oil- or natural gas-free technology for starting up of a cold utility boiler and for stabilisation of the flame during the combustion of low rank coals in coal-fired power stations. Thus, with the addition of plasma coal could be 'prepared', usually within a separate chamber, and used as supporting (auxiliary) fuel. The immediate benefit is the requirement of only one fuel being supplied, stored and used to achieve the full operation of a boiler of coal-fired power plant.

Generally, this concept involves the separation of a proportion of pulverised coal - air mixture from the bulk flow, and the treatment of this separated flow with the electric arc plasma (within a separate plasma chamber, Figure 1). The ratio between pulverised coal and air provides oxygen deficient conditions. As a heat source and oxidiser, the electric arc plasma provides high temperature and chemically reactive environment. In such conditions, the complete release of volatiles and partial gasification of carbon residue takes place. This highly reactive and burning mixture of hot particles of unburned char and combustible gases (CO, H_2 and CH_4), is introduced into the main fuel stream, where the main fuel is ignited when mixed with the secondary air inside the combustion chamber of the boiler.

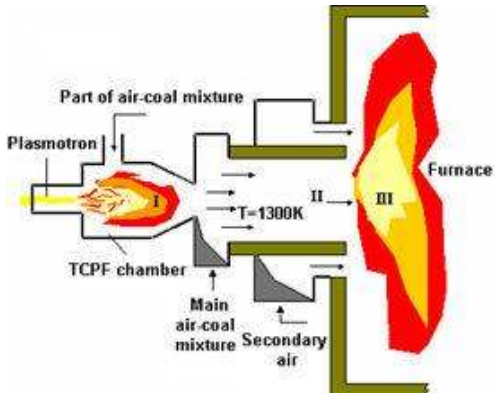

Figure 1. Schematic view of plasma burner

Slika 1. Shematski prikaz plazma plamenika

The described concept is one of the possible solutions of application of plasma systems in coal combustion technology. The design of the plasma system primarily depends on its application, on the configuration of existing boiler, type of burners and on the properties of used coal. This technology has already proved its potentials through the industrial scale implementations in some 25 utility boilers of thermal power plants in Russia, Kazakhstan, Ukraine, Slovakia, China, Korea and Mongolia, utilising a wide range of coals [9].
However, wider application of such technology is still limited, mainly due to the shortage of the fundamental knowledge of the physics involved. Some of these involve the interaction between the coal particles and plasma, or the possible negative effects of plasma systems on the performance of utility boiler.

2.2. Plasma Generator (Plasmatron)

The most important part of the plasma system is a plasma generator. The type and the arrangement of the plasma generator depend primarily on the application of the plasma system. In this paper, low-temperature plasma generator that creates a non-transferred arc plasma discharge is presented (Figure 2).

As a result of electric arc formation between two electrodes and the injection of high velocity air through the area of arc formation, a plasma discharge is created. As a source of energy, a direct current (DC) electric power supply is used. Due to the high concentration of energy within the arc formation region, the injected air is rapidly heated to the high temperature level, which in this case may reach up to 10000 K within the arc region [10]. The mass-averaged temperature of the plasma flame at the exit from the plasma generator may reach around 5000 K. To prevent the plasma generator from overheating, the whole body and the electrodes are water-cooled.

The body of plasma generator is made of electrical copper with the graphite electrodes designed as insets (Figure 2). This arrangement prevents the wearing of the plasma generator body, and allows easier replacement of electrodes after they have been consumed. The attached electromagnetic coils around the graphite electrodes give the rotational motion to the electric arc. This concept increases the lifetime of the electrodes by distributing the electric arc formation point over the whole area of both electrodes. In addition it increases the heat transfer between the electric arc and the plasma gas (air). The plasma formation gas at high velocity is tangentially supplied to the plasma generator, rotating in the same or the opposite direction of the electric arc.

The geometry and operational data of plasma generator from Figure 2 are presented in Table 1.

Table 1. Plasma generator specification

Tablica 1. Specifikacija plazma generatora

PLASMA GENERATOR	
Weight (kg)	30
Length (m)	0.25
Outer diameter (m)	0.20
Nozzle outlet diameter (m)	0.09
Electric power (kW)	72
Plasma gas	air
Mass flow of plasma gas (kg/h)	18.0
Inlet air temperature (K)	293
Outlet air temperature* (K)	5460
Thermal efficiency (%)	81
Propane (C_3H_8) mass flow (g/h)	100

(*) estimated by thermodynamic calculations

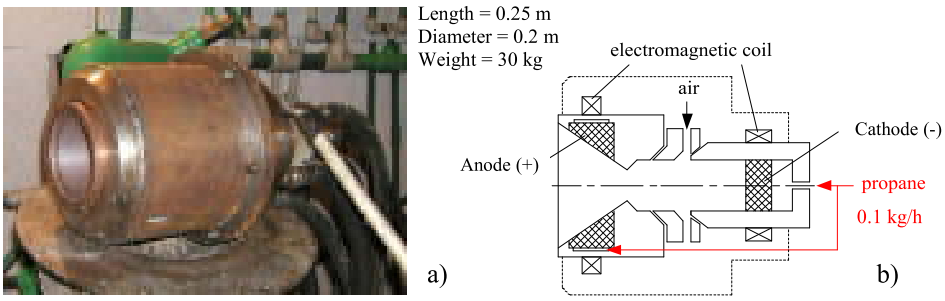

Figure 2. Photo and schematic of plasma generator

Slika 2. Fotografija i shematski prikaz plazma generatora

2.3. Plasma Burner

The rearrangement of a typical pulverised coal "direct flow" burner into the plasma burner is illustrated by the schematic sketches in Figure 3. Since the stable ignition of pulverised coals of lower rank could not be achieved by direct introduction of open plasma flames into the combustion chamber of utility boiler, the preparation of coal for combustion within the separate chamber is applied [7].

As shown on Figure 3, a part of the primary stream of air-pulverised coal mixture is separated from the main flow and supplied to the boiler through the coaxially placed additional cylinder. The plasma generator is attached on the cylinder body. This additional cylinder represents a plasma chamber. The proportion of the air-coal mixture that is delivered to the plasma chamber depends primarily on the properties of coal. In this example it is assumed as 30% of the total fuel supply of the burner. The ratio between the mass fraction of coal and air delivered to the plasma chamber may vary depending on the composition of coal, from 0.3 to 0.75 [11]. This ratio provides the oxygen deficient conditions.

Within the plasma chamber, the pulverised coal particles are treated by high temperature plasma flame,

releasing their volatiles. Due to the lack of oxygen volatiles are partially combusted, while the residual char may experience partial gasification, depending on the local conditions. At the exit from the plasma chamber, a highly reactive mixture of combustible gases (mainly CO with small addition of H_2 and CH_4) and unburned char is coaxially delivered to the primary section of the burner, prior to its introduction into the combustion chamber of boiler [7].

In order to maintain successful and efficient preparation of coal for combustion, it is particularly important to prevent the mixing of the produced highly reactive mixture with the main air-fuel mixture before they enter the combustion chamber of the boiler [11]. Through this, the process is well balanced since it consumes as little as possible energy for coal preparation, while on the other hand, the output from the plasma burner carries exactly the required amount of energy for igniting the main fuel stream inside the combustion chamber [10].

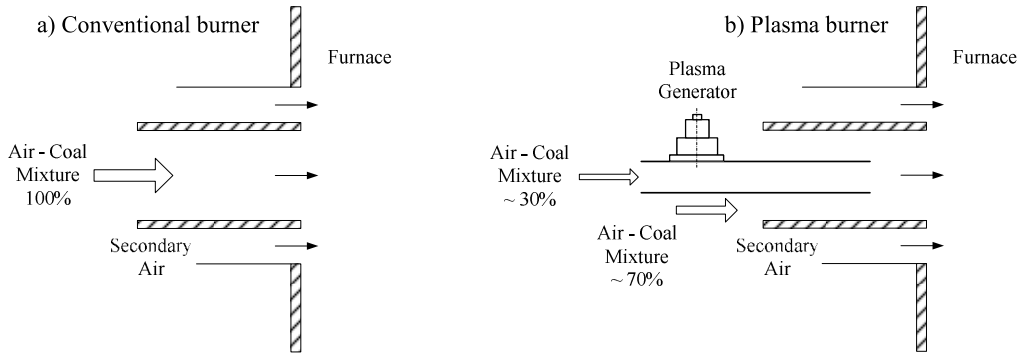

Figure 3. Schematic view of conventional pulverised coal "direct flow" burner rearrangement into plasma burner

Slika 3. Shematski prikaz prilagodbe standardnog plamenika ugljene prašine u plazma plamenik

3. Numerical Study

Numerical simulations have been carried out using the two-phase flow combustion code 'FAFNIR 3D', developed within the Thermo-fluids group at Imperial College London.
The code has been extensively validated with the data obtained from variety of practical combustion configurations [12, 13]. A detailed account on features of the main code is beyond the scope of this study.

3.1. Plasma generator

In order to simulate the operation of plasma generator, the measured values of temperature profiles are used, as shown on Figure 4.

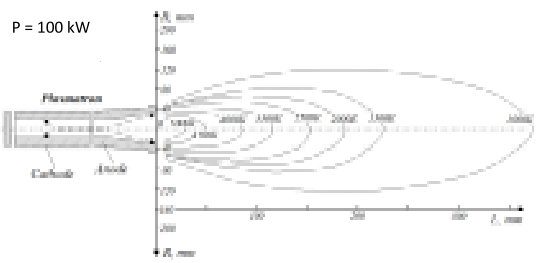

Figure 4. Measured isotherms of plasma flame

Slika 4. Izmjerene vrijednosti izotermi plazma plamena

This included the simulation of the spreading rate of plasma jet emerging from the plasma generator nozzle.

Predicted isothermal profiles are presented in Figure 5. The comparison of experimental and numerical data for the spreading length of several isothermal contours along the symmetry line is presented in Table 2.

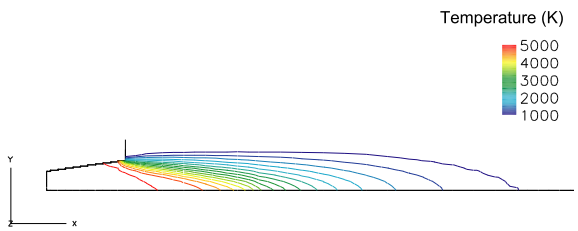

Figure 5. Predicted isotherms of air-plasma flow from the plasma generator

Slika 5. Izoterme na izlazu iz plazma generatora

As shown in Table 2, a good correlation is achieved between predicted and measured results of the spreading length of isotherms along the symmetry.

Table 2. Comparison of measured and predicted data for the spreading length of isotherms along the symmetry axis

Tablica 2. Usporedba mjerenih i simulacijskih vrijednosti za dužinu izotermi uzduž osi simetrije plamena

	Temperature (K)							
Length (m)	5000	4500	4000	3500	2500	2000	1500	1000
Experimental data	0.030	0.050	0.086	0.116	0.153	0.188	0.227	0.375
Numerical data	0.030	0.086	0.109	0.123	0.167	0.202	0.255	0.370

3.2. Plasma Burner

The plasma burner (chamber) is a horizontal cylinder with the plasma generator placed on the burner body as shown in Figure 6. The plasma generator provides the heat necessary for preparation of coal for combustion, which means the partial combustion and gasification of pulverised coal within the length of the burner.
Different arrangements and designs of plasma burners are possible, depending on the type of existing burners, the configuration of furnace and the properties of utilised fuel. In this study, a cylindrical direct flow burner is considered.

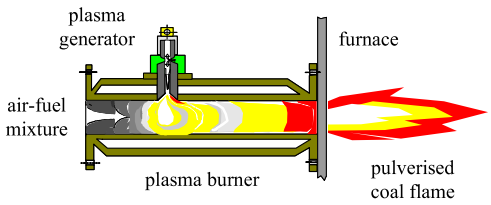

Figure 6. Illustration of cylindrical direct flow plasma burner [14]

Slika 6. Ilustracija cilindričnog plazma plamenika s direktnim strujanjem

The schematic of plasma burner is presented in Figure 7. The burner is a cylinder, 0.25 m in diameter and 2.35 m in length. On the inlet side (left), the plasma burner (PB) is attached by a mounting flange to the fuel-delivery pipe. On the outlet side (right), the burner interfaces the furnace. The supply of air/pulverised coal mixture is delivered to the PB at a slightly preheated temperature of 350 K, and at velocity of around 20 m/s.

The body of PB is lined with a ceramic material which is not water-cooled, since the objective of the wall is to prevent the heat loss from the combustion chamber of the plasma burner maintaining a hot environment. During the stabilised operation of plasma burner, the temperature of non-cooled wall is around 800 K. According to the measurements [10], the wall could be considered nearly adiabatic.

At axial distance of 0.35 m from the inlet plane of PB, the plasma generator is placed on the top of horizontal cylinder of plasma burner body. For the nominal electric power supplied to the plasma generator of 100 kW, the thermal efficiency of plasma generator of around 85%, and the mass flow rate of plasma gas of 54 kg/h, the plasma generator produces a low-temperature plasma flame. At the outlet of the generator, a mean temperature of the flame is around 2800-3000 K.

The specifications of geometry and operational data of the plasma burner are summarised in Table 3.

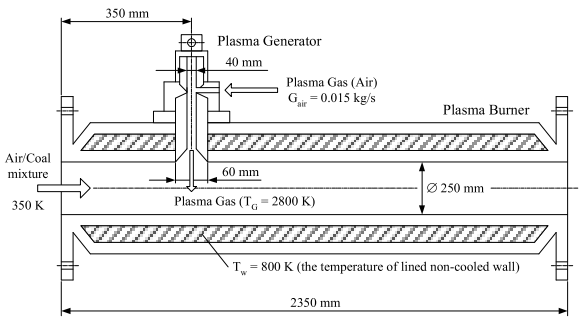

Figure 7. Schematic of plasma burner

Slika 7. Shematski prikaz plazma plamenika

The mass flow rates of pulverised coal and air supplied to the PB are 1750 kg/h and 3500 kg/h respectively (Table 4). This gives the ratio between the fuel and air (μ) defined as 0.5 kg of pulverised coal per 1 kg of air. At such fuel/air mixture concentration, the conditions within the plasma burner may be classified as highly fuel-rich, having the equivalence factor (Φ) around 3.35.

Table 3. Geometry and operational data of plasma burner and attached plasma generator

Tablica 3. Dimenzije i radni parametri plazma plamenika, te spojenog plazma generatora

OPERATING DATA	
Plasma Burner	
Length (m)	2.35
Inner diameter (m)	0.25
Air flow (kg/h)	3500
Velocity (m/s)	20.0
Temperature (K)	350
Coal dust concentration (kg/kg)	0.50
Plasma Generator	
Electric power (kW)*	100
Plasma gas	air
Mass flow (kg/h)	54
Inlet air temperature (K)	298
Outlet air temperature (K)	2800
Nozzle diameter 1 (m)	0.04
Nozzle diameter 2 (m)	0.06
Outlet velocity (m/s)	94.6

* at U =380 (V) and I = 300 (A)

The pulverised coal supplied to the burner is 'Tugnuiski' black coal, having some 60.5% of carbon and 35.6% of volatile matter. The composition and properties of test coal, and its particle size distribution are summarised in Table 4.

Figure 8 shows the predicted temperature contours along the burner axial direction and in the symmetry plane. It can be seen that the plasma jet temperature dissipates rapidly as the mass flow of plasma gas (54 kg/h) is significantly smaller than the mass flow of the main stream (3500 kg/h). By deflecting the plasma jet in the direction of the main cross flow, the penetration of the plasma jet in the radial direction is reduced, also reducing the region of plasma flame interaction with the coal particles. It may be concluded that the plasma flame acts as an ignition source, similar to the electric spark found in internal combustion engines. Furthermore, the contribution of radiative heat transfer (coming from surrounding walls and coal particles), and the contribution of convective heat transfer (coming from flue gases) play the important role.

Table 4. The specification of Tugnuiski coal

Tablica 4. Specifikacija Tugnuiski ugljena

TUGNUISKI COAL		
Proximate analysis (wb)	mass %	Particle size distribution*
Moisture	2.80	D = 160 μm 5 %
Volat. matter	35.6	D = 130 μm 15 %
Fixed carbon	42.7	D = 74 μm 20 %
Ash	18.9	D = 50 μm 40 %
Ultimate analysis (wb)	mass %	D = 24 μm 20 %
Carbon	60.5	Lower calorific value: 23.0 MJ/kg
Hydrogen	4.10	
Nitrogen	1.20	
Sulphur	0.40	Coal feed rate: 1750 kg/h
Oxygen	12.1	

* assumed particles size distribution (mass %)

The measured and predicted temperature profiles at the outlet from the plasma burner can be seen in Figure 9.

Generally, the temperature profile is in good agreement with measured data. Some discrepancies are evident on the left side of the graph, which could be related to the quality of the measurements (non-symmetric data).

Further discrepancies are evident in the centreline region, showing some over predictions of the temperature level. These may be related to the possible underestimation of the plasma jet penetration depth into the cross-flow stream.

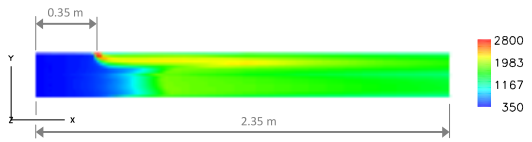

Figure 8. Temperature contours at the plasma jet symmetry plane

Slika 8. Temperaturna polja u ravnini simetrije s plazma plamenom

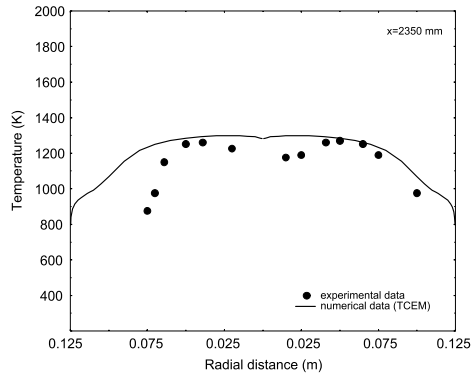

Figure 9. Temperature contours at the plasma jet symmetry plane

Slika 9. Temperaturna polja u ravnini simetrije s plazma plamenom

The predicted profiles for species concentrations are given in Figure 10. It can be seen that the concentration of CO has reached some 25%, while CO_2 around 7%. The concentration of H_2 (1.2%) was over-predicted while CH_4 is nearly zero. Generally, it could be concluded that the simulations give satisfactorily predictions of species concentrations, especially of carbon monoxide.

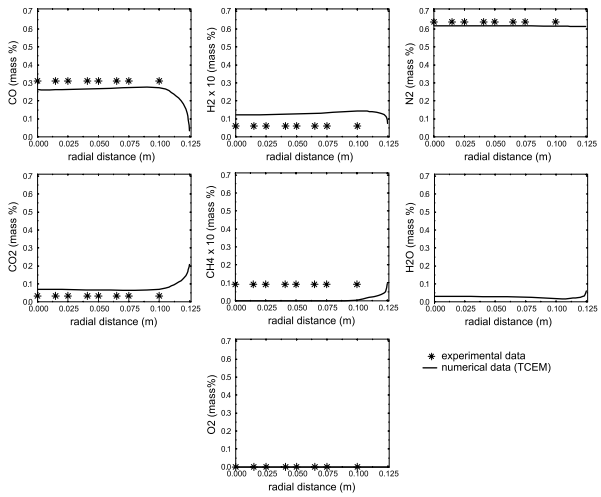

Figure 10. Radial species concentration profiles at the exit of the plasma burner

Slika 10. Koncentracija plinova u radijalnom smjeru na izlazu iz plazma plamenika

4. Experimental study

An experimental plasma reactor shown in Figure 11 is developed in RDP-Almaty (Kazakhstan) [15]. The experimental equipment is conceived to investigate the process of pulverised coal gasification in plasma conditions, with special emphasis on the composition of the product gas and the conversion degree of coal as a function of operational conditions. The experimental concept involves the direct injection of pulverised coal particles into the plasma generator, which is in this case a cylinder with an inserted graphite rod electrode. The input power supplied to this laboratory-scale reactor may be varied within the range 30 to 100 kW, the pulverised coal feed rate from 3 to 12 kg/h, while the gaseous reagent mass flow from 0.5 to 15 kg/h.

The pulverised coal particles are directly injected into the region of electric arc formation, where particles experience higher temperatures and increased residence times, achieved by placing a diaphragm at the outlet from the plasma reactor. Coal particles completely release their volatiles within the plasma reactor volume, while further reactions of volatile gases and residual carbon depend on the operational conditions. The remaining particulate phase is separated from the gaseous phase, which may be then further treated and purified after the outlet from the installation.

Different operational conditions could be attained by supplying the air or water vapour into the reactor or by manipulating the feed rate of reactants. Finally, by regulating the electric power supply to the plasma generator, different temperature levels may be achieved within the reactor (higher than 5000 K), affecting the extension and the intensity of chemical reactions of pulverised coal.

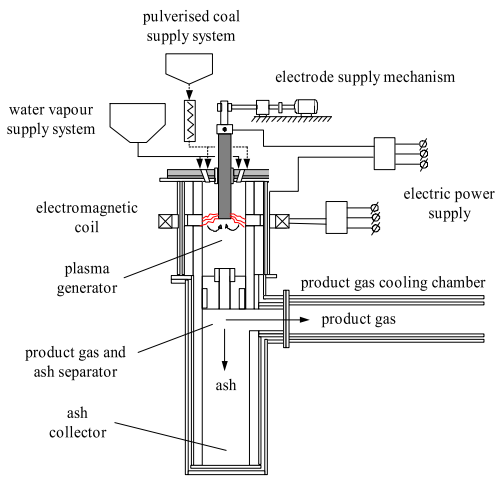

Figure 11. Laboratory-scale plasma reactor [9]

Slika 11. Laboratorijski plazma reaktor

A respectable amount of data has been collected from a number of experimental tests, comprising a variety of coals and operating conditions of plasma reactor [15 and 16].

Generally, it was observed that during the gasification of pulverised coals with water steam supply, the produced gas was mainly formed of CO and H_2, around 90-95% vol., with smaller amounts of N_2, CO_2 and CH_4. The concentrations of NO_x and SO_x were usually insignificant [9].

During the gasification with air supply, the concentration of CO and H_2 was diluted due to the existence of molecular nitrogen coming from the air. In most of the experiments, the product gas was formed of CO and H_2 (25-35% vol.), and N_2 (around 65% vol.), with small additions of CO_2 and CH_4. The concentrations of NO_x and SO_x were dependent on nitrogen and sulphur contents of the parent coal and the available oxygen.

Table 5. The example of experimental results for air-gasification

Tablica 5. Primjer eksperimentalnih rezultata za plinifikaciju u atmosferi zraka

Air Gasification, Exp. No. 2	
G coal (kg/h)	4.0
G air (kg/h)	4.7
μ (kg/kg)	0.85
P (kW)	60
η (%)	50
Section 4	
H_2 (vol. %)	/
O_2 (vol. %)	/
CO_2 (vol. %)	/
N_2 (vol. %)	/
CO (vol. %)	/
$CO+H_2$ (vol. %)	/
Section 6	
H_2 (vol. %)	8.8
O_2 (vol. %)	0.1
CO_2 (vol. %)	5.5
N_2 (vol. %)	64.6
CO (vol. %)	21.0
$CO+H_2$ (vol. %)	29.8
Temperature (K)	2313
Gasification (%)	/

During the experimental program, a small portion of the product gas was separated from the main flow at the outlet from the cooling chamber. To demonstrate its combustibility, the product gas (synthesis gas) was ignited by the electric spark. The test flame is shown in Figure 12.

Figure 12. Pilot flame of the produced gas

Slika 12. Pilot plamen proizvedenog sintetskog plina

5. Closure

The specific application of plasma systems in coal-fired power plants have been briefly elaborated, while some of the operational data numerically and experimentally presented. As already mentioned, the presented plasma system is already applied in coal-fired power plants proving its technical and economic benefits [8, 17, 18 and 19].

Apart from coal combustion, plasma systems have found their important role in waste treatment technology, where various industrial and municipal wastes [20] are treated by plasma. This technology has already been proposed as a possible solution to increasing problems related to storage, treatment and land filling of wastes.

The waste materials used for incineration or gasification in industrial-scale applications include the municipal solid waste, auto shredder residue, industrial liquid and solid wastes, sludge, biomass and so on.
Significant work on gasification of wastes using plasmas has been carried out by number of companies, such as 'Westinghouse Plasma Corporation' [21] and "Advanced Plasma Power [22], through construction of commercial plants worldwide. More details on operating plants could be found on corresponding web pages.

Plasma systems have found their application in pollution control technology as well, where for example products of combustion are treated in post combustion stage by thermal or non-thermal plasmas [23].
Other applications of plasma systems include the production of basalt fibres used for the manufacturing of basalt filaments for heat and sound insulation materials [10].

In all of the above mentioned applications plasma has proved as reliable and feasible technology. The application of plasma systems is expected to increase in the future. Some of the reasons could be found in special characteristics of plasma's flame when compared with "standard" flames. These include higher temperature levels and oxidising or non-oxidising conditions, ease of application, flexibility, low inertia and time required to achieve the operational conditions, etc.

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Investigation of surface roughness of aluminium alloy and brass using experimental design

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Abstract: In this paper, the results of surface roughness investigation for the face milling of aluminium alloy and brass using two types of cutting tools (high speed steel tool and tool with cutting inserts), have been presented. By the application of central composite design and statistical analysis of experimental data, regression models have been developed to predict the surface roughness relating to the three quantitative factors (depth of cut, feed rate and number of revolutions) and one qualitative factor (material type), for the machining with certain type of tool. Also, for each level of qualitative factor (aluminium alloy and brass), and for each tool, regression models have been developed to predict surface roughness as a function of three numerical factors. For the machining with the first type of tool a significant quadratic regression model with nonsignificant lack of fit has been developed. Statistical analysis of experimental data of machining with the second type of tool, gives the linear model with two factor interactions.

Istraživanje hrapavosti površine aluminijske legure i mjedi pomoću eksperimentalnog dizajna

Izvorni znanstveni rad

Sažetak: Predmet istraživanja ovog članka je statističko modeliranje hrapavosti obrađene površine pri obradi aluminijske legure i mjedi čeonim glodanjem, korištenjem dvije vrste alata (brzorezni čelik i alat s pločicama od tvrdog metala). Primjenom centralno kompozitnog plana pokusa i statističkom obradom rezultata pokusa, dobiveni su regresijski modeli za procjenu vrijednosti hrapavosti u ovisnosti o tri numerička, odnosno kvantitativna faktora (dubina rezanja, posmak i broj okretaja) i jednom kvalitativnom faktoru (vrsta materijala), za obradu pojedinom vrstom alata. Također, za svaku razinu kvalitativnoga faktora, odnosno za svaki materijal, dobiveni su, pri obradi određenom vrstom alata, statistički modeli za predviđanje hrapavosti u ovisnosti o tri kvantitativna faktora. Za obradu prvom vrstom alata, dobiven je kvadratni regresijski model. Statistička obrada rezultata pokusa obrade drugim alatom, dala je linearni regresijski model s interakcijama dva faktora.

1. Introduction

Surface roughness is a very important indicator of surface quality and therefore there is a wide interest of many researchers to study and model as well as optimize this property. Furthermore, by the optimisation of input variables influencing the surface roughness, much savings can be achieved. Thus, many different approaches to investigation of surface roughness can be found. Very often, experimental investigations with the main aim of deriving regression models as well as optimisation are performed, by the use of different approaches of design of experiments methodology (factorials, different response surface methods and designs, Taguchi design,…). Recently, the methods of artificial intelligence (especially neural networks and genetic algorithms) are used frequently and compared to experimental data. Response surface methodology (RSM) is used by the following authors: Fuh and Wu [1] studied the face milling of Al alloy concerning the tool geometry and machining parameters; Wattanutchariya and Pintasee [2] investigated the face milling of Al, brass and steel by varying the number of revolutions and feed rate; Mansour and Abdalla [3] investigated surface roughness of face milled steel EN32; Wang et al. [4] studied the influence of machining parameters on surface roughness of face milled brass using a milling machine of small power; Al alloy Al6061-T6 is investigated by Kadirgama et al. [5, 6] using the carbide tool inserts – apart from RSM methodology, Radial Basis Function Network method is used; RSM methodology and neural networks are used by Soleymani and Khorram [7] in studying the optimal machining parameters with the main aim of decreasing the roughness and increasing the amount of

Symbols/Oznake

a	- depth of cut, mm - dubina rezanja	**Greek letters/Grčka slova**	
s	- feed rate, mm/min - posmak		- the distance of the axial runs from the design center
n	- number of revolutions, rev/min - broj okretaja	α	- udaljenost aksijalnih stanja od središnje razine

material removed; Oktem et al. [8, 9] optimised machining parameters of face milled Al and polymer by combining the RSM methodology, neural networks and genetic algorithm. Optimisation of the process of machining Al by the use of Taguchi method is performed in the paper of Moshat et al. [10, 11]. The methods of the artificial intelligence are used in the following investigations too: Lou and Chen [12] studied the influence of number of revolutions, feed rate and depth of cut on surface roughness of face milled Al by means of neural networks; Dweiri et al. [13] and Palani and Natarajan [14] also used neural networks to model surface roughness of face milled Al; genetic programming is used by Brezocnik et al. [15] to predict surface roughness of face milled Al6061considering the vibrations too; Čolak et al. [16] also used the evolutionary programming method.

Regarding the machining parameters in face milling process, feed rate, number of revolutions, depth of cut, type of cooling, vibrations, tool wear, tool diameter [17] and many others are taken into the consideration. The properties of workpiece material are also considered by Sivarao et al. [18]. Kopač and Krajnik [19] studied the milling of Al alloy and analysed machining parameters with the main aim of optimisation of cutting forces, surface roughness and increasing of productivity. High profitability and increased quality of high speed cutting of light metals aluminium and magnesium is proved by Cus et al. [20] who claimed that the quality of surface roughness was approximately the same as for grinding. The surface roughness is affected by many controlled process parameters (including cutting speed, depth of cut and feed rate) and uncontrolled process parameters (cutting conditions, material properties of tool and workpiece, workpiece quality, tool geometry, tool machine vibrations, tool wear etc.) that are difficult to achieve and continuously monitor [21, 22].

The main aim of this study is to derive regression models, by varying the feed rate, depth of cut and number of revolutions for two types of face milled materials (aluminium alloy and brass) machined with two different tools (high speed steel tool and tool with cutting inserts).

2. Experimental details and results

For this study, two types of materials are used - rolled aluminium alloy EN AW-6061 (ultimate tensile strength 115 MPa, hardness 30 HB) and rolled brass EN CW614N (ultimate tensile strength 600 MPa, hardness 175 HB), which chemical composition is shown in Tables 1 and 2. A small power vertical CNC milling machine, type PC Mill 55 was used for the experimental machining. Its technical characteristics are as follows: maximal power - 750 W, maximal spindle speed - 3500 rev/min and maximal feed rate - 2000 mm/min.

Table 1. Chemical composition of Al alloy EN AW-6061(AlMg1SiCu)

Tablica 1. Kemijski sastav aluminijske legure EN AW-6061 (AlMg1SiCu)

Chemical Element/ Kemijski element	Al	Cr	Cu	Fe	Mg	Mn	Si	Ti	Zn
wt. (%)/ Težinski udio (%)	97,4	0,3	0,2	0,1	1,0	0,1	0,6	0,1	0,2

Table 2. Chemical composition of brass EN CW614N (CuZn39Pb3)

Tablica 2. Kemijski sastav mjedi EN CW614N (CuZn39Pb3)

Chemical Element/ Kemijski element	Cu	Pb	Zn	Ni	Fe	Sn	Al	Other/ Ostalo
wt. (%)/ Težinski udio (%)	58,35	3,1	37,2	0,3	0,5	0,3	0,05	0,2

For the experimental procedure, two tools are used: a high speed steel milling cutter of diameter 40 mm, HSS Mayestag ∅40×32×16 N3074-Q45 with 6 cutting edges (Figure 1) and the tool WALTER F4042.B.040.Z04.15 (Figure 2) with four cutting inserts ADMT160608R-F56 WKP35S. The tools are preset and measured before use, on a measuring machine Zoller Venturion 800 so that all the cutting edges are the same height.

Figure 1. Tool 1 HSS Mayestag ∅40×32×16 N3074-Q45

Slika 1. Alat 1 HSS Mayestag ∅40×32×16 N3074-Q45

Surface roughness measurements were performed by the contact type device Talysurf Surtronic duo (commercial name) using a 5 μm diamond tip with 200 mg stylus load. For this kind of device, the diamond stylus is moved across the peaks and valleys of the surface to be measured. The main principle is the transformation of mechanical movement into an electrical signal which is digitised and processed so the average value of surface roughness R_a can be obtained (among others).

From the standpoint of terminology of designed experiments the following can be determined:

- Four input variables (design factors): material type (categorical factor), depth of cut, feed rate and number of revolutions, respectively (numerical factors)
- One output variable (response): surface roughness.

Since the rotatable central composite design is chosen (with α=1,68179), the three numerical factors have 5 levels at which runs will be made, while the categorical factor, that is material, has two levels (aluminium alloy and brass). In Table 3, the coded and actual (in brackets) values of factors are presented. In Tables 4 and 5 the results of performed central composite design of experiment are shown.

Figure 2. Tool 2 WALTER F4042.B.040.Z04.15

Slika 2. Alat 2 WALTER F4042.B.040.Z04.15

By the statistical analysis of experimental data for the first tool (Table 4), the following descriptive parameters are obtained: the mean surface roughness is equal to 4,96 μm, minimum and maximum surface roughness amount to 0,52 μm and 7,11 μm, respectively. Standard deviation amounts to 1,67 μm. By the statistical analysis of experimental data for the second tool (Table 5), the following descriptive parameters are obtained: the mean surface roughness is equal to 0,418 μm, minimum and maximum surface roughness amount to 0,14 μm and 0,65 μm, respectively. Standard deviation amounts to 0,152 μm.

Table 3. Coded (actual) values of factor levels

Tablica 3. Kodirane (stvarne) vrijednosti razina faktora

Factor/ Faktor	Coded (actual) values of factor levels/ Kodirane (stvarne) vrijednosti razina				
A (*a*)	-1,68179 (0,13)	-1 (0,30)	0 (0,55)	1 (0,80)	1,68179 (0,97)
B (*s*)	-1,68179 (32,96)	-1 (50,00)	0 (75,00)	1 (100,00)	1,68179 (117,04)
C (*n*)	-1,68179 (329,55)	-1 (500,00)	0 (750,00)	1 (1000,00)	1,68179 (1170,45)
D		-1 (Al alloy)		1 (Brass)	

Table 4. The results of performed experiment with tool 1

Tablica 4. Rezultati pokusa korištenjem alata 1

Standard Order/ Broj uzorka	Run/ Broj pokusa	Factor 1 A: Depth of cut (mm)/ Faktor 1 A: Dubina rezanja (mm)	Factor 2 B: Feed rate (mm/min)/ Faktor 2 B: Posmak (mm/min)	Factor 3 C: Number of revolutions (rev/min)/ Faktor 3 C: Broj okretaja (o/min)	Factor 4 D: Material/ Faktor 4 D: Materijal	Average surface roughness R_a (μm)/ Aritmetička sredina hrapavosti R_a (μm)
7	1	0,30	100,00	1000,00	Aluminium alloy	6,19
35	2	0,55	75,00	750,00	Brass	5,81
30	3	0,97	75,00	750,00	Brass	4,97
26	4	0,80	50,00	1000,00	Brass	2,63
38	5	0,55	75,00	750,00	Brass	6,30
40	6	0,55	75,00	750,00	Brass	5,42
4	7	0,80	100,00	500,00	Aluminium alloy	6,70
17	8	0,55	75,00	750,00	Aluminium alloy	5,81
28	9	0,80	100,00	1000,00	Brass	5,47
18	10	0,55	75,00	750,00	Aluminium alloy	5,85
9	11	0,13	75,00	750,00	Aluminium alloy	5,86
39	12	0,55	75,00	750,00	Brass	4,58
32	13	0,55	117,04	750,00	Brass	6,33
20	14	0,55	75,00	750,00	Aluminium alloy	5,21
25	15	0,30	50,00	1000,00	Brass	2,78
29	16	0,13	75,00	750,00	Brass	5,32
14	17	0,55	75,00	1170,45	Aluminium alloy	2,75
16	18	0,55	75,00	750,00	Aluminium alloy	5,76
8	19	0,80	100,00	1000,00	Aluminium alloy	5,82
3	20	0,30	100,00	500,00	Aluminium alloy	7,11
15	21	0,55	75,00	750,00	Aluminium alloy	6,21
33	22	0,55	75,00	329,55	Brass	5,03
23	23	0,30	100,00	500,00	Brass	4,85
34	24	0,55	75,00	1170,45	Brass	3,43
31	25	0,55	32,96	750,00	Brass	1,94
11	26	0,55	32,96	750,00	Aluminium alloy	0,52
27	27	0,30	100,00	1000,00	Brass	4,94
5	28	0,30	50,00	1000,00	Aluminium alloy	1,15
19	29	0,55	75,00	750,00	Aluminium alloy	6,18
12	30	0,55	117,04	750,00	Aluminium alloy	6,97
13	31	0,55	75,00	329,55	Aluminium alloy	6,11
1	32	0,30	50,00	500,00	Aluminium alloy	6,25
2	33	0,80	50,00	500,00	Aluminium alloy	5,14
10	34	0,97	75,00	750,00	Aluminium alloy	5,76
36	35	0,55	75,00	750,00	Brass	5,72
22	36	0,80	50,00	500,00	Brass	5,06
24	37	0,80	100,00	500,00	Brass	5,74
37	38	0,55	75,00	750,00	Brass	4,52
21	39	0,30	50,00	500,00	Brass	5,27
6	40	0,80	50,00	1000,00	Aluminium alloy	0,83

Table 5. The results of performed experiment with tool 2

Tablica 5. Rezultati pokusa korištenjem alata 2

Standard Order/ Broj uzorka	Run/ Broj pokusa	Factor 1 A: Depth of cut (mm)/ Faktor 1 A: Dubina rezanja (mm)	Factor 2 B: Feed rate (mm/min)/ Faktor 2 B: Posmak (mm/min)	Factor 3 C: Number of revolutions (rev/min)/ Faktor 3 C: Broj okretaja (o/min)	Factor 4 D: Material/ Faktor 4 D: Materijal	Average surface roughness R_a (μm)/ Aritmetička sredina hrapavosti R_a (μm)
23	1	0,30	100,00	500,00	Brass	0,65
39	2	0,55	75,00	750,00	Brass	0,53
22	3	0,80	50,00	500,00	Brass	0,63
10	4	0,97	75,00	750,00	Aluminium alloy	0,52
29	5	0,13	75,00	750,00	Brass	0,51
4	6	0,80	100,00	500,00	Aluminium alloy	0,40
38	7	0,55	75,00	750,00	Brass	0,45
1	8	0,30	50,00	500,00	Aluminium alloy	0,14
2	9	0,80	50,00	500,00	Aluminium alloy	0,36
19	10	0,55	75,00	750,00	Aluminium alloy	0,28
34	11	0,55	75,00	1170,45	Brass	0,47
15	12	0,55	75,00	750,00	Aluminium alloy	0,31
8	13	0,80	100,00	1000,00	Aluminium alloy	0,39
13	14	0,55	75,00	329,55	Aluminium alloy	0,32
40	15	0,55	75,00	750,00	Brass	0,57
30	16	0,97	75,00	750,00	Brass	0,61
7	17	0,30	100,00	1000,00	Aluminium alloy	0,14
17	18	0,55	75,00	750,00	Aluminium alloy	0,19
18	19	0,55	75,00	750,00	Aluminium alloy	0,37
28	20	0,80	100,00	1000,00	Brass	0,44
26	21	0,80	50,00	1000,00	Brass	0,44
11	22	0,55	32,96	750,00	Aluminium alloy	0,23
31	23	0,55	32,96	750,00	Brass	0,39
6	24	0,80	50,00	1000,00	Aluminium alloy	0,58
36	25	0,55	75,00	750,00	Brass	0,54
16	26	0,55	75,00	750,00	Aluminium alloy	0,29
21	27	0,30	50,00	500,00	Brass	0,54
20	28	0,55	75,00	750,00	Aluminium alloy	0,42
24	29	0,80	100,00	500,00	Brass	0,58
5	30	0,30	50,00	1000,00	Aluminium alloy	0,18
37	31	0,55	75,00	750,00	Brass	0,62
12	32	0,55	117,04	750,00	Aluminium alloy	0,32
14	33	0,55	75,00	1170,45	Aluminium alloy	0,26
35	34	0,55	75,00	750,00	Brass	0,54
27	35	0,30	100,00	1000,00	Brass	0,59
33	36	0,55	75,00	329,55	Brass	0,52
25	37	0,30	50,00	1000,00	Brass	0,41
9	38	0,13	75,00	750,00	Aluminium alloy	0,15
32	39	0,55	117,04	750,00	Brass	0,59
3	40	0,30	100,00	500,00	Aluminium alloy	0,25

3. Analysis of variance

The statistical analysis, as well as randomization, is carried out by the use of the licensed software Design Expert (version DX8, 8.0.7.1, Stat-Ease, Inc. Minneapolis, 2010). The results of the Analysis of variance for the full regression model (tool 1) are shown in Table 6. Expression (1) shows the reduced regression model in terms of coded factors (see the Table 3 for the values of coded factors) for the first tool. Expressions (2) and (3) show the reduced models in terms of natural factors for the first level of qualitative factor – material type (aluminium alloy), and for the second level of

qualitative factor – material type (brass), respectively, for the first tool (see the Table 3 for the values of natural factors). Figure 3 shows 3D graph of the reduced model for the aluminium alloy for the first tool.

Table 6. ANOVA for the full regression model, tool 1

Tablica 6. Analiza varijance za regresijski model, alat 1

Source/ Izvor varijacije	Sum of squares/ Suma kvadrata odstupanja	Degress of freedom/ Broj stupnjeva slobode	Mean square/ Srednje kvadratno odstupanje	F value/ Vrijednost F varijable	p value/ Vjerojatnost F varijable
Model/ Model	100,3208185	13	7,716986037	25,70971002	< 0,0001
A-Depth of cut/ B-Dubina rezanja	0,134665551	1	0,134665551	0,448648249	0,5089
B-Feed rate/ B-Posmak	47,23932309	1	47,23932309	157,3813004	< 0,0001
C-Number of revolutions/ C-Broj okretaja	22,2690885	1	22,2690885	74,19111621	< 0,0001
D-Material/ D-Materijal	0,9211225	1	0,9211225	3,068787769	0,0916
AB	0,3721	1	0,3721	1,239678684	0,2757
AC	0,016469444	1	0,016469444	0,054869173	0,8166
AD	0,294037292	1	0,294037292	0,979606997	0,3314
BC	9,5481	1	9,5481	31,81020168	< 0,0001
BD	4,157863034	1	4,157863034	13,85222837	0,0010
CD	3,017764095	1	3,017764095	10,05390439	0,0039
A^2	$6{,}97138E\cdot10^{-5}$	1	$6{,}97138\cdot10^{-5}$	0,000232257	0,9880
B^2	8,547030721	1	8,547030721	28,4750653	< 0,0001
C^2	4,739069845	1	4,739069845	15,78856187	0,0005
Residual/ Ostatak	7,80411902	26	0,300158424		
Lack of fit/ Odstupanje od modela	4,608228279	16	0,288014267	0,901201858	0,5886
Pure error/ Pogreška	3,195890741	10	0,319589074		
Total/ Ukupno	108,1249375	39			

$$R_a = 5{,}61 + 1{,}32 \cdot B - 0{,}9 \cdot C - 0{,}15 \cdot D + 0{,}77 \cdot B \cdot C - 0{,}39 \cdot B \cdot D + 0{,}33 \cdot C \cdot D - 0{,}54 \cdot B^2 - 0{,}41 \cdot C^2 \quad (1)$$

$$R_a = 2{,}75244 + 0{,}10617 \cdot s - 0{,}00448330 \cdot n + 0{,}000123600 \cdot s \cdot n - 0{,}000871040 \cdot s^2 - 0{,}00000648537 \cdot n^2 \quad (2)$$

$$R_a = 2{,}79555 + 0{,}074954 \cdot s - 0{,}00182415 \cdot n + 0{,}000123600 \cdot s \cdot n - 0{,}000871040 \cdot s^2 - 0{,}00000648537 \cdot n^2 \quad (3)$$

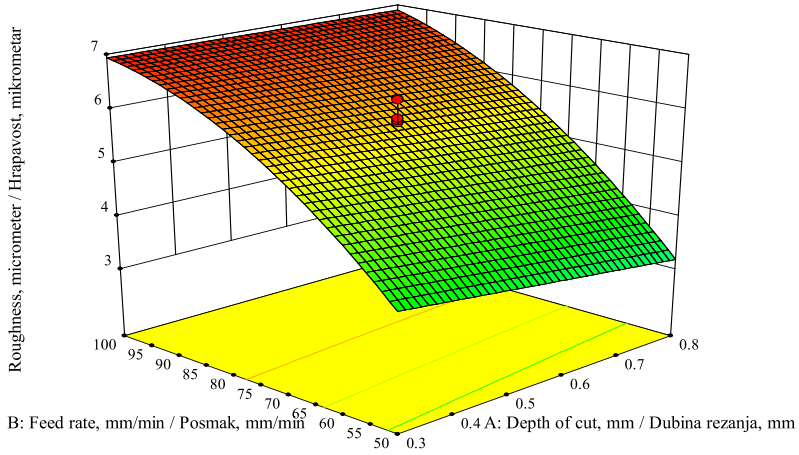

Figure 3. Response surface of the regression model, aluminium alloy, number of revolutions 750 rev/min, tool 1

Slika 3. Odzivna ploha za regresijski model, aluminijska legura, broj okretaja 750 o/min, alat 1

The results of the Analysis of variance for the full regression model (tool 2) are shown in Table 7. Expression (4) shows the reduced regression model in terms of coded factors (see the Table 3 for the values of coded factors) for the second tool. Expressions (5) and (6) show the reduced models in terms of natural factors for the first level of qualitative factor – material type (aluminium alloy), and for the second level of qualitative factor – material type (brass), respectively, for the second tool (see the Table 3 for the values of natural factors). Figure 4 shows 3D graph of the reduced model for the brass for the second tool.

Table 7. ANOVA for the full regression model, tool 2

Tablica 7. Analiza varijance za regresijski model, alat 2

Source/ Izvor varijacije	Sum of squares/ Suma kvadrata odstupanja	Degress of freedom/ Broj stupnjeva slobode	Mean square/ Srednje kvadratno odstupanje	F value/ Vrijednost F varijable	p value/ Vjerojatnost F varijable
Model/ Model	0,789071	10	0,078907	20,30728682	< 0,0001
A-Depth of cut/ A-Dubina rezanja	0,106411	1	0,106411	27,38549247	< 0,0001
B-Feed rate/ B-Posmak	0,015678	1	0,015678	4,034816474	0,0540
C-Number of revolutions/ C-Broj okretaja	0,011876	1	0,011876	3,056379489	0,0910
D-Material/ D-Materijal	0,514534	1	0,514534	132,4187325	< 0,0001
AB	0,020544	1	0,020544	5,287252833	0,0289
AC	0,001225	1	0,001225	0,315262101	0,5788
AD	0,089826	1	0,089826	23,11725953	< 0,0001
BC	0,004011	1	0,004011	1,032286789	0,3180
BD	0,009506	1	0,009506	2,446334435	0,1286
CD	0,015461	1	0,015461	3,979051562	0,0555
Residual/ Ostatak	0,112684	29	0,003886		
Lack of fit/ Odstupanje od modela	0,066586	19	0,003505	0,760229979	0,6829
Pure error/ Pogreška	0,046098	10	0,00461		
Total/ Ukupno	0,901755	39			

$$R_a = 0{,}41758333 + 0{,}06241689 \cdot A + 0{,}02395817 \cdot B - 0{,}0208519 \cdot C + 0{,}11341667 \cdot D - 0{,}0358333 \cdot A \cdot B - \\ - 0{,}0573469 \cdot A \cdot D - 0{,}023792 \cdot C \cdot D \quad (4)$$

$$R_a = -0{,}2765086 + 0{,}90905518 \cdot a + 0{,}00411166 \cdot s + 0{,}000011761 \cdot n - 0{,}0057333 \cdot a \cdot s \quad (5)$$

$$R_a = 0{,}34540331 + 0{,}45027992 \cdot a + 0{,}00411166 \cdot s - 0{,}0001786 \cdot n - 0{,}0057333 \cdot a \cdot s \quad (6)$$

When comparing the first and second tool, there is a larger difference between the maximum and minimum value of surface roughness for aluminium than brass. By the use of tool 1 (high speed steel) for the machining of aluminium alloy there is the highest range between maximum (7,11 μm) and minimum surface roughness (0,52 μm). For the machining of aluminium alloy by the use of tool 2, the lowest surface roughness (0,14 μm) is obtained for the depth of cut of 0,3 mm, feed rate of 100 mm/min and the number of revolutions of 1000 rev/min. Better surface roughness is achieved by the use of tool 2.

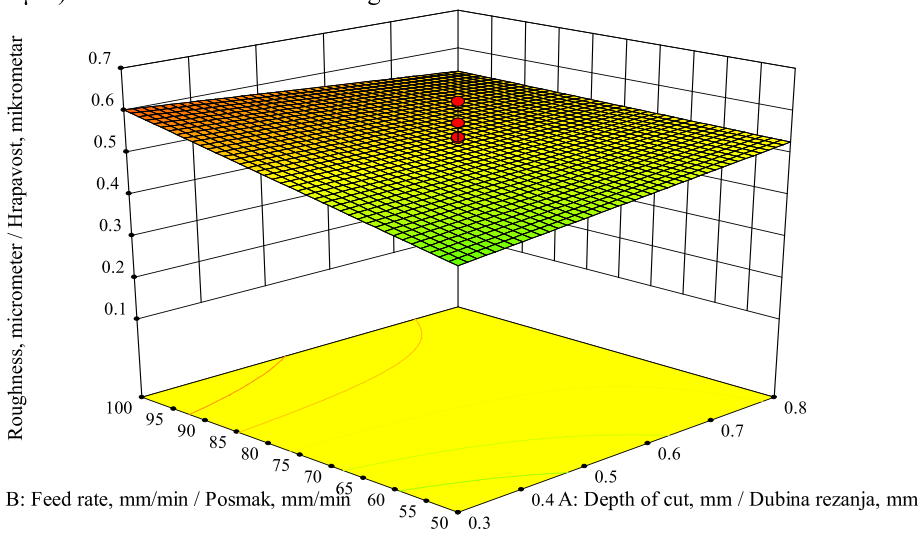

Figure 4. Response surface of the regression model, brass, number of revolutions 750 rev/min, tool 2

Slika 4. Odzivna ploha za regresijski model, mjed, broj okretaja 750 o/min, alat 2

4. Conclusion

For the machining with the first type of tool (high speed steel), a quadratic regression model with a coefficient of determination 0,928 (original model) and 0,89 (reduced model) is obtained. Significant terms of the model are feed rate, number of revolutions, the interaction of the linear feed rate with the number of revolutions, the interaction of the linear feed rate with material type, the interaction of the linear number of revolutions with material type together with quadratic effects of feed rate and the number of revolutions. Nonsignificant factors are the depth of cut and material type and all the remaining terms. Lower surface roughness can be achieved by the lower feed rate and higher number of revolutions.

From the statistical analysis of experimental data for the machining with the second type of tool (with inserts), a linear model with two factor interaction is derived. Coefficient of determination is equal to 0,875 for the original model, or 0,83 for the reduced model. The terms of the model: depth of cut, material type, the interaction of the linear depth of cut with the feed rate and the interaction of the linear depth of cut with the material type are significant. Nonsignificant terms of the regression model are as follows: feed rate, number of revolutions, the interaction of the linear depth of cut with the number of revolutions and the interaction of the linear feed rate with the number of revolutions and material type as well as the interaction of the linear number of revolutions with the material type. However, it should be noted that the probability of the F value for the factor feed rate which amounts to 0,054 (Table 7) is very near to the probability of the type I error (0,05). Therefore it is possible that slightly different results of surface roughness would give different value of F variable probability. Consequently, we can conclude that the feet rate might be significant term in the model. The same statements may apply for the interaction of the linear number of revolutions with the material type. When taking into account the hierarchy of the model, the previously mentioned terms are already included.

From the regression models for specific materials for the machining with the second tool, it is evident that the roughness of aluminium is lower than the roughness of the brass.

The further research will include application of some other methods of the surface roughness prediction as well as the optimisation of machining process.

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Optimization of cutting parameters in three axis surface milling

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Abstract: A correctly designed machining process can substantially affect overall production cost. In this article, intention is mainly focused on the determining the cutting parameters in three axis surface milling required to minimize the cutting time and at the same time maintaining an acceptable quality level of the workpiece with complex geometry. Experimental data will be obtained by performing the experiments, according to the adopted plan of experiments, in a virtual environment, i.e. experiments will be simulated on the computer software package CATIA. To determine the optimal cutting parameters, a cutting time equation has to be formulated to correlate the cutting parameters with the cutting time. The cutting time equation is formulated as an objective function in the form of mathematical programming. The problem is usually subjected to constraints for design variables and to inequality and equality constraints for process outputs, such as surface roughness and physical capacities of the machine tool.

Optimiranje parametara obrade kod troosnog oblikovnog glodanja

Vrsta članka

Sažetak: Pravilan odabir operacija u procesu obrade može znatno utjecati na ukupne troškove proizvodnje. U ovom članku, namjera je odrediti parametre obrade u troosnom oblikovnom glodanju koji će osigurati najkraće vrijeme obrade i istovremeno zahtijevanu kvalitetu obrađene površine. Eksperimentalni podaci će se dobiti, prema usvojenom planu pokusa, izvođenjem eksperimenata u virtualnom okruženju, tj. eksperimenti će biti simulirani na računalu u softverskom paketu CATIA. Nezavisne veličine u jednadžbi koja modelira vrijeme rezanja su parametri rezanja. Jednadžba za predviđanje vremena izrade formulirana je i kao funkcija cilja u postupku optimizacije, u matematičkom programiranju. Problem optimizacije se najčešće primjenjuje na granične uvjete ulaznih varijabli i na izlazne veličine procesa izražene kao jednadžbe ili nejednadžbe kao što su fizičkim sposobnostima alata i alatnog stroja te hrapavost obrađene površine.

1. Introduction

Finding optimum machining strategies in surface machining is a widely researched problem and certainly has many aspects such as: determination of regions to be cut, allocation of tool path strategies to each of them, selection of cutting conditions and selection of tools. Common criteria for evaluating the optimum machining conditions are: machining time, machining costs, surface quality, machining errors and other output process's variables. Surface quality is more often expressed as cusp height, and machining errors as shape deviation from the ideal. The above mentioned issues need to be considered at the same time, which would make the optimization problem quite complex. Optimization techniques that have been used in this context include integer and dynamic programming, genetic algorithms, simulated annealing etc. Although the importance of using optimal cutting parameters was identified in the early 1900s, advances in the development of optimisation strategies have been very slow, since the problem is too complex due to the nonlinear dependence of machining variables [1].

There are several different types of methods which are used in metal cutting processes such as statistical regression [2, 3], arificial neural network [4] Taguchi method [5], response surface design methodology [6], genetic algorithm for computer numerically controlled (CNC) milling and multi-pass turning [7].

Tool making and mould production tehnology became a key aspect in product inovation because of wide scale application of design features based on formed and free-form surface. Software development, computer aided design (CAD) and computer aided manufacturing (CAM) products, programming and controlling of

machine tools as well as advanced metal cutting tools represent main driving forces associated with mould

Symbols/Oznake

Ra	- average surface roughnes, µm - srednje aritmetičko odstupanje profila	X_i, X_j	- the coded values of input parameters - kodirane vrijednosti ulaznih parametara
Rmax	- maximal surface roughness, µm - najveća visina profila	w_i	- weighted factors - težinski faktori
f	- feed, mm/rev - posmak	*CT*	- cutting time, min - vrijeme obrade
n	- spindle speed, min^{-1} - frekvencija vrtnje glavnog vretena	*CT**	- target numerical value, min - ciljna numerička vrijednost
r_ε	- tool nose radius, mm - radijus zaobljenja alata	*Ra**	- target numerical value, µm - ciljna numerička vrijednost
$b_0, b_i\ b_{j...}$	- regression coefficients - regresijski koeficijenti		

making in various industrial sectors. The production of formed and free form surfaces by milling has replaced non traditional technologies such as electro-discharge machining and electro-chemical machining. This is important because mentioned non traditional technologies have a high power consumption rate.

The methodology proposed in this paper, was applied on surface milling process of moulds which are used for servo cover producing. Methodology includes the following steps: determining of cutting time equation using response surface methodology and finding the optimal cutting parameters for surface machining. The optimization is based on the two popular criteria: minimum cutting time and satisfactory surface quality. In this paper, optimization analysis, strategy and CAM software module for the selection of economic cutting conditions in surface milling on computer numerically controlled machine tools are outlined.

2. Machining time

Machining is set of processes or operations in which excess material is removed from a starting workpiece by a sharp cutting tool so the remaining part has the desired geometry and the required shape. One of the important aspects in manufacturing calculation is how to find and calculate the machining time in a machining operation. Machining or cutting time is dependent on the length of cutting materials, the feed rate, the cutting speed, the depth of cut, the tool diameter and percentage of tool diameter engagement.

Some researchers have been determined cutting time based on known analytical functions. But, it is difficult to define these functions in a number of practical applications of machining complex geometry workpieces. In this sense, CATIA V5R19, module Surface Machining, was used to predict the underlying cutting time.

Three axis surface machining is a new generation product that defines and manages NC programs. It is dedicated to the machining of 3D geometry workpieces with 3-axis machining techniques. It is particularly adapted to the needs of mould, die and tool makers and prototype manufacturers in all branches and at all levels of industry [8].

3. Surface roughness

The quality of a component is often associated with its surface aspect and appearance. However, this can be misleading in the sense that the surface may contain features that are not reflected in its appearance. Beyond aspect, a machined surface may contain imperfections and deviations from the nominal expected surface that compromise the quality of the component. Hence, it is necessary to clearly define a measure of surface roughness. Surface roughness is defined as the irregularities of any material resulting from machining operations. There are many parameters for characterizing surface roughness, but the most used measure in industry is roughness average, *Ra*. An acceptable quality level, that should be no more than the maximum surface rougness, *Rmax* is defined with following equation:

$$Ra \leq Rmax \quad (1)$$

and

$$Ra \approx 0.032 \frac{f_t^2}{r_\varepsilon} [11, 12] \quad (2)$$

- f - feed rate [mm/rev]
- r_ε – tool nose radius [mm]

4. Response surface methodology

Cutting time has been modelled using response surface methodology. The method consists of a set of statistical and mathematical techniques that are useful for the modelling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response. The first step of RSM is to find a suitable approximation for response using a second-order polynomial in some region of the

independent variables. Experimental design for fitting surface response is a rotatable central composite design (RCCD). The RCCD models the response using the empirical second-order polynomial:

$$y = b_0 + \sum_{i=0}^{k} b_i X_i + \sum_{1 \le i \le j}^{k} b_{ij} X_i X_j + \sum_{i=1}^{k} b_{ii} X_i^2 \qquad (3)$$

where:

- b_0, b_i, b_{ij}, b_{ii} - are the regression coefficients,
- X_i, X_j - the coded values of input parameters.

Based on the RSM results, the designer engineer can select the critical process controllable factors for reducing the variation in quality level significances.

The goal of RSM is to determine the prediction function in the system and apply this function in optimization process.

5. Optimization technique

The machining process optimization can be defined as constrained, nonlinear programming problem. The general form of machining process optimization is presented as:

Optimize (minimize or maximize):

$$f(X), \quad X \in F_s, \quad X = \{x_1, x_2, \ldots, x_n\} \qquad (4)$$

Subject to constraints:

- physical constraints, the boundaries of independent variables $x_i min \le x_i \le x_i max$
- constraints expressed as inequality and equality:

$$g_j(X) \ge 0, \quad j = 1,2,....,k$$

$$h_j(X) = 0, \quad j = 1,2,....,m$$

where

- $f(X)$ - objective function for the design problem,
- X - n-dimensional design vector, the subject of optimization,
- F_s - a space of satisfactory solutions.

Objective functions are used to evaluate a design solution within the optimization context. The number of objective functions, their nature and whether they are separable determines the complexity of the optimization task.

In real life most of the optimization problems are multi-objective, i.e. they are often composed of several partial objectives that individually do not have a common optimum at the same point. Unified criterion of excellence solutions and integrated objective function is formed by combining the partial set of criteria. In this paper the optimization is performed by using the sum of "weighted" criteria with weights w_i that show the relative importance of each criterion in the overall excellence:

$$f(x) = \sum w_i f_i(x), \quad \sum w_i = 1, \quad w_i > 0 \qquad (5)$$

6. Practical application of the described methodology

Practical application of the described methodology was performed with cutting time minimization of the finish milling operations for the geometrical solid parts shown in figure 1. Surface roughness had to meet a required level.

The geometrical solid model of the parts which present two-parts mould was defined in a part design module according to the CAD model of the servo cover, shown in figure 1.

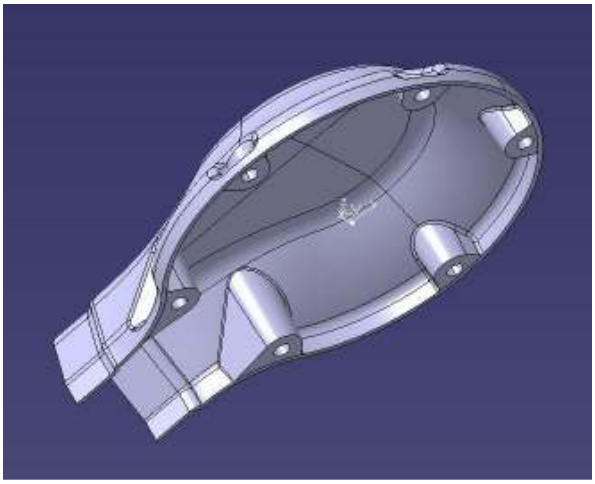

Figure 1. CAD model
Slika 1. CAD model

Two-parts mould, figure 2, for producing servo cover are obtained in *Surface design* CATIA module, using function such as *Offset*, *Fill* and *Thick Surface Definitions*. For the purpose of facilitated extraction of the model from the mould, all vertical surfaces are inclined at an angle of 3 degrees. Dimension of the each part is 100×100×40 mm. Manufacturing program for moulds machining consists of three operations: roughing, finishing and profile contouring. Roughing was performed so as to remove the greater amount of material in the shortest possible time. The subject of optimization is finishing because of the obtaining the required surface quality in minimum cutting time. Profile contouring was performed as last operation to achieve mentioned inclination.

An operation where the tool progressively follows the part surface at different constant Z values (heights) is *Z-level* operation which is commonly used for finishing in three axis machining operations. This operation is performed by means ball-end mill. Tool geometry included a nominal diameter of 6 mm, overall length of 100 mm, measuring cutting length of 10 mm.

The technology of the tool included two flutes, right-hand rotation, and the tool material was a hard metal (HM). The tool path was helical.

The surface quality of plastic product produced in plastic injection moulding is greatly affected by that of the mould parts obtained from the milling process. The surface quality of these products is associated with surface roughness of moulds. For quality consideration, the required surface roughness is less than 0.60 µm.

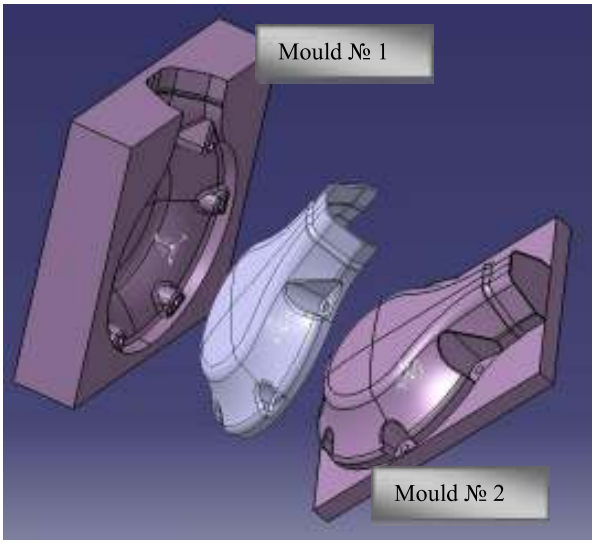

Figure 2.Two-parts mould and the model
Slika 2. Dvodijelni kalup i model

The parameters influencing the cutting time are the feed rate and cutting speed, i.e. spindle speed and these parameters have been called controllable factors in the following analysis. Depth of cut and percentage of tool diameter for a given part were defined via scallop height on the machined surface and they remain constant throughout the experiment.
Hence, two-factorial RCCD of experiment demands 4 experiments (2 factors on two levels, 2^2), 5 experiments on the average level and 4 experiments on the central axes, which makes total of 13 experiments.
In this study the region of interest for the spindle speed and feed rate are 8000 do 10600 min^{-1} and 0.10 to 0.20 mm/rev, respectively. The original values of cutting parameters as well as their coded values are given in Table 1.
Cutting time was simulated using module Surface machining in CATIA V5R19 following the suggestion from figure 3.

Table 1. Physical and coded values of input factors

Tablica 1. Fizičke i kodirane vrijednosti ulaznih faktora

Physical parameters	n (min^{-1})	7461	8000	9300	10600	11138
	f (mm/rev)	0.08	0.10	0.15	0.20	0.22
Coded parameters		-1.4142	-1	0	1	1.4142

Instead of real physical experiments performed on real machine tool, the present approach used virtual experiment with CATIA software, and also is not restricted to any particular geometric shape. The number of experimental runs, which can be reduced by other experiment plan, like Taguchi method, is less important for the present approach because these experiments do not consume time and material resources needed for real experiment. The cutting time equation and ranking importance for any geometric configuration can be obtained before the process is actualized. This mean that proposed approach is suitable for off-line applications.
With reference to response surface analysis, the approximate prediction function of the cutting time was for mould labelled with number 1:

$$CT_1 = 270.29101 - 0{,}01785 * n - 1321.54058 * f + \\ +4.128624 * 10^{-7} n^2 + 2256.75 * f^2 + \\ +0.033538 * n * f \qquad (6)$$

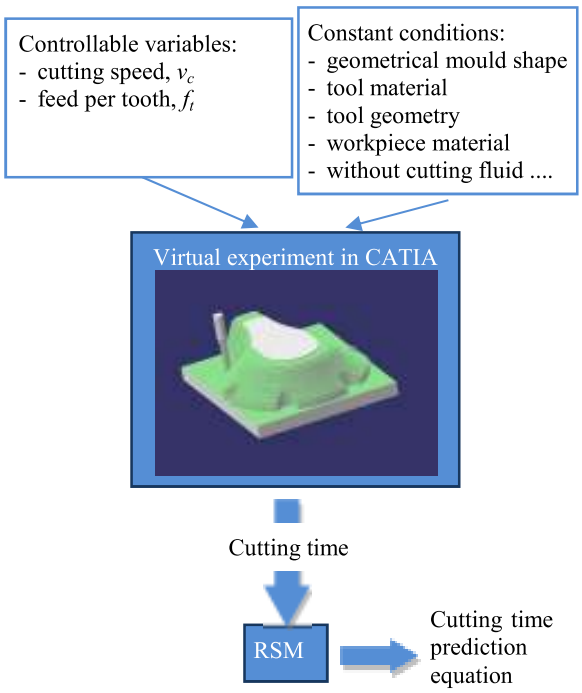

Figure 3. Experiment in virtual environment
Slika 3. Eksperiment u virtualnom okruženju

The goal of optimization, in this work, is to determine the optimum cutting parameters to achieve the minimum unit machining time with satisfactory surface roughness. According to the Eq. (5), the problem is mathematically formulated as follows:
Minimize:

$$f(x) = w\frac{CT}{CT^*} + (1-w)\frac{Ra}{Ra^*} \qquad (7)$$

where

- w is weighted factor, $0 \leq w \leq 1$,
- CT^* is target numerical value, cutting time,
- Ra^* is target numerical value, surface roughness.

Constraints of cutting parameters were determined with respect to workpiece and tool material. Target numerical values, CT^* and Ra^* have been obtained minimizing the actual function equation (6), presented below and using required quality level, respectively.

Multi-objective approach, the genetic algorithm (GA) based on the evolution of members of the population, was used to find the optimal solution. The members of the population are vectors of independent variables. Number of population is determined arbitrarily provided that the minimum recommended number of members of the population equals the number of independent variables. A greater number of members of the population means a greater likelihood of finding the global extreme of the objective function. During the performance of GA, population size is constant. Initial population is the population with which GA begins with the work, and it is randomly generated.

The GA requires the solution from the population counting individual goodness, and the objective function. If no individual is good enough, then genetic operators to generate new populations would be applied over the population. After a certain number of completed generations the process stops, and the best member of the current population represents a solution that should be close to optimum. Conditions for completing the evolutionary process are: a solution that meets the objective function has reached a predetermined number of generations or a predetermined time duration of the procedure has been found, there is no improvement in results achieved solutions with the highest degree of kindness or a combination of the above.

Planning and optimization process is important in building the economic and quality viability of surface milling as a possible replacement for the non-traditional technologies such as electro-discharge machining and electro-chemical machining parts with complex geometry. The optimum machining parameters will be determined for following values of GA parameters: population size – 100, the number of generations – 100, the probability of crossing – 0.75, mutation probability – 0.01, two–point crossover, tournament selection size – 5. Minimization of the fitness function, Eq. (6), is subjected to the boundaries of cutting condition. The same priority has been chosen for both minimal cutting time and surface roughness function.

7. Results and discussion

Unlike the conventional approach, the critical cutting parameters were justified statistically with importance rankings and jointly with multiple objectives in the presented approach. If improved cutting operations are needed, these critical parameters must be closely monitored and considered a high priority for enhancement. Consequently, a global and robust optimal solution for quality improvement and cost reduction could be reached in the presented approach. The dimensional accuracy and surface finish of any manufacturing process have become critical because of increased quality demands. There are various factors which influence on the surface finish in milling, and hence, the development of models helps us better understand the machining process. To obtain practical predictive quantitative relationships, it is necessary to model the milling responses. In the present work, the mathematical models were developed on the basis of the results achieved in virtual experiments. The experimental results were used to model the cutting time using response surface methodology. The significance of the parameters on the response in the model could be found using analysis of variance (ANOVA). In this work, the software package Design Expert was used for the computation of the regression of constants and parameters. Hence, this model would be used in optimization using genetic algorithms. Optimization of machining parameters enhances not only the economics of machining, but also the product quality to a great extent. The convergence of genetic algorithm is shown in figure 4.

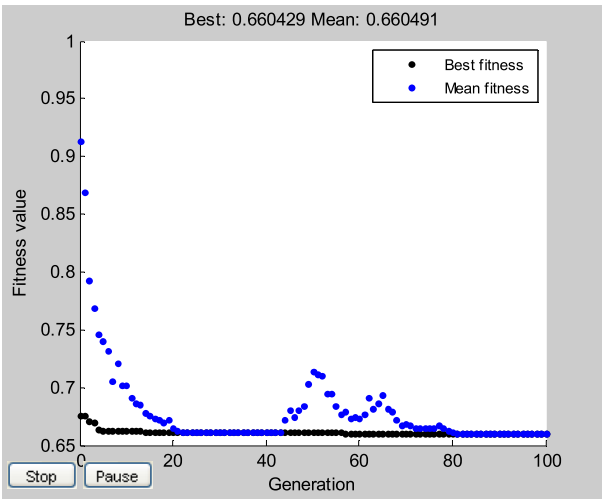

Figure 4. The convergence of GA
Slika 4. Konvergencija GA

The optimal values of the above formulation are shown in Table 2.

The same described methodology has been performed for the machining of the mould labelled with number 2.

Table 2. Optimal values obtained by means GA

Tablica 2. Optimalne vrijednosti dobivene pomoću GA

	Mould № 2
Symbol	Value
n [min^{-1}]	11101.99

f [mm/rev]	0.086
Ra [μm]	0.32
CT [min]	27.70
FC	0.660429

8. Conclusions

The need for a method to determine optimal parameters for the cutting operation process has become increasingly important. The present study developed a computer model which incurred minimal cutting time of the cutting process with the aid of the statistical method, RSM, and the optimization technology, GA. This study used CATIA software to generate experimental data and cutting time, followed by RSM to find the cutting time prediction equation and the critical cutting parameters. Then, cutting time equations, process capability ranges, and surface roughness conditions were formulated into mathematical programming collectively. The example of cutting the two-parts mould was presented in this study.

The result demonstrated that a minimal production time which maintains quality could be achieved for the cutting process in the early stages of design.

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Izbor optimalnog postrojenja i mogućnosti iskorištenja vodnog potencijala malog vodotoka za gradnju održive mHE

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Keywords

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Ključne riječi

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održiva gradnja
mini hidroelektrana

Stručni rad

Sažetak: Potencijali malih vodotokova u Bosni i Hercegovini su slabo iskorišteni. Ideje o izgradnji mini hidroelektrana se aktuelizirala, od kako je otkupna cijena električne energije iz obnovljivih izvora, uključujući i mini hidroelektrane, veća od otkupne cijene električne energije iz fosilnih goriva. Ovakva otkupna cijena je definisana dosadašnjim Uredbama a što će uskoro biti i potvrđeno Zakonom o obnovljivim izvorima energije.
Međutim, vrlo je važno za inžinjersku praksu i društvo u cjelini, odrediti isplativost iskorištenja malih vodotokova za proizvodnju električne energije. Održivost projekata izgradnje mini hidroelektrana zavisi od odnosa očekivane dobiti od proizvedene električne energije i troškova izgradnje i eksploatacije i održavanja postrojenja. Kroz pregled do sadašnjih teoretskih i praktičnih dostignuća u izgradnji mini hidroelektrana, predstavit će se mogućnosti primjene ovih dostignuća u implementaciji novih postrojenja, primjenom efikasnih tehnika koji su na granici najmanje isplativih proticaje za izgradnju mini hidroelektrana. Postrojanje najmanjih isplativih proticaja za gradnju mini hiroelektrana, će se eksperimentalno obraditi bar na četiri lokacije datog primjera malog vodotoka. Pogodnim modelom se treba omogućiti praktični proračun hidroenergetskog iskorištenja i odabir opreme mini hiroelektrana. Analizom ranijih podataka o proticajima odabranog vodotoka u poređenju sa rezultatima novih mjerenja, koji su rađeni u vrijeme izrade ovog rada, doći će se do zaključka o izboru optimalnog postrojenja i mogućnostima održive gradnje mini hidroelektrana na odabranom vodotoku.

Selection of the optimal plant and possible exploitation of the water potential of small streams in a profitable mini hydro power plant

Professional article

Abstract: The potential of small rivers in Bosnia and Herzegovina are underutilized. The idea of building a mini hydro power plant raised the issue, since the purchase price of electricity from renewable sources, including mini hydro power plant, is higher than the purchase price of electricity from fossil fuels. Such purchase price is defined in the previous Regulations which will soon be confirmed by the Law of renewable energy resources. However, it is very important for the civil engineering practice and society in general to determine the feasibility of utilization of small streams for the electric power generation. Sustainability mini hydropower construction projects depend on the relationship of the expected profit from the electricity produced and the cost of construction and operation and maintenance costs. Through a review of the current theoretical and practical advances in the construction of mini-hydro power plant, will be presented the possibilities of application of these achievements in the implementation of new systems, by using efficient techniques that are on the border of the least cost-effective of flow to build mini hydro power plant. Plant of smallest units less feasible flow for the construction of mini-hydro power plant, will be experimentally handle at least on the four locations of given examples of a small stream. Suitable model should allow practical calculation of hydropower equipment selection and utilization of mini-hydro power plant. Analysis of earlier data on discharges selected streams in comparison with the results of new measurements were performed at the time of this study, there will be a conclusion on the optimal plant and opportunities of sustainable building mini hydro power plants on the selected stream.

1. Uvod

Iako je slabo iskorištenje vodnih potencijala na cijelom prostoru Bosne i Hercegovine, vidljiv je velik broj lokacija za koje još nema zainteresovanih investitora, a na kojima je kroz ranije studije predviđena mogućnost gradnje ovih postrojenja. Uvođenjem diferenciranih otkupnih cijena električne energije, pokušava se potencijalni investitor zaineresovati za izgradnju mini hidroelektrana. I pored veće otkupne cijene električne energije iz obnovljivih izvora, potencijalni investitori nisu u očikivanoj mjeri zaineresovani za izgradnju ovih postrojenja. Postoji više razloga koji utiču na izuzetno spor razvoj izgradnje pogona za iskorištavanje obnovljivih izvora energije. Od ekonomskih mogućnosti potencijalnih investitora, preko pravnih i administrativnih uslova, do legislative koja male proizvođače električne energije (umreživač) postavlja u položaj kom su unaprijed uslovljeni neodrživi zahtjevi. Vjerovatno bi se komplesnijim istraživanjem kroz kontakte sa potencijalnim investitorima, u svim segmentima investiranje, moglo doći, makar, do približnog odgovora na pitanje; zašto budući investitori radije ulažu u izgradnju tržnih centara ili razvoja lanca sportskih kladionica nego u poljoprivrednu prizvodnju ili izgradnju pogona za iskorištavanje obnovljivih izvora energije? Određivanje optimalne granice isplativosti iskorištenja malih vodnih potencijala za proizvodnju električne energije, ima višestruko značenje. Za inženjersku praksu je uvijek novi izazov, iznalaženje optimalnih rješenja. Za društvo u cjelini pored toga što se snižava ekonomska vrijednost izgradnje, odnosno zaduženja, smanjuje se vremenski period povrata sredstava, što može da znači i smanjenje koncesionog perioda. U svakom slučaju, održivost projekata izgradnje mini hidroelektrana je u direktno proporcionalnom odnosu prema očekivanoj dobiti od proizvedene električne energije, troškova izgradnje, eksploatacije i održavanja postrojenja. Pod pretpostavkom da i pored diferencirane otkupne cijene električne energija, kojom je povoljnija otkupna cijena iz mini hidroelektrana nego iz pogona na fosilna goriva, zainteresovanost potencijalnih investitora je izuzetno mala za investiranje u ova postrojenja. Do ublažavanja, bar djelimično, uslova koji čine ove projekte ne održivim, moglo bi dovesti stvaranje povoljnih uslova kroz realizaciju pretpostavke kod koje izbor postrojenja sa optimalnim parametrima velikih raspona iskoristivog proticaja omogućuje održiv rad na minimalnom proticaju, čime se povećava broj radnih sati i ukupna očekivana godišnja proizvodnja, koja uz povoljnu otkupna cijena iz mini hidroelektrana daje dodatnu garanciju zainteresovanim investitorima za investiranje u ova postrojenja. Kod dokazivanja pretpostavki, korištena je metoda; čitanje javno publikovanih tekstova u Naučnim člancima, zvaničnim portalima nadležnih Ministarstava Vodoprivrede, Okoliša i Enervetike, Zakonima kao i intervjue sa potencijalnim investitorima. Nakon pregleda zvaničnih portala nadležnih Ministarstava Vodoprivrede, Okoliša i Enervetike, potvrđeno je da je tek 20-tak izdatih Odobrenja ili podnijetih Zahtjeva za korištenje vodnih potencijala za proizvodnju električne energije. S obzirom na ranije donijetu odluku o diferenciranoj otkupnoj cijeni električne energija, jasno je da postoji drugi razlog slabe zainteresovanosti za gradnju mini hidroelektrana. Utvrdili smo da su neki investitori naišli na administrativne probleme u toku ishođenja potrebnih Saglasnosti. U nekim sredinama su nevladina udruženja za brugu o okolišu, kao glavni cilj postavile odbojnost prema gradnji hidroenergetskih postrojenja, ističući svoju listu mogućih problema, po kojoj su ova postrojenja problem za okoliš. Upitno je koliko su njihovi ciljevi argumentovani ili su u suprotnosti sa globalnim ciljevima većeg iskorištenja obnovljivih izvora energije? Ovu smetnju navodi investitor, «Alpaka sz» d.o.o. Tuzla, koji je bio zainteresovan za gradnju mHE Ujiča od 1 MW u Kladnju, za koji je «Elaborat hidrološke podloge za objekat mHE na rijeci Ujiči općina Kladanj radilo Javno preduzeća za vodoprivrednu djelatnost «Spreča» Tuzla, a hidrološka mjerenja radio Institut za hemijsko inžinjerstvo-Tuzla, d.d.p.o. (Sodaso, Holding), mjerenja protoka hidrometrijskim krilom «A.OTT – Kempten».

2. Osvrt na do sadašnja teoretska i praktična dostignuća u izgradnji mini hidroelektrana

2.1. Razvoj gradnje mHE

Prapočetci gradnje mHE polaze od 1883 godine i Sjeverne Irske, da bi danas u Evropi bilo više od 17.400 malih hidroelekrana ispod 10 MW. U globalnoj proizvodnji električne energije u svijetu, hidroelektrane učestvuju sa od 17 do 22 %, od čega mHE je od 2 do 3 %. U području iskorištavanja obnovljivih izvora energije, hidropotencijal učestvuje sa oko 80% udjela u ukupnoj proizvodnji iz obnovljivih izvora. Računa se da mali vodotoci imaju značajan potencijal koji u zemljama bivše Jugoslavije iznosi oko 14% ukupnog vodnog potencijala, koji je u do sadašnjem periodu iskorišten jako malo. Od svih sljednica bivše Jugoslavije, možda je Slovenija sa najvećim, ali ipak, još uvijek samo 27 % izgrađenih

mini hidroelektrana od ukupnog njihovog potencijala.[1]

2.2. Preporuke EU kroz Direktive parlamenta EU o Obnovljivim izvorima energije

Preporuke EU kroz Direktive parlamenta EU o Obnovljivim izvorima energije (Renewable energy); 2009/28/EC, 2003/30/EC i 2001/77/EC podstiču korištenja energije iz obnovljivih izvora. Očito je da u većini lokalnih zajednica ove preporuke nisu dovoljno jasno shvaćene te je i izuzetno slab razvoj postrojenja za korištenja energije iz obnovljivih izvora. Postoji rok koji je dala EU, prema kome sve članice moraju do 2020 godine smanjiti emisiju stakleničkih plinova. Neke zemlje iz okruženja, poput Slovenije, su pokrenulu razne fondove, ECO fond, kojima se podupiru i subvenciraju ekološki prihvatljivi projekati. Na ovaj način se uvodi novi termin „zelena energija", gdje se povoljnom otkupnom cijenom električne energije, podstiče ekološka svijest i pomaže u održavanju čistog i zdravog okoliša za budućnost.

Konkretno donijete preporuke se odnose na:

1. Direktiva 2009/28/EC Europskog parlamenta i Vijeća od 23. aprila 2009 o podsticanju korištenja energije iz obnovljivih izvora i izmjenama i naknadno ukidanju Direktive 2001/77/EC i 2003/30/EC (Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC)
2. Direktiva 2003/30/EC Europskog parlamenta i Vijeća od 8. maja 2003 o podsticanju korištenja biogoriva ili drugih obnovljivih goriva za prijevoz (Directive 2003/30/EC of the European Parliament and of the Council of 8 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport)
3. Direktiva 2001/77/EC Europskog parlamenta i Vijeća od 27. septembra 2001 na podsticanju električne energije proizvedene iz obnovljivih izvora energije u interno tržište električne energije (Directive 2001/77/EC of the European Parliament and of the Council of 27 September 2001 on the promotion of electricity produced from renewable energy sources in the internal electricity market)

Slijedeći preporuke EU jasmo je da bi trebao biti puno veći intenzitet izgradnje pogona za proizvodnju energije iz obnovljivih izvora.

Table 1. Example table of development planning construction mini hydropower plants in BiH

Tablica 1. Primjer tablice planiranog razvoja gradnje mini hidroelektrana u BiH, prema; [2]

	EP HZHB	EP BIH	ERS
Odnosilo se na planski period 2005-2008			
Planirana ukupna instalirana snaga u malim hidroelektranama	oko 40 MW	oko 34 MW, Turboinštitut (Slovenija) za 31 mHE, na vodotocima Neretvice i Ljute u Općini Konjic	oko 212 MW, na oko 160 lokacija, od čega je za oko 99 investitora odobrila koncesije za ukupno 102 lokacije malih HE
Planirana prosječna godišnja proizvodnja	oko 186 GWh	oko 127 GWh	oko 650 GWh
Trenutno u pogonu male hidroelektrane ukupne instalirane snage		23,7 MW (Una Kostela, Krušnica, Kanal Una, Modrac, Osanica, Hrid, Snježnica i Bogatići (28%))	14 MW (Vlasenica, Bogatići, Mesići, Tišća i Štrpci (mini HE))

2.3. Planirana postrojenja mHE u BiH

Prema podacima preuzetim iz [2], vidljivo je da Elektroprivreda RS ima za nekoliko puta veću planiranu ukupnu instaliranu snagu u malim hidroelektranama, odnosno planiranu prosječnu godišnju proizvodnju električne energije iz malih hidroelektrana, u odnosu na EP HZHB i EP BiH.

Dakle, s obzirom na prikazano, potencijal malih hidroelektrana u Bosni i Hercegovini predstavlja značajnu vrijednost, koju treba uvrstiti u planiranove razvoja elektroenergetskog sistema.U periodu do 2008 godine na prostoru EP BiH postoji 8 izgrađenih mHE, dok na prostoru EP RS postoji 5 malih i mini hidroelektrana, od čega je samo jedna u privatnom vlasništvu.

3. Mogućnosti primjene do sadašnjih teoretskih i praktičnih dostignuća u izgradnji mini hidroelektrana

Prema do sadašnjim istraživanjima osim rijeke Sane postoji bar pet njenih pritoka sa energetskim potencijalom koji bi budućim investitorima moga garantovati isplativost ulaganja u izgradnju mini hidroelektrana. Prema ovim podacima radi se o 15 lokacija i to na vodotocima: Bliha na 6 lokacija, Sanica na 3 lokacije, Dabar na 1 lokaciji, Kijevska rijeka na 2 lokacije i Sasina na 3 lokacije.

Table 2. Five streams with 15 locations of mini hydropower plants, which were discussed feasibility of construction, the size of specific investments, ie investments needed and possible annual production

Tablica 2. Pet vodotoka sa 15 lokacija budućih mini hidroelektrana, na kojima je razmatrana isplativosti izgradnje, prema veličini specifičnih investicija, odnosno, potrebnih investicija i moguće godišnje proizvodnje.[4]

			I	II	III	IV
B.r	mHE	Vodotok	Snaga (kW)	Proizvodnja u MWh/god	Investicije	II/III
1	Skok	Bliha	1356	4730	2414	0,51
2	Hatiraj	Bliha	1436	6536	4665	0,71
3	Pećina	Sanica	582	2765	1998	0,72
4	Kamengrad	Bliha	1591	7265	5883	0,8
5	Dabar	Dabar	645	2760	2662	0,96
6	Saleševići	Sanica	3338	11040	11422	1,03
7	Kljajići	Sanica	5897	16090	18473	1,15
8	Ljutovik	Bliha	1037	4837	7582	1,56
9	Kijevo 1	Kijevska rijeka	85	518	897	1,73
10	Kijevo 2	Kijevska rijeka	118	735	1427	1,97
11	Šumari	Bliha	95	491	996	2,03
12	Sasina 3	Sasina	83	452	1276	2,82
13	Sasina 1	Sasina	31	122	590	4,83
14	Sasina 2	Sasina	37	170	870	5,11
15	Skucani Vakuf	Bliha	45	153	1295	8,62

U Tabeli 2. su prikazani parametri na 15 lokacija sa 5 vodotoka na kojima će se graditi buduće mini hidroelektrana na općini Sanski Most.[4] Najveći odnos proizvodnje električne energije MWh/god i investicije je na lokaciji Skucani Vakuf na vodotoku Bliha, a najmanji odnos je o,51 na lokaciji Skok na vodtoku Bliha. Ukupna proizvodnja električne energije na ovih 15 mHE iznosila bi 58665 MWh/god.[3]

4. Primjena efikasnih tehnika na granici najmanje isplativih proticaje

Kod iskorištenja hidropotencijala koriste se već poznati tipovi turbina; Pelton, Francis, Kaplan i Bankijeve turbine. Vodene turbine su različitih oblika i položaja vodnog kola, prema čemu je i ostali dio turbine prilagođen vodnom kolu. Zbog ovih mehaničkih i njihove tehničke karakteristike se značajno razlikuju i svaki tip turbine ima optimalno opterećenje i učinke samo unutar određenog raspona. Kod svakog tipa turbine specifičnost uslova rada je uslovljena visinskom razlikom i količinom vode, odnosno brzine. Za male hidroelektrane se, najčešće, upotrebljavaju Pelton hidro turbine, dok za srednja i manja se upotrebljavaju Francis i Kaplan turbina, a za velika postrojenja, takođe, Pelton turbine. Turbina pogodna za male protoke i velike padove, u rasponu od 60 do 2000 metara je Pelton pogonska turbina čije je vodno kolo tangencijalno na tok. Ova turbina može biti: horizontalna i vertikalna.Turbine za srednje padove i od 2 do 200 metara i od 40 do 500 metara, su Francis, kod kojih je kretanje vode radijalno. Za velike protoke i male padove, do 70 metara, koristi se Kaplan turbina, koja je, zapravo, nadogradnja Francis turbine. Turbine koje su u performansama jednake Pelton turbinama su Bankijeve turbine. Kod Bankijeve turbine postoje značajna tehnička poboljšanja, tako da im je iskorištenost dostigla 68%. Učinak ovih turbina zavisi od promjene raspoložive vode, starosti i održavanja. Ove turbine u najboljim uslovima imaju iskorištenost 0,76 do 0,84 %, odnosno korisnu energiju. Do sadašnjim praktičnim i naučnim istraživanjem došlo je do značajnih poboljšanja kod izvedbe postrojenja hidroelektrana, tako da postrojenja koja se danas ugrađuju mogu odgovoriti svakom konkretnom zahtjevu po pitanju područja primjene i optimalnih cijena i vijeka trajanja.

5. Analiza odabira postrojenja, najmanjih isplativih proticaja, na četiri lokacije malog vodotoka

Za izračunavanja raspoloživih proticaja uzeti su podaci mjerenja na vodomjernoj letvi za desetogodišnji period osmatranja, kao i podaci aktuelnih kontrolnih mjerenja u vrijeme obrade podataka, kao i podataci o padavinama sa kišomjernih stanica na konkretnom slivnom području. Na osnovu ovih podataka određeni su srednji višegodišnji proticaji na vodotoku za osmatrani period.

5.2. Analitički empirijski model proračuna hidroenergetskog iskorištenja

Na osnovu raspoloživih podataka izračunavan je proticaj, na sljedeći način:

Qn(m³/s) = (Fn x Rn)/(Fp x Rp) x Qp

Gdje su:

Fp , Rp i Qp - slivna površina, padavine i proticaj referentnog profila
Fn , Rn i Qn - poznate slivne površine, poznate padavine i nepoznat proticaj profila

Na osnovu dobivenih podataka, za izracun se određuju koeficijenti za četiri unaprijed pretpostavljene lokacije, sa još četiri pretpostavljene opcije, od kojih se na kraju treba odabrati po jedna za svaku lokaciju.

5.3. Podaci za analizu mogućeg hidroenergetskog iskorištenja rijeke Sasina.

Oznake u tabeli imaju značenje:

Qsr-srednji godišnji proticaj na zahvatu (m^3/s) ,
Qi-instalisani proticaj (m^3/s) ,
Qisk-iskoristivi proticaj za datu instalaciju (m^3/s) ,
Hn-neto pad postrojenja (m^1) ,
Ni-instalisana snaga postrojenja (kW) ,
Egod-godišnja proizvodnja postrojenja (MWh).

Kod mHE-Sasina-1 ulazni parametri za analizu su;

Qsr=0,036 m^3/s
Dužina derivacionog cjevovoda, Ld=1350 m^1
Dužina tlačnog cjevovoda, Lt=105 m^1
Prečnik derivacionog cjevovoda, 300 mm
Prečnik tlačnog cjevovoda, 200 mm

oznaka	mjera	Opcije analize			
		1	2	3	4
Qi	m^3/s	0,018	0,036	0,054	0,072
Qisk	m^3/s	0,014	0,023	0,028	0,030
Hn	m^1	50,10	50,33	53,81	53,58
Turbina					
Ni	kW	7	14	23	31
Egod	MWh	52	89	113	122

Kod mHE-Sasina-2, ulazni parametri za analizu su;

Qsr=0,078 m^3/s
Dužina derivacionog cjevovoda, Ld=1800 m^1
Dužina tlačnog cjevovoda, Lt=120 m^1
Prečnik derivacionog cjevovoda, 400 mm
Prečnik tlačnog cjevovoda, 250 mm

oznaka	mjera	Opcije analize			
		1	2	3	4
Qi	m^3/s	0,039	0,078	0,117	0,156
Qisk	m^3/s	0,031	0,047	0,056	0,062
Hn	m^1	30,82	35,91	39,44	41,90
Turbina					
Ni	kW	10	22	37	52
Egod	MWh	77	135	170	191

Kod mHE-Sasina-3, ulazni parametri za analizu su;

Qsr=0,295 m^3/s
Dužina derivacionog cjevovoda, Ld=1900 m^1
Dužina tlačnog cjevovoda, Lt=130 m^1
Prečnik derivacionog cjevovoda, 600 mm
Prečnik tlačnog cjevovoda, 500 mm

oznaka	mjera	Opcije analize			
		1	2	3	4
Qi	m^3/s	0,150	0,300	0,450	0,600
Qisk	m^3/s	0,123	0,194	0,233	0,251
Hn	m^1	24,02	22,93	23,18	24,88
Turbina					
Ni	kW	29	54	83	118
Egod	MWh	218	359	452	503

Kod mHE-Sasina-4, ulazni parametri za analizu su;

Qsr=0,413 m^3/s
Dužina derivacionog cjevovoda, Ld=1750 m^1
Dužina tlačnog cjevovoda, Lt=70 m^1
Prečnik derivacionog cjevovoda, 600 mm
Prečnik tlačnog cjevovoda, 500 mm

oznaka	mjera	Opcije analize			
		1	2	3	4
Qi	m^3/s	0,210	0,410	0,620	0,820
Qisk	m^3/s	0,173	0,259	0,311	0,336
Hn	m^1	19,30	17,62	19,87	20,90
Turbina					
Ni	kW	32	57	98	136
Egod	MWh	243	367	469	517

Na osnovu odabranih opcija za svaku lokaciju se određuje optimalno postrojenje, prema raspoloživim parametrima turbina proizvođača koji je dostupan na

tržištu regiona. Kod ovog izračuna određene su lokacije za: mHE-1 na koti 292,00 m.n.m., odnosno visinskom razlikom od 60 metara i Qsr=0,078 m³/s; mHE-2 na koti 240,00 m.n.m., odnosno visinskom razlikom od 45 metara i Qsr=0,295 m³/s; mHE-3 na koti 210,00 m.n.m., odnosno visinskom razlikom od 30 metara i Qsr=0,388 m³/s; i mHE-4 na koti 180,00 m.n.m., odnosno visinskom razlikom od 22,5 metara i Qsr=0,484 m³/s. [2]

Figure 1. Satellite model sites watercourses Sasinka, BiH

Slika 1. Satelitski model lokaliteta vodotoka Sasinka, BiH

Analizom ranijih podataka o proticajima odabranog vodotoka u poređenju sa rezultatima novih mjerenja, koji su rađeni u vrijeme izrade ovog rada, došlo se do zaključka o izboru optimalnog postrojenja sa mogućom održivom gradnjom mini hidroelektrana na odabranom vodotoku. Prema dobijenim rezultatima, pregled karakterističnih parametara za izbor postrojenja izgleda kao u tabeli 3.

Table 3. Selection of installed flow for 4 mini hydro on the river Sasinka
Tablica 3. Izbor instalisanog proticaja za 4 mini hidroelektrane na vodotoku Sasinka, [3]

parametri	Jed.mj.	mHE-1	mHE-2	mHE-3	mHE-4
Srednji proticaj na profilu zahvata, Qsr	m³/s	0,036	0,078	0,295	0,413
Dužina derivacionog cjevovoda, Ld	m	1350	1800	1900	1750
Dužina tlačnog cjevovoda, Lt	m	105	120	130	70
Bruto pad postrojenja, Hb	m	60	45	30	22,5
Optimalni instalisani proticaj, Qopt=2Qsr	m³/s	0,072	0,117	0,450	0,410
Usvojeni instalisani proticaj, Qi=2Qsr	m³/s	0,072	0,117	0,450	0,410
Instalisana snaga postrojenja	kW	31	37	83	57
Godišnja proizvodnja el. energije	10³ kWh	122	170	452	367
Ukupne investicije	10³ KM	590	870	1276	1033
Specifične investicije	KM/kW	19032	23513	15373	18122
Specifične investicije	KM/kWh	4,83	5,11	2,82	2,81

Prema dobivenim podacima prizilazi da se održiva gradnja mHE postrojenja može očekivati na mHE-Sasina 3 i mHE-Sasina 4, dok je i dalje najnepovoljnije ulaganje u mHE-Sasina 2, gdje je specifična investicija čak 5,11 KM/kWh.

6. Zaključak

Iako je nadležna Elektroprivreda definisala diferencirane otkupne cijene električne energija, kojom je povoljnija otkupna cijena iz mini hidroelektrana nego iz pogona na fosilna goriva, zainteresovanost potencijalnih investitora je izuzetno mala za investiranje u ova postrojenja. Do ublažavanja, bar djelimično, uslova koji čine ove projekte ne održivim, moglo bi dovesti stvaranje povoljnih uslova kroz realizaciju pretpostavke kod koje izbor postrojenja sa optimalnim parametrima velikih raspona iskoristivog proticaja omogućuje održiv rad na minimalnom proticaju, čime se povećava broj radnih sati i ukupna očekivana godišnja proizvodnja, koja uz povoljnu otkupna cijena iz mini hidroelektrana daje dodatnu garanciju zainteresovanim investitorima za investiranje u ova postrojenja. Radi utvrđivanja mogućnosti gradnje samoodrživih postrojenja malih hidroelektrana na riječnom toku Sasinka analizirane su četiri lokacije. Duž vodotoka prolazi regionalna cesta R 405 Bihać – Banja Luka, koja je jednim dijelom asfaltirana dok je drugi dio pod makadamom i pristup svim lokacijama je mogluć sa ove ceste, izuzev samo mHE-1 do koje treba koristiti oko 300 metara poljskog puta. Ovako povoljna lokacija budućih mHE u odnosu na saobraćajnicu u startu garantuje racionalne troškove transporta materijala u toku gradnje, i održavanja u eksploataciji. Teren na kom se naliziraju ove lokacije je izgrađen od mezozojskih karbonatnih stijena krečnjaka i dolomita.[2] Na osnovu ovako građenog terena može se zaključiti da pruža znatnu nosivost i stabilnost kod temeljenja. Tamo gdje postoje tanje aluvijalno-deluvijalne raspadine, ista će se prije fundiranja zamijeniti nosivim materijalom. Inače, ni na jednoj od razmatranih lokacija nisu uočena mjesta sa tragovima klizišta. S obzirom na preporuke iz Direktiva EU i značajne energetske potencijale vodotoka kako u BiH tako i u Sanskom Mostu, izgradnja ovakvih postrojenja se odvija veoma sporo. U narednom periodu je neophodno otkloniti sve eventualne prepreke investiranju u obnovljive izvore energije. Nakon provedene analize za odabrane opcije mHE-Sasinka, prema dobivenim rezultatima održiva gradnja mHE postrojenja se može očekivati na mHE-Sasinka 3 i mHE-Sasinka 4, a najnepoljnije ulaganje je u mHE-Sasinka 2, gdje je specifična investicija čak 5,11 KM/kWh.

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Identifikacija uticajnih parametara na okoliš za gradnju održive mHE na osnovu istraženih karakteristika vodotoka

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Stručni rad

Sažetak: S ciljem smanjenja klimatskih promjena koje izazivaju staklenički gasovima nastali sagorijevanjem fosilnih goriva, Evropskim Direktivama su postavljeni ciljevi popularno zvane "20-20-20" do 2020. godine, kojima se promoviše korištenje savremenih tehnologija za kvalitetnije sagorjevanje fosilnih goriva i za korištenje Obnovljivih izvora energije. U preporukama Evropskih direktiva, posebno mjesto zauzima iskorištenje vodnih potencijala malih vodotokova primjenom savremenih tehnika. S obzirom na karakteristike postrojenja, u smislu najmanje instalisane snaga, i minimalnih srednjih godišnjih proticaja, odabranog vodotoka, kao i troškova izgradnje i održavanja u eksploataciji postrojenja, postoji sumnja da će se samo na nekim vodotocima moći graditi isplative mini hidroelektrane. U radu će se na konretnom primjeru odabranog vodotoka, identifikovati i analizirati uticajni parametri na okoliš za gradnju održive mini hidroelektrane na osnovu istraženih karakteristika vodotoka. U zaključku će se, na osnovu rezultata istraženog modela, dati preporuke za identifikaciju uticajnih parametra na okoliš za gradnju održive mini hidroelektrane.

Identification of the influential parameters on the environment to build profitable mini hydro power plants on the basis of the studied characteristics of the water streams

Professional article

Abstract: In order to reduce climate change caused by greenhouse gases produced by burning fossil fuels, European Directives have set goals popularly called "20-20-20" by 2020, which promotes the use of modern technology for better combustion and the use of renewable energy sources. In the recommendations of the European directive have a special place utilization of the water resources of small streams using modern techniques. Concerning the characteristics of the plant, at least in terms of installed power, and minimum mean annual flow, selected watercourse and the costs of construction and maintenance of plant operation, there is a suspicion that only in some streams can build cost-effective mini-hydro power plants. In this work will be focused on selected streams example, to identify and analyze the significant parameters of the environment for building profitable mini hydro power plants on the basis of the studied characteristics of the channel. The conclusion will be based on the results of the investigated models, make recommendations to identify influential parameters on the environment to build profitable mini-hydro power plant.

1. Uvod

Ranijom Studijom [3] izvršen je grubi izračun energetske iskorištenosti značajnijih vodotoka na općini Sanski Most. Od 9 vodotoka koji po kategorizaciji imaju naziv rijeka na rijeci Sani je planirana izgradnja HE Vrhpolje i HE Čaplje, dok je na drugih 5 manjih rijeka planirana izgradnja 15 mHE. Prema podacima iz regiona, o izgradnji mHE, cijena građenja se kreće oko 1500 €/kW, odnosno prema vrsti radova oko 70 % su građevinski, 20 % mašinski i 10 % elektro radovi. Prema ovim pokazateljima vrijednost investicije jedne mHE instalisane snage do 3 MW bi iznosila oko 4,5 miliona €. Kako su mHE; fleksibilne, komercijalno opravdane, lake za izgradnju, imaju niske troškove održavanja, dobre ekološke karakteristike, mogu služiti za pokrivanje potreba; lokalnog stanovništva i malih privrednih objekata na tom lokalitetu a uključivanjem u sistem mogu služiti i kao rezerva kod iznenadnih problema u mreži poput vršnih opterećenja i slično. S obzirom na niz nejasnoća koje se, objektivno, javljaju kod budućih investitora i projektanata, kroz ovaj osvrt će se bar donekle pokušati ukazati na neka jasnija objašnjenja i optimalnija rješenja.

2. Utjecaj gradnje mHE prema okolinskoj politici

2.1. Utjecaj gradnje mHE na životno okruženje

Kod izgradnje malih hidroenergetskih postrojenja bitne karakteristike uticaja na okruženje su; mala emisija štetnih plinova koja je ispod granice dopuštenih, ne ugrožavaju flori i faunu a za prirodnu pokretljivost riba grade se riblje staze, osiguravaju ekološki prihvatljiv proticaj, potpuno se uklapaju u sredinu tako da ne ugrožavaju kolturno i prirodno nasljeđe, spječavaju ugroženost od poplave kontrolisanim ispuštanje, voda koja je pokretala turbine se ponovno bez promjene vraća u prirodno korito, nivo buke koji iz mašinske zgrade dospijeva u okolnu sredinu je ispod dopuštenog i preporučenog nivoa, nemaju nepovoljan vizuelni efekat, tz., arhitektonsko onečišćenje, jer su u potpunostu uklopiti u pejzaž.

Table 1. Analysis the mini hydropower (mHP) living environment

Tablica 1. Analiza utjecaja mHE na životno okruženje

uticaji na okruženje	karakteristike uticaja
emisija štetnih plinova	ispod granice dopuštenih
flori i faunu	Ne ugrožava se ugrožavaju flori i faunu
pokretljivost riba	Za prirodnu pokretljivost riba grade se riblje staze
ekološki prihvatljiv proticaj	ekološki prihvatljiv proticaj određen Pravilnikom
kolturno i prirodno nasljeđe	Uklapanje mHE u sredinu ne ugrožavaju kolturno i prirodno nasljeđe
ugroženost od poplave	Spriječena ugroženost od poplave kontrolisanim ispuštanje
evakuacija voda koja je pokretala turbine	voda koja je pokretala turbine se ponovno bez promjene vraća u prirodno korito
nivo buke mašinske zgrade	nivo buke koji iz mašinske zgrade dospijeva u okolnu sredinu je ispod dopuštenog i preporučenog nivoa
arhitektonsko onečišćenje	Ne postoji nepovoljan vizuelni efekat, tz., arhitektonsko onečišćenje
uklopivost u pejzaž	Svi objekti su u potpunosti uklopiti u pejzaž

2.2. Očekivani godišnji prihod od prodaje smanjenja emisija CO2

Određivanje smanjenja emisije CO2, a procjenjuje se da je ta emisija oko 750 g/kWh. Na primeru ovih mHE, za godišnju proizvodnju od 1,111 GWh, odnosno za 4 postrojenja mHE Sasina (mHE-1=122 kWh*10³, mHE-2=170 kWh*10³,, mHE-3=452 kWh*10³, i mHE-4=367 kWh*10³,) ukupno smanjenje emisija CO2 bi bilo 1.111.000 (kWh) × 750 (g/kWh) = 833.250.000 grama, odnosno 833,250 tona CO2. Trenutna cjena smanjenja 1 tone emisije CO2 kroz CDM projekat je 4 €, [7], što bi za naš primer značilo da je ukupan prihod od prodaje smanjenja emisije CO2 ukupno 24.9975 € (0,3 €c/kWh). Iskazani izračun ima samo slikovito predstavljanje ekološki opravdanog projekta, naravno, ne očekuje se realizacija ovog izračuna na Berzi ni u skorijem realnom vremenu.

2.3. Analiza sljedivosti pristupa okolinskoj politici EP, kod gradnje mHE

Slijedom smjernica koje su donijete na globalnom nivou u vezi politike očuvanja životne sredine, nadležna EP je donijela Odluku o okolinskoj politici, kojom se daju osnovni okvirni parametri svim sudionicima od projektovanja do krajnjeg potrošača elaktrične energije za racionalno korištenje električne energije, kao i niz drugih prioriteta koji su u skladu sa načelima održivog razvoja i standardima zaštite okoline. Kroz tabelu se analizirala sljedivost pristupa okolinskoj politici EP, kod gradnje mHE, pri čemu su za svaku preporuku EP pridružen adekvatan odgovor, koji je proistekao iz analiziranja konkretnog slučaja.

Table 2. Analysis traceability approach the environmental policy EP, in the construction mHP

Tablica 2. Analiza sljedivosti pristupa okolinskoj politici EP, kod gradnje mHE

Prioriteti okolinske politike Elektroprivrede	Sljedivost pristupa okolinskoj politici EP, kod gradnje mHE
• Razvojni planovi programi i aktivnosti, usklađeni sa načelima održivog razvoja i standardima zaštite okoline.	Planiranje mHE locirati na mjestima ranijih vodenica, stupa ili drugih građevina na vodotoku koje se ne koriste.
• Optimizirano upravljanje okolinskim aspektima do okolinske prihvathisosti, odnosno do verifikacije okolinski prijateljskih djelatnosti u evropskom okruženju.	mHE graditi u blizini potrošača da bi se izbjegi nepotrebni transportni gubitci i isijavanja.
▪ Odgovorno i kontinuirano poduzimati organizacione i tehničke mjere sistematskog upravljanja i poticanja okolinskih aspekata djelatnosti te, u skladu sa tehno - ekonomskim mogućnostima peventivno pratiti učinke na okolinu, preventivnim i korektivnim mjerama smanjivati negativne uticaje.	Organizaciono ustrojiti mehanizam rada i nazora nad postrijenjem mHE, tako da se uz minimalan broj osoblja, obavlja optimalan rad i održavanje kao i peventivno praćenje učinaka na okolinu, preventivnim i korektivnim mjerama smanjivanja negativnih uticaje.
• U cilju ostvarivanja poslovnih i okolinskih rezultata, prioritetno će se vršiti;	
- edukacija, stručno osposobljavanje i konsultacije zaposlenika iz domena zaštite okoline,	Svakodnevno nadograđivati postojeća saznanja o zaštiti okoline, racionalnim postupanjem sa materijalima sa kojima se radi
• povećanje energetske etikasnosti (smanjenje gubitaka električne energije u distributivnoj mreži),	Blizina postrojenja mHE i distributivne mreže smanjuje gubitke električne energije u distributivnoj mreži,
okolinski zahtjevi u okviru projektovanja, održavanja i izgradnje (izbor najboljih raspoloživih tehnika (BAT) i tehnologija. te okolinski podobnih materijala i opreme),	U potpunosti će se raditi na implementaciji okolinskih zahtjeva u okviru projektovanja, održavanja i izgradnje (izbor najboljih raspoloživih tehnika (BAT) i tehnologija. te okolinski podobnih materijala i opreme),
procjena rizika i mogućih incidentnih uticaja na okolinu, planirunje i poduzimanje preventivnih, te eventualno sanacionih mjera radi zaštite stanovništva i okoline,	Planskom i periodičnom procjenom rizika i mogućih incidentnih uticaja na okolinu, radit će se na planirunju i poduzimanju preventivnih, te eventualno sanacionih mjera radi zaštite stanovništva i okoline,
upravljanje opasnim i otpadnim materijalima, uređajima i opremom, kao i njihovom zbrinjavanju ili ponovnoj upotrebi i reciklaži.	Vršit će se adekvatno upravljanje opasnim i otpadnim materijalima, uređajima i opremom, kao i njihovom zbrinjavanju ili ponovnoj upotrebi i reciklaži.
• Poslovna disciplina i nadzor te objektivno i transparentno izvještavanje o zaštiti okoline.	Propisanom poslovnom disciplinom i nadzorom, osigurat će se individualna i funkcionalna odgovornost za objektivno i transparentno izvještavanje o zaštiti okoline.

Mini hidroelektrane su po svojim osobinama; fleksibilne jer se mogu prilagoditi svakom uslovu na terenu, komercijalno opravdane jer imaju relativno mali otplatni period, lake za izgradnju jer ne zahtijevaju specijalne uslove ugradnje betona i drugog a cijena troškova održavanja je izuzetno niska i imaju adaptativne ekološke karakteristike jer se mogu idealno uklopiti u postojeći prirodni ambijent. Mini hidroelektrane mogu pokrivati potreba za električnom energijom lokalnog stanovništva, malih privrednih objekata, a kada se uključe u energetski sistem mogu služiti i kao rezerva kod iznenadnih problema u mreži kao što su vršna opterećenja i slično.

Figure 1. Satellite model sites watercourses Sasinka, BiH

Slika 1. Satelitski model lokaliteta vodotoka Sasinka, BiH

3. Energetska efikasnost mini hidroelektrana u dosadašnjem periodu i projekcija budućih aktivnosti,

Prema elementarnoj definiciji, energetska efikasnost je najbolje moguće iskorištenje rada neke mašine, koje se može predstaviti kroz uštede koje se ostvaruju korištenjem rezultata rada te mašine. Dakle mHE će biti energetski efikasnija ako za što manju potrošnju vodene snage, maziva, rezervnih dijelova i drugo dobijemo što veći rad, odnosno količinu proizvedene električne energije. Energetska efikasnost mHE se može pratiti kroz način upravljanja, tako da bi se najbolji efekti postigli; uspostavom sistema daljinskog nadzora i upravljanja za jednu ili više mHE, optimiziranjem telekomunikacijske i informatiče podrške mHE, maksimiziranje proizvodnje i minimiziranjem troškova, kako gradnje tako i održavanja kod ekspolatacije.

4. Identifikacija i detaljna analiza uticajnih parametara na održivost mini hidroelektrane,

Kod gradnje mHE imamo ekološki najmanje prodoran tip objekata, koji se najčešće maksimalno uklapaju u postojeće uslove u prirode. Kod definisanja uticajnih parametara na održivost gradnje i rada u koncesionom periodu, neophodno je detaljno analizirati i odabrati optimalne; tokove snage, struja kratkih spojeva, mogućnosti prihvatanja proizvedene električne energije, detaljnu analizu dinamičke stabilnosti sistema, neophodnosti gradnje vodova i trafo stanice 100 kW, stvarne nadležnosti za gradnju i planiranje elektroprenosne mreže, financiranje i dinamika priključenja mHE. Analiza uticajnih parametara kod gradnje i eksploatacije mHE je data u donjoj tabeli;

Table 3. Analysis influential parameters during the construction and exploitation mHP

Tablica 3. Analiza uticajnih parametara kod gradnje i eksploatacije mHE

Opis uticajnih parametara	Preporučeni pristup pravilnom rješavanju
Protočni rad i akumulacija	Iznimno malo sa minimiziranim utjecajem na vodotok
Paralelan rad i vrsta generatori	Paralelan rad sa mrežom i ugradnja asinhronih generatora
Trafo stanica	Kod objekata sa instaliranom snagom manjom od 100 kW nema gradnje trafostanice već se predviđa izvođenje transformatora na stubu
Finkcionalne osobine glavnih građevinskih cjelina	Postrojenje se sastoji od brane, niskog prelivnog praga, dovodnog kanala, cjevovoda, mašinske zgrade i odvodnog kanala
Prelivni prag	Prelivni prag služi samo za uspor vodotoka prije ulaska u dovodni kanal

Tirolski zahvat	Umjesto niskog prelivnog kanala može se izgraditi tzv tirolski zahvat
Zatvoreni dovodni cjevovod	Dovodni kanal zatvorenog tipa je predviđen za vođenje zahvaćene vode po strmom terenu i većim dijelom se ukopava
Otvoreni dovodni kanal	Dovodni kanal otvorenog tipa se gradi kod većih količina vode na strmom terenu
Potisni cjevovod	Potisni cjevovod mora biti što manjih dimenzija i da vodu najkraćim putem dovede do postrojenja
Mašinska zgrada	Mašinska zgrada mora biti što manjih dimenzija
Odvodni kanal	Odvodni kanal treba biti otvoren i kratak ikojim se voda što kraćim putem vraća u prirodno korito

Figure 2. Watercourses Sasinka, BiH, concrete remains grip objects earlier mill

Slika 2. Vodotok Sasinka, BiH, betonski ostaci zahvatnih objekata ranijih vodenica

5. Analiza najbolje raspoloživih tehnika za Projektovanje i izgradnju mini hidroelektrana,

5.1. Oblici partnerstva javnog i privatnog sektora kod iskorištavanja hidroenergetskih potencijala

Do sadašnja praksa poznaje nekoliko načina saradnje javnih i privatnih preduzeća u održivom poslovanju, dobra koje se daje na korištenje. Takozvani Public-Private-Partnership, odnosno PPP ili javno-privatno-javno ima više modela:

- BOT – Build Operate Transfer,
- BTO - Build Transfer Operate,
- BOO – Build Own Operate,
- BOOT – Build Own Operate Transfer,
- DCMF – Design Construct Manage Finance,
- DBFO – Design Build Finance Operate,

Do sada su najčešće korišteni modeli;

- BOOT – Build Own Operate Transfer, ili izgradi-koristi-posjeduj-prenesi i
- DBFO – Design Build Finance Operate, ili projektuj-izgradi-financiraj-koristi.

Ne ulazeći u detaljniju analizu pojedinačnih prednosti između ova dva modela, model BOOT je do sada primijenjivani model, odnosno, projektovanje, izgradnja, korištenje i prijenos, kada je u pitanju iskorištavanje energetskog potencijala vodotoka, za izgradnju malih hidroelektrana.

5.2. Najbolje raspoloživa tehnika kod odabira opreme za iskorištavanja hidroenergetskih potencijala

Prema raspoloživ potencijalima i karakteristikama konkretnog lokaliteta, vrši se odabir postrojenja koje se ugrađuje u mHE, od do sada poznatih tipovi turbina; Pelton, Francis, Kaplan i Bankijeve turbine. Kod malih hidroelektrana se upotrebljavaju Pelton hidro turbine a za srednja i manja postrojenja Francis i Kaplan turbina. Pelton turbina je pogodna za male protoke i velike padove, u rasponu od 60 do 2000 metara, čije je vodno kolo tangencijalno na tok. Ova turbina može biti: horizontalna i vertikalna.Turbine za srednje padove i od 2 do 200 metara i od 40 do 500 metara, su poznate pod nazivom Francis, kod kojih je kretanje vode radijalno. Za velike protoke i male padove, do 70 metara, koristi se Kaplan turbina, koja je, zapravo, nadogradnja Francis turbine. Turbine koje su u performansama jednake Pelton turbinama su Bankijeve turbine. Kod Bankijeve turbine postoje značajna tehnička poboljšanja, tako da im je iskorištenost dostigla 68%. Učinak ovih turbina zavisi od promjene raspoložive vode, starosti i održavanja. Ove turbine u najboljim uslovima imaju iskorištenost 0,76 do 0,84 %, odnosno korisnu energiju.

5.3. Druga prateća podrška za optimalan rad postrojenja

Softverske nadogradnje za projektovanje i rukovođenje postrojenjem mogu značajno doprinijeti racionalizaciji u svakom pogledu, međutim neophodo je razraditi manuelni nadzor, kojim bi se izvršila

kontrola i temeljit odabir naprednih i najracionalnijih opcija rješenja. U praksi a i na tržištu se mož naći više praktični primjera softverske nadogradnje kojom se nadgleda rad ovakvih postrojenja. Ovdje je od izuzetne važnosti umreženost sa operatorima centralne elektrodistribucije radi potpunog balansa proizvodnje i potrošnje električne energije svih umreživača u sistemu.

6. Obrada i analiza rezultata na osnovu istraženih karakteristika vodotoka saglasno EU standardima,

Na osnovu višegodišnjeg osmatranja i mjerenja vodostaja, odnosno izračuna proticaja na karakterističnim tačkama na vodotoku, pristupa se analizi prikupljenih podataka. Ono što je od izuzetne važnosti su ekološki zahtjevi legislative lokalne zajednice koji su usklađeni sa Evropskim standardima. Ovdje se prvenstveno, kada je riječ o empirijskoj analizi, mora u izračunu uzeti u obzir prethodno izračunat Ekološki prihvatljiv proticaj (EPP), koji se prethodno izračunava prema Pravilniku kojeg je donijela lokalna zajednica.

Figure 3. Watercourses Sasinka, BiH, backflow threshold about 200 meters under pouring Kruharuša in Sasinka

Slika 3. Vodotoka Sasinka, BiH, usporni prag oko 200 metara ispod ulijevanja Kruharuše u Sasinku

Analiza prikupljenih podataka izvodi se analitičkom metodom pomoću empirijskih izrada koji se standardno primijenjuju u hidraulici, odnosno, hidrotehnici. Ovdje će se analiza raditi preko izvedenih izraza iz izraza za snagu (W=mgh) i Bernulijeve jednačine ($p/\rho + g*h + ½ *c^2 + wt = wo$ = konstant). S obzirom na specifične uslove konkretnog slučaja u poznate izraze se unose različiti koeficijenti koji karakterizuju osobine materijala i uslove tečenja.

Ako u izrazu W=mgh...[J], oznaku W zamijenimo sa N i cijeli izraz predstavimo kao:;

dW/dt=N=dm/dt*g*h=m*g*h...[W],..gdje je (m) maseni protok...[kg/s]

N=V*ρ*g*h=Q*ρ*g*h...gdje je (V) zapreminski protok ..[m³/s]....za Q=A*c

N=9,81*10³*Q*h...[W],

Snaga HE...N=9,81*Qsi*h... [kW],

Vjerojatna energija...W=8760*N.. k[Wh],

Snaga male hidroelektrane je;...N=η*ρ*g*Q*H

Gdje je;

(η) – ukupna efikasnost – 70 – 80 % za mHE

(ρ) – gustoća vode (1000 kg/m³)

(g) - akceleracija gravitacije (9,81 m/s²)

(Q) - protok (m³/s)

(H) – neto pad (m) – uključuje gubitke

7. Primjer proračuna primjenom istraženog modela te definisanje karakteristika mini hidroelektrane uključujući i procjenu isplativosti,

7.1. Standardni izraz za izračun neto snage

Snaga hidroenergije nekog vodotoka se izračunava kroz izraz;

N = g*Q *H , odnosno, N = ρ·*g *Q *H ,

odnosno, N = η *Q *H , gje je (η = ρ·*g)

Gdje su;

N – snaga postrojenja

η – koeficijent efikasnosti

ρ – gustoća vode 1000 (kg/m³)

g – akceleracija gravitacije (9,81 m/s²)
Q – protok (m³/s)
H - neto pad (m) – uključuje gubitke

Dakle kako snaga definiše brzinu iskorišćenja energije, odnosno, diferencijal energije po vremenu, odnosno, energija je integralna kriva izvedena iz krive snage u funkciji vremena, koje je kod ovakvih izračuna vremenski period jedna godina, zato se svi bilansi godišnje proizvedene energije računaju u godišnjem iznosu.

7.2. Učešće specifičnih karakteristika materijala i izvedbenih detalja postrojenja

Specifičnih karakteristika materijala, unutrašnje stijenke cjevovoda, lopatica turbine i drugog, i izvedbenih detalja, radnog kola ili lopatica , određuju vrijednosti koje korektivno učestvuju u izračunu.

Kod ovakvih izračuna moguće je učešće koeficijenata od kojih se najčešći;
(ρ) – gustoća vode (1000 kg/m³), je standarna jedinica, koja je zavisna od nadmorske visine, kada može da doprinosi dobivanju nešti većih ili manjih vrijednosti ukupnog rezultata.
(η) – ukupna efikasnost, koje se kreće između 70 – 80 % za mHE, dok u pojednostavljenim proračunima se uzima i manja (η=50 %); a, zapravo ukupna efikasnost se često sastoji iz produkta;
(ηg) = 0,95 – koeficijent korisnog dejstva generatora, i
(ηt) = 0,85 – koeficijent korisnog dejstva turbine,
(khrap) – koeficijent apsolutne hrapavosti za cijevi potisnog i derivacionog cjevovoda, koji najčešće imaju vrijednosti; k=0,01 mm - za „tesal" cijevi i k=0,40 mm - za čelične cijevi,
Dok se lokalni gubici, najčešće, ne uzimaju u obzir.

Da bi se smanjili otpori izazvani trenjam usljed povećanih brzina unutar cjevovoda, proračun derivacionog i tlačnog cijevovoda određuju se na osnovu usvojene brzine tečenja, koja bi trebala da ima vrijednosti;

(vd) = 1,5 m/s – kod derivacionih cjevovoda i
(vt) = 2,5 m/s – kod tlačnih cjevovoda

7.3. Modifikovani izraz za izračun neto snage

S obzirom na razvoj tehnologija za izvedbu vodnih turbina, i prateće opreme za rad mHE, u novije vrjeme projektanti primijenjuju modifikovani izraz za izračun neto snage. Prema preporukama stručnjaka iz struke koeficijenti koji učestvuju kod izračuna u obrazcu, postali su nešto veći. Ovdje se konkretno misli na koeficijent k.k.d. (η). Uzimajući ovo u obzir imamo da je umjesto do sada standardne formule

$$Ni = 9{,}81*Qi*Hn*\eta g*\eta t \text{ ....(MW)}$$

Gdje su;
(ηg) = 0,95 – koeficijent korisnog dejstva generatora, i
(ηt) = 0,85 – koeficijent korisnog dejstva turbine,

Odnosno, pojednostavljenog oblika;

$$N = 8*Q*H \text{ .....(MW)}$$

Moguće je primijeniti modifikovani izraz za pojednostavljeni oblik

$$N = 8{,}5*Q*H \text{ .....(MW)}$$

U praktičnom smislu ovako modifikovan izraz omogućuje dobivanja nešto većih vrijednosti od rezultata dobivenih izvođenjem standardnih izraza. Dobivene vrijednosti modifikovanim izrazom su povoljnije kod izrade Studija izvodivost, jer objektivnije daju rješenja koja garantuju održivost ovih postrojenja.

8. Zaključak

Na osnovu rezultata istraženog modela, izvršena je identifikacija uticajnih parametra na okoliš za gradnju održive mini hidroelektrane, pri čemu je evidentirano da je; emisija štetnih plinova ispod granice dopuštenih, da ne ugrožavaju flori i faunu da je obezbjeđena prirodna pokretljivost riba gradnjom riblje staze, da je osigurat ekološki prihvatljiv proticaj, da se objekti potpuno uklapaju u sredinu tako da ne ugrožavaju kolturno i prirodno nasljeđe, da je sprječena ugroženost od poplave kontrolisanim ispuštanje, da se voda koja je pokretala turbine, ponovno bez promjene vraća u prirodno korito, da je nivo buke koji iz mašinske zgrade dospijeva u okolnu sredinu ispod dopuštenog i preporučenog nivoa, da objekti ne stvaraju nepovoljan vizuelni efekat, tz., arhitektonsko onečišćenje, jer su u potpunostu uklopiti u pejzaž. Na osnovu rezultata o smanjenju emisije CO2 u atmosferu kod 4 postrojenja mHE Sasina, sa godišnjom proizvodnjom od 1,111 GWh, odnosno za (mHE-1=122 kWh*10³, mHE-2=170 kWh*10³,, mHE-3=452 kWh*10³, i mHE-4=367 kWh*10³,) ukupno smanjenje emisija CO2 je

1.111.000 (kWh) × 750 (g/kWh) = 833.250.000 grama, odnosno 833,250 tona CO2, tako da je ukupan prihod od prodaje smanjenja emisije CO2 ukupno godišnje 24.9975 € (0,3 €c/kWh). Najprihvatljiviji oblik partnerstva javnog i privatnog sektora kod iskorištavanja hidroenergetskih potencijala, prema analizi do sadašnje prakse, način saradnje javnih i privatnih preduzeća u održivom poslovanju, nad dobrima koja se daje na korištenje. Takozvani Public-Private-Partnership, odnosno PPP ili javno-privatno-javno, proizilazi da je kao najprihvatljiviji model BOOT, odnosno, projektovanje, izgradnja, korištenje i prijenos. Upotrebom modifikovanog izraza kod izračuna snage postrojenja, moguće je dobivanja nešto većih vrijednosti od rezultata dobivenih izvođenjem standardnih izraza. Dobivene vrijednosti modifikovanim izrazom su povoljnije kod izrade Studija izvodivost, jer objektivnije daju rješenja koja garantuju održivost ovih postrojenja.

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Computational modelling and characterization of lightweight cellular materials

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Abstract: Cellular materials have an attractive combination of physical properties for use in engineering applications. Their micro- and macroscopic properties make them suitable for use in automotive, rail, naval, aerospace and armour industry as heat exchangers, filters, bearings, acoustic dampers, bio-medical implants, blast protectors and especially as elements for impact energy absorption. Characterization of three types of cellular materials is presented in this paper: cellular materials with unidirectional pores, aluminium foams and Advanced Pore Morphology (APM) foam. Characterization of their geometrical and mechanical properties was based on quasi-static and dynamic nonlinear computational simulations and experimental testing. Newly developed methodology for proper 2D and 3D geometrical modelling of irregular porous structure and consequent formation of computational models is presented.

Računalno modeliranje i karakterizacija lakih ćelijastih materijala

Stručni rad

Sažetak: Ćelijasti materijali posjeduju posebnu kombinaciju svojstava koji ih čine atraktivnim strukturnim materijalima u tehnici. Njihova mikro i makro svojstva omogućavaju široku primjenu u cestovnoj, željezničkoj, brodograđevnoj, vojnoj i svemirskoj tehnici gdje se koriste kao izmjenjivači topline, filtri, ležajevi, akustični prigušivači, bio-medicinski implantati, zaštite od eksplozije te naročito kao apsorberi energije udara. U ovom radu su dana mehanička svojstva za tri vrste ćelijastih materijala i to: ćelijasti materijali s dužinski usmjerenim ćelijama, aluminijske pjene i kuglice iz APM pjene. Utvrđivanje mehaničkih i geometrijskih svojstava je temeljeno na kvazi-statičkim i dinamičkim nelinearnim numeričkim simulacijama i laboratorijskim ispitivanjima. U radu je prezentirana nova metodologija za dvodimenzionalno i trodimenzionalno modeliranje struktura s neravnomjernom raspodjelom ćelija.

1. Introduction

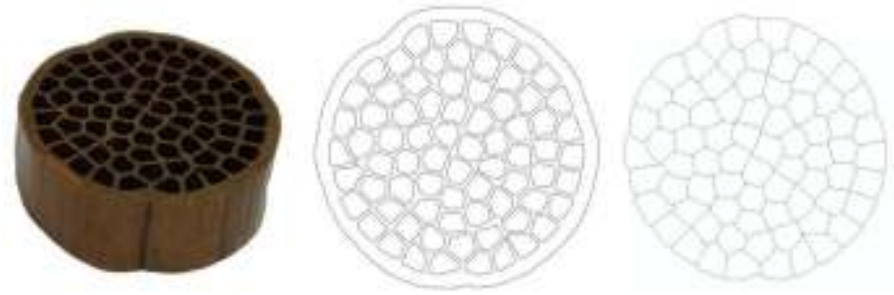
Cellular materials have an attractive combination of mechanical properties and are increasingly being used in modern engineering applications [1]. Consequently, the research of their behaviour under quasi-static and dynamic loading is valuable for engineering applications such as those related to mechanical energy absorption through deformation [2, 3]. However, the structure of industrial cellular materials in terms of shape, size and distribution of cellular pores cannot be fully controlled with existing mass production technologies. This results in a certain scatter of mechanical characteristics of these materials and their components. Some recently developed fabrication methods of porous metals can produce more homogeneous pore structures [4-7]. This paper focuses on reconstruction and computational modelling of three different types of cellular materials: cellular materials with unidirectional pores, aluminium foams and Advanced Pore Morphology (APM). Characterisation of their mechanical properties was done with computational simulations using ABAQUS and LS-DYNA and validated by experimental testing.

2. Unidirectional porous structure - UniPore

Some innovative manufacturing approaches have been investigated recently in search of cellular materials with more regular distribution of pores, constant wall thickness and pore sizes. One such approach is explosive compaction of thin-walled tubes, which are being compressed together and thus form a cellular structure with perfectly parallel unidirectional pores –

the UniPore structure (Fig. 1a). UniPore material was recently developed at Shock Wave and Condensed Matter Research Center at Kumamoto University in Japan. The advanced geometrical properties of the UniPore structure assure wide opportunities for its application due to its particular and unique mechanical and thermal properties. The study reported hereafter focuses on computational simulations of mechanical behaviour of the UniPore material under dynamic loading.

The computational model was based on realistic (reconstructed) irregular geometry of the manufactured specimens (Fig. 1b and Fig. 1c). The outer and inner pipes tubes were made of phosphorus deoxidized copper (Cu 99.98 % and P 0.02 %). The compressive mechanical properties of UniPore structure have been investigated by means of parametric computational simulations considering various materials and geometrical parameters using the LS-DYNA [8].



a) b) c)

Figure 1. UniPore sample and reconstruction of its structure: a) UniPore specimen, b) CAD reconstruction, c) mid-surface representation

Slika 1. UniPore uzorak i rekonstrukcija geometrije strukture: a) UniPore uzorak, b) CAD model c) površinski model geometrije

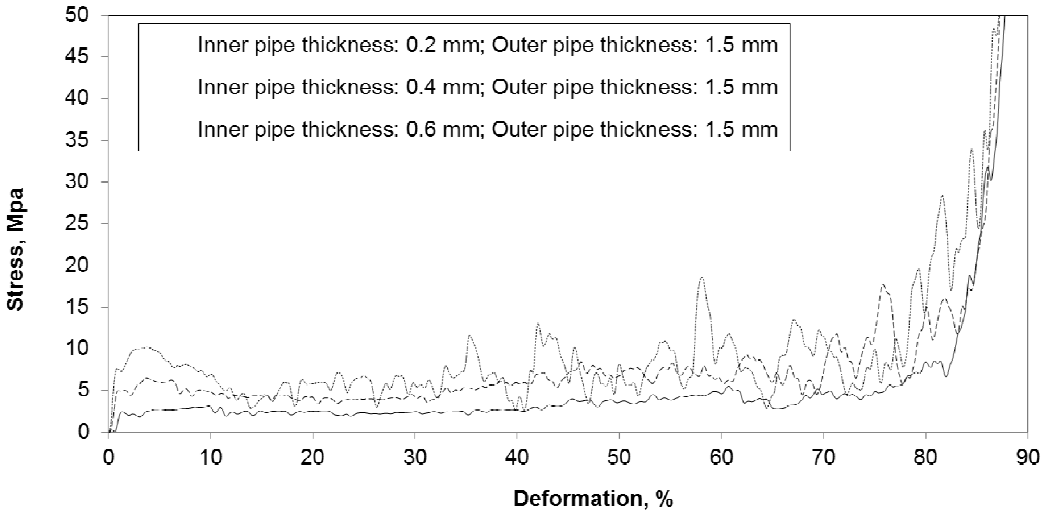


Figure 2. Influence of the inner pipe thickness on the compressive behaviour of UniPore structure at strain rate of 100 s^{-1}

Slika 2. Utjecaj debljine unutrašnjih cjevčica pri tlačenju UniPore strukture kod brzine deformacije od 100 s^{-1}

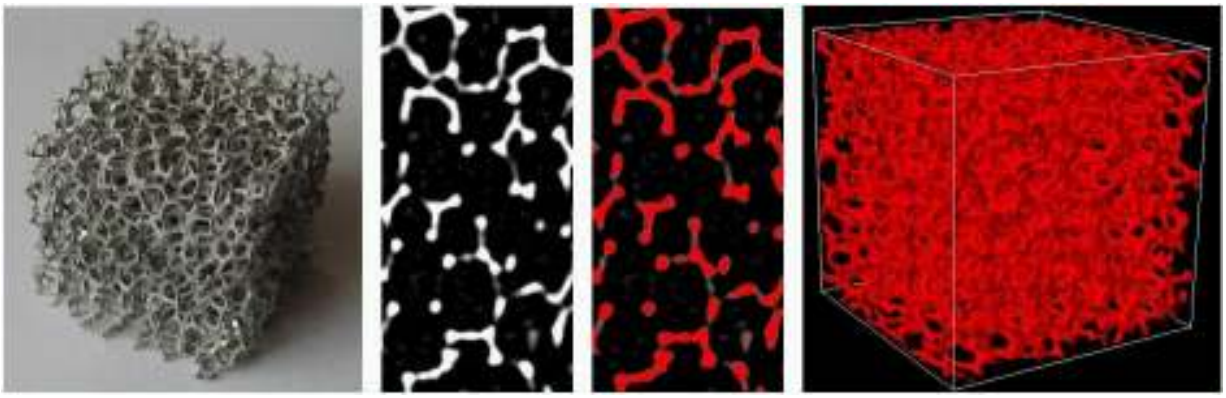
The simulations have shown that the UniPore structures exhibit characteristic cellular material behaviour, i.e. onset of yielding after the initial elastic response which is then followed by typical stress plateau until the final densification (Fig. 2).

3. Open-cell aluminium foam - m.pore

The open-cell foam specimens are manufactured using an investment casting process. Starting point is a porous polymer precursor. The pores are filled with a fire-resistant slurry that is dried and burned. During the burning the precursor pyrolises while the slurry hardens and forms the mould for subsequent investment casting of the metallic matrix. The final step is the removal of the moulding material resulting in a porous metallic geometry that closely resembles the polymer precursor [9]. The base material of the open-cell foam is Al99.7% and the relative density of the structure is 6.1 % (porosity is 93.9 %). The average pore size is 20 pores per inch (ppi). The cube shaped aluminium foam

specimen with dimensions 40 x 40 x 40 mm (Fig. 3a) was CT scanned at the Department of Radiology, University Medical Centre Maribor. The obtained CT images were then segmented and the specimen was virtually reconstructed as a solid CAD model (Fig. 3) [2, 10].

The reconstructed models were discretised with solid finite elements. Explicit dynamic finite element analysis of specimen compressive behaviour was performed using the engineering code LS-DYNA. The results of the structural analysis are shown in Fig. 4, in which the localised stress concentrations during loading can be clearly observed.



a) b) c) d)

Figure 3. Aluminium cellular material (a); CT scan (b); virtual reconstruction (c); solid CAD model (d)
Slika 3. Aluminijski ćelijasti materijal (a); CT sken (b); virtualna rekonstrukcija (c); CAD model (d)

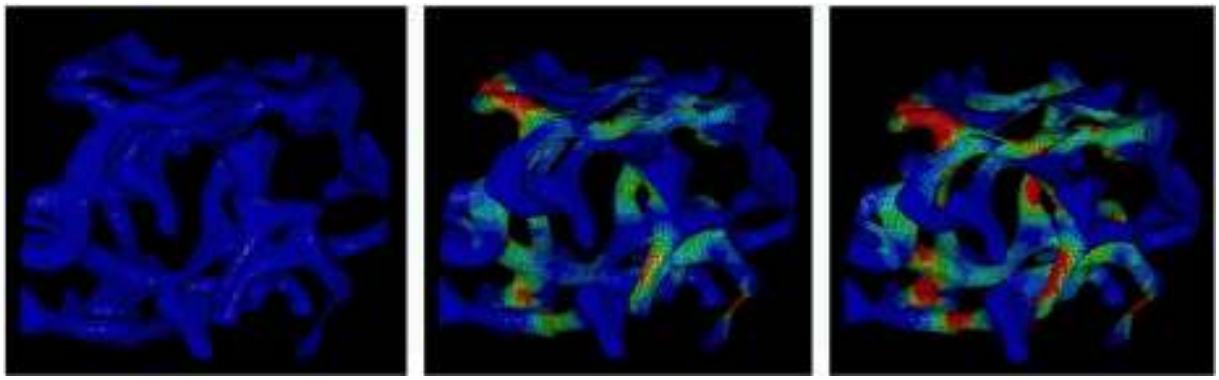


Figure 4. Structural analysis of the aluminium cellular material
Slika 4. Numerička analiza deformiranja aluminijskog ćelijastog materijala

Another modelling approach of the open-cell foam is based on representative lattice of beam finite elements [11]. First, the topological model is generated from the volume model. Topological model is used to determine the majority of the geometrical features present in the volume model, which includes positions of cell edges, windows and cells of the cellular structure of the foam. Topological model is generated from a voxel representation of volume model using the volume thinning image processing method. This method gradually removes outer layers of voxels of the volume model until the structure reaches a thickness of one voxel (Fig. 5). Developed algorithm ensures that the resulting topological model maintains connectivity from the volume model and that the resulting skeleton is located as close as possible to the centre line of a volume model [12].

A lattice model is then created from the topological model (Fig. 6). First the edge vertices (joints) in the topological model are identified. They are represented by voxels which are connected with at least three other neighbouring voxels. The connectivity of identified joints is determined next by using the method of breadth-first search. The edge between two selected joints exists, if those joints are connected through voxels in such a way, that no other joints are between them. This results in the foam lattice model, which contains the positions of the joints and appropriate connections (edges). The resulting lattice model contains some geometric distortions caused by the noise

in the scanned images and by the foam geometry imperfections. Thickened edge joints can result in two or more separate joints in the topological model at the position where the volume model has only one joint. However, the distance between these joints is very small and such imperfections can be removed using automatic model smoothing [13]. The results of described image analysis method are foam models, which are directly based on the positions of cell edges in obtained 3D image. This ensures the accuracy and reliability of such models in respect to the structure of real foam. Fig. 6 shows the comparison between the lattice and volume model of the selected foam sample. Produced lattice models include all geometric features of the foam and are thus used for creation of the corresponding finite element model.

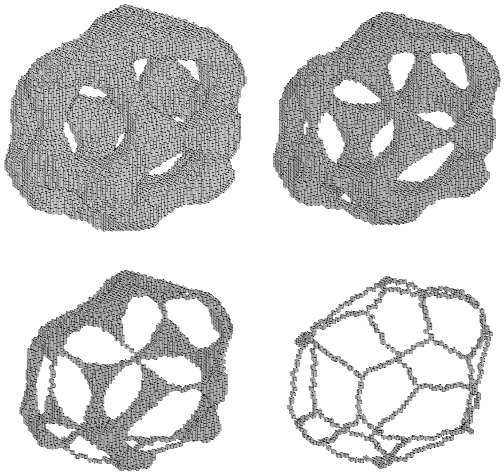


Figure 5. The process of volume thinning by voxel removal
Slika 5. Postupak smanjenja volumena uklanjanjem voksela (3D piskel)

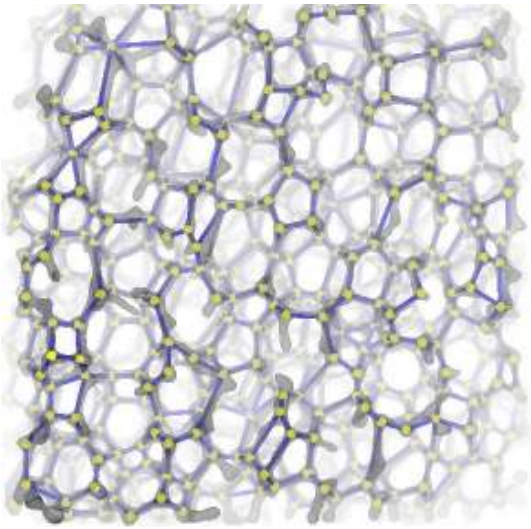


Figure 6. Overlay of the surface and lattice models of the foam sample
Slika 6. Preklapanje realne pjene i rešetkastog modela

The cell edges of the lattice model were meshed with linear beam elements, since the used computer code LS-DYNA incorporates only such beam elements. To properly capture the effect of local buckling of cell edges, which is the dominant mechanism responsible for the failure of the open-cell foams in compression [14], longer cell edges are discretised by several beam elements. Two criteria were used for discretisation. The first criterion was the maximum number of linear beam elements on a single cell edge, which was set to 3 and the second criterion was that the shortest element in the finite element mesh after the division should not be smaller than the length of the smallest finite element before the division (time step). The result is the finite element mesh where cell edges are modelled using one, two or three linear beam elements, depending on the edge length.

4. Advanced Pore Morphology (APM) Foam

Advanced pore morphology (APM) foam (Fig. 7) in form of sphere-like metallic foam elements (from 5 to 15 mm in diameter), proves to have advantageous mechanical properties and unique application adjustability [15-18].

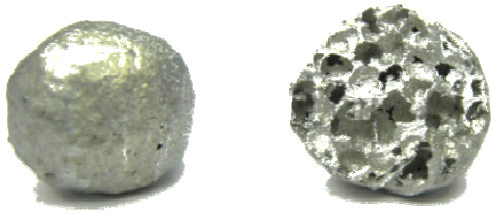


Figure 7. APM foam element
Slika 7. APM pjenasti element

The APM spheres can be used individually or bonded with a matrix as fillers of engineering parts, as core layers for sandwich structures or other composite materials. They have a characteristic stress-strain behaviour under compressive loading (Fig. 8) [19]. Since the APM foam manufacturing procedure has been developed only recently, the mechanical characterization of these materials is still limited.

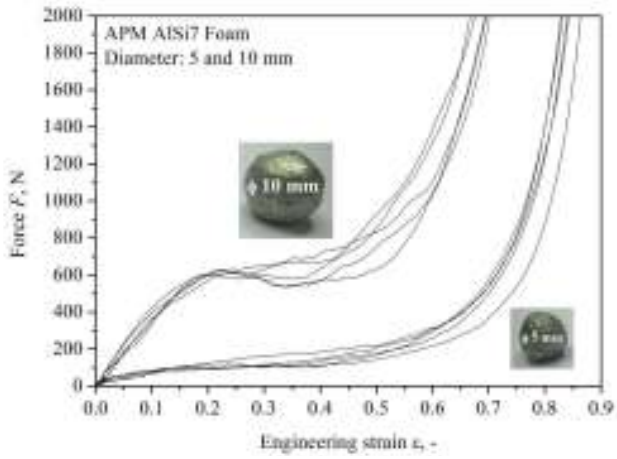


Figure 8. Behaviour of APM foam elements under compressive loading [19]

Slika 8. Tlačenje APM pjenastog elementa

Single APM elements have a characteristic cellular material behaviour where the larger foam elements experience lower densification strain, which corresponds to their observed higher inner porosity. The use of IR thermography has demonstrated the importance of studying also the heat generation due to fast plastic deformation during dynamic loading. The yielding starts at the contact between the loading/support plate and the APM element and then propagates through the sphere in a shear band, finally resulting in a fully plastically compressed APM foam element. The study of single APM elements provided valuable mechanical properties and the basic knowledge for an efficient composition of composite APM structures [19, 20].

A recent structural analysis of APM foam element using micro computed tomography revealed different levels of porosity (Fig. 9). Pore size from micro level (several micrometres in diameter) up to macro level (several millimetres in diameter) can be found resulting in high total number of pores in only one APM foam element.

The computational simulations of APM foam elements behaviour were based on computer models built from the three-dimensional CT scans of APM elements by using reconstruction modelling technique.

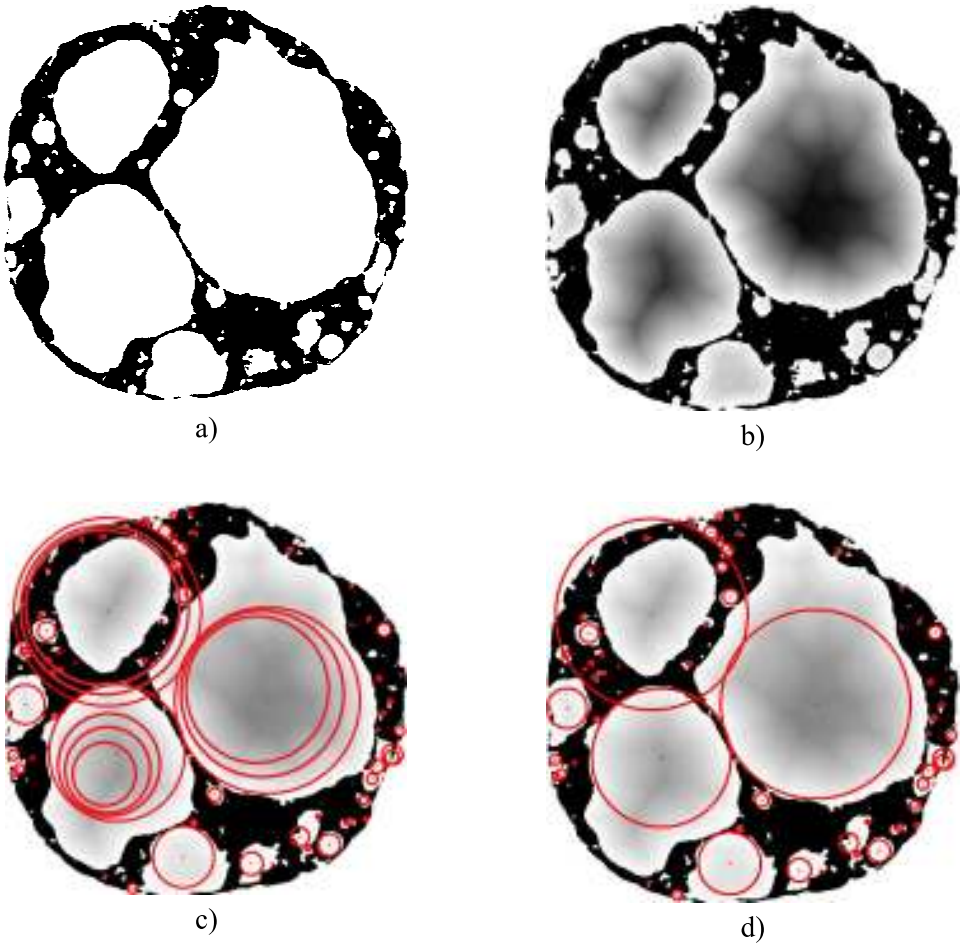


Figure 9. Pore search algorithm based on the μCT figures

Slika 9. Algoritam lociranje ćelija na temelju mikro CT snimka

5. Conclusions

Computational models of some different novel types of cellular materials have been presented. It has been shown that complex and irregular geometry of the cellular structure can be reproduced as appropriate computational models by using porous structure CT scanning and relevant reconstruction techniques. The use of computational simulations consequently allows for faster geometrical and mechanical characterization and unique insight in the deformation mechanics and behaviour of novel cellular materials under different types of loading.

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Innovative high-tech products made of aluminium foam

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phase changing material

Ključne riječi
aluminijeva pjena
napredne tehnologije
inženjerski materijali
prenos znanja
fazno promjenjivi materijali

Professional article

Abstract: Economically successful high-tech innovation is one of the driving forces for global welfare. The requirements in high-tech innovation marketing are an on-going dialogue between technology, ecology, finance and marketing. This paper aims to show the requirements of multidisciplinary communication in B2B and B2R&D marketing of high-tech innovation and methodical approaches in research and academic education.
Recent trends in development of sustainable products and processes indicate the need for using of new science-based approaches for achievement of appropriate values of all factors influencing sustainability. At the Institute of Materials & Machine Mechanics of the Slovak Academy of Sciences in Bratislava (IMSAS), newly developed engineering materials and advanced technologies have been long time successfully applied in various industrial fields. Material research and development of innovative products is therefore systematically further focused preferably on those with great potential to achieve particularly high added value thanks to effectively utilized know-how. These innovative products and their manufacturers are therefore predicted to obtain a good competitiveness which will ensure sustainable development of their entrepreneurial activities in specific industrial sectors in the nearest future.
The guide to fulfil needs of industrial companies to increase their innovation capacity and particularly to improve their competitiveness on world-wide markets by applications of aluminium foam in design of new sustainable products has been outlined in this contribution.

Inovativni proizvodi visoke tehnologije iz aluminijeve pjene

Stručni rad

Sažetak: Gospodarski uspjeh visoko tehnoloških inovacija je bitna pokretačka snaga globalne dobrobiti. Zahtjevi kod „high-tech" inovacija traže stalni dijalog između različitih tehnologija, ekologije, financija i marketinga. Cilj ovog rada je da prikaže zahtjeve multidisciplinarne komunikacije u B2B i B2R&D marketingu „high-tech" inovacija i metodički pristup istraživanjima kao i akademskom obrazovanju.
Najnoviji trendovi u razvoju održivih proizvoda i procesa ukazuju na potrebu za korištenjem novih znanstveno utemeljenih pristupa za postizanje odgovarajuće vrijednosti svih čimbenika koji utječu na održivost. U Institutu za materijale i strojarstvo Slovačke akademije znanosti u Bratislavi (IMSAS), novorazvijeni inženjerski materijali i napredne tehnologije se dugo vremena uspješno primjenjuju u raznim područjima industrije. Istraživanje materijala i razvoj inovativnih proizvoda sustavno se usmjeravaju na mogućnosti razvoja onih proizvoda s velikim potencijalom za postizanje posebno visoke dodane vrijednosti zahvaljujući djelotvorno iskorištenom znanju („know-how"). Proizvođači ovih inovativnih proizvoda predviđaju dobru konkurentnost, a koja će osigurati održivi razvoj njihovih poduzetničkih aktivnosti u pojedinim industrijskim sektorima u bliskoj budućnosti.
Smjernice za ostvarivanje potreba industrijskih poduzeća da povećaju svoju sposobnost inovacije, a pogotovo da povećaju svoju konkurentnost na svjetskim tržištima, omogućuje primjena aluminijske pjene u dizajnu novih održivih proizvoda.

1. Introduction

The development, exploiting and commercializing of new engineering materials and advanced technologies of their production is absolutely essential if a country is to stay competitive in modern industrialized world. High-tech sectors are key drivers for economic growth and productivity. They are generally the main source of high value added as well as well-paid employment. While the concept of product sustainability continues to grow and becomes more compelling, the assessment of product sustainability has become difficult and challenging. The sustainable products are fully compatible with nature throughout their entire life cycle. The recycling, reuse and remanufacturing effort has in recent times emerged with innovative and viable engineering materials, advanced manufacturing processes and systems to provide multiple life-cycle products. The increasingly important consideration is given to eco-efficiency and the environmental concerns often associated with minimum toxic emissions into the air, soil and water, production of minimum amount of useless waste and minimum energy consumption at all levels. This multi-life-cycle approach and associated need for product sustainability principles bring out an enormous technological challenge for the future.

History shows that innovations in technology can cause the dramatic increase in productivity, transforming industries and setting whole societies on new paths of growth.

The implementation of the revised Lisbon strategy and new strategy document Europe 2020 require establishment of a general framework for effectiveness of modern economy, based on high quality research and innovative products, instruments for marketization and good balance between interests of consumers and owners facilitating free circulation of knowledge. Similarly, like rise of wireless technologies fundamentally altered telecommunications, the energy markets are on the way of such dramatic transformation just now. With prices of steel, aluminium, copper, oil and other commodities soaring to historic highs, energy-technology innovators are taking advantages in development in areas such as software, pharmaceutical, semiconductors, etc. to greatly improve how the world produces and consumes energy.

Knowledge transfer is a unique element of the innovation system aiming to overcome shortcomings of the system and to create a sustainable link between research and business communities. The difference in intellectual property management approaches implemented by the industry and research organizations is the main barrier in creating an effective and sustainable competitive economy.

2. Knowledge transfer and innovations

Innovation – the motor of any economy - is today measured against the global conditions of international competition. The entrepreneurs must therefore have tremendous comprehensive and in-depth knowledge about their own specific R&D areas, brand strategy and design as well as the activities of the competition.

Scientists and inventors involved with developing innovations should use the authoritative databases on their own, as many ideas can be found that are suggestive of further-reaching solutions.

Differentiation between one's own ideas and those located through professionally conducted research should be evaluated to demonstrate the limits of innovation as part of the overview (over multiple patents in various countries).

Furthermore, even the thorough brainstorming is unavoidable prior initializing of any research. The key question to clear up by professionally managed knowledge transfer is whether an idea is truly new at the global level, or whether the novel character is solely for any particular industrial company with an excellent innovative potential or within a national framework.

Various governments of European countries have a range of business assistance programs to support innovators. The following five sections discuss particular examples of these programs with illustrative practices for industrialized as well as also developing and emerging economies:

- ✓ sector-oriented entities and technology transfer centres, serving mainly new and small enterprises,
- ✓ national or regional small business policies that seek to meet the needs of entrepreneurs at various stages of the innovation process (design, development, diffusion),
- ✓ access to equity and venture capital to help develop new products and processes and to mitigate the risks of commercialization,
- ✓ government support of clusters and networks as they become major actors in innovation,
- ✓ new policy approaches to intermediaries and bridging institutions.

The users of knowledge acquired by R&D activities of scientists in the field of materials science and engineering expect to benefit significantly by finding appropriate solutions to their needs. They often develop new innovative products themselves because they can't or don't want to wait for them to become available commercially. The needs of new sustainably developed products and services are general in a marketplace, but the industrial companies with a large innovative potential face them months or years before the bulk of the market encounters them.

The requirements in high-tech innovation marketing are an on-going dialogue between technology, finance and marketing. An experimental method of marketing test beds briefly described in this paper is therefore the guide for multidisciplinary approach to creating of innovative high-tech start-ups unavoidable

in the nowadays world full of high-tech engineering solutions.

The successful case studies of innovations allowing to increase innovation capacity of industrial companies and particularly to improve their competitiveness on world-wide markets by applications of aluminium foam in design of new sustainable products have been outlined in this contribution.

3. R&D in the field of aluminium alloys

The sustainable products are fully compatible with nature throughout their entire life cycle. The recycling, reuse and remanufacturing effort has in recent times emerged with innovative and viable engineering materials, advanced manufacturing processes and systems to provide multiple life-cycle products. The increasingly important consideration is given to eco-efficiency and the environmental concerns often associated with minimum toxic emissions into the air, soil and water, production of minimum amount of useless waste and minimum energy consumption at all levels. The multi-life-cycle approach based on design – manufacturing – assembling – using – service/maintaining/upgrading – disassembling – recycling or reusing and associated need for product sustainability principles bring out an enormous technological challenge for the future.

The use of new science-based approaches for achievement of appropriate values of all factors influencing sustainability of developed innovative products is unavoidable. The Institute of Materials & Machine Mechanics of the Slovak Academy of Sciences in Bratislava (IMSAS) has been long time successfully applied newly developed engineering materials and advanced technologies in industrial practice due to the fact that the development of innovative products is systematically focused preferably on those with great potential to achieve particularly high added value thanks to effectively utilized know-how.

R&D activities of IMSAS in the field of lightweight structural materials based on aluminium alloys are mainly devoted primarily to development of advanced techniques of their preparation via powder metallurgy (PM) as well as the design, development and optimisation of:

- ✓ complex Al alloys with extraordinary mechanical properties prepared via consolidation of rapidly solidified highly alloyed Al powders and melt-spun ribbons;
- ✓ aluminium matrix composites reinforced with ceramic particles with increased ratio of elastic modulus to density, controlled thermal expansion and improved wear resistance;
- ✓ ultra-fine grained $Al+Al_2O_3$ composites in situ formed during PM consolidation of fine atomised commercial purity Al powders with enhanced structural stability and properties at elevated temperatures;
- ✓ Al+AlN composites containing nanoscale AlN crystallites prepared via partial in situ nitridation of Al powder green compacts in gaseous nitrogen followed with full densification;
- ✓ Al+TiC composites prepared using pellets manufactured via self-propagating synthesis of Al+Ti+C powdered mixture which were diluted in aluminium melt cast and extruded into structural lightweight profiles with enhanced *E* modulus;
- ✓ novel powder compaction techniques, in particular those based on severe plastic deformation such as equal channel angular pressing (ECAP);
- ✓ novel techniques for foaming of aluminium and its alloys at significantly reduced processing costs;
- ✓ production of components made from aluminium foam, in particular various crash boxes for the protection from sudden impact, cooling/heating floor or ceiling panels, extremely lightweight structural components made of reinforced aluminium foam, etc.

4. Successful industrial applications of aluminium foam

The industrial technology for extrusion of aluminium powders has been developed and established in SAPA Profily Žiar nad Hronom, Inc. This technology enables extrusion of hardly-formable aluminium alloys incl. production of foamable aluminium precursor as well as extrusion of composite mixtures into complex profiles with extraordinary properties, in particular enhanced structural stability at elevated temperatures, increased wear resistance, elastic modulus and dimensional stability. New technology line was built including new continuous 4-zone furnace for controlled heating of powdered billets prior to extrusion, cutting and thermal treatment stations and quality control unit. This high added value technology developed by IMSAS is unique in Europe from the point of view of complexity as well as production volume of produced components. The technology has been successfully used for mass production (ca 900 thousands per year) of stator rings for camshaft phaser for automotive BMW engine. This application represented the worldwide largest production of structural components made of aluminium powders.

The aluminium foam panels made by foaming of foamable precursor manufactured by abovementioned PM technology with stainless tubes embedded in the structure of foam are very promising high-tech products for efficient heating and cooling of walls/ceilings in interiors of future buildings, ships or railway wagons (Figure 1). Thanks to their low heat capacity and thus quick response to temperature changes, uniform temperature distribution due to excellent heat

conduction of aluminium, lightweight design, self-supporting capability, shape and surface flexibility, low hydraulic resistance, the huge potential for commercialization is expected. The large active surface of foamed panels with extremely quick response to temperature changes enables to use heating/cooling fluids with the temperature nearly the same as the achieved and maintained room temperature.

The large active surface of foamed panels and extremely quick response to temperature changes enables to use heating/cooling fluids with the temperature nearly the same as is the achieved and maintained temperature of interior air. This allows to effectively utilize various available alternative energy resources such as solar or geothermal energy during winter for heating, or even simply cold air during summer nights for cooling. These novel systems of high-tech aluminium foam panels supplied with proper heat storage tanks enables to increase cost efficiency of interior heating and cooling. Moreover, the filling of aluminium foam porous structure with appropriate phase changing materials (PCM) able to melt or solidify at desired temperature and thus spend or release into the interior certain amount of heat at constant temperature. In combination with smart temperature control systems, this feature makes possible further energy and thus also cost savings of air conditioning systems designed for interiors of future building, ships, trains, etc.

Figure 1. Cooling/heating wall and ceiling panels developed by IMMM utilizing aluminium foam as very effective heat spreader.

Slika 1. Paneli za podno i zidno hlađenje/grijanje razvijeni u IMMM koristeći aluminijevu pjenu kao učinkovit prijenosnik topline

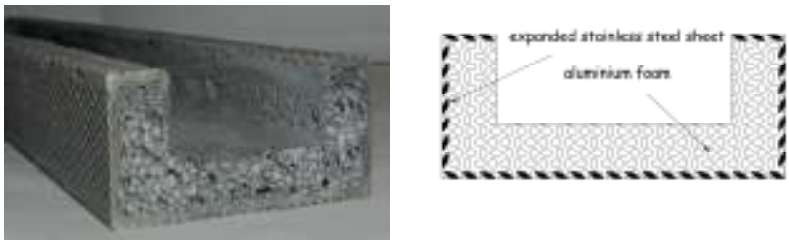

Figure 2. Ultra-light foamed aluminium profile with the outer surface reinforced by stainless expanded steel sheet.

Slika 2. Ultra lagani profil iz aluminijske pjene sa ojačanom vanjskom površinom razvučenim limom iz nehrđajućeg čelika

The main obstacle for use of aluminium foams in structural applications is their insufficient ability to resist excessive tensile stresses in critically exposed surfaces of foamed components. The skin of foams has obviously variable thickness and contains small cracks. These inevitable defects can initiate premature fracture of the foam even at low mechanical loading, especially if they appear on the tensile loaded surface of foamed component. This can be solved very effectively by reinforcing tensile loaded surface skin with various metallic stiffeners in the form of perforated sheets or wires woven into grids. According to the unique recently developed powder metallurgical foaming technique for the production of aluminium foam plates and complex shaped parts with reinforced surface skin, the stiffeners are put into the cavity of foaming mould together with foamable precursor. The expansion of the foam during foaming moves stiffeners to the mould surface where they are infiltrated with molten cell-wall aluminium (Figure 2). The stresses which usually cause the yielding or even fracture of surface skin are by this way overtaken by reinforcements. Thus the stiffness, strength, plasticity, energy absorption capacity and damage tolerance of foamed parts can be significantly improved without an excessive weight increase. Moreover, the reinforcements have additional stabilizing effect for liquid foam: they prevent foam from collapsing, and increase the thickness of surface skin. The excellent properties of reinforced foamed aluminium parts simplify their joining and enable

eventually limited shaping after foaming process [3]. The possibility to reinforce aluminium foam component partially or even gradually according to expected tensile load enables to obtain required mechanical property-to-weight ratio. Easy manufacturing at reasonable production costs make the reinforced aluminium foams very attractive especially for light-weight stiff body structures of future cars, trains, buses, ships, airplanes, etc.

In order to enhance passive safety in railway carriages the novel crash boxes have been developed using aluminium foam component (Figure 3). Thanks to this innovation, deformable foamed component is able to reduce high crash forces in case the absorbing capability of existing (conventional) damping elements is exhausted. It is expected from the crash box to protect chassis of 22 ton heavy carriage in a case of frontal crash at the velocity of 8 km/h. The kinetic energy is by this way dissipated within about 30 mm deformation length. The special 3D shaped component of aluminium foam has been developed, whereas the shape of its natural "foam skin" and preferred orientation of pores were carefully designed to meet these requirements. The cell walls are made of heat treatable AlMgSi aluminium alloy and the porosity is gradiently changing along the thickness of the part in order to guarantee gas release from the foam structure during dynamic compaction. The production of this part started in 2008 with the amount of about 800 pieces per year. This development was awarded with „Best Application Award" at the International Conference CELLMET 2008, Dresden, Germany (Figure 3) and "Innovation product 2007" awarded by the Minister of Economy SR (bilateral cooperation with Gleich GmbH, Kaltenkirchen, Germany).

Figure 3. Innovative crash absorber of railway carriage made for aluminium foam.

Slika 3. Inovativni ublaživač udara na željezničkim vagonima napravljen iz aluminijeve pjene

5. Marketing of innovative products

5.1. Knowledge transfer platform INNOVMAT

In order to promote the generation of knowledge in the field of engineering materials and to support its subsequent transfer into the industry and other socioeconomic bodies, the concept of platform INNOVMAT (www.innovmat.eu) was conceived within the project co-financed by the European Regional Development Fund under the program of Slovak-Austrian cross-border cooperation 2007-2013. Upon the creation of knowledge transfer platform INNOVMAT various objectives were defined:

- ✓ to identify scientific results generated by the associated research groups and assessing their knowledge transfer capacity;
- ✓ to ensure adequate dissemination of knowledge acquired by R&D activities of the most appropriate research groups mainly in collaboration with other industrial, scientific and financial intermediating organizations by organizing thematic workshops on actual topics of materials science in order to offer an overview of current trends (INNOVMAT / academy);
- ✓ to mediate contacts through the cross-border cooperation B2B and R&D2B meetings of scientists from R&D institutions and developers, mainly from industrial SMEs during innovation days organized regularly on both sides of the Austrian – Slovak border;
- ✓ to facilitate the transfer of disseminated knowledge to industry or, where appropriate, the correct assimilation of novel advanced technologies;
- ✓ to support the funding and legal issues (intellectual property, preparation of license agreements, etc.) during cooperation in R&D through consultations, development and dissemination of manuals, mapping reports, etc.;
- ✓ to manage the R&D and licensing contracts with the aid of administrative services of universities or scientific institutions;
- ✓ to create a database of knowledge, infrastructure and R&D capacities of corresponding universities and scientific institutions;
- ✓ to create a virtual network of professionals which provides direct access to experts, equipment and

services in the field of engineering materials, technologies of their production and processing, related legal issues, grants, etc.;

- ✓ to provide information regarding European R&D programs and offer technical support in the drafting and management of these types of projects, etc.

5.2. Market entry of high-tech products

Platform INNOVMAT cooperates with Cross-border High-tech Center (CHC – www.hitechcentrum.eu) in organizing creative workshops for economics and business students. The guiding principles of engineering materials development as well as basic information on material properties and potential applications are presented to marketing students of the Faculty of Commerce of the University of Economics in Bratislava (see figure 4). Students have taken their own thesis on topics related to innovative products made of advanced engineering materials. This approach recently developed by Marketing Management Institute of Vienna University of Economics and Business is so-called Marketing Test Bed (MTB) [6] and it is an outstanding tool to effective multidisciplinary communication in B2B marketing by linking together various technical disciplines based on high-tech knowledge obtained by R&D with highly professional marketing activities. The market entry of high-tech innovations of industrial companies, mainly SMEs, is thus supported by evaluation of MTB based on qualitative market research procedures such as problem-centred interviews and focus groups.

Each topic of future diploma works of economy students is by this way checked by experts from both disciplines, i.e. materials engineering and marketing. The objectives are obviously focused on the market acceptance, business model preparation and new product designs.

Figure 4. Creative Workshop: "Product innovations using aluminium foam" organized by CHC and INNOVMAT on 10th October 2012 at the University of Economics in Bratislava.

Slika 4. Kreativna radionica "Product innovations using aluminium foam" organizirana od strane CHC and INNOVMAT 10. listopada 2012. na Ekonomskom fakultetu u Bratislavi

6. Conclusions

The knowledge transfer from R&D to industry has become one of the key priorities for policy makers worldwide. Innovative products made of aluminium foam described in this contribution help producers acquire their leading position in worldwide markets because:

- ✓ they are associated with innovation, and hence tend to gain a larger market share, create new product and service markets, and use resources more efficiently (environmental aspects play also very important role in this context);
- ✓ they are linked to high value-added production and success in foreign markets, which helps to support higher returns to the workers they employ;
- ✓ the industrial R&D in cooperation with research institutions and universities has spill-over effects which benefit other commercial sectors by generating new products and processes, often leading to productivity gains, business expansion and creation of high-wage jobs [4].

Knowledge transfer platform INNOVMAT is therefore focused preferably on commercialization of innovative products with extremely large potential to achieve particularly high added value thanks to effectively utilized know-how. Transfer of knowledge requires the professional management and must be adequately secured by resources and by a long-term commitment of providing an access to the necessary funds and expertise.

7. Acknowledgements

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Ultra lightweight structural components based on reinforced aluminium foam

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reinforced aluminium foam
expanded steel sheet
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Professional article

Abstract: The possibility to produce the structural components made of aluminium foam appropriately reinforced in surface locations, where the greatest tensile strength are assumed, leads to the potential for significant weight savings keeping required mechanical properties. The low density of reinforced aluminium foam (~ 0.4 – 0.5 g/cm^3), simultaneously with sufficient high bending stiffness and strength, enables to attain extremely lightweight structural components. The technology for production of various lightweight panels, profiles, as well as various 3-D-shaped shelled structures, has been outlined in this contribution. This advanced technology enables to combine the unique mechanical properties of expanded stainless steel sheets reinforcements with advantageous stiffness and energy absorption response in such a manner, that resulting reinforced aluminium foam products fulfil the requirements not achievable by any other previously known solution utilizing single monolithic engineering material.

Reinforced aluminium foams can be successfully applied in lightweight crash energy absorbers and machine parts with request to enhance vibration damping and sound absorption, as well as panels created thermal barriers and noise attenuators. They can be in nearest future even used for novel 3D-shaped frameless shell structures of cars, buses, trains, ships, airplanes, cableways, etc., where excellent performance (stiffness, strength and passive safety) is expected at minimum weight. Because of their excellent corrosion resistance, non-inflammability and the fact, that they do not evolve toxic fumes in fire, they can be utilized also as decorative material for design applications, e.g., for passenger cabins in ships, dividing walls in airplanes, trains, cinemas, theatres, etc.

Ključne riječi

ojačana aluminijeva pjena
razvučeni čelični lim
inženjerski materijali
oblikovanje konstrukcija

Ultra lagane konstrukcijske komponente temeljene na ojačanoj aluminijevoj pjeni

Stručni rad

Sažetak: Proizvodnja konstrukcijskih komponenata izrađenih iz površinski ojačane aluminijeve pjene, gdje se traži povećana čvrstoća, omogućava značajne uštede na masi uz zadržavanje potrebnih mehaničkih svojstava. Niska gustoća ojačane aluminijeve pjene (~ 0,4-0,5 g/cm^3), istodobno s dovoljno visokom krutosti na savijanje i čvrstoćom, omogućuje postizanje izuzetno lakih konstrukcijskih komponenata. U ovom radu prikazane su tehnologije za proizvodnju različitih laganih ploča, profila, kao i raznih 3-D oblika konstrukcijskih komponenti. Ova napredna tehnologija omogućuje da se kombiniraju jedinstvena mehanička svojstva razvučenih limova iz nehrđajućeg čelika s povoljnom krutosti i apsorpcijom energije. Kao rezultat navedene kombinacije su proizvodi iz ojačane aluminijeve pjene, koji ispunjavaju zahtjeve a koji nisu ostvarivi bilo kojim drugiom ranije poznatim rješenjem temeljenim na korištenju monolitnog inženjerskog materijala.

Ojačane aluminijske pjene mogu se uspješno primijeniti kod lakih konstrukcija za upijanje energije sudara kao i dijelova za poboljšano prigušenje vibracija i zvuka, te za izradu panela namjenjenih toplinskoj i zvučnoj izolaciji. Ojačane aluminijeve pjene mogu se u bliskoj budućnosti koristiti nove 3D oblike konstrukcije karoserije automobila (bez čeličnih profila), autobusa, vlakova, brodova, zrakoplova, žičara, itd. kod kojih se traže izvrsna svojstva (krutost, čvrstoća i pasivna sigurnost) iz minimalnu masu. Zbog svoje izvrsne otpornosti na koroziju, ne-zapaljivost i činjenice da se ne razvija otrovni plin kod požara, mogu se koristiti i kao dekorativni materijal npr. za oblikovanje kabina na brodovima, pregrade u zrakoplovima, vlakovima , kinima, kazališta, itd.

1. Introduction

The cellular structure frequently used in various natural load-bearing solids (wood, bone) provides very good tool for highest stiffness and buckling resistance at minimum weight [1]. The Al-foam is porous material, which offers relatively good mechanical properties combined together with low weight of the structure. The material provides good heat conduction as well as good energy and sound absorption, proved by various experiments. Therefore, it can be applied in many branches of the industry, where light materials are required. The main interest of this material comes from transport industry (e.g., applications in airplanes interiors, cars, trains). In spite of a long time since the first patents concerning manufacturing of aluminium foams appeared [2-3], the material has not been put into the large commercial production up to now. This discouraging result can be attributed to inadequate design of applications, low reproducibility of the properties, missing of testing procedures and calculation approaches, absence of concepts for secondary treatment, as well as to complicated and relatively expensive preparation technology [4].

Mechanical properties of pure Al-foam can be improved by so called sandwich construction (e.g., with thin Al sheets firmly attached on the bottom and/or top sides of the structure loaded in tension) or using reinforcement materials. The aim of the presented work is to investigate the second type of improvement and optimize the amount of the reinforcing material to reach required mechanical properties (especially higher strength in tension) and reduce weight of the structure.

2. Manufacturing and structural use of reinforced aluminium foam

2.1. Manufacturing of reinforced aluminium foam

Powder compact foaming technique for aluminium foam manufacturing, at first patented in USA [3], comprises foaming of the precursor prepared by compacting of powdered metal with foaming agent (e.g., TiH_2 powder) by cold isostatic pressing followed by hot extrusion. The obtained precursor of various shapes (rods, wires, open profiles) possesses gas tightly sealed particles of foaming agent within metallic matrix. The pore forming hydrogen is evolved during melting of metallic matrix from admixed foaming agent. If the precursor is inserted in a suitable mould before foaming, foam follows the shape of mould cavity. Subsequent rapid solidification of the foam enables to obtain solid foam with dense surface skin and cellular inner structure.

Similar technology can be used also for manufacturing of reinforced aluminium foams [5]. They can be prepared either by foaming in the mould or by injection of foam into the mould (Fig. 1).

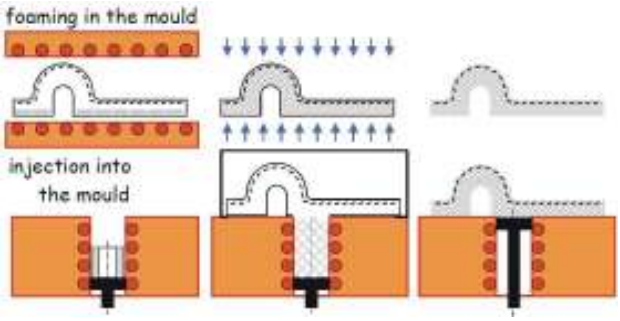

Figure 1. Manufacturing methods of reinforced aluminium foam.

Slika 1. Proizvodnja ojačane aluminijeve pjene.

When foamed in the mould, reinforcement, such as expanded stainless steel sheet or other mesh, net or woven textile made from metal or ceramic wires, etc., are placed in the foaming mould together with foamable precursor. The foam infiltrates the reinforcement during foaming or flows around it. After cooling, the foam adheres to the solid reinforcement and creates mechanical or optionally diffusion bonds.

Situation is similar when foam is injected into the mould: here the reinforcement is placed in the mould and liquid foam is cast on it. The applied pressure allows foam to infiltrate the reinforcement properly. It is often necessary to preheat the mould and/or reinforcement before foam injection to improve infiltration and bonding between foam and reinforcement.

Both methods allow the use of various types of reinforcements (ceramic, metal, or both simultaneously).

The opening and growth of cracks in cell walls can be prohibited by strengthening the foam with some kind of reinforcing elements, similarly as it is in a case of reinforced concrete (see Fig. 3).

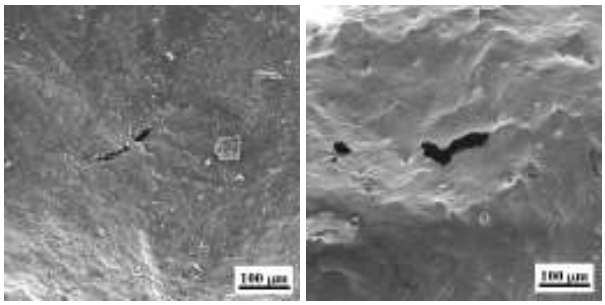

Figure 2. Defects and cracks present in aluminium foam cell walls (left – casting AlSi12, right – wrought AlMg1Si0.6 alloy).

Slika 2. Greške i pukotine na stjenkama ćelija aluminijeve pjene (lijevo – lijev AlSi12, desno – otkivak AlMg1Si0.6 legura)

If the reinforcements have higher elasticity modulus and sufficient yield strength, the tensile stresses are transferred from the foam onto these elements and existing cracks in cell walls become inactive. The reinforcements must be located in the surface areas where highest tensile stresses are expected, if possible, also with preferred orientation according to loading direction [5]. It is not necessary to reinforce compression-loaded locations. These features allow the use of reinforcements very effectively, saving weight and costs.

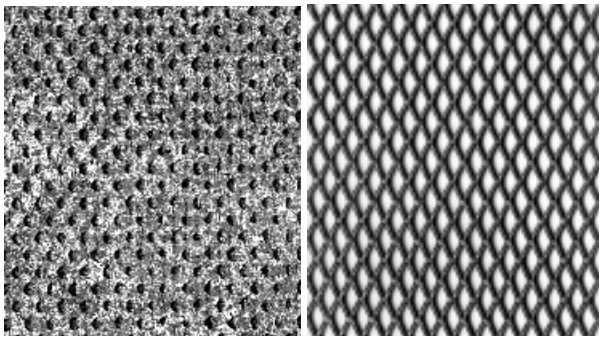

Figure 3. Surface skin of aluminium foam reinforced with expanded stainless steel sheet (M 1:1).

Slika 3. Površinski sloj aluminijeve pjene ojačane razvučenim limom iz nehrđajućeg čelika (M 1:1)

2.2. Industrial applications of aluminium foam

Typical use of aluminium foam in structural parts is usually in various cores, e.g. in hollow profiles, in sandwiches or in aluminium castings [6]. In all these cases the foam is use as a filler or space holder and its main role is to increase inertial moments of initially hollow cross section. Foam filled bulk parts possess thus increased stiffness and exhibit higher resistance to buckling. However, this alone is not sufficient for successful application of foam, because increasing of shell thickness can easily enhance the stiffness of hollow profile, as well, sometimes even more effectively.

The applying of reinforced aluminium foam is most competitive in comparison with other technical solutions, particularly if two or more advantages are used at once (see Fig. 4). Typical example of its multifunctional usage is its application within car crash zones. Not only its high stiffness and lightweight design are utilized, but also the ability to absorb large amount of crash energy and high efficiency to damp down unfavourable vibrations, thus reducing overall noise within the vehicle. It is important to understand the main structural principles for achievement of required combination of component properties in order to avoid the improper use of reinforced aluminium foam, which can cause disproportionate growth of production cost.

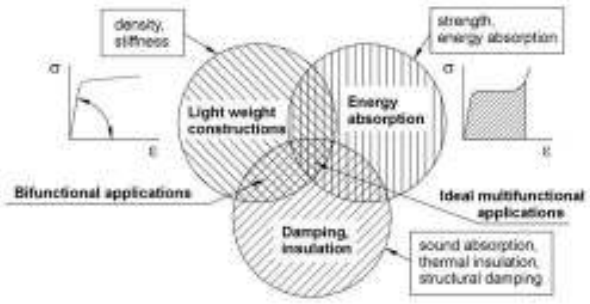

Figure 4. The benefits achieved by use of aluminium foams. [7].

Slika 4. Moguće pogodnosti korištenja aluminijevih pjena [7]

The unique combination of apparently concurrent properties of reinforced aluminium foam opens a huge potential for industrial applications such as:

- ✓ light and stiff structures of robots, manipulators, various transport and conveying systems,
- ✓ impact energy absorption components for crash zones of vehicles as protection for passengers,
- ✓ safety pads for lifting and conveying systems,
- ✓ protective covers for high-speed rotating machines,
- ✓ stiff permanent cores of hollow aluminium castings,
- ✓ machine castings and profiles with improved sound and vibration damping,
- ✓ stiff self-supporting heat shields and covers for encapsulation of heat sources,
- ✓ heat resistant, non-flammable and stiff doors, ceilings and wall panels with improved thermal and sound insulation,
- ✓ heat exchangers, filters, catalysts,
- ✓ industrial floaters resistant to high temperature and pressure, e.g., floaters for liquid level control in chemical processes,
- ✓ housings for electronic devices providing electromagnetic and heat shielding,
- ✓ covers for noise encapsulation and sound absorbing panels for difficult conditions (high temperature, moisture, humidity, sea water, dust, flowing gas, vibrations, sterile environment, etc.),
- ✓ highly efficient heat spreader for cooling/heating of interiors serving simultaneously as decorative sound absorbing lining in rooms where inflammability is vital (aircrafts, ships, hotels, theatres, cinemas, etc.),
- ✓ self-supporting, stiff and ultralight-weight panels for buildings and transport vehicles,
- ✓ fillings of hollow structural components serving as the prevention against buckling,
- ✓ light armours of military vehicles, aircrafts and helicopters reinforced by alumina ceramics with enhanced resistance against not only projectile penetration but also against blast wave caused by explosion of ammunition,

- ✓ isotropic properties, non combustibility, form stability and simple recycling make aluminium foam as an unique alternative to wood (no problems from wood pests is one of the most crucial advantages).

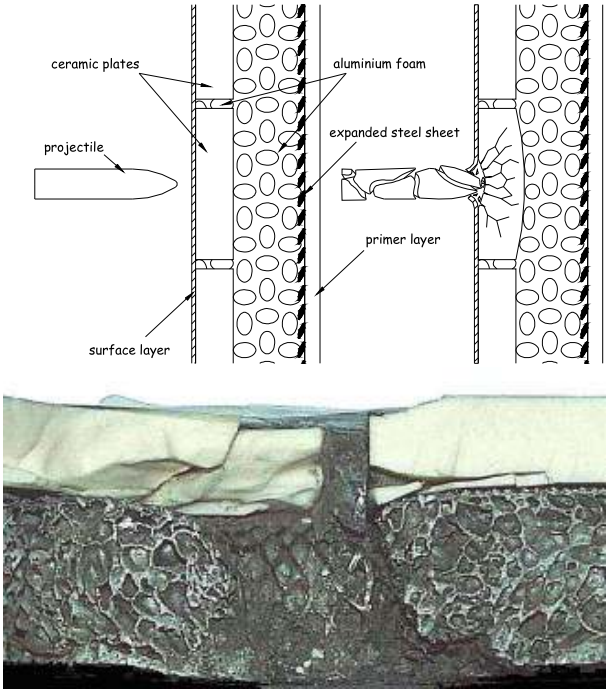

Figure 5. Structural component made of reinforced aluminium foam for ballistic protection (above – principle of ballistic protection, below – multilayer armour after ballistic impact). [8]

Slika 5. Komponenta izrađena iz ojačane aluminijeve pjene za balističku zaštitu (gore – princip balističke zaštite, ispod – višeslojni oklop nakon balističkog udara). [8]

3. Mechanical properties of reinforced aluminium foam

The bending stiffness of reinforced aluminium foam panels has been tested by four point bending tests in [9]. Two forms of loading are employed, the choice depending upon the type specified by standards for the particular material. In the first, a simply supported beam is subjected to a 'two-point' loading system as shown in Fig. 6 (a). Two concentrated loads are applied symmetrically to the beam, producing no shear force and constant bending moment in the central span of the beam (Fig. 6 (b), (c)). Therefore the condition of pure bending is achieved in the central span.

The second form of loading system consists of a single concentrated load at midspan (Fig. 6 (a)), which produces the shear force and bending moment diagrams shown in Fig. 6 (b) (c).

Loads are produced by a testing machine; deflections are measured by a gauge placed underneath the beam. From the recorded results a load-deflection diagram is plotted.

For most ductile materials the test beams continue to deform without failure and fracture does not occur. Thus the plastic properties, e.g. ultimate strength in bending, cannot be determined for such materials. The failure does occur only in the case of brittle materials.

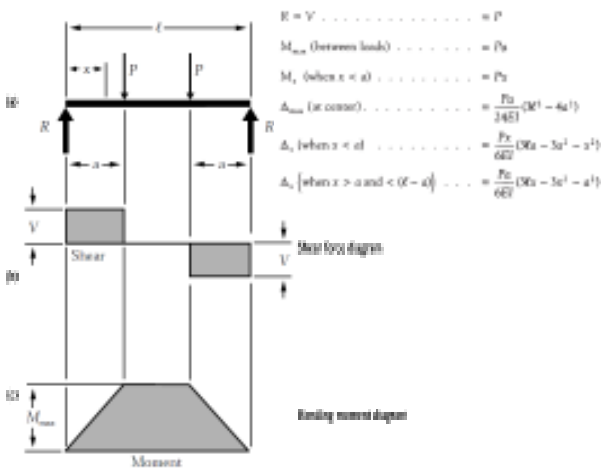

Figure 6. Bending test on a beam by four point bending tests, V = shear force, M = bending moment, Δ = deflection [14].

Slika 6. Test savijanja grede pomoću savojnog opterećenja u četri točke
V = sila smicanja, M = moment savijanja, Δ = progib [14]

Bending tests of reinforced aluminium foam have been carried out as four point bending tests in [9]. As can be seen from Fig. 7, the bending stiffness as well as the fracture resistance of panels can be significantly improved by reinforcing with expanded steel sheet placed on tensile loaded surface of the sample.

The further bending tests of reinforced Al-alloy AlSi10 foam have been performed in this contribution by four point bending tests in order to determine:

- ✓ attainable mechanical properties of castings made from reinforced aluminium foam (bending stiffness and strength),
- ✓ influence of various reinforcing expanded stainless steel sheets to bending behaviour of reinforced foamed samples.

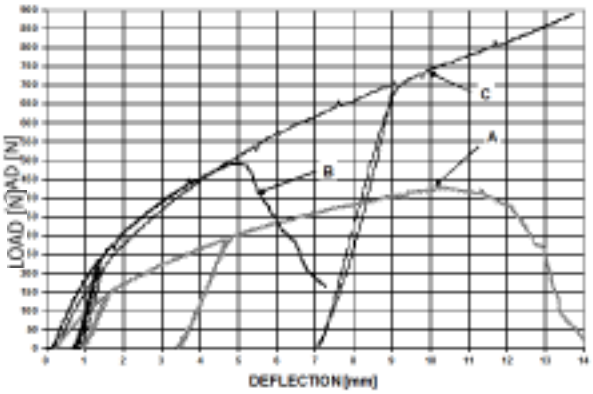

Figure 7. Four point bending test of aluminium foam samples (thickness 15 mm, width 50 mm, length 400 mm, cross head speed 10 mm/min, span between supports 150/300 mm, A – without reinforcement, density 0.4 g.cm^{-3}, B – upper surface reinforced with expanded steel sheet with the weight of 3.4 kg.m^{-2}, apparent density 0.6 g.cm^{-3}, C – bottom surface reinforced with steel mesh [9].

Slika 7. Test savijanja pomoću savojnog opterećenja u četri točke uzoraka iz aluminijske pjene (debljina 15 mm, širina 50 mm, duljina 400 mm, prosječna brzina10 mm/min, razmak oslonaca 150/300 mm, A – bez ojačanja, gustoća 0.4 g.cm^{-3}, B – gornja površina ojačana razvučenim čeličnim limom spec. mase t of 3.4 kg.m^{-2}, gustoće 0.6 g.cm^{-3}, C – donja površina ojačana čeličnom mrežom [9].

For these experiments, samples of size 150 mm × 50 mm × 25 mm were produced with the apparent density of 0.7 g/cm^3 by foaming of Al-alloy AlSi10 with two types of reinforcing expanded stainless steel sheets located in tensile loaded surface of the sample (dimensions of reinforcement see in table 1). The results of four point bending tests are shown in Fig. 8.

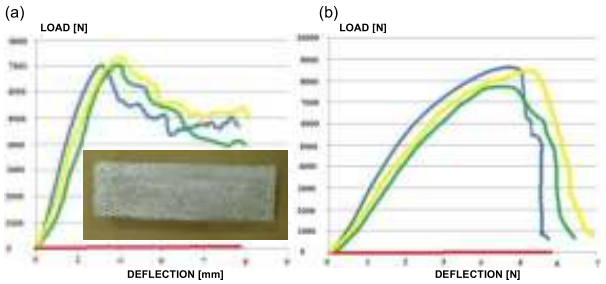

Figure 8. Four point bending tests on six Al-alloy AlSi10 foam samples (thickness: 25 mm; width: 50 mm; length: 150 mm; distance between – upper pushing cylinders: 40 mm and lower pushing cylinders: 120 mm; diameter of – upper pushing cylinders: 20 mm and lower pushing cylinders: 30 mm) reinforced in tensile loaded surface by two types of reinforcing expanded stainless steel sheets: (a) – MR 6, (b) – MR 10 (the reinforced surface of the sample is shown in the diagram left).

Slika 8. Test savijanja pomoću savojnog opterećenja u četri točke na 6 uzoraka iz AlSi10 pjene (debljina: 25 mm; širina: 50 mm; duljina: 150 mm; razmak između – gornjih potisnih cilindara: 40 mm i donjih potisnih cilindara: 120 mm; promjer gornjih potisnih cilindara: 20 mm i donjih potisnih cilindara: 30 mm) ojačane sa strane vlačno opterećene površine sa dva tipa razvučenih limova iz nehrđajućeg čelika: (a) – MR 6, (b) – MR 10 (ojačana površina uzorka je prikazana u dijagramu na lijevoj strani).

As can be seen from the results of these bending tests, the using of expanded stainless steel sheets MR 10 as the reinforcement leads to a slight improvement of mechanical properties, which may be caused primarily by better penetration of liquid aluminium alloy during foaming into the larger openings of this type of reinforcement. Moreover, various technological experiments related to assessing of the impact of foaming method to bending behaviour showed that any significant influence has been shown.

Tab. 1. Table of basic dimensions of expanded stainless steel sheets [12] (Notice: Feed – displacement of metal sheet during one sheering technological step; Thickness – initial thickness of metal sheet before manufacturing of the expanded stainless steel sheet.

Tab. 1. Tablica osnovnih dimenzija razvučenih limova iz nehrđajućeg čelika [9] (Napomena: "Feed" – pomak lima za vrijeme jednog tehnološkog koraka smicanja; "Thickness" – inicijalna debljina lima prije proizvodnje razvučenog lima iz nehrđajućeg čelika

Designation	**Length of mesh** (mm)	**Width of mesh** (mm)	**Feed** (mm)	**Thickness** (mm)
MR 6 (a)	6	3	0.8	0.5
MR 10 (b)	10	5	1	0.5

(a)

(b)

4. Conclusions

The new concept for design and manufacturing of lightweight load-bearing structural components based on utilization of reinforced aluminium foam prepared by PM techniques has been presented in this contribution. Utilization of aluminium foam core with reinforced surface layer will increase the capability of components to absorb crash energy in multiple impact directions, and also the significant reduction of noise and vibration of initially commonly manufactured hollow components is expected.

The approach proposed in this contribution allows the distribution of load-bearing material in most convenient way according to loading conditions, without need to increase the overall weight or volume of the part.

The extraordinary high stiffness-to-weight ratio of structural components manufactured by presented technique could be beneficial. As can be seen from this contribution, the fracture resistance and damage tolerance can be significantly improved without excessive weight increase by this way. Moreover, the reinforced components can be easily joined, what opens their enormous potential for applications in transport industry, especially for lightweight body structures of future cars, airplanes, ships, trains, etc.

5. Acknowledgements

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Laser interferometry investigation of polymer cement concrete samples for vibration measurements

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Keywords

Cement stones
Polymer cement concretes
Laser interferometry
Vibration measurements

Ključne riječi

Cementni blokovi
Polimer-cement-beton
Laserska interferometrija
Mjerenje vibracija

Professional article

Abstract: Analysis of dense cements and related materials such as polymer cement concrete (PCC) is significant to produce original innovative components for different types of buildings and structures. These materials can present elevated functional properties (e.g., ageing resistance, cracks' formation, durability, hardness and stability of mechanical modules) and they can be used for various purposes, for instance as corrosion resistive coatings for cement constructions.
In this paper, the experimental tests are reported, performed by laser interferometry, on different samples made of Portland or aluminous cement with added γAl_2O_3 and redispersible dry polymer, in order to identify the vibration characteristic parameters.
The obtained result allow carrying out a first analysis of the resonance modes for each investigated sample, thus contributing to discriminate the various natures of the considered PCCs.

Mjerenje vibracija laserskom interferometrijom uzoraka polimer-cement-betona

Stručni rad

Sažetak: Analiza cementa povišene gustoće i srodnih materijala kao polimer-cement-betona (PCC) je važna da se proizvodu izvorne inovativne komponente za različite tipove građevina i konstrukcija.
Ovakvi materijali mogu dati povišena funkcijska svojstva (npr. otpornost na starenje, nastajanju pukotina, izdržljivost, tvrdoća i nepromjenjivost mehaničkih modula) te mogu biti upotrebljeni za različite svrhe, kao što su prevlake otporne na koroziju za cementne konstrukcije.
U ovom radu, prikazani su pokusi, provedeni pomoću laserske interferometrije, na različitim uzorcima izrađenim iz Portland ili cementa sa dodatkom γAl_2O_3 i fino raspršenog suhog polimera, sa svrhom da se odrede karakteristični parametri vibracija. Dobiveni rezultati omogućuju preliminarnu analizu rezonantnih oblika za svaki ispitivani uzorak, te na taj način doprinosi razlučivanju različitih svojstva promatranog PCCs.

1. Introduction

Study of cements and related materials is important to create novel advanced components with elevated functional properties such as hardness, durability, resistance to ageing, stability of mechanical modules and ecological criteria [1]. Investigations of cements can use different methodologies to obtain information on aspects related to micro- and nano-structure, fatigue behaviour and computational mechanics. These investigations rely on tests, theoretical studies and simulation-based analyses. The study of parameters such as hydration degree of binder, balance between crystalline and gel phases of formed hydrated compounds, morphology and sizes of crystal hydrates, is also essential. For their research, different methods are normally applied, in particular X-ray and differential thermal analysis, infrared spectroscopy, optical and electronic microscopy. Various studies are being carried out, moreover, subjecting weathered materials to diverse stresses and conditions and using modal-based simulations; the aim is to obtain indication to predict the cement's behaviour after ageing and improve buildings and structures. A crucial parameter for cement is porosity, which affects mechanical and heat-insulation properties. This factor can be assessed by using gravimetric methods, gas and liquid porosimetry (e.g., mercury intrusion porosimetry), innovative approaches such as neutron techniques [1, 2] and acoustic methods: an acoustic-electric procedure was studied, e.g., which established the interrelation between porosity and the characteristics of electric and acoustic responses to their

pulsed mechanical excitation [3]. It is clear that the development in diagnostics of these materials is directly dependent on the application of different methods, in order to establish the relationship between their characteristics and macroscopic functional properties.

Symbols/Oznake

f_R	- resonance frequency, kHz - rezonantna frekvencija, kHz	Q	- quality factor - faktor kvalitete
Δf	- line breadth, s^{-1} - širina područja, s^{-1}		
	Greek letters/Grčka slova		
τ_c	- characteristic decay time of the excitement, m^2s^3 - karakterističnо vrijeme raspada od uzbude, m^2s^3		

The cement stone is a very delicate material and polymer's supplement is one of the ways to reduce this disadvantage. Different types of organic macromolecular substances of natural origin, e.g., rubber, synthetic polymers in the form of solutions, water dispersions or dry redispersible powders, may be used as polymer additives. The dispersion of thermoplastic polymers, such as polyvinyl acetate and its copolymers, butadiene-styrene and acrylic, is especially used to modify cement. The addition of polymer for cement can range from 1-2% to 20%. It is also known that the presence of polymers change the hardening mechanisms of Portland cement. In particular, X-ray phase analysis has shown that such presence is able to reduce the crystallization degree of hydro aluminate of calcium, which often leads to reduce the compressive strength of cement stone. In this work, PCC samples with different additives ratios, produced by the Department of Building Materials of the Ural Federal University (DBM-URFU), made of Portland or aluminous cement with added γAl_2O_3 and redispersible dry polymer have been investigated by laser interferometry (LI), with the aim to identify the vibration characteristic parameters and analyse the resonance modes for each investigated material. This work is a part of a full study of novel cements and related materials that Rogante Engineering Office has designed by adopting advanced methodologies. These specific measurements have been planned to verify the possibility of analysing the actual features of different PCCs. It is important, for instance, to be able to define the resistance and durability properties (and to be able to discriminate them initially), since they influence the destination of use. Moreover, the study of mechanical impacts in the form of vibration is a very interesting topic: materials resistant to vibrations can be regarded as promising for the creation of earthquake-resistant building structures. LI is a very sensitive measurement technique without contact, which permits to study the vibrations that, by adopting adequate stimuli, are given to the investigated bodies: from these vibrations, a first analysis of the resonance modes (e.g., resonance frequency and decay times of the stimulation) has been carried out for each considered PCC sample, in order to study the vibrational mechanical energy dissipation linked to each vibrational mode.

2. Materials and Methods

2.1. Polymer cement concretes

PCCs and polymer cement mortar (PCM) are cement-based concretes with the addition of different high-molecular compounds as aqueous dispersions. The supplement of polymers permits varying the cement stone's structure towards the crucial direction [4-9]. Two active components can be contemplated, i.e. mineral binding agent and organic matter. Binding agent and water form the cement stone, which joints particles of aggregate together, in order to create a monolith. In the composite binding, material polymer component and mineral binder are selected to be efficiently combined and to show their benefits, amplifying the strong points. The polymer, during the removal of water from the concrete, forms a thin layer on the surface of pores, cement and aggregate nodules, this layer having a good adhesive performance.

The principal requirement to the polymer addition is to retard the hardening process of cement stone with the minimum possible rate. Cement neo-formations produce the crystalline - coagulation structure; the rigid mineral skeleton formed strengthens in depressed defect points (pores and cracks) with polymer, leading to generate a composite material with enhanced strength and

elasticity, owing to articulated joint of hydrates with more flexible particles, nets and films of strong elastic organic polymers possessing adhesiveness. The concrete's main properties influenced by the supplement of polymer are abrasive resistance, deformability and strength. In particular, strength is one of the most important characteristics related with the structural properties. Strength values, for such heterogeneous material, can be evaluated to determine the phase composition. In this case, bending and tensile strengths increase significantly, furthermore compressive strength is enough improved. Abrasive resistance increases notably by enhancing the polymer rate. Polymer acts as a binder that prevents tearing of cement stone components from the surface. The concrete's elasticity modulus ordinarily decreases by increasing the polymer/cement ratio.

A research carried out by DBM-URFU is devoted to find out the interaction between cement, polymer and Al_2O_3 (γ type). Initially, γ-Al_2O_3 is made by thermal hydrolysis process [10]. The produced material, subsequently, is joint grinded in a planetary-type mill, to reach the average size of 70-90 nm. Both ways of polymer mixing have been studied, i.e. the joint grinded in polymer dispersion and the dry blended. The nature of interaction is supposed to be either physical or chemical. The polymer cements' hardening procedure involves a combination of two opposite processes, i.e. Portland cement clinker hydration and autohesion of polymer dispersion. A mineral-binding material may harden only in presence of water, and film formation occurs by drying. The γ Al_2O_3 grains, from a chemical point of view, can be the centres of clinker minerals' crystallization.

Polymer cement compositions, nowadays, find wide application in industry. Since these compositions possess increased bending strength, water and frost resistance, high adhesive properties, low abradability and porosity, they can be used as construction materials of high quality, such as coatings, plasters and insulation.

The chemical composition of the samples investigated includes: ordinary Portland cement; alumina cement; copolymer of vinyl acetate in powdered form, i.e., redispersible dry polymer (vinyl acetate and vinyl versatate having a temperature of vitrification of 5°C, a 100% content of solid substance and a particle size of 80 μm); Al_2O_3. Different γ-Al_2O_3/copolymer cement ratios are involved, the water/cement ratio remaining stable. Specimens of these materials are usually submitted to the following tests: bending and compressive strength, water absorption and density.

Table 1 reports the information on three the investigated samples, in particular the related additions and the type of the mixing procedure.

Table 1. Information on the investigated cement samples

Tablica 1. Informacije o pokusnim uzorcima

sample/	cement/	additions/ (% from the cement mass)	mixing/
a	Portland cement	1.5% copolymer 1.5% Al_2O_3	wet
b	Alumina cement	2.5% Al_2O_3	dry
c	Portland cement	2.5% Al_2O_3	dry

The used mixing methods are the following: for dry blending, powder of polymer and γ-Al_2O_3 added to cement, being mixed for 2-3 minutes; for wet blending, joint grinding copolymer and γ-Al_2O_3 in tempering water using a planetary mill.

2.2. Laser interferometry

Any solid body has some vibrational resonance frequencies, which depend from its shape and from its constitutive material. The resonance frequencies are excited from mechanical stimuli, such as collisions, vibrations and acoustic excitements. These frequencies define the formal procedure in which each body releases or transmits mechanical energy, once submitted to an excitement. Each vibrational mode is characterized by a resonance frequency f_R and by a characteristic decay time τ_c of the excitement (vibration) that describes how much rapidly the vibrational mechanical energy associated to the mode is dissolved. The line breadth of each mode depends on the decay time by the relation:

$$\Delta f = 1/\tau_c \quad (1)$$

For each mode, the quality factor Q is defined as:

$$Q = f_R/\Delta f \quad (2)$$

Larger it is Q, greater is the duration of the vibration once excited. Each vibrational mode, furthermore, is characterized from a specific space profile of the deformation. Within the excitement of a specific mode, all the points of the body oscillate with the same frequency and with different amplitudes and directions from point to point. The vibrational modes depend in identical measures from the shape of the body and from the constitutive material, and imperfections and defects can alter considerably their characteristics. The shape defines, in general, the resonance frequency, while the material defines the losses of the various modes, i.e. their quality factor.

The vibrational modes can be excited by collisions or blows, or from acoustic stimuli. A collision of short duration (ideally, infinitesimal) is able to excite all of the modes, having different resonance frequencies. An acoustic pressure wave that it is propagated in the air is able, likewise, to transfer energy to the vibrational modes, above all in those cases in which the frequency of the acoustic wave and the resonance frequency of the

mode coincide. The so called "modal analysis" [11] allows verifying the goodness of both project and fabrication of a product. By using appropriate mathematical models and software, it is possible to calculate and to identify the features of the vibrational modes of each body. The comparison between the forecasts of the model and the experimental measures allow emphasizing eventual problems either of the project or of the manufacture. The produced feedback consents to reconsider the project or the manufacture process, in order to improve the object performances. Conventional vibration techniques, including vibration monitoring and analysis, have a long, recognized reputation covering decades. The classical methodology to measure vibrations adopts contact sensors (i.e., accelerometers), which are electromechanical devices able to convert an acceleration into an electrical signal. These devices have been used, in the past, for different purposes, e.g. for monitoring machine tool vibrations [12]. A disadvantage of the accelerometers is that they should be connected rigidly to the body under measure, with the following main consequences: complication of the measurement procedure, since a shift of the sensor requires a new bolding; the not negligible mass of the sensor and of the electric cables disrupt the measured object, substantially modifying the resonance frequency; the accelerometers do not allow carrying out vibration measurements in particular points such as inside of cavities or of holes. The use of contact sensors such as the accelerometers, on objects of reduced dimensions or characterized from vibrations of small amplitude, is generally dissuaded as, having an actual mass, it can alter the physical property and the natural vibration of the system under analysis. Laser and optical sensing techniques include simple optical barriers, laser sensors for distance speed and vibrations, up to vision systems for color and shape recognition. These techniques range from traditional ones (e.g., LED+photodetector and laser triangulation) to novel collinear laser beam techniques such as confocal, self-mixing interferometry and coherent laser radar. Laser interferometry is a well established technique that permits remote and contactless measurement of the vibration of a solid target. It relies on the coherence properties of a laser beam, and on the high sensitivity of the coherent detection exploited in a Michelson interferometer, which allows detecting the very small echo signal backscattered by a rough diffusing surface. The features of the same investigated object, in this case, are not altered. The laser allows exploring the whole surface simply varying the incidence point of the beam. High resolutions can be obtained also for high frequency, allowing to carry out measurements on different typologies of surfaces and in difficult attainable points.

In the present work, the vibration measurement have been performed by using a VSM 100 laser vibrometer (Julight Co., Pavia, Italy) [13], presenting the following peculiarities: optical head with compact dimension that eases use and manageability; presence of an automatic mechanism that allows to find and to maintain the alignment during the measurement phase, suitable to measure any typology of surface, also very diffusive like in the present case.

3. Experiment, results and discussion

Fig. 1 shows the experimental set-up. The optical head of the laser vibrometer was positioned to a distance of 0.40 m from the investigated object. Fig. 2 shows that the measurements have been carried out also varying the position of the laser spot on each sample. Besides, for a same sample, also its free portion (outside from the bench vice) was varied. The laser vibrometer, measuring the vibrations of the surface, allowed obtaining an interferometric signal containing information on the resonance frequency and amplitude for each vibrational mode.

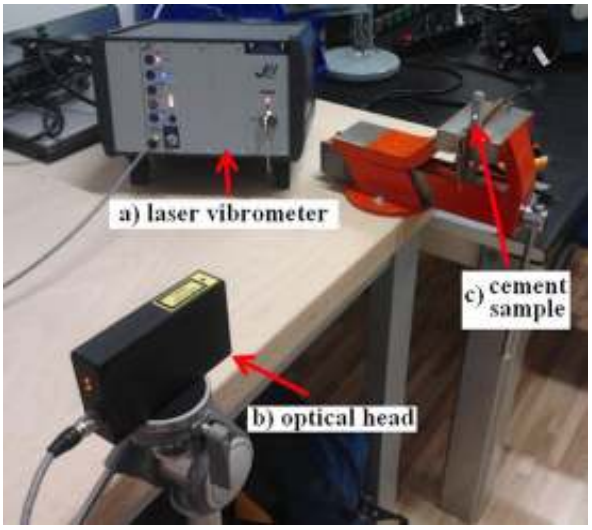

Figure 1. The experimental set-up.

Slika 1. Postavljanje pokusa

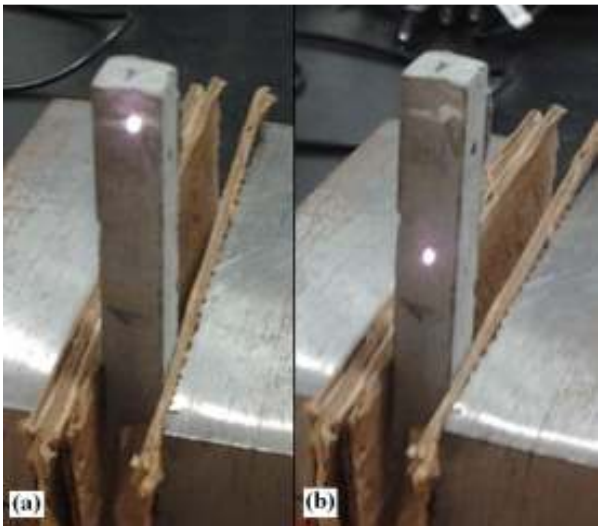

Figure 2. A polymer cement sample during the vibration measurements: a first (a) and a second (b) position of the laser spot are shown.

Slika 2. Uzorak iz polimer-cementa za vrijeme mjerenja vibracija: prva (a) i druga (b) pozicija laserske točke

After computing such signal, the laser vibrometer supplied in exit an analogue signal that is the exact replication of the measured vibration (1mV/μV). The obtained signals have been directly acquired by means of an oscilloscope (for the display in time) and elaborated off-line by means of a Matlab developed program.

To obtain a stimulation of all of the vibrational modes, a small hammer was used that, producing a collision of short duration, allowed the contemporary excitement of all of the modes. The use of the hammer, besides, consented to obtain collisions of known constant intensity, favouring measurements repeatable in the time.

For each analysed sample, the acquired signals and the measured frequency of resonance have been obtained.

Some examples of the signals obtained during the measurements are reported in Figs. 3-9 Fig. 3 refers to sample "a" (length = 55 mm; length of the sample's portion fixed in the grip = 15 mm; length of the sample's free portion = 40 mm) and represents a sequence of 2 blows towards the high.

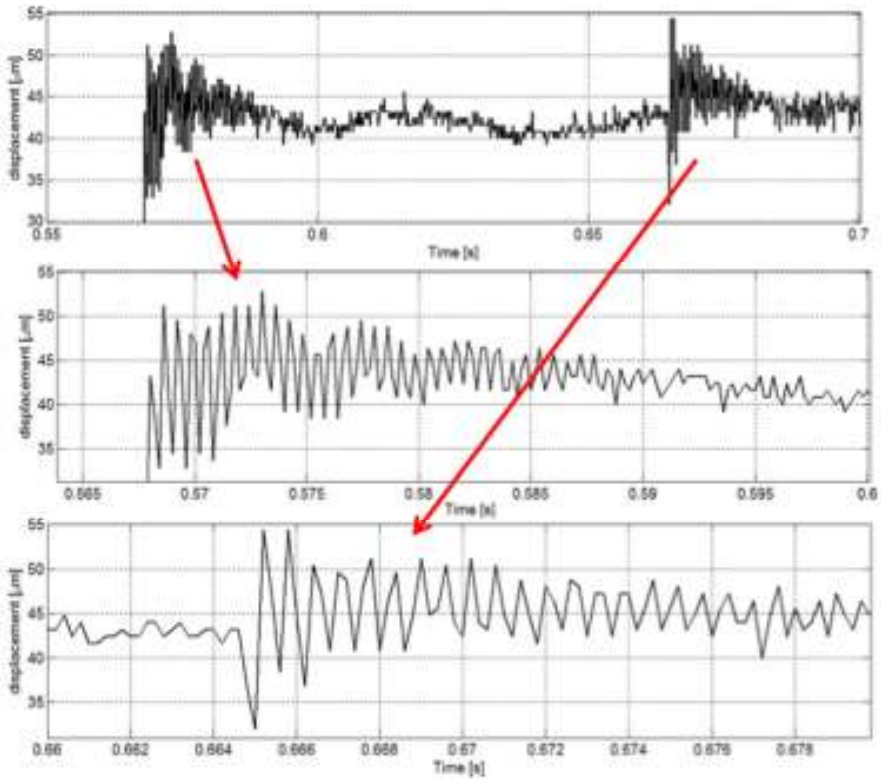

Figure 3. Vibration signal (upper graph) measured on sample "a" following an instantaneous excitement of the vibration modes; 2 zoom (middle and lower graphs) related to the instants in which the excitement has been given (free part = 40 mm)

Slika 3. Signal vibracija (gornji graf) mjeren na uzorku “a” nakon trenutne pobude forme vibracije; uvećanje 2 puta (srednji i donji graf) odnose se na trenutak davanja pobude (slobodni dio=40mm)

The vibration period corresponds to 0.6 ms and the resulting resonance frequency is f_R = 1.67 kHz. Figs. 4-6 refer to sample "b" (length = 55 mm) and each represents a sequence of 1 blow towards the high.

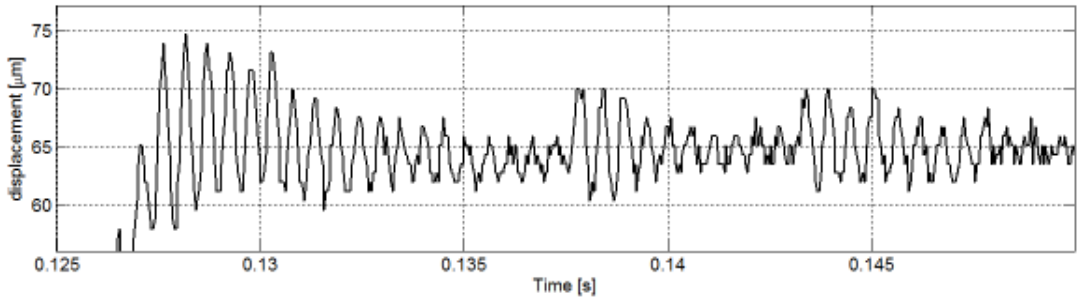

Figure 4. Vibration signal measured on sample "b" following an instantaneous excitement of the vibration modes (free part = 35 mm)

Slika 4. Signal vibracija mjeren na uzorku “b” nakon trenutne pobude forme vibracije (slobodni dio=35mm)

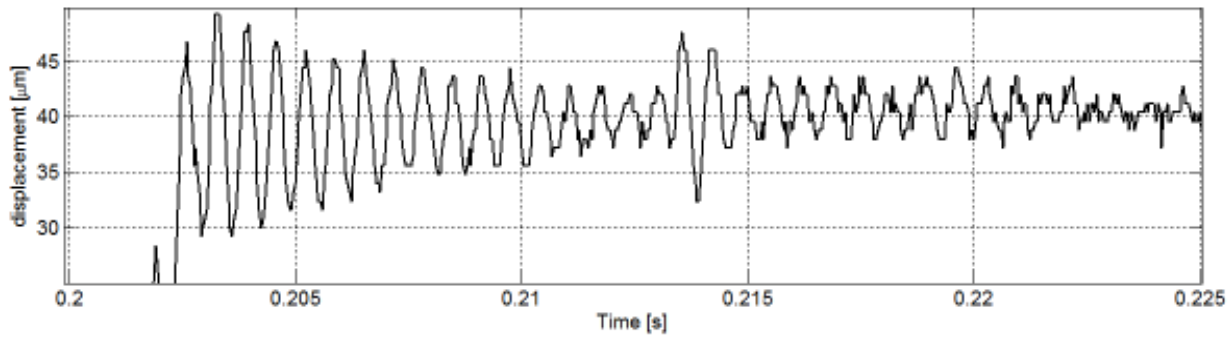

Figure 5. Vibration signal measured on sample "b" following an instantaneous excitement of the vibration modes (free part = 40 mm)

Slika 5. Signal vibracija mjeren na uzorku “b” nakon trenutne pobude forme vibracije (slobodni dio=40mm)

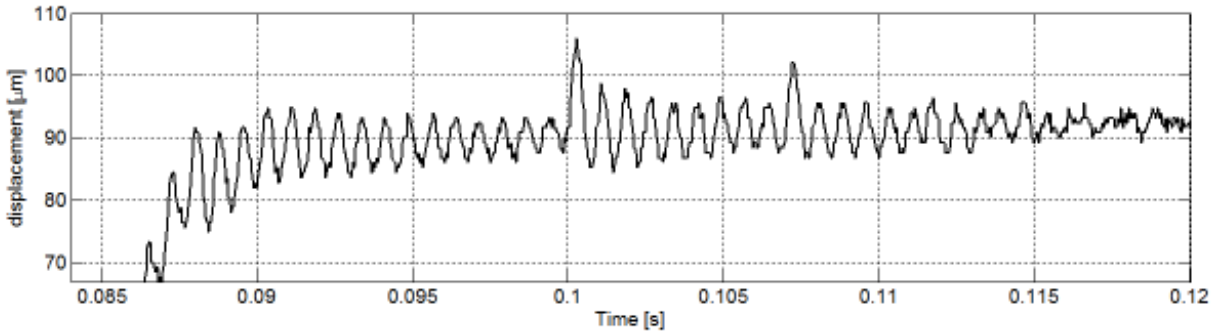

Figure 6. Vibration signal measured on sample "b" following an instantaneous excitement of the vibration modes (free part = 45 mm)

Slika 6. Signal vibracija mjeren na uzorku “b” nakon trenutne pobude forme vibracije (slobodni dio=45mm)

With reference to Fig. 4 (length of the sample's portion fixed in the grip = 20 mm; length of the sample's free portion = 35 mm) the vibration period corresponds to 0.55 ms and the resulting resonance frequency is f_R = 1.82 kHz. With reference to Fig. 5 (length of the sample's portion fixed in the grip = 15 mm; length of the sample's free portion = 40 mm) the vibration period corresponds to 0.65 ms and the resulting resonance frequency is f_R = 1.54 kHz. With reference to Fig. 6 (length of the sample's portion fixed in the grip = 10 mm; length of the sample's free portion = 45 mm) the vibration period corresponds to 0.75 ms and the resulting resonance frequency is f_R = 1.33 kHz.

Figs. 7-9 refer to sample "c" (length = 50 mm).

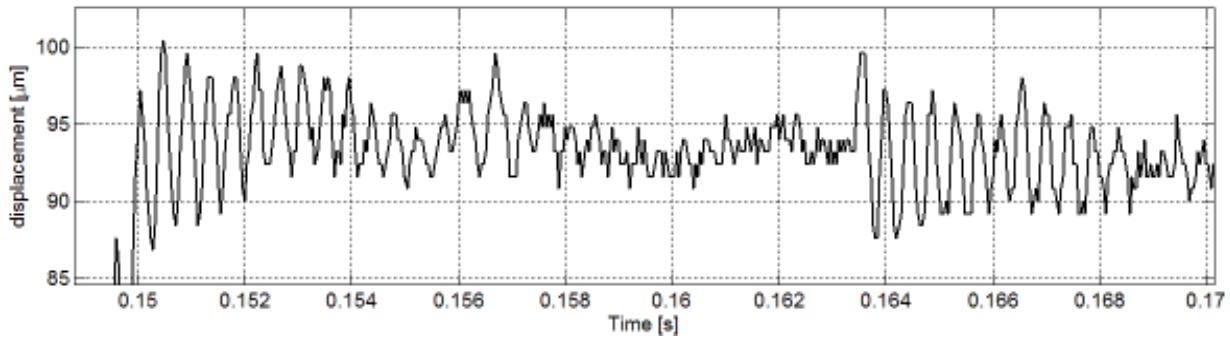

Figure 7. Vibration signal measured on sample "c" following an instantaneous excitement of the vibration modes (free part = 35 mm)

Slika 7. Signal vibracija mjeren na uzorku “c” nakon trenutne pobude forme vibracije (slobodni dio=35mm)

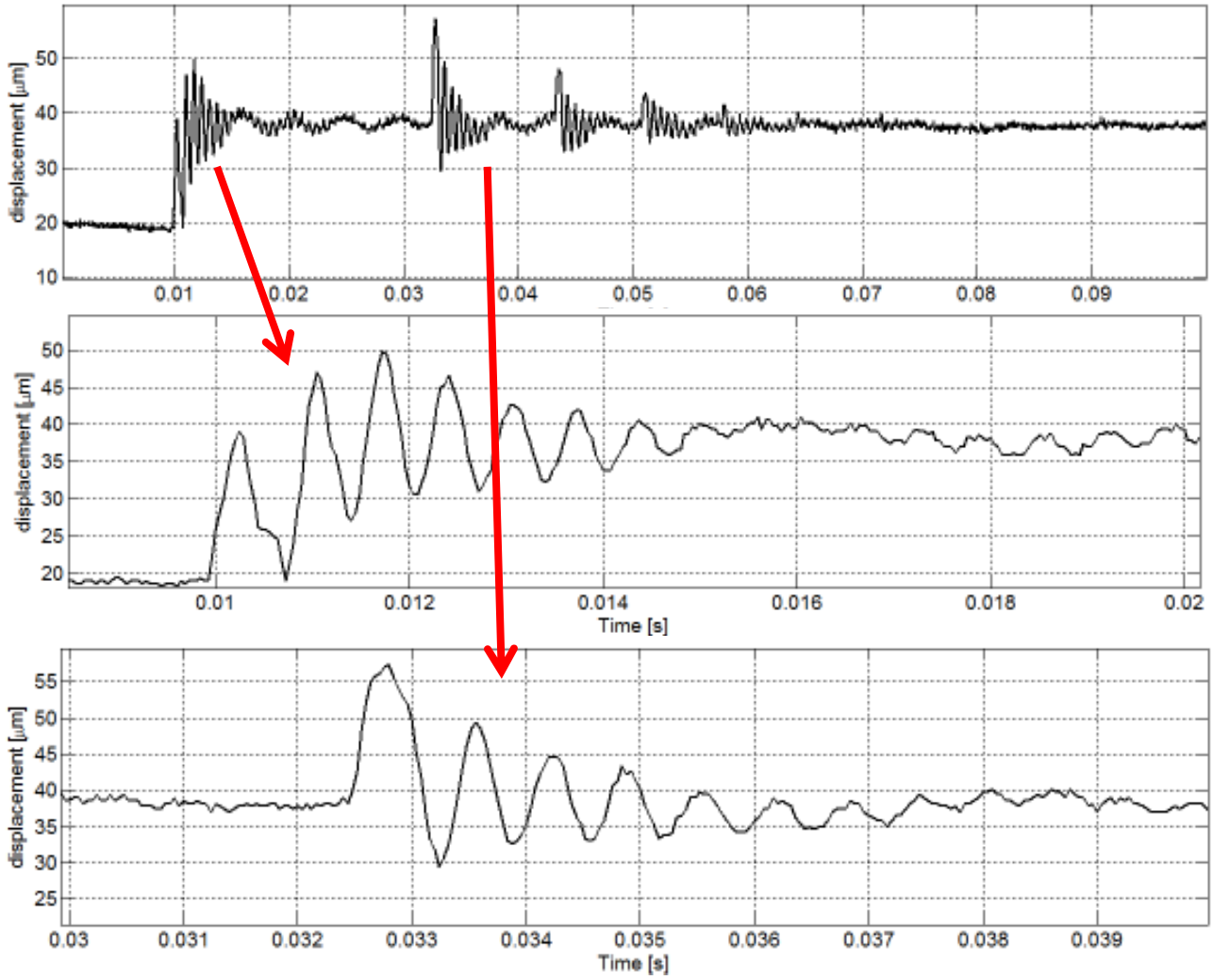

Figure 8. Vibration signal (upper graph) measured on sample "c" following an instantaneous excitement of the vibration modes; 2 zoom (middle and lower graphs) related to the instants in which the excitement has been given (free part = 40 mm)

Slika 8. Signal vibracija (gornji graf) mjeren na uzorku “c” nakon trenutne pobude forme vibracije; uvećanje 2 puta (srednji i donji graf) odnose se na trenutak davanja pobude (slobodni dio=40mm)

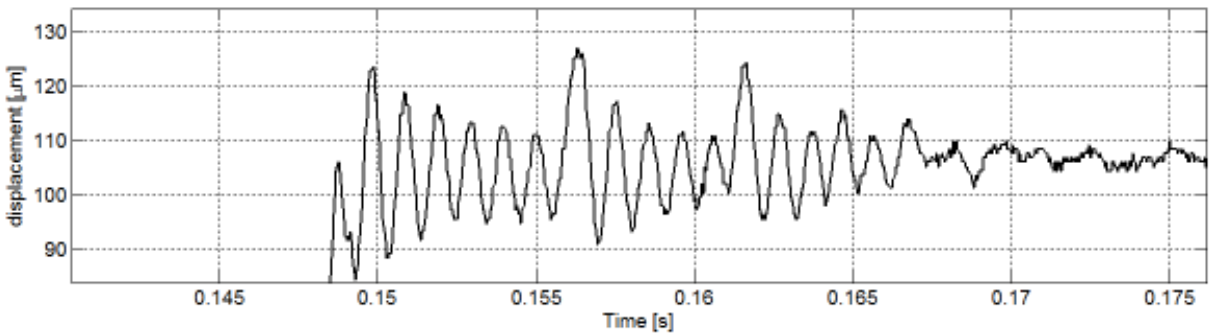

Figure 9. Vibration signal measured on sample "c" following an instantaneous excitement of the vibration modes (free part = 45 mm)

Slika 9. Signal vibracija mjeren na uzorku "c" nakon trenutne pobude forme vibracije (slobodni dio=45mm)

Fig. 7 (length of the sample's portion fixed in the grip = 15 mm; length of the sample's free portion = 35 mm) represents a sequence of 1 blow towards the high: the vibration period corresponds to 0.40 ms and the resulting resonance frequency is f_R = 2.50 kHz.
Fig. 8 (length of the sample's portion fixed in the grip = 10 mm; length of the sample's free portion = 40 mm) represents a sequence of more blows towards the high: the vibration period corresponds to 0.70 ms and the resulting resonance frequency is f_R = 1.42 kHz.
Fig. 9 (length of the sample's portion fixed in the grip = 5 mm; length of the sample's free portion = 45 mm) represents a sequence of 1 blow towards the high: the vibration period corresponds to 1.05 ms and the resulting resonance frequency is f_R = 0.952 kHz.
Tab. 2 resumes the resonance frequencies considering the different lengths of the free part of the sample (i.e., the part outside the bench vice).

Table 2. Resonance frequency of the investigated samples

Tablica 2. Rezonantne frekvencije ispitanih uzoraka

length of the free part/ (mm)	resonance frequency/ (kHz)		
	sample/ a	sample/ b	sample/ c
35	-	1.82	2.50
40	1.67	1.54	1.42
45	-	1.33	0.952

As shown in Tab. 2, the resonance frequency of every analysed sample changes depending on the length of the free part. At equal measurement conditions, however, it is possible in general to carry out a comparison between the different typologies of analysed samples. Such assertion is easily deductible analysing the case of the free part = 40 mm. At equal measurement conditions, in fact, the three samples present very similar resonance frequency values, but easily recognizable: in this case, Portland cement wet mixed with 1.5% PAV22 and 1.5% Al_2O_3 presents the higher resonance frequency. Passing from 45 mm to 35 mm of length of the free part, Portland cement, with respect to the aluminous cement (both dry mixed with 2.5% Al_2O_3) shows a much wider range of frequencies. In the comparison, only the free part of the sample's length was considered and not the whole length. Better and more significant results can be obtained using longer samples (i.e., having a greater flexibility). Concerning the decay time of the excitement, from the acquired signals it is hardly deductible since the speed of the damping. More significant signals could be obtained using excitements of greater intensity, but it should be underlined the risk of breaking due to the fragility of the analysed samples. Better results could be obtained using a different excitement method, not impulsive but by mean of a shaker for the excitement by the so called "white noise": in particular, it would allow obtaining a continuous excitement of all of the vibrational modes as well as acquiring significant signals in the time, which can be easily processed also by Fast Fourier Transform.

4. Conclusions

LI technique has allowed to identify easily the resonance frequencies of different PCC samples. By analysing either these resonance frequencies, or ideally the decay time of the vibration, it is possible to carry out a discrimination between different typologies of PCCs. The chemical composition (including binding agents, paste, etc.), in fact, influences on the rigidity/flexibility and on the mass of the body, which in turn contribute to determine the value of the resonance frequency of the body. From the resonance frequency, finally, it is possible to extract the value of the Young modulus connected with the elasticity of the investigated body. LI also allowed performing dynamical measurements by easily and rapidly varying the work point, which is not possible by using contact sensors.

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Green manufacturing through sustainable machining process

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Hlađenje zrakom
Vrtložna cijev

Early information
Abstract: Metal cutting industry is under increasing pressure as a result of competition, rigid environmental and health regulations and supply chain demand for improved environmental performance. In such a difficult time and circumstances for manufacturers, an advanced manufacturing mode called green manufacturing has become popular as sustainable development strategy in industrial processes. Green manufacturing from the perspective of modern manufacturing strategy has the purpose of reducing and minimizing environmental impact and resource consumption. The fulfillment of these objectives in case of metal cutting would represent a sustainable machining process. Cutting fluids used in machining for a variety of reasons, due to their environmental, social and economical influence has a great impact on sustainability of machining process. More attention focused to the negative effects of the cutting fluids has led to the necessity of finding new solutions. Alternative types of cooling in combination with new materials for making tools are presented as an area for appropriate replacement of the cutting fluids. This paper examines possibilities in metal cutting process improvements considering economic aspects, precisely the cost associated with cutting fluids. The benefits and capabilities of air cooling using vortex tube in milling process in terms of reaching a better surface quality with longer tool life were shown.

Ostvarenje zelene proizvodnje primjenom održive strojne obrade

Prethodno priopćenje
Sažetak: Industrija strojne obrade nalazi se pod stalnim pritiskom uslijed visoke konkurencije na tržištu, strogih regulativa po pitanju okoliša i zaštite na radu te visokih zahtjeva od strane dobavljača kao i krajnjih korisnika. U tako teškim vremenima i uvjetima za proizvođače razvijen je napredni pristup proizvodnji poznatiji kao zelena proizvodnja koja predstavlja održivu razvojnu strategiju industrijskih procesa. Zelena proizvodnja predstavlja pristup proizvodnji koji za glavni cilj ima smanjenje otpada i štetnog utjecaja na okoliš. Ostvarenje ovih ciljeva u slučaju obrade odvajanjem čestica predstavljalo bi održiv proces obrade. Sredstva za hlađenje, ispiranje i podmazivanje korištena prilikom strojne obrade imaju veliki utjecaj na ostvarenje održivih uvjeta uslijed njihovog negativnog utjecaja na ekonomiju procesa, društvo i okoliš. Prepoznavanjem negativnih učinaka ovih sredstava potaknuta je potreba za pronalaženjem boljih rješenja. Alternativne vrste hlađenja u kombinaciji sa novim alatima prezentirane su kao prikladna zamjena sredstvima za hlađenje, ispiranje i podmazivanje. Ovaj rad predstavlja mogućnosti unapređenja obrade odvajanjem čestica s ekonomskog, odnosno aspekta troška upotrebe sredstava za hlađenje i podmazivanje. Mogućnosti i prednosti hlađenja komprimiranim hladnim zrakom korištenjem vrtložne cijevi u procesu glodanja u svrhu postizanja bolje kvalitete obrađene površine uz duži vijek trajanja alata dane su u radu.

1. Introduction

Nowadays, mankind is no less dependent on technology than nature. Healthy environment is main criterion in order to ensure preservation of the human race. The manufacturing industry is one of the main causes of environmental pollution. The global environmental problems caused by the consumption of natural resources and the pollution resulting from the life of technical products have led to increasing political pressure and stronger regulations being applied to both the manufacturers and users of such products [1].

Symbols/Oznake			
F_c	- cost of machining per piece - trošak obrade odvajanjem po komadu	C_S	- storage cost of CFs - trošak skladištenja sredstava za hlađenje, ispiranje i podmazivanje
CFs	- cutting fluids - sredstva za hlađenje, ispiranje i podmazivanje	C_{DC}	- cost of distribution and collection of CFs - trošak distribucije i prikupljanja sredstava za hlađenje, ispiranje i podmazivanje
C_d	- direct operating costs - izravni operativni troškovi	C_M	- cost of maintenance of CFs - trošak održavanja sredstava za hlađenje, ispiranje i podmazivanje
C_i	- indirect operating costs - neizravni operativni troškovi	C_T	- treatment cost of CFs - trošak prethodnog tretiranja sredstava za hlađenje, ispiranje i podmazivanje
C_o	- operating costs per unit time - operativni troškovi po jedinici vremena	T_p	- total production time per piece, % - ukupno proizvodno vrijeme po komadu
C_t	- costs associated with tool change - troškovi povezani sa izmjenom alata	T_{tR}	- total cutting time of rough machining - ukupno vrijeme grube obrade
C_o	- operating costs per unit time - operativni troškovi po jedinici vremena	T_R	- tool life per rough machining - vijek trajanja alata pri gruboj obradi
C_F	- costs associated with the cutting fluid - troškovi povezani sa sredstvima za hlađenje, ispiranje i podmazivanje	T_{tF}	- total cutting time of finish machining - ukupno vrijeme završne obrade
C_P	- purchase cost of CFs - trošak nabave sredstva za hlađenje, ispiranje i podmazivanje	T_F	- tool life per finish machining - vijek trajanja alata pri završnoj obradi

Minimizing the negative impact of the manufacturing industry on environment and society should be the fundamental task and an important concern for all manufacturers. As a result of such efforts an advanced manufacturing mode called green manufacturing was developed.

Figure 1. Interaction between society, ecology, economy, and technology for sustainable machining process

Slika 1. Interakcija između društva, ekologije, ekonomije i tehnologije u svrhu ostvarenja održivosti strojne obrade

Green manufacturing is a subset of green engineering which is concept used to indicate environmental concerns in engineering. Green manufacturing can be realized through concept of sustainable manufacturing which considers environmental, economical and social aspects. In considering a sustainable machining process, the interaction between economy, ecology, society and technology has to be considered, as shown in Figure 1. Research and development (R&D) in machining processes have, on one hand, improved machining performances through advanced tool materials, higher productivity, and quality, while on the other hand, environmentally and health-friendly technologies are becoming increasingly important for achieving cleaner, healthier, and safer machining [2].

2. Traditional machining

Machining process is generally performed after other manufacturing processes such as casting, forging or bar drawing. Those processes create the general shape of the starting workpiece, and machining provides the final geometry, dimensions, and finish.

Machining is a term used to describe a variety of material removal processes in which a cutting tool

removes unwanted material from a workpiece to produce the desired shape. The predominant cutting action in machining involves shear deformation of the work material to form a chip; as the chip is removed, a new surface is exposed. Higher values of the cutting parameters offer the possibility to achieve higher productivity, but at the same time present a risk of deterioration surface quality and tool life. In traditional machining, cutting fluids (CFs) are commonly used during the machining of metals. There are various reasons for this, such as providing lubrication and cooling, improving tool life, reducing workpiece thermal deformation, improving surface finish and flushing away chips from the cutting zone.

Despite various advantages achieved by the machining process, they may generate solid, liquid, or gaseous by-products that present hazards for workers, machine and the environment

3. Main concerns in using of cutting fluids

In early 1960s, researchers have begun to recognize and express concern about the impact of CFs on the environment and health of workers. Today's cutting fluids manufacturers are in the position that they must follow and abide by the rules and regulations of various governments about the impact of certain chemicals on the environment and a society. Manufacturers around the world currently use about 2.4 billion liters of CFs forming a significant demand for this type of non-renewable raw materials [3].

Most of the CFs used in machining processes are petroleum-based oils which represent a big problem in disposing of such a resources. Petroleum-based oils cause water contamination, air pollution and soil pollution. Storage and disposal of used cutting fluids raises many environmental issues especially since it is one of the most complex types of waste. The total amount of satisfactory disposed (removed) lubricant is the amount of lubricant recycled or incinerated as a fuel, and according to the data from the EU area, it is only 32% of total consumption [4].

Figure 2. Scheme of losses in the machining process
Slika 2. Shema gubitaka sredstava za hlađenje ispiranje i podmazivanje u procesu obrade odvajanjem

Losses of cutting fluid from the manufacturing process occur through evapourisation, loss with chips and workpieces as they leave the machine, loss with machine components such as manipulation and transport devices, as well as losses through vacuum and air pressure systems and through droplet formation and ensuing leakage (Figure 2) [5]. In Western Europe alone, the total amount of lubricant that enters the environment can be said to be roughly the equivalent of 12 oil tankers or one 'Exxon Valdez' per month [4]. It is noteworthy that 155 million gallons of used cutting fluids are discharged into the environment yearly only in the United States [6].

CFs have negative health effects on the machinists, machinery mechanics, metalworkers and other machine operators and setters which have the greatest contact with these fluids. Prolonged exposure to CFs and its negative health effects during machining may lead to dermatological, malignant and nonmalignant respiratory and pulmonary disease, (Figure 3). According to the U.S. National Institute of Health estimates that the annual state-level 1.2 million workers adversely affected by CFs [7].

Different terms to characterize the physical-chemical properties of a CFs like explosive, oxidize, extremely flammable, highly flammable and flammable, and the toxicity of CFs such as very toxic, toxic, dangerous, corrosive, irritant, carcinogenic indicate high the risk of adverse impacts of CFs on health when handling such assets. Those hazards associated with CFs using, present CFs as hot button issues with a number of potential short-and long-term consequences for humans [8].

Figure 3. Skin damage (hand dermatitis) caused by long exposure to CFs
Slika 3. Oštećenja kože (kožni dermatitis) uzrokovan izloženosti sredstvima za hlađenje ispiranje i podmazivanje

3.1. Economical issues associated with cutting fluids

Metal cutting industry in a globalized and turbulent competitive environment faces rising economic cost pressures. The sustainable secure of the future for industrial production becomes a challenge. Many optimization potentials concerning efficiency

improvements of value adding production processes have already been raised in the past. Thus, cost reductions by optimizations of non-direct value adding processes in production are getting focused in recent times [9]. For example, the percentage of manufacturing sector of the total consumption of electricity in Germany of 519 TWh was about 47% in the year of 2009 [10]. Studies have shown that around 12,5% of manufacturing sector consumption is caused by the installed metal cutting machine tools [11]. In the field of metal cutting, up to 60% of the energy consumption is needed for the supply and reprocessing of cooling lubricants [12]. Such a high percentage presents a serious problem due to the continuing trend of growth in energy prices (Figure 4).

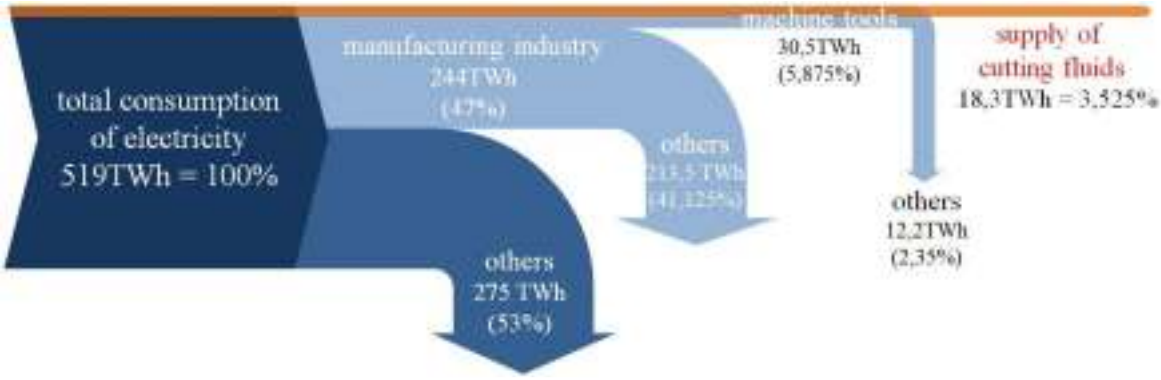

Figure 4. Sankey diagram for the consumption of the electricity in Germany in year 2009
Slika 4. Sankey dijagram za potrošnju električne energije u Njemačkoj 2009. godine

Many studies bring consumption data in tons, costs in the billions of dollars which is evidence of the extent of cutting fluids usage and costs in amounts to 17% [13].

Figure 5. Overview of the total manufacturing costs and cutting fluids costs
Slika 5. Pregled udjela troška sredstava za hlađenje, ispiranje i podmazivanje u ukupnim troškovima strojne obrade

Disposal costs of the cutting fluids can be up to two or four times their purchase price in the United States and Europe respectively [14]. Bierma and Waterstraat in their studies have been measured the costs of the two components of CFs, and the results showed that the ratio of the CFs cost and hidden costs (costs associated with use of CFs) are from 1.0 : 1.5 as well as up to 1.0 : 5.5 for some studies, favor of the hidden costs [15].
In manufacturing, failing to account for the total cost of materials can lead to poor management decisions with significant implications for profitability.

As engineers strive to continuously improve the efficiency of machining processes, they must rely on data about the cost of each operation and input material in the manufacturing process. Underestimating the true cost of operations and input materials can make an machining process appear to be far more efficient than it truly is.
The expression for cost of machining per piece can be provided as:

$$F_c = C_o T_p + C_t \left(\frac{T_{tR}}{T_R} + \frac{T_{tF}}{T_F}\right) + C_F T_P \quad (1)$$

The precise determination of C_o and C_F is not an easy task and require some knowledge and experience. The operating cost per unit time C_o can be expressed as:

$$C_o = C_d + C_i \quad (2)$$

The major components of direct cost are the direct labor cost and electricity. From previously published data of the energy consumption needed for the supply and reprocessing of cooling lubricants, it is important to pay attention to the electricity cost in component of direct costs. The high energy in the cooling lubricant loop is mainly caused by the energy demand of the applied pumping systems and the required cooling power for tempering the cooling lubricant. Indirect cost includes managerial overhead, indirect labor, and rent for the space occupied by machine tool, depreciation and maintenance.
In order to capture the real total cost of using CFs, which involves a process of procurement CFs, its storage, use, maintenance, collection, treatment and

disposal, it is necessary to take into account all the stages in the life cycle of CFs with detailed costs of each (Figure 6). In that case the expression for cost associated with the CFs can be expressed as:

$$C_F = C_P + C_S + C_{DC} + C_M + C_T + C_D \quad (3)$$

Ecological and health concerns are very important and must be followed strictly. However, a manufacturing industry is driven by profit motive and technological solution is difficult to implement unless it is profitable in monetary form. For this reason, cost calculation methodology for machining process described on previous page considering the cost associated with CFs is very important for understanding the true cost of traditional machining and benefits of implementing some sustainable alternative to CFs.

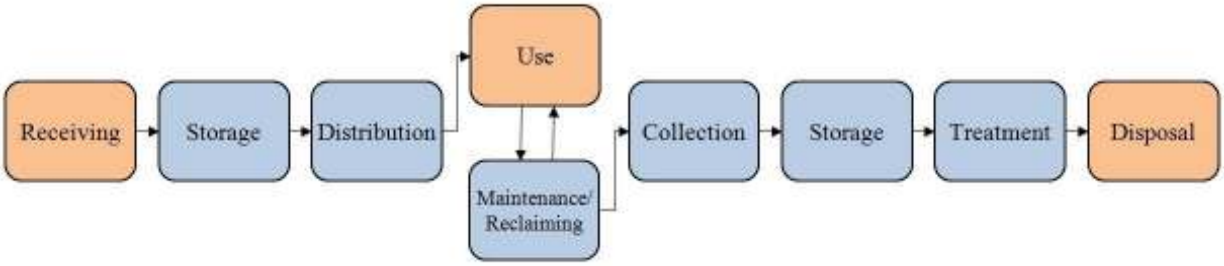

Figure 6. The typical in-plant life-cycle of a CFs
Slika 6. Životni ciklus sredstava za hlađenje, ispiranje i podmazivanje unutar proizvodnog poduzeća

4. Sustainable alternatives to liquid coolant in machining

4.1. Dry machining

Dry machining is ecological desirable process of metal removal that does not involve the use of wet cutting fluids. The elimination of coolant also imposes the loos of its positive effects, namely lubrication, cooling and flushing away the chips. Consequently, the mechanical and thermal loads on the cutting tool are increased. This means that there is more friction and adhesion between tool and workpiece. Therefore, cutting tool for dry machining applications can be designed in three different ways: by using new cutting tools material, by adapting new cutting tool geometries or by applying special cutting tool coatings [16].

Important factor affecting the choice of dry machining is the workpiece. Sometimes, a cutting fluid can stain the part or contaminate it. Consider a medical implant, such as a ball joint for a hip. Fluids are undesirable where there is the fear of contamination. A cutting fluid can be superfluous for cutting most alloys of cast iron, and carbon and alloyed steel, for example. These materials are relatively easy to machine and conduct heat well, allowing the chips to carry away most of the heat generated. The exception is low-carbon steel, which becomes more adhesive as the carbon content falls. These alloys might need a fluid as a lubricant to prevent welding. Machining stainless steels dry is a little more difficult. Heat can cause problems in these materials.

4.2. Near dry machining

In the machining of the above mentioned materials, an interesting option is the use a lubrication/coolant system based on the injection of pressurized air with small quantities of media. This technique is designated as minimum quantity of cooling and lubrication (MQCL). There are two type, minimum quantity cooling (MQC) and minimum quantity lubrication (MQL), depending on the type and on the main function of the fluid medium supplied. When oils are used as the fluid medium, the emphasis is on their good lubrication properties. Their function is to reduce friction and adhesion between the workpiece, the chip and the tool. As a result, the amount of friction heat generated is also reduced. Consequently, the tool and the workpiece are exposed to less heat than they would be if the machining operation was performed completely dry [17]. However, the minimum quantity cooling technique can make a major contribution to the solution of thermal problems affecting the tool and/or the part in dry machining operations.

4.3. Cryogenic machining

Cryogenic machining relates to delivering a super cold medium to the cutting region of the cutting tool, which is exposed to the highest temperature during the machining process, or to the part in order to change the material characteristics and improve machining performance.

The coolant is usually nitrogen fluid which is liquefied by cooling to 196°C (liquid nitrogen). Nitrogen in particular is an inert gas which forms 78% of the atmosphere and is lighter than air. As a result it is dispersed into the atmosphere and does not harm the workers on the shop floor, and is not considered as pollutants for the atmosphere [18].

4.4. Compressed cold air cooling

Employing compressed cold air for cooling in machining operations is a relatively new technique which has attracted many researchers. As in this technique the cooling media is air, it could be defined as the cleanest and most environmentally friendly method of cooling in cutting operations.
In this paper for experimental investigation compressed cold air was produced by the vortex tube (Figure 7). The vortex tube (also called the Ranque–Hilsch vortex tube) is a mechanical device operating as a refrigerating machine without any moving parts, by separating a compressed gas stream into a low total temperature region and a high one [19], [20] and [21].The only processes required in vortex tube compressed cold air cooling system are to compress, dry, and discharge the air with a set pressure. In most cases, the compressed air is already available for doing various types of task. Thus no additional arrangements are required.

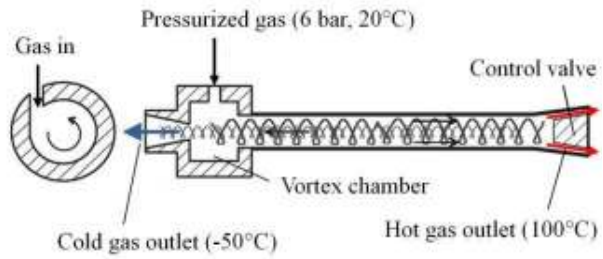

Figure 7. Process of the separation of a compressed air into a hot stream and a cold stream in vortex tube

Slika 7. Proces razdvajanja dviju struja zraka unutar vrtložne cijevi

5. Experimental settings

MQCL systems and cryogenic machining posses many advantages over traditional machining using CFs. However, there are some certain difficulties implementing them. For example, they aquire some modifications on machine tools and there is the additional cost involved in the equipment for both of the systems. In that case, choice of alternative types of cooling in the form of compressed cold air would mean a relatively small investment and application cost, almost no maintenance requirements with maximum fulfillment of sustainability terms (Figure 8).

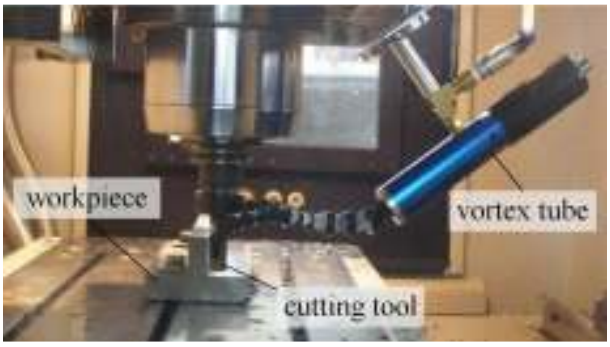

Figure 8. End milling process with alternative type of cooling, vortex tube compressed cold air system

Slika 8. Proces glodanja hlađen komprimiranim hladnim zrakom korištenjem vrtložne cijevi

However, the efficiency of the process in terms of tool life, the quality of the machined surface, the material removal amount is lower in some cases compared to the MQL technique and cryogenic cooling procedures. Notwithstanding of that, the selection of an alternate type of cooling creates opportunities in comparison with conventional cooling methods for the investigation purposes of the process sustainability
Machine tool used for the milling test was machining centre VC 560 manufactured by Spinner with added Vortec cooling system Cold Air Gun 610BSP with dual point nozzle. Cold air gun consumes 425 l/min (at 6,9 bar) of air and contains a vortex tube with isolation for noise and heat reduction. The temperature of compressed cold air was -2˚C.
Test samples were made of steel 42CrMo4 with dimensions 100x250x100 mm. The end milling experiments were executed by a tool CoroMill 390 with three TiN coated inserts, produced by Sandvik.
Average surface roughness *Ra* of machined workpieces was measured by a Surftest SJ-301, produced by Mitutoyo.

6. Results and discussion

The relationship between the tool wear and time of insert engagement under different machining environments are shown in Figures 9. It can be seen that changes in tool wear are least pronounced in the machining with air cooling.

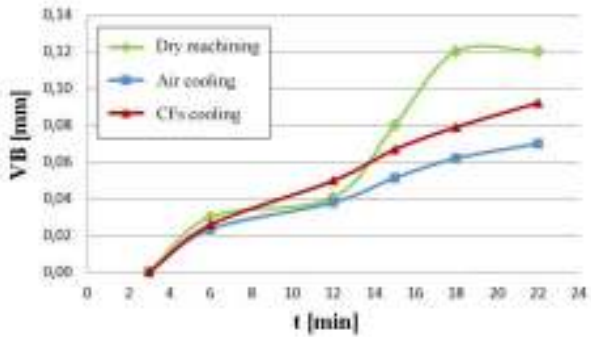

Figure 9. Tool wear progression with cutting time for different machining environments (v_c=100 m/min, f_z=0,05 mm/tooth, a_p=5 mm, a_e=1 mm)

Slika 9. Zavisnost trošenja alata o vremenu obrade za različite uvjete hlađenja korištene prilikom strojne obrade(v_c=100 m/min, f_z=0,05 mm/zub, a_p=5 mm, a_e=1 mm)

The relationship between the surface roughness and time of insert engagement under different machining environments, with pictures and values of tool wear at the end of the process (after 22 minutes of machining) are shown in Figure 10.

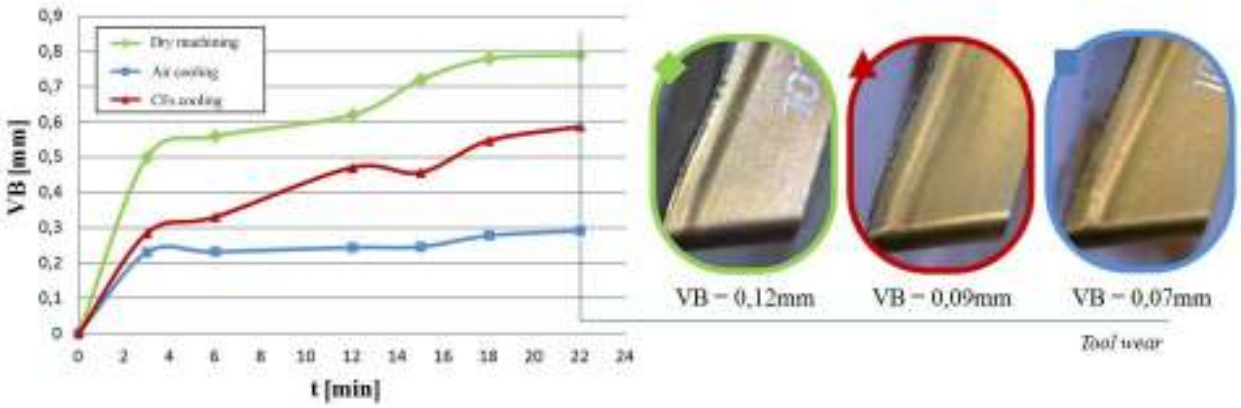

Figure 10. Surface roughness progression with cutting time for different machining environments and tool wear values at the end of machining process (after 22 minutes of machining), (v_c=100 m/min, f_z=0,05 mm/tooth, a_p=5 mm, a_e=1 mm)

Slika 10. Rast površinske hrapavost u ovisnosti o vremenu obrade i fotografije stanja alata sa pripadajućim vrijednostima trošenja alata na kraju obrade (nakon 22 minute strojne obrade) u različitim uvjetima strojne obrade, (v_c=100 m/min, f_z=0,05 mm/zub, a_p=5 mm, a_e=1 mm)

In terms of surface roughness and tool wear, the best conditions are achieved during machining with air cooling for both combinations of cutting parameters. The increase in surface roughness approximately corresponds to an increase in tool wear.

7. Conclusion and future work

This paper gives an overview of the machining process with the respect to the sustainability manufacturing. The emphasis is given to the impact of machining process on the environment, health and specially on economic conditions. Competitive cost pressures and increasingly stringent environmental and occupational health standards are inspiring current machining industry to seek ways to minimize or eliminate their use of CFs. The CFs viewed from three different aspects such as ecological, economical and sociological, represents a big challenge to scientists in their looking for better solutions in the field of cooling and lubrication in the machining, which will be technically and economically competitive and will not be a threat to the future, or to the sustainability machining. According to the theoretical study and the result of the experiment presented in the paper, there is a great potential in replacing the traditional ways of cutting fluids applications with compressed air cooling, in terms of shorter cycle times, better surface finish, longer tool life, and higher recycling value for clean chips.
Alternative types of cooling in combination with new materials for making tools and special coatings represent an area of future research.

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Identification of critical operating conditions to avoid premature failure of gearbox components due to early detection of the associated aging of lubricating oil

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Keywords
premature bearing failures
vibration loading
chemical oil aging
industrial gearboxes
wind energy generation

Ključne riječi
prijevremeno oštećenje ležaja
vibracijsko opterećenje
kemijsko starenje ulja
industrijski mjenjači
vjetrogeneratori

Review article

Abstract: The main gearbox components are bearings, gears and shafts. In industrial, particularly in wind energy gearboxes, premature failures of rolling bearings are a severe application problem. A novel web-based oil sensor diagnosis system for continuous lubricant monitoring and early identifying of the critical operating conditions is presented.

The fundamental innovation is that gearbox operating conditions critical for premature failures are detected in an early stage before bearing damage by loading induced changes of the lubricant. Existing systems, such as vibration analysis, visual inspection, filters and particle counters, only respond to spalling.

The mainly larger roller bearings in wind energy gearboxes often fail prematurely, clearly before their calculate L10 life, due to so-called white etching cracks. These failures are characterized by usually axial raceway cracks, from which deep branching and spreading crack systems develop into the material by corrosion fatigue. The root cause of these premature bearing failures is vibration loading. The resulting specific mixed friction operating conditions involve high localized friction coefficients that initiate tensile stress induced brittle spontaneous cleavage-like surface cracking. The basic idea of the new premature failure detection condition monitoring system is the early identification of chemical aging of the lubricant and its additives under the influence of vibration loading.

The WearSens® sensor effectively controls the proper operation conditions of bearings and gears in gearboxes. The online diagnostics system measures components of the specific complex impedance of oils. For instance, metal abrasion due to wear debris, broken oil molecules, forming acids or oil soaps, result in an increase of the electrical conductivity, which directly correlates with the degree of contamination of the oil. Thus, incipient wear is also detected early and efficiently. For additivated lubricants, the stage of degradation of the additives can also be derived from changes in the dielectric constant. The determination of impurities or reduction in the quality of the oil and the quasi continuous evaluation of wear and chemical aging follow the holistic approach of a real-time monitoring of an alteration in the condition of the oil-machine system.

The measuring signals can be transmitted to a web-based condition monitoring system via LAN, WLAN or serial interfaces of the sensor system. The monitoring of the tribiological loading and wear mechanisms during proper operation below the tolerance limits of the components then allows preventive, condition-oriented maintenance to be carried out, if necessary, long before regular overhauling. Outages caused, e.g., by the impact of vibrations or wear are reduced while simultaneously the overall lifetime of the oil-machine system is increased.

Prepoznavanje kritičnih pogonskih uvjeta komponenti mjenjača na temelju praćenja starenja ulja za podmazivanje s ciljem izbjegavanja prijevremenih kvarova

Pregledni rad

Sažetak: Glavne komponente mjenjača su ležajevi, zupčanici i osovine. U industriji, a osobito u mjenjačkim kutijama vjetrogeneratora, preuranjeni kvarovi kotrljajućih ležajeva predstavljaju ozbiljan problem. Novi senzori za kontinuirano praćenje sustava podmazivanje i rano otkrivanje kritičnih pogonskih uvjeta prikazani su u ovom radu.

Temeljna inovacija sastoji se u tome da se kritični pogonski uvjeti za nastajanje prijevremenih kvarova prepoznaju u ranoj fazi prije nego što nastane oštećenje ležajeva, a na temelju opterećenjem izazvanih promjena u mazivu. Postojeći sustavi, kao što su analize vibracija, vizualni pregled, filteri i detektori čestica, samo upućuju na trošenje.

U glavnom veliki valjkasti ležajevi u mjenjačkim kutijama vjetrogeneratora često otkazuju prerano, točnije prije njihovog proračunatog vijeka L10, zbog pukotina uslijed umora površine. Ove greške su karakterizirane kao pukotine aksijalnog smjera, koje se granaju i šire prema unutrašnjosti materijala kao posljedica korozijskog umora. Izvor ovih prijevremenih grešaka je dinamičko vibracijsko opterećenje. Rezultirajući posebni uvjeti trenja uključuju visoke lokalne koeficijente trenja, a koji iniciraju vlačno naprezanje uslijed čega dolazi do nastajanja površinskih pukotina. Osnovna ideja ovog sustava za rano otkrivanje kvara zasnovana je na praćenju starenja maziva i njegovih dodataka pod utjecajem dinamičkog vibrirajućeg opterećenja.
Senzor WearSens ® učinkovito kontrolira odgovarajuće uvjete rada ležaja i zupčanika u mjenjaču. „Online" sustav dijagnoze mjeri složene impedancijske karakteristike ulja. Na primjer, kod abrazije metala čestice trošenja, razložene molekule ulja, nastale kiseline i metalni sapuni, rezultiraju povećanjem električne vodljivosti, što izravno utječe na stupanj onečišćenja ulja. Početno trošenje se također otkriva rano i učinkovito. Za maziva sa dodatkom aditiva, stupanj degradacije dodataka također može biti određen iz promjene dielektrične konstante. Određivanje nečistoća ili smanjenje kvalitete ulja i kontinuirana procjena trošenja i kemijskih starenja slijedi holistički pristup praćenja u stvarnom vremenu promjena stanja sustava podmazivanja.

Mjerni signali mogu se prenijeti na web preko LAN , WLAN ili serijskog sučelja sustava senzora. Praćenje triboloških opterećenja i mehanizama trošenja za vrijeme ispravnog rada unutar dozvoljenih granica omogućava preventivno, održavanje prema stanju sustava., ako je potrebno, znatno prije redovitog servisa. Zastoji izazvani npr. zbog utjecaja vibracija ili trošenja, su smanjeni, dok se istodobno ukupni pogonski vijek sustava podmazivanja povećava.

1. Introduction

The online WearSens® system for continuous monitoring of oil enables reliable detection of incipient damage and the early identification of critical conditions in lubrication of bearings and other transmission elements. Bearing and raceway wear result in metal dust, foreign particles and suspended solids, as well as chemically broken oil molecules which form acids or soaps leading to an increase in electrical conductivity. Conductivity directly correlates with the degree of contamination and transmission wear.

Simultaneously an additional high precision measurement of the dielectric constant indicates the reduction of additives in the oil. Continuous evaluation of the chemical aging of the lubricant in the operation opens up a new method for preventing premature bearing failure occurring due to vibration induced, mixed friction stresses [1]. Applications such as wind power and other industrial gears benefit from timely implementation of appropriate corrective measures, such as load reduction or oil change. This innovative approach goes far beyond the simple detection of already incurred, irreversible damage to the raceway. The measurement of the dielectric constant of lubricating oils not containing additives allows in the determination of water content. The basic components of the sensor measure the complex impedance of the oils. For example, metal debris, broken oil molecules, acids or oil soaps all increase the electrical conductivity. Although the oil and the resulting ions from acidification are buffered in high quality oils with additive, even so the additives react to changes in the oil in minutes whilst the sensor detects any change in seconds – before the additives work.

The fast speed of response of WearSens® enables quasi-continuous monitoring, preventive condition-based maintenance and wear-limit rules for equipment and systems, such as wind turbines, turbines, industrial gears, paper machines, motors and transformers. This online monitoring permits the reduction of downtime and increases overall service life. The measured signals can be transmitted to a condition monitoring system via a serial interface or LAN or WLAN.

The less stable nature of gear on wind turbine towers often leads to increased stresses on the components by vibration. In rolling contact bearings and toothed wheels specific mixed friction is generated [3]. A possible consequence is micropitting. In addition, under certain load conditions local friction can be greatly increased in micro-regions, leading to the formation of brittle fracture cracks. This damage is characterized by axial raceway cracks, as shown in Figure 1 and Figure 2.

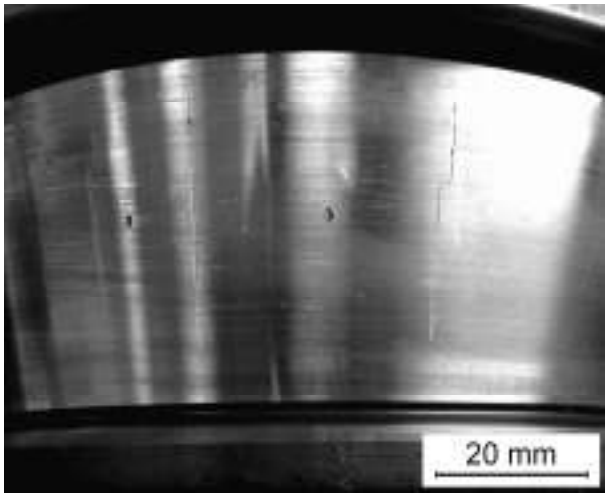

Figure 1. Damaged raceway of a tapered roller bearing inner ring from a wind energy transmission box with typical axial cracks and the beginning of small spalling [2].

Slika 1. Oštećena površina unutrašnjeg prstena koničnog valjkastog ležaja iz mjenjača vjetrogeneratora s tipičnim aksijalnim pukotinama i početkom ljuštenja

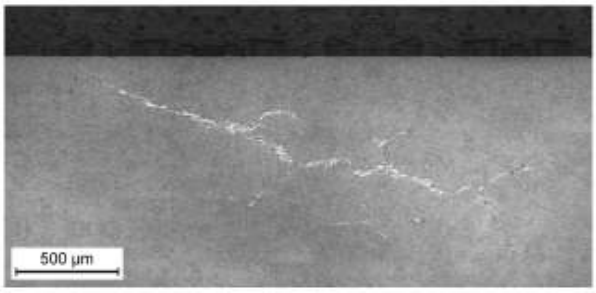

Figure 2. Branched crack system in the etched scale section of a roller bearing inner ring [3].
Slika 2. Raširena pukotina na unutrašnjem prstenu valjkastog ležaja

So the cause of early bearing failure is understood. Ions generated by vibration-induced aging of the oil are detected by WearSens® before they can be chemically converted and buffered by additives. To do this the sensor system measures the complex impedance of the oil components, in particular the electrical conductivity, κ, and the relative dielectric constant, ε_r, and the oil temperature, T. The effect of temperature on the other measurements is eliminated by an integrated, self-learning adaptive temperature compensation. From changes in the measured signals of the oil, bearing and gear wear can be identified.

2. Physical principles

The WearSens® sensor measures the components of the complex impedance X of the oils, in particular the electrical conductivity κ, the dielectric constant ε_r and also the oil temperature T. The values of κ and ε_r are determined independently of one another [2].

The electrical conductivity κ and the dielectric constant ε_r of the oil are temperature dependent, this requires an additional measurement of the oil temperature. The ionic mobility, and therefore the conductivity κ, depends on the internal friction of the oil and the temperature. The conductivity κ of the oil increases with temperature T. To improve the comparability of the measurements an adaptive temperature compensation algorithm was developed.

The sensor base comprises two or more sensor base plates which are attached to each other at a constant distance by metal pins with a glass/metal seal. The plates are placed in the center of the measuring chamber to ensure a smooth flow. Special alignment or adjustment of the sensor housing parts is not necessary with this structure. The sensor will withstand pressure greater than 100 bar. Figure 3 shows a photograph of the base sensor with three plates.

Figure 3. Basic sensor with three plate design.

Slika 3. Osnovni senzor

3. Interpretation of sensor measurements

At a transmission test stand different load cycles were run and the conductivity κ, the dielectric constant ε_r and the temperature of the transmission oil were measured. The results of the experiment are presented below.

During loading, the conductivity κ of the transmission oil changes. The cause of the increase in conductivity (in addition to temperature changes) includes wear particles, pollution products, broken oil molecules and acids or oil soaps formed by the breakdown. The temperature dependence of the electrical conductivity κ of the gear oil used is automatically compensated by a self-learning algorithm and a mathematical conversion of the measured oil conductivity to the corresponding conductivity reference value at 40°C performed.

Figure 4 shows the change in the electrical conductivity against time. The graph shows in each case about three minutes intervals Δt and the calculated mean values $\Delta\kappa_{40}$. In the first low load, the electric conductivity

increases linearly with time. Presumably, the low bearing wear in this area also grows proportionally over time. During the shutdown and startup of the engine to 330 Nm, the conductivity is practically constant. After switching to the higher load, the oil conductivity increases greatly. The shrinkage (import) of the bearing is shown here in a reduction in the increase in the conductivity. Starting about 30 minutes before shutting down (from a vibration sensor measurement), the conductivity remains approximately constant to the end when a short-term increase occurs.

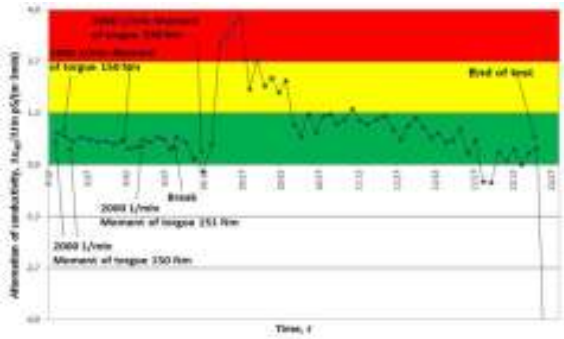

Figure 4. Change of conductivity over time, expressed as $\Delta\kappa_{40}/\Delta t$.

Slika 4. Promjena vodljivosti u odnosu na vrijeme izražena kao $\Delta\kappa_{40}/\Delta t$

After the shutdown of the load, oil conductivity drops sharply. This clearly shows the effect of the additives. During periods of stress pollution products are produced more quickly than the additives can bind them. After the shutdown of the test rig will be oil contamination stops increasing and the effect of the additives can be seen.

When starting with 2000 rpm and a torque of 150 Nm, a relatively constant change in conductivity results from 0.6 to 0.8 pS/m (over 3 minute intervals), corresponding to 3.3 to 4.4 fs · $m^{-1}s^{-1}$. After the change in the torque to 330 Nm and the rotational speed to 3000 rpm, the change in conductivity increases significantly, indicating the formation of the first raceway damage.

After the load increase the change in conductivity of the oil shows a rising momentum. This suggests fluctuating pollution accumulation and changes in the bearing loads, as is to be expected with the formation of spalling. The jumps in the slope of the electrical conductivity before switching off are an indication of the final bearing damage. Figure 5 shows the inner ring of the failed planet bearings with highly degraded raceway after completion of the test run.

Figure 5. Damaged inner ring raceway of the failed planetary cylindrical roller bearing.

Slika 5. Oštećena površina unutarnjeg prstena planetarnog cilindričnog valjkastog ležaja

In addition to the electrical conductivity κ, the sensor measures the dielectric constant ε_r of the oil. The declining effectiveness of additives can be detected by dielectric constant measurement.

Before the experiment, 30 minutes before end of the test and after the test, the test gear oil samples are taken for laboratory analysis. The measurements include the determination of the abrasion components, wear particles and contamination to DIN 51396-1, the change in viscosity according to DIN 51562-1, and the determination of the viscosity index according to DIN ISO 2909. In addition, a measurement of the neutralization number (acid number) is carried out in accordance with DIN 51558-1.

The analysis of the three oil samples taken show virtually no differences even though there was massive raceway damage to the planet wheel bearing. The very small deviations between the measured values of the three samples are within the statistical deviation of the analytical method for the determination of wear components, wear particles, etc. This is causally attributable to the high quality of the oils and means that even such massive damage cannot be reliably detected by particle detection or oil analysis [4].

4. Dielectrical constant of gearbox oil

In addition to electrical conductivity, permittivity ε_r of the oil is also measured. For non-additive oils the water content can be thus determined. There is a view that the declining effectiveness of additives on the dielectric constant measurement can be detected benefits.

Figure 6 shows the schematic profile of the temperature compensated dielectric constant ε_{r40} for additivised oil when loaded with contaminants, such as abrasion particles, water and acids as they occur through oil aging. With the consumption of additives, the curve falls and after their removal, it rises again. Using this

gradient of the dielectric constant the additive consumption can be detected.

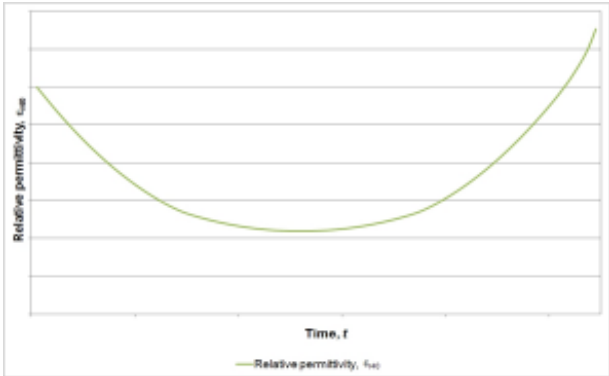

Figure 6. Schematic of the temperature compensated dielectric constant ε_{r40} against time.

Slika 6. Shematski prikaz temperaturno ispravljene dielektričke konstante ε_{r40} u funkciji vremena

5. Discussion of the practical application

Figure 7 shows the schematic profile of the depleted condition of a machine (e.g. the test experiment described above). The damage that occurred here was created at the time of overload and leads to spalling and component failure. In the example of the transmission test rig measurement, conventional technologies were only responsive after the onset of bearing damage, too late to prevent failure. Only further damage could be reduced.

The basic advantage of the presented online oil sensor system is that critical operational areas and stress conditions are determined in e.g. wind turbine gearboxes. Changes in oil characteristics are detected so accurately that they are noticeable before initiation of component damage. For example, starting oil acidity is registered reliably by the sensor. By establishing permissible operating conditions using limit values of conductivity and dielectric constant of oil the wear (damage) tolerance and thus optimal operating times and lifetimes are achieved. The system also allows the identification of critical stresses and the timely initiation of corrective measures before a gearbox failure. Downtime and high repair costs can be dramatically reduced.

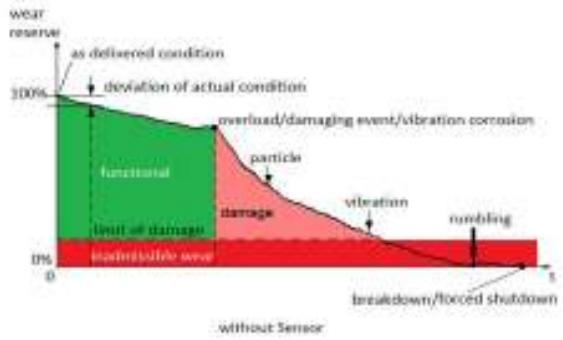

Figure 7. Schematic of the course of wear against time in a machine.

Slika 7. Shematski prikaz trošenja u funkciji vremena

6. Summary and outlook

The proposed online analysis system measures the components of the complex impedance of oils, in particular, the electrical conductivity, the dielectric constant and the oil temperature. Aging of the oil caused by acids and soap, cracked oil molecules and metal debris (from wear of the bearing or tribological contact) lead to an increase in electrical conductivity, which correlates directly with the degree of contamination of the oil and machine wear. This continuous analysis of wear by the detection of chemical contaminants and aging of the oil follows a holistic approach of real-time monitoring of the oil machine system before damage occurs. The detection of critical wear and stress conditions is at a very early stage, unlike conventional technologies, such as vibration analysis, oil particle measurement, filter systems and oil analysis, whose lower detections limits are crossed only after damage has occurred.

Information about the degradation of additives can be made by the change in the dielectric constant. After installation of the oil in the system, the sensor data can be viewed and evaluated remotely. The system allows the analysis and presentation of the measured signals to be performed, for example, by externally commissioned, off site, service providers thus relieving the operator of the critical decisions. The data allows for the quantitative evaluation of changes in the system oil machine, including recommendation resulting preventive maintenance measures, increasing reliability, lengthening lifetime, lowering downtime and reducing costs. Preferably the sensor data signals are transmitted over the internet to a database server and can be made available to multiple users. After authentication, a simple web browser allows access via LAN or WLAN. Alarm messages can be generated automatically as an e-mail and/or SMS.

Figure 8 presents the online oil analysis system, WearSens®. It consists of a base communication unit and sensor communication module.

Figure 8. WearSens® online oil analysis system with sensor and communication unit.

Slika 8. WearSens® "online" sustav analize ulja sa senzorom komunikacijskom jedinicom.

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Compression of Aluminium Foams with Different Strain Rate

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Keywords
Aluminium foam
Compression test
Strain rate

Ključne riječi
Aluminijska pjena
Tlačno ispitivanje
Brzina tlačenja

Early information
Abstract: Aluminium foam is, principally, a composite material consisting of aluminium or aluminium alloy matrix and of pores filled up with a gas distributed throughout the matrix. Foamed materials in general, and aluminium foams in particular, demonstrate a number of interesting properties due to their porous structure, which makes them usable in a wide range of applications. Under compression, foamed materials show a unique stress – strain response with a plateau region in which the stress is nearly constant over a wide range of strain.
In this paper, several samples of closed cell aluminium foams were produced from an Alulight AlMgSi 0,6 TiH_2 - 0,4 precursor. The compressive deformation was examined using universal test machine. The strain rate was 10^{-3} s^{-1} and 10^{-2} s^{-1}. Results show that the stress-strain curves depends on strain rate in a range of quasi-static compression and curves are similar but not overlapping. The higher speed tests have less expressed and lower value of the plateau stress.

Tlačenje aluminijske pjene s različitim stupnjem deformacije

Prethodno priopćenje
Sažetak: Aluminijska pjena je u osnovi kompozitni materijal koji se sastoji od aluminijske osnove ili osnove od neke aluminijske legure i pora ispunjenih plinom. Pjene općenito, kao i aluminijske pjene imaju mnoga povoljna svojstva zahvaljujući njihovoj poroznoj strukturi što ih čini pogodnima za mnoge primjene. Pri tlačnom naprezanju metalne pjene pokazuju specifičnu ovisnost naprezanja i deformacije pri čemu tijekom opterećivanja postoji gotovo konstantno naprezanje pri velikom dijelu deformacije.
U ovom je radu proizvedeno nekoliko uzoraka aluminijskih pjena iz Alulight AlMgSi 0,6 TiH_2 - 0,4 prekursora. Brzina deformacije iznosila je 10^{-3} s^{-1} odnosno 10^{-2} s^{-1}. Rezultati pokazuju da krivulja naprezanje-deformacija ovisi o brzini deformacije u području kvazi-statičkog opterećenja pri čemu je oblik krivulja isti, ali se vrijednosti ne preklapaju. Ispitivanje većim brzinama ima slabije izraženo područje konstantnog naprezanja pri čemu su za istu deformaciju vrijednosti naprezanja niže.

1. Introduction

Foamed aluminium is, principally, a composite material consisting of aluminium or aluminium alloy matrix and of pores filled up with a gas distributed throughout the matrix. This unique structure possesses an unusual combination of properties, such as low thermal conductivity, high impact energy absorption capacity, very high specific toughness and good acoustic properties, especially in the case of interconnected porosity. Moreover, this exceptionally lightweight material is nonflammable, ecologically harmless and easily recyclable [1].

Metallic foams are excellent impact energy absorber, and they can convert impact energy into deformation energy and absorb more energy than bulk metal at low stress [2].

At present metal foams are incompletely characterized, and the processes used to make them are imperfectly controlled, resulting in some variability in properties [3]. Cellular metals foamed by blowing agents usually exhibit a non-uniform cell architecture with considerable local density variations within the sample [4].

Symbols/Oznake

ε	- strain, % - deformacija, %	σ	- stress, MPa - naprezanje
ρ	- density, kgm^{-3} - gustoća		

2. Experimental Part

For the production of Alulight foamed aluminium, Al powder is mixed with a product releasing gas at higher temperature and then compacted. This foaming agent is placed into a mold form and heated up until the agent starts to foam. Immediately thereafter the mold is taken out of the furnace and cooled off, so the aluminium foam part is frozen in shape. The outcome of this process is a closed cell aluminium foam showing a thin casting skin on the surface [5].

An electric resistance furnace with a power of 7,5 kW (situated in the Faculty of Mechanical Engineering and Naval Architecture in Zagreb, Croatia) was used for producing aluminium foam samples, Figure 1.

Figure 1. The process of producing aluminium foam samples

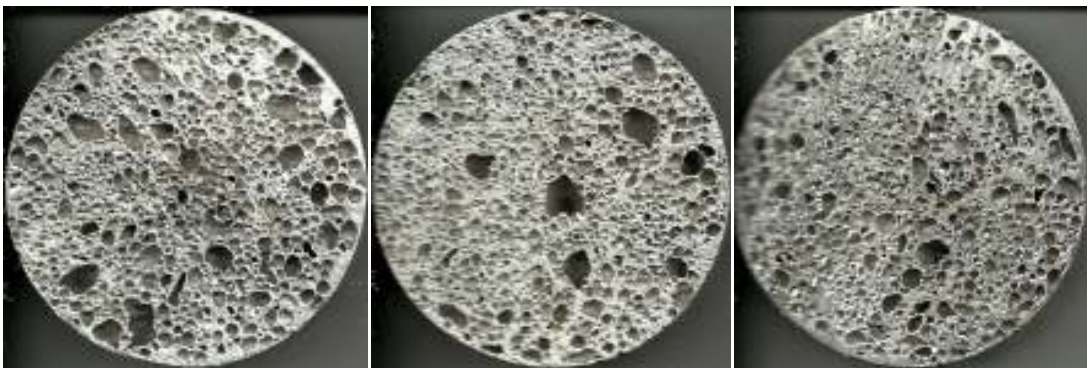
Slika 1. Postupak izrade uzoraka aluminijske pjene

Seven samples of aluminium foams (dimension ϕ 84 × 100 mm, density of foam ρ = 0,81 g/cm^3) were produced from an Alulight AlMgSi 0,6 TiH_2 - 0,4 precursor.

One sample was cut crosswise in three places as shown in Figure 2. Figure 3 shows a cross section of aluminium foam sample.

Figure 2. Cutting of aluminum foam samples: cross-section I, II and III

Slika 2. Rezanje uzoraka aluminijske pjene, poprečni presjeci I, II i III



a) b) c)

Figure 3. Cross-section a) I, b) II c) III

Slika 3. Poprečni presjek a) I, b) II c) III

The pores are irregular in shape and in most cases equivalent diameters ranging from 1-5 mm. In each section there are several larger pores of equivalent diameter, Table 1

Compression test was carried out in the Laboratory for Mechanical Properties Testing at the Faculty of Mechanical Engineering and Naval Architecture in Zagreb. A universal test machine, with a maximum compressive force of 400 kN was used. The feed rate was 6 mm/min and 60 mm/min which is the equivalent to strain rate of 10^{-3} s^{-1} and 10^{-2} s^{-1}.

Figure 4 shows compression of samples.

Table 1. Analysis of the pores in the metal foam sample

Tablica 1. Analiza pora u uzorku metalne pjene

Cross-section	Number of pores with equivalent diameter > 5 mm	Eq. diameter of the largest pore, mm
I	15	8,6
II	9	9,3
III	8	7,2

Figure 4. Compression of aluminium foam sample

Slika 4. Tlačenje uzorka aluminijske pjene

3. Results and discussion

The recorded load-displacement curves were used to calculate the compressive engineering stress-strain (σ-ε) curves.

Figure 5 present approximated "stress – strain" diagram. The compressive stress-strain curve exhibits three deformation regions: a linear-elastic response, an extended plateau region with nearly constant flow stress and final densification as collapsed cells are compacted together.

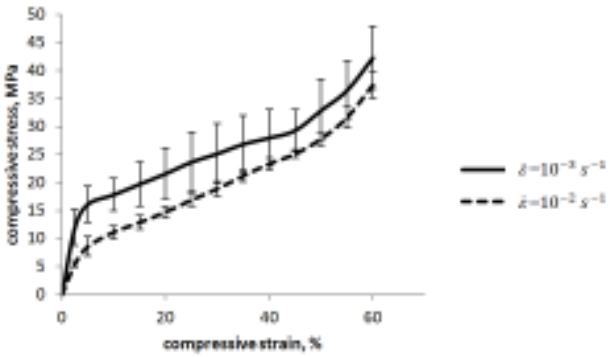


Figure 5. Compressive engineering stress-strain diagram

Slika 5. Dijagram naprezanje-deformacija pri tlačenju

It can be seen that the shapes of the two stress-strain curves are similar but not overlapping. Figure 5 shows that the higher speed test has better reproducibility of properties. Also they have less expressed and lower value of the plateau stress.

Conclusions

Energy absorption characteristics of closed-cell aluminium foam (Alulight) were investigated through quasi-static uniaxial compression with different strain rate. It was found that:

- aluminium foams foamed by blowing agents exhibit a non-uniform cell with different sizes and shapes and with density variations within samples
- non-uniform structure and local density variations resulting in variability of the properties of aluminium foams
- test results show that the stress-strain curves depends on strain rate in a range of quasi-static compression
- the higher speed tests have less expressed and lower value of the plateau stress

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An analysis of thermal properties of steel during the quenching

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Ključne riječi
Kaljenje čelika
Numeričko modeliranje
Tvrdoća

Original scientific article
Abstract: Since, during the quenching of workpieces, transient temperature field in them depends on specific heat capacity, c, heat conductivity coefficient, λ, density, ρ, heat transfer coefficient α, these variables were evaluated in creation of quenching model of workpieces. Estimation of dependency on temperature of specific heat capacity, heat conductivity and heat transfer coefficients, which are involved in mathematical model of quenching of steel workpieces, was done using a calibration, based on Crafts-Lamont diagrams.

Analiza toplinskih svojstava čelika za vrijeme gašenja
Izvorni znanstveni rad
Sažetak: Budući da promjena temperaturnog polja u obradcima tijekom gašenja, između ostalog, ovisi o specifičnom toplinskom kapacitetu, *c*, koeficijentu toplinske vodljivosti, *λ*, gustoći, *ρ*, koeficijentu prijelaza topline *α*, ove je varijable potrebno poznavati pri razvoju modela gašenja čelika. Temperaturna ovisnost specifične topline te koeficijenata toplinske vodljivosti i prijelaza topline, koji su uključeni u matematički model gašenja čelika procijenjena je kalibracijom na temelju *Crafts-Lamont* dijagrama.

1. Introduction

Research of numerical simulation of hardening degree, i.e. hardness and microstructure distribution in quenched steel specimen is one of the priority researches in simulation of phenomena of steel quenching [1]. Rate of steel specimen cooling essentially depends on workpiece geometry and characteristic physical properties of quenched steel and quenchant. Relevant physical properties about which cooling rate depends are specific heat capacity of steel, heat conductivity coefficient of steel, steel density and heat transfer coefficient of quenchant. For precise mathematical modeling these variables must be estimated with good precision. These variables can be predicted by inversion method based on achieved results and qualitative analysis of cooling curve [2] and [3]. In this way physical properties are adjusted or calibrated according to the results of quenching. Physical properties predicted by this method are usable for large spectra of quenchants with the same intensity of cooling, and for large spectra of steels [4].

2. Mathematical model of specimen cooling

The temperature field change in an isotropic rigid body without heat sources can be described by Fourier's law of heat conduction:

$$\frac{\delta(c\rho T)}{\delta t} = div\lambda\, gradT \quad , \tag{1}$$

Characteristic boundary condition is:

$$-\lambda \left.\frac{\delta T}{\delta n}\right|_{s} = \alpha\left(T_{s} - T_{f}\right) , \tag{2}$$

Solution of equation (1) can be found out using the finite volume method [5], [6] and [7]. For example, transient temperature field in circle symmetrical body can be defined by 2-D finite volume formulation (Figure 1):

$$T_{ij}^{1}\left(\sum_{m=1}^{2} b_{\mathrm{I}(i+n)j} + \sum_{m=1}^{2} b_{\mathrm{J}i(j+n)} + b_{ij}\right) =$$
$$= \sum_{m=1}^{2}\left(b_{\mathrm{I}(i+n)j}T_{(i+k)j}^{1} + b_{\mathrm{J}i(j+n)}T_{i(j+k)}^{1}\right) + b_{ij}T_{ij}^{0} \quad , \tag{3}$$
$$i = 1,2,...,i_{\max}, \quad j = 1,2,...,j_{\max}$$
$$n = 2-m, \quad k = 3-2m$$

where T_{ij}^{0} /K is the temperature in the beginning of time step Δt/s, T_{ij}^{1} /K is the temperature in the end of time step Δt/s, $b_{ij} = (\rho_{ij}c_{ij}\Delta V_{ij})/\Delta t$, $b_{\mathrm{I}(i+n)j} = W_{\mathrm{I}(i+n)j}^{-1}$ and $b_{\mathrm{J}i(j+n)} = W_{\mathrm{J}i(j+n)}^{-1}$, where variables $W_{\mathrm{I}(i+n)j}$ and $W_{\mathrm{J}i(j+n)}$ are the thermal resistances between *ij* and (*i*+*k*)*j* volume and between *ij* and *i*(*j*+*k*) volume.

Symbols/Oznake

A_1	- equilibrium temperature of eutectoid transformation - ravnotežna temperatura eutektoidne transformacije
A_3	- equilibrium temperature at which transformation of austenite to ferrite begins - ravnotežna temperatura na kojoj počinje transformacija austenita u ferit
B_s	- temperature of start of bainitic transformation - temperatura početka bainitne transformacije
c	- specific heat capacity, $Jkg^{-1}K^{-1}$ - specifični toplinski kapacitet
D	- diameter, m - promjer
E_d	- distance from a quenched end of *Jominy* specimen with 50 % of martensite in the microstructure - udaljenost od gašenog čela *Jominy*jevog uzorka s 50 % martenzita u mikrostrukturi
F	- boundary area, m^2 - granična površina
H	- *Grossmann* severity of quenching - *Grossmann*ov intenzitet gašenja
HRC_{max}	- maximum hardness HRC in *Jominy* curve - maksimalna tvrdoća HRC na *Jominy*jevoj krivulji
HRC_{M50}	- hardness HRC of steel with 50 % of martensite in the microstructure - tvrdoća HRC čelika s 50 % martenzita u mikrostrukturi
HRC_{M95}	- hardness HRC of steel with 95 % of martensite in the microstructure - tvrdoća HRC čelika s 95 % martenzita u mikrostrukturi
HRC_{P50}	- hardness HRC of steel with 50 % of pearlite in the microstructure - tvrdoća HRC čelika s 50 % perlita u mikrostrukturi
K	- coefficient, $Jm^{-2}K^{-1}$ - koeficijent
l	- distance, m - udaljenost
M_f	- temperature of finish of martensitic transformation - temperature završetka martenzitne pretvorbe
M_s	- temperature of start of martensitic transformation - temperature početka martenzitne pretvorbe
N	- total number of control volumes - ukupni broj kontrolnih volumena
r	- radius, m - polumjer
R	- radius, m - polumjer
t	- time, s - vrijeme
$t_{8/5}$	- time of cooling from 800 to 500 °C, s - vrijeme ohlađivanja od 800 do 500 °C
t_{M95}	- cooling time from 800 to 500 °C for characteristic points in *Jominy* specimen with 95 % of martensite in microstructure - vrijeme ohlađivanja od 800 do 500 °C za karakterističnu točku u *Jominy*jevom uzorku s 95 % martenzita u mikrostrukturi

Symbols/Oznake

HRC_{P100}	- hardness HRC of steel with 100 % of pearlite in the microstructure - tvrdoća HRC čelika s 100 % perlita u mikrostrukturi
t_{M50}	- cooling time from 800 to 500 °C for characteristic points in *Jominy* specimen with 50 % of martensite in microstructure - vrijeme ohlađivanja od 800 do 500 °C za karakterističnu točku u *Jominy*jevom uzorku s 50 % martenzita u mikrostrukturi
t_{P100}	- cooling time from 800 to 500 °C for characteristic points in *Jominy* specimen with 100 % of pearlite in microstructure - vrijeme ohlađivanja od 800 do 500 °C za karakterističnu točku u *Jominy*jevom uzorku s 100 % perlita u mikrostrukturi
t_{P50}	- cooling time from 800 to 500 °C for characteristic points in *Jominy* specimen with 50 % of pearlite in microstructure - vrijeme ohlađivanja od 800 do 500 °C za karakterističnu točku u *Jominy*jevom uzorku s 50 % perlita u mikrostrukturi
T	- temperature, K - temperatura
v	- cooling rate, Ks^{-1} - brzina ohlađivanja
V	- volume, m^3 - volumen
W	- thermal resistance, KW^{-1} - toplinski otpor
x	- portion of specific microstructure, % - udjel određene mikrostrukture

Greek letters/Grčka slova

α	- heat transfer coefficient, $Wm^{-2}K^{-1}$ - koeficijent prijelaza topline
φ	- angle between the heat flux and coordinate axes - kut između toplinskog toka i koordinatne osi
λ	- coefficient of heat conductivity, $Wm^{-1}K^{-1}$ - koeficijent toplinske vodljivosti
ϑ	- Temperature, °C - Temperatura
ρ	- density, kgm^{-3} - gustoća

Subscripts/Indeksi

a	- austenitization - austenitizacija
A	- austenite - austenit
B	- bainite - bainit
f	- quenchant - medij za kaljenje
F	- ferrite - ferit
M	- martensite - martenzit
M	- number of time steps during the cooling from 800 to 500 °C - broj koraka ohlađivanja od 800 do 500 °C
P	- pearlite - perlit
s	- surface - površina

$$W_{1(i+n)j} = \frac{1}{\Delta F_{1(i+n)j}} \left(\frac{l_{1ijm}}{\lambda_{ij}} + \frac{l_{1(i+k)j(3-m)}}{\lambda_{(i+k)j}} \right), \quad (4)$$

$$W_{Ji(j+n)} = \frac{1}{\Delta F_{Ji(j+n)}} \left(\frac{l_{Jijm}}{\lambda_{ij}} + \frac{l_{Ji(j+k)(3-m)}}{\lambda_{i(j+k)}} \right), \quad (5)$$

Thermal resistances for boundary volume are:

$$W_{\mathrm{I}(i+n)j} = \frac{1}{\Delta F_{\mathrm{I}(i+n)j}} \left(\frac{l_{\mathrm{I}ij}}{\lambda_{ij}} + \frac{1}{\alpha_{\mathrm{Ts\,I}(i+n)j} \cos\varphi_{\mathrm{I}(i+n)j}} \right), \quad (6)$$

$$W_{\mathrm{J}i(j+n)} = \frac{1}{\Delta F_{\mathrm{J}i(j+n)}} \left(\frac{l_{\mathrm{J}ij}}{\lambda_{ij}} + \frac{1}{\alpha_{\mathrm{TsJ}i(j+n)} \cos\varphi_{\mathrm{J}i(j+n)}} \right), \quad (7)$$

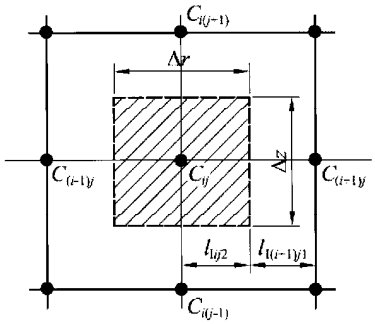

Figure 1. Control volume

Slika 1. Kontrolni volumen

Discretization system has N linear algebraic equations with N unknown temperatures of control volumes, where N is total number of control volumes. Time of cooling from T_a to specific temperature in particular point is determined as sum of time steps, and in this way, the diagram of cooling curve in every grid-point of a specimen is possible to found out.

$$t_M = \sum_{m=1}^{M} \Delta t_m \ , \quad (8)$$

where M is the number of time steps during the cooling from 800 to 500 °C.

3. Estimation of thermal properties of steel

For creation of good model of temperature field change in rigid body, input data, i.e., specific heat capacity of steel, c, heat conductivity coefficient of steel, λ, steel density, ρ, heat transfer coefficient of quenchant, α must be consistent with the achieved results of microstructure and mechanical properties. Calibration of input data should be done according to achieved experimental results.

Density, ρ for steel is equal ~ 7800 kgm^{-3}. Values of specific heat capacity, c can be accepted from literature (Table 1 [8]).

If the variables ρ and c were accepted from other literature, variables λ and α must be estimated, i.e., calibrated according to variables ρ and c, based on experimental results.

The input values of heat transfer coefficient have been optimized using *Crafts-Lamont* diagrams. Optimization was done for large spectra of a specimen bar diameter. Estimation of heat transfer coefficient was provided by varying of heat transfer coefficient values in the established 1-D model of cooling of steel bar. For different *Grossmann* severity of quenching and different bar diameters the cooling time from 800 to 500 °C was calculated in characteristic distance from bar surface. After that the distance from a quenched end of *Jominy* specimen was estimated using a relation which exists between cooling time from 800 to 500 °C and distance from a quenched end of *Jominy* specimen [9]. Calculated values of distances from a quenched end of *Jominy* specimen have been compared with those evaluated by *Crafts-Lamont* diagrams (Figure 2). It was accepted that the temperature of a bar in the beginning of cooling is equal to 850 °C. Characteristic boundary condition for steel quenching is same as was in equation (2). The cooling time at the particular points was estimated by finite volume method [5], [6] and [7]. The bar radius was discretizated into 10 volumes.

For small specimens of materials with high thermal conductivity where the thermal resistance is insignificant, the heat transfer coefficient, α/Wm^{-2}K^{-1} is approximately equal to:

$$\alpha \approx -\frac{c\rho V}{F(T_s - T_f)} \frac{dT}{dt} = \frac{K}{T_s - T_f} v \ , \quad (9)$$

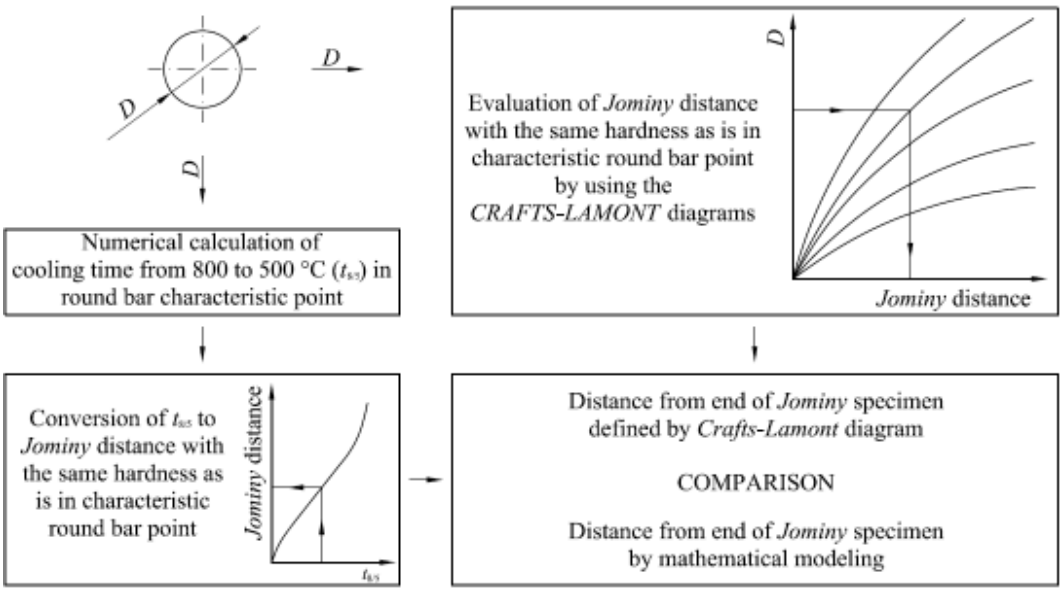

Figure 2. Calibration of input data of thermal properties based on *Crafts-Lamont* diagrams

Slika 2. Kalibracija ulaznih podataka toplinskih svojstva na temelju *Crafts-Lamont* dijagrama

Coefficient K and cooling rate depend on temperature. For precise estimation of coefficient α, the dependence of cooling rate and coefficient K on temperature must be known. If the coefficient K is known heat transfer coefficient α can be estimated directly from diagram cooling rate vs. temperature in Figure 3 by equation (9). But diagram in Figure 3 is suitable just for calculation of rate between values of heat transfer coefficient at characteristic temperature.

Optimization of input data heat transfer coefficient was done for large spectra of a specimen bar diameters. Temperature field change of specimen was calculated for radius position r/R=0, r/R=0.5 and r/R=0.9. Relative differences between distance from a quenched end of *Jominy* specimen estimated by modelling and by *Crafts-Lamont* diagrams were negligible, relative errors were less than 10%. Calibrated values of heat transfer coefficient, α for *Grossmann* severity of quenching H=0.35 are presented in Table 2.

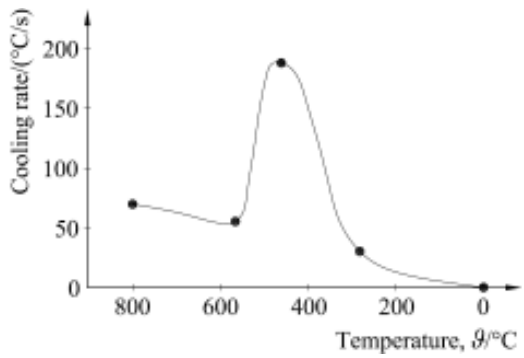

Figure 3. Typical cooling rate for quenching of small dimension workpieces in oil

Slika 3. Tipične brzine gašenja obradaka malih dimenzija u ulju

Table 1. Accepted values of specific heat capacity

Tablica 1. Prihvaćene vrijednosti specifičnog toplinskog kapaciteta

	Temperature/ Temperatura, ϑ/°C	Pearlite + Ferrite (Bainite)/ Perlit + ferit (bainit)	Martensite/ Martenzit	Austenite/ Austenit
Specific heat	0	378	376	415
	300	446	445	440

capacity/Specifični toplinski kapacitet, c/Jkg^{-1}K^{-1}	600	509	507	467
	800	570	-	490
	950	596	-	520

Table 2. Calibrated values of heat transfer coefficient

Tablica 2. Kalibrirane vrijednosti koeficijenta prijelaza topline

Temperature/ Temperatura, ϑ/°C	19.5	322	415	553	950
Heat transfer coefficient/ Koeficijent prijelaza topline, α/Wm^{-2}K^{-1}	498	645	1533	829	696

Simultaneously with estimation of temperature dependences of heat transfer coefficient for different *Grossmann* severity of quenching, an analysing of correlations which exist between heat conductivity coefficients and temperature, as well as, between hardenability properties was done.

Regression relations between heat conductivity coefficients for different temperature and hardenability properties are expressed by the equations (10), (11) and (12) in Table 3.

Distance E_d was estimated by the *Jominy* curve based on hardness of steel with 50 % of martensite in the microstructure. Hardness of steel with 50 % of martensite in the microstructure was calculated by:

$$\mathrm{HRC}_{\mathrm{M50}} = 0.73\mathrm{HRC}_{\max} \ , \tag{13}$$

Heat conductivity coefficients of microconstituents (ferrite, pearlite, bainite, martensite, austenite) at some temperature which is between specified temperature in Table 3 was estimated by interpolation. Total heat conductivity coefficients of steel at some temperature, ϑ were estimated by:

$$\lambda_{\mathrm{T}} = \left(x_{\mathrm{F}}\lambda_{(\mathrm{F+P})\vartheta} + x_{\mathrm{P}}\lambda_{(\mathrm{F+P})\vartheta} + x_{\mathrm{B}}\lambda_{\mathrm{B},\vartheta} + x_{\mathrm{M}}\lambda_{\mathrm{M},\vartheta} + x_{\mathrm{A}}\lambda_{\mathrm{A},\vartheta}\right)/100 \ , \tag{14}$$

Contents of ferrite, pearlite, bainite, martensite and austenite at some temperature could be estimated by characteristic cooling times and characteristic temperatures [10].

Characteristic cooling times are equal to:

$$t_1 = t_{\mathrm{M95}} \ , \tag{15a}$$

$$t_2 = \exp\left(\log t_{\mathrm{M95}} + 0.25\left(\log t_{\mathrm{M50}} - \log t_{\mathrm{M95}}\right)\right) \ , \tag{15b}$$

$$t_3 = \exp\left(\log t_{\mathrm{M95}} + 0.75\left(\log t_{\mathrm{M50}} - \log t_{\mathrm{M95}}\right)\right) \ , \tag{15c}$$

Table 3. Regression relations between heat conductivity coefficients and hardenability properties of steel

Tablica 3. Regresijski odnosi između koeficijenata toplinske vodljivosti i svojstava prokaljivosti čelika

Microstructure/ Mikrostruktura	Temperature/ Temperatura, ϑ/°C	Heat conductivity coefficients/ Koeficijent toplinske vodljivosti, λ/Wm^{-1}K^{-1}	
Pearlite + Ferrite (Bainite)/ Perlit + ferit (bainit)	20	$\lambda_{(\mathrm{F+P})20} = \lambda_{\mathrm{B}20} = 63 - 0.29\mathrm{HRC}_{\max} - 9\dfrac{E_{\mathrm{d}}}{\mathrm{HRC}_{\max} - 20}$	(10a)
	300	$\lambda_{(\mathrm{F+P})300} = \lambda_{\mathrm{B}300} = 51 - 0.14\mathrm{HRC}_{\max} - 4.8\dfrac{E_{\mathrm{d}}}{\mathrm{HRC}_{\max} - 20}$	(10b)
	500	$\lambda_{(\mathrm{F+P})500} = \lambda_{\mathrm{B}500} = 42 - 0.08\mathrm{HRC}_{\max} - 2.4\dfrac{E_{\mathrm{d}}}{\mathrm{HRC}_{\max} - 20}$	(10c)
	800	$\lambda_{(\mathrm{F+P})800} = \lambda_{\mathrm{B}800} = 31 - 0.02\mathrm{HRC}_{\max} - 1.2\dfrac{E_{\mathrm{d}}}{\mathrm{HRC}_{\max} - 20}$	(10d)
Martensite/ Martenzit	20	$\lambda_{\mathrm{M}20} = 63 - 0.29\mathrm{HRC}_{\max} - 9\dfrac{E_{\mathrm{d}}}{\mathrm{HRC}_{\max} - 20}$	(11a)
	300	$\lambda_{\mathrm{M}300} = 45 - 0.13\mathrm{HRC}_{\max} - 4.3\dfrac{E_{\mathrm{d}}}{\mathrm{HRC}_{\max} - 20}$	(11b)
	500	$\lambda_{\mathrm{M}500} = 37 - 0.07\mathrm{HRC}_{\max} - 2.2\dfrac{E_{\mathrm{d}}}{\mathrm{HRC}_{\max} - 20}$	(11c)
Austenite/ Austenit	20	$\lambda_{\mathrm{A}20} = 19 - 0.09\mathrm{HRC}_{\max} - 2.8\dfrac{E_{\mathrm{d}}}{\mathrm{HRC}_{\max} - 20}$	(12a)
	300	$\lambda_{\mathrm{A}300} = 22 - 0.06\mathrm{HRC}_{\max} - 2.1\dfrac{E_{\mathrm{d}}}{\mathrm{HRC}_{\max} - 20}$	(12b)
	500	$\lambda_{\mathrm{A}500} = 26 - 0.05\mathrm{HRC}_{\max} - 1.6\dfrac{E_{\mathrm{d}}}{\mathrm{HRC}_{\max} - 20}$	(12c)
	800	$\lambda_{\mathrm{A}800} = 29 - 0.02\mathrm{HRC}_{\max} - 1.1\dfrac{E_{\mathrm{d}}}{\mathrm{HRC}_{\max} - 20}$	(12d)

$$t_4 = \exp(\log t_{M50} + 0.25(\log t_{P100} - \log t_{M50})) \ , \quad (15d)$$

$$t_5 = \exp(\log t_{M50} + 0.75(\log t_{P100} - \log t_{M50})) \ , \quad (15e)$$

$$t_6 = \exp(\log t_{P100} + 0.25(\log t_{P50} - \log t_{P100})) \ , \quad (15f)$$

$$t_7 = \exp(\log t_{P100} + 0.75(\log t_{P50} - \log t_{P100})) \ , \quad (15g)$$

where t_{M95}, t_{M50}, t_{P100}, t_{P50} are cooling time from 800 to 500 °C for characteristic points in *Jominy* specimen with 95 % of martensite, 50 % of martensite, 100 % of pearlite and 50 % of pearlite in microstructure, respectively. The times t_{M95}, t_{M50}, t_{P100}, t_{P50} was estimated by the conversion of distance from a quenched end of *Jominy* specimen (*Jominy* distance) of characteristic microstructure composition to cooling time, $t_{8/5}$ by using both, the relation between cooling time, $t_{8/5}$ and *Jominy* distance and the *Jominy* hardenability curve. The diagram of *Jominy* distance vs. cooling time, $t_{8/5}$ is shown in Figure 2. Cooling time between 800 and 500 °C should be estimated by extrapolation if the temperature in specimen point is higher than 500 °C.

If hardnesses of characteristic microstructure are known, characteristic *Jominy* distance can be found out using the *Jominy* test results. Characteristic time of cooling $t_{8/5}$ can be found out using a relation which exists between cooling time from 800 to 500 °C and distance from a quenched end of *Jominy* specimen [9].

Hardness of characteristic steel microstructure was calculated by equations (16) shown in Table 4.

Table 4. Hardness of characteristic steel microstructure

Tablica 4. Tvrdoća karakterističnih mikrostruktura čelika

Microstructure/ Mikrostruktura	Hardness/Tvrdoća	
95 % M + 5 % B	$HRC_{M95} = 0.93HRC_{max}$	(16a)
50 % M + 50 % B	$HRC_{M50} = 0.73HRC_{max}$	(16b)
100 % P	$HV_{P100} = 0.2308HV_{max} + 100$	(16c)
50 % P + 50 % F	$HV_{P50} = 0.1504HV_{max} + 100$	(16d)

M - martensite/martenzit; B - bainite/bainit; P - pearlite/perlit; F - ferrite/ferit

Characteristic temperatures are equal to:

$$T_1 = M_s - 0.75(M_s - M_f) \ , \quad (17a)$$

$$T_2 = M_s - 0.25(M_s - M_f) \ , \quad (17b)$$

$$T_3 = B_s - 0.75(B_s - M_s) \ , \quad (17c)$$

$$T_4 = B_s - 0.25(B_s - M_s) \ , \quad (17d)$$

$$T_5 = A_1 - 0.75(A_1 - B_s) \ , \quad (17e)$$

$$T_6 = A_1 - 0.25(A_1 - B_s) \ , \quad (17f)$$

$$T_7 = A_3 - 0.75(A_3 - A_1) \ , \quad (17g)$$

$$T_8 = A_3 - 0.25(A_3 - A_1) \ , \quad (17h)$$

Between critical temperatures A_3, B_s, M_s and M_f of austenite decomposition and hardenability properties, regression relations are established:

$$A_3 = 862 - 0.04(HRC_{max.} - 20)^2 - \frac{6E_d}{HRC_{max} - 20} \ , \quad (18a)$$

$$B_s = 586 - 0.02(HRC_{max} - 20)^2 - \frac{30.6E_d}{HRC_{max} - 20} \ , \quad (18b)$$

$$M_s = 502 - 0.09(HRC_{max} - 20)^2 - \frac{9E_d}{HRC_{max} - 20} \ , \quad (18c)$$

$$M_f = 502 - 0.2(HRC_{max} - 20)^2 - \frac{9E_d}{HRC_{max} - 20} \ , \quad (18d)$$

It was accepted that equilibrium temperature of eutectoid transformation A_1 is equal to 721 °C.

4. Application example

Calibrated values of heat transfer and conductivity coefficients were applied in computer simulation of steel specimen with complex form made of steel EN 37Cr4. *Jominy* test results of the investigated steel are shown in Table 5. The specimen was austenitized at 850 °C for 45 min and quenched in oil with *Grossmann* severity of quenching H=0.35.

The distribution of hardness in quenched steel specimen is shown in Figure 4a. Geometry of steel specimen is shown in Figure 4b. Hardness distribution of the quenched steel specimen is calculated using the computer software BS-QUENCHING [11]. The numerical model of quenching is consisted of numerical simulation of transient temperature field change of cooling process and of numerical simulation of hardening. Hardness in specimen points was calculated by the conversion of calculated time of cooling from 800 to 500 °C ($t_{8/5}$) to hardness (Figure 5).

Table 5. *Jominy* test results of steel EN 37Cr4

Tablica 5. Rezultati *Jominy*jevog pokusa čelika EN 37Cr4

Jominy distance/ *Jominy*jeva udaljenost/mm	1.5	3	5	7	11	15	20	25	30	40	50
Hardness HRC/ Tvrdoća HRC	55	55	53	51	44	39	34	31	30	28	27

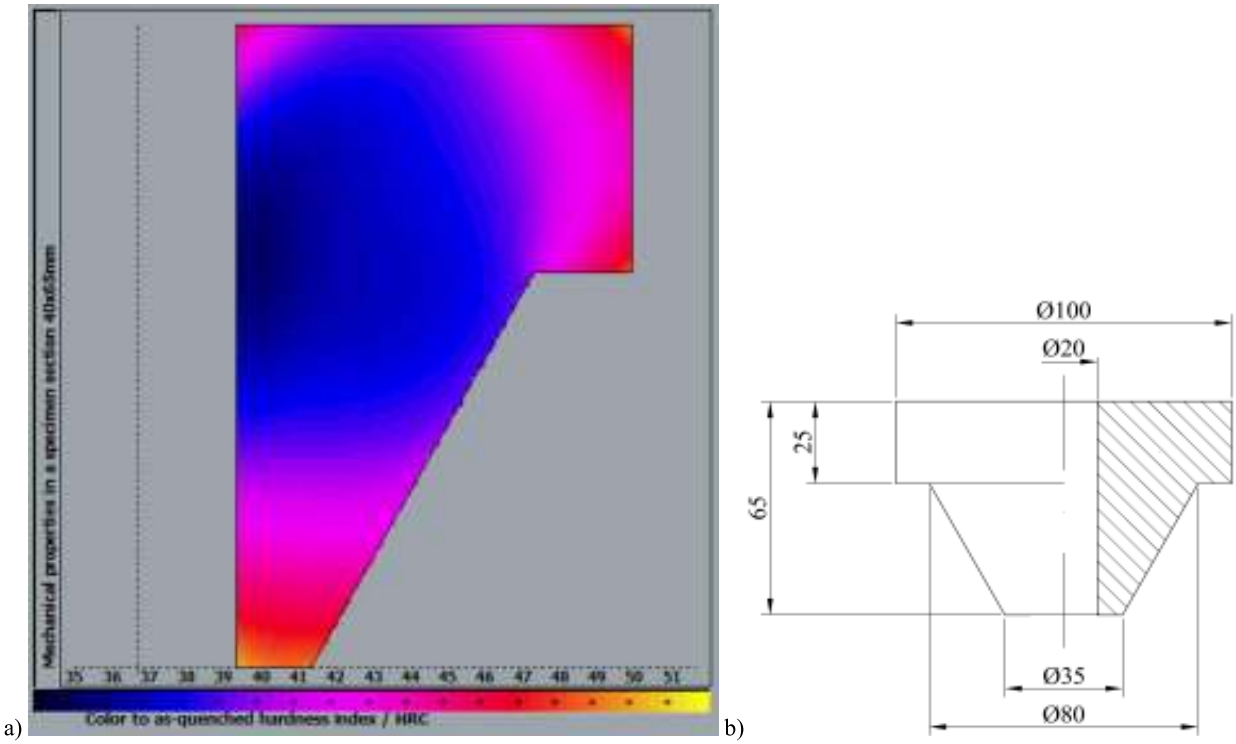

Figure 4. Simulation of hardness distribution in quenched steel specimen, a) hardness distribution, b) specimen geometry

Slika 4. Simulacija raspodjele tvrdoće kaljenog čeličnog uzorka, a) raspodjela tvrdoće, b) geometrija uzorka

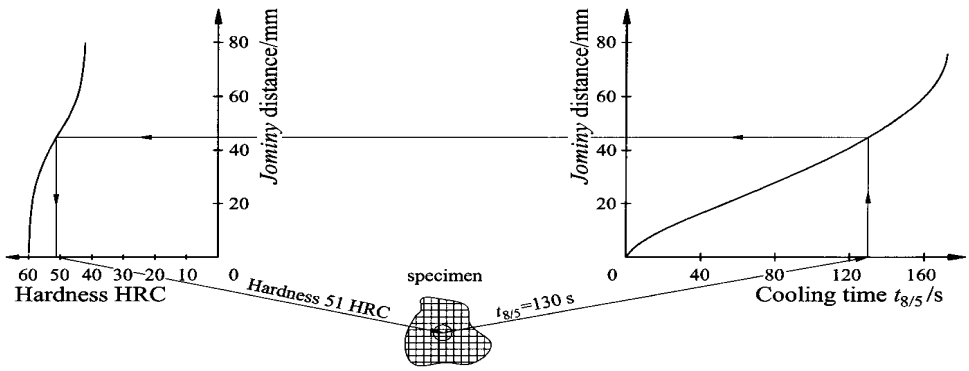

Figure 5. Conversion of the cooling time $t_{8/5}$ to the hardness

Slika 5. Pretvaranje vremena ohlađivanja $t_{8/5}$ u tvrdoću

5. Conclusion

Accuracy of numerical simulation of steel quenching directly depends on application of real input data in model of specimen cooling. Numerical simulation of quenching, by using of calibrated values of heat transfer and heat conductivity coefficients, is generalized way of simulation and suitable for application in design offices.

In proposed method of evaluation of input data in mathematical model of quenching, density and specific heat capacity of steel have been accepted from literature. Since steel density and specific heat capacity were accepted from literature other input data was ca1ibrated. Heat transfer coefficient and heat conductivity coefficient have been successfully calibrated by using results of quenching given in *Crafts-Lamont* diagrams. Since *Crafts-Lamont* diagrams were used, heat transfer and heat conductivity coefficients are predicted by inversion method by using a mathematical model of quenching of steel bars. The model is based on the finite volume method.

Moreover, the calculated input data have been used in developed numerical model of quenching of circle symmetrical steel workpiece. It can be concluded, that hardness in quenched steel specimen can by successfully calculated by proposed method.

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Preliminary investigation of the existence of correlation between cyclic Ramberg-Osgood parameters and monotonic properties of low-alloy steels

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estimation

Ključne riječi

cikličko opterećenje
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vlačna čvrstoća
granica tečenja
procjena

Original scientific paper

Abstract: This article presents the results of a preliminary investigation of the existence of correlation between the experimentally determined cyclic parameters: cyclic strength coefficient K', cyclic strain hardening exponent n' and cyclic yield stress R'_e and a number of monotonic properties such as: ultimate strength R_m, yield stress R_e and R_m / R_e ratio, for a representative group of low-alloy steels. A very good correlation was established between the ultimate strength R_m and the cyclic yield stress R'_e. Also, a good correlation was established between the cyclic strength coefficient K' and the combination of the ultimate strength R_m and the R_m / R_e ratio. No such correlation was found to exist between n' and any of mentioned monotonic parameters or their combinations for the group of low-alloy steels. These results were compared to those obtained for a group consisting of various steel types. The comparison confirmed the assumption that different steel groups should be considered separately when estimating cyclic parameters. Finally, a good agreement between the values of stress amplitudes calculated using the experimental and the estimated values of K' and n' shows that the cyclic parameters of low-alloy steels can be successfully estimated from their monotonic properties.

Preliminarno istraživanje korelacije između cikličkih Ramberg-Osgood parametara i monotonih značajki niskolegiranih čelika

Izvorni znanstveni rad

Sažetak: Ovaj rad predstavlja rezultate preliminarnog istraživanja postojanja korelacije između eksperimentalno dobivenih cikličkih parametara (koeficijenta cikličkog deformacijskog očvršćivanja K', eksponenta cikličkog deformacijskog očvršćivanja n' i cikličke granice tečenja R'_e) i monotonih značajki (vlačne čvrstoće R_m, granice tečenja R_e i omjera vlačne čvrstoće i granice tečenja R_m / R_e) reprezentativne grupe niskolegiranih čelika. Dobra korelacija utvrđena je između vlačne čvrstoće R_m i cikličke granice tečenja R'_e te koeficijenta cikličkog deformacijskog očvršćivanja K' i kombinacije vlačne čvrstoće R_m i omjera R_m / R_e dok korelacija između eksponenta n' i spomenutih monotonih parametara ili njihovih kombinacija nije utvrđena. Spomenuti rezultati uspoređeni su sa rezultatima istovjetne analize provedene za skupinu različitih grupa čelika. Usporedba rezultata potvrdila je da se pri procjeni cikličkih parametara različite grupe čelika trebaju razmatrati zasebno. Utvrđeno dobro poklapanje amplituda naprezanja proračunatih za niz amplituda plastične deformacije na osnovi eksperimentalnih i procijenjenih vrijednosti cikličkih parametara niskolegiranih čelika potvrđuje pretpostavku da se spomenuti ciklički parametri mogu uspješno procjenjivati iz monotonih značajki niskolegiranih čelika.

1. Introduction

Product development nowadays is more challenging than ever – among many demands that must be fulfilled, shortening of the development time and cutting down the expenses are certainly among most important ones. In order to reduce the time and money spent, various calculations and simulations of product models are increasingly being performed during the early stages of theproduct development.

Symbols/Oznake

E	- Young's modulus, MPa - modul elastičnosti	R_m / R_e	- ultimate strength and yield stress ratio, - - omjer vlačne čvrstoće i granice tečenja
K'	- cyclic strength coefficient, MPa - koeficijent cikličkog deformacijskog očvršćivanja		
n'	- cyclic strength hardening exponent - eksponent cikličkog deformacijskog očvršćivanja		**Greek letters/Grčka slova**
R^2	- coefficient of determination - koeficijent determinacije	$\Delta\varepsilon / 2$	- true elastic strain amplitude, - - stvarna ukupna amplituda normalne deformacije
R_m	- ultimate strength, MPa - vlačna čvrstoća	$\Delta\varepsilon_e / 2$	- true elastic strain amplitude, - - stvarna amplituda elastične normalne deformacije
R_e	- yield stress, MPa - granica tečenja	$\Delta\varepsilon_p / 2$	- true plastic strain amplitude, - - stvarna amplituda plastične normalne deformacije
R'_e	- cyclic yield stress, MPa - ciklička granica tečenja	$\Delta\sigma / 2$	- true stress amplitude, MPa - stvarna amplituda normalnog naprezanja

In these stages, the possibilities of influencing the costs are biggest, the changes are relatively easy to make, and, if proper decisions are made, expensive and time-consuming changes at latter development stages can be prevented. One of the most important design decisions that must be made in the early design phases is the proper choice of material. Performing durability calculations and computer simulations of dynamically loaded components or structures is possible only if material behaviour, i.e. cyclic and fatigue properties are known. Experimental determination of these properties is most accurate but cyclic experiments are expensive, complex, time-consuming and thus, often not available in the early design phases. On the other hand, monotonic experiments are inexpensive, simple and fast, and their results are readily available. This is why continuous efforts are being made in the last 50-60 years to develop and improve the methods for determination and estimation of cyclic [1]-[7] and strain-life fatigue [8]-[14] parameters based on monotonic properties of material. In number of papers reviews of these methods are provided [15]-[20] which show some of their disadvantages – most methods consider only 4 of 6 cyclic and fatigue parameters to be independent [12], so that they provide estimation methods of only fatigue parameters. Some methods were developed on a modest number of datasets and mostly for all material groups together (steels, aluminium and titanium alloys), which is shown to be inadequate for some material groups. Basan et al. [20] showed that there is statistically significant difference among the strain-life fatigue parameters and behaviour of different groups of metallic materials. This work presents a preliminary investigation of the existence of correlation between the experimentally determined cyclic parameters and monotonic properties. The analyses were performed separately on a low-alloy steels group and a control group consisting of various steels.

2. Cyclic stress-strain curves

Different materials exhibit different stress-strain responses when cyclically loaded. During loading, materials can show strain hardening, strain softening, stable behaviour but also transient behaviour i.e. they behave differently in various loading phases. For the majority of cyclically loaded metallic materials, a well accepted and widely used method for describing their stress-strain response is the stabilized or mid-life true stress – true strain curve which is determined from the strain-controlled cyclic experiments performed on a number of standard material specimens [21], [22]. Figure 1. shows the set of representative hysteresis

curves with resulting cyclic stress-strain and monotonic curves.

Cyclic stress-strain curves of most metallic materials can be successfully defined with the Ramberg-Osgood equation [22]:

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}} \quad (1)$$

3. Material data

Data for the two representative groups of materials were gathered from the relevant literature ([15], [24]) through

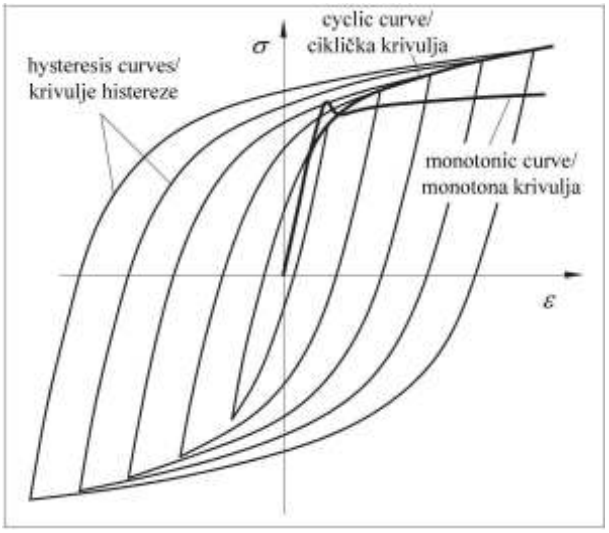

Figure 1. Hysteresis and monotonic and cyclic stress-strain curves

Slika 1. Krivulje histereze, ciklička i monotona krivulja naprezanje-deformacija

the MATDAT.COM system - an online material properties database [25]. The first group contained only low-alloy (LA) steels (271 datasets) and the other, mixed group of steels consisted of unalloyed (UA), low-alloy (LA), and high-alloy (HA) steels (687 datasets).

Only results of strain-controlled, fully reversed axial cyclic tests ($R = -1$) were considered. In order to keep the material data consistent and relevant, material data obtained through tests at the temperatures below or above the room temperature (cryogenic or high-temperature conditions), or in medium other than air, were excluded from the analysis. The data for materials tested at less than four different strain amplitudes and/or at range of total strain amplitudes of less than 0,4% were also excluded from the analysis.

Finally, only datasets which had all the necessary parameters available were taken into account. After filtering, data for total of 108 material datasets for LA steels and 219 datasets for mixed group of steels were available for use in the analysis.

4. Analysis, results and discussions

4.1. Methodology

The approach according to which the cyclic material parameters are estimated directly from the monotonic properties, is widely used [3]-[7] and is chosen for estimation of cyclic parameters in this paper as well.

Series of simple and multiple linear regressions without weight factors have been performed for each of the following cyclic parameters as dependent variables: cyclic yield stress R'_e, cyclic strength coefficient K' and cyclic strain hardening exponent n'. Since the ultimate strength R_m, the yield stress R_e and the ultimate strength to yield stress ratio R_m / R_e are beside material hardness the most readily available monotonic properties of the material, they are chosen as independent variables in the regression analyses. In simple regression analyses, the monotonic parameters were considered individually as the independent variables while in multiple linear regressions, combinations of two or three of the above mentioned parameters were taken as the independent variables and were "paired" with the corresponding cyclic parameters R'_e, K' and n'.

As one of the main goals of this paper is to establish the potential necessity for separation of different material groups to improve estimation of cyclic material parameters, results from regression analyses performed on LA group of steels were compared to those determined for mixed group of steels.

4.2. Cyclic yield stress R'_e

Among simple regression analyses performed on LA steel group with the cyclic yield stress R'_e as dependent variable, the highest coefficient of determination $R^2 = 0{,}915$ was obtained from the analysis with the ultimate strength R_m as a predictor variable (Figure 2.).

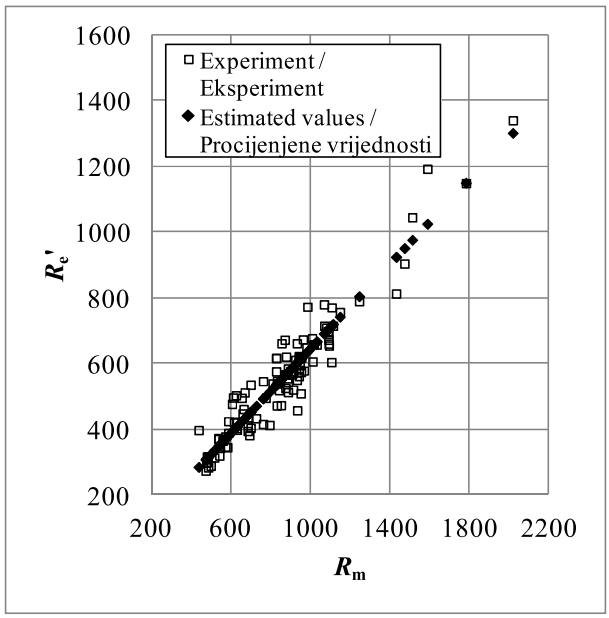

Figure 2. Experimental and estimated values of R_e' for LA steels

Slika 2. Eksperimentalne i procijenjene vrijednosti R_e' za niskolegirane čelike

For the mixed group of steels, a simple regression analysis revealed strongest correlation with the same independent variable R_m, but with slightly weaker coefficient of determination ($R^2 = 0{,}871$).

For both groups of steels, the best coefficients of determination from multiple linear regression analyses were obtained for the combination of the ultimate strength R_m and the ultimate strength to yield stress ratio R_m / R_e. When compared to simple regression analyses, the coefficients of determination for both LA group of steel and mixed group were slightly better, $R^2 = 0{,}92$ and $R^2 = 0{,}877$ respectively. Regression surface for LA steel group is given in Figure 3.

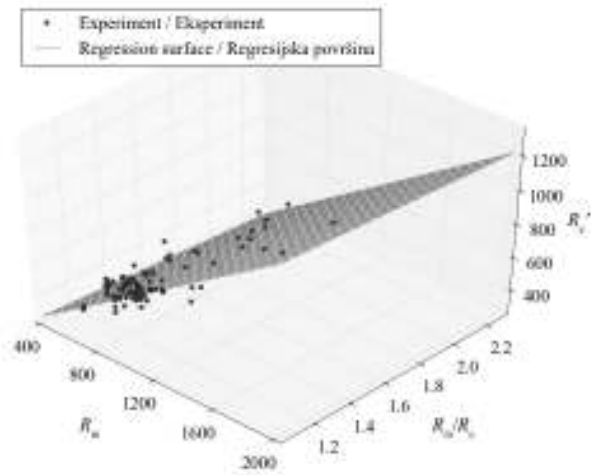

Figure 3. Regression surface (independent variables: R_m and R_m / R_e, dependent variable R_e')

Slika 3. Regresijska površina (nezavisne varijable: R_m i R_m / R_e, zavisna varijabla R_e')

4.3. Cyclic strength coefficient K'

Of all regression analyses for K' performed on the LA steel group, simple regression analysis with the ultimate strength R_m as the independent variable resulted with the highest value of coefficient of determination, $R^2 = 0{,}635$ (Figure 4.).

Multiple regression analysis of LA steel group with K' as dependent variable and the combination of two independent variables, R_m and R_m / R_e ratio, resulted in somewhat better coefficient of determination $R^2 = 0{,}698$ (Figure 5.).

For the mixed group of steels, only weak correlation was found to exist between K' and R_m, R_e or R_m / R_e as independent variables (simple regressions) or their combinations (multiple regressions). This directly indicates the necessity of separate consideration of steel groups when estimating their cyclic parameters (as suggested in [20]).

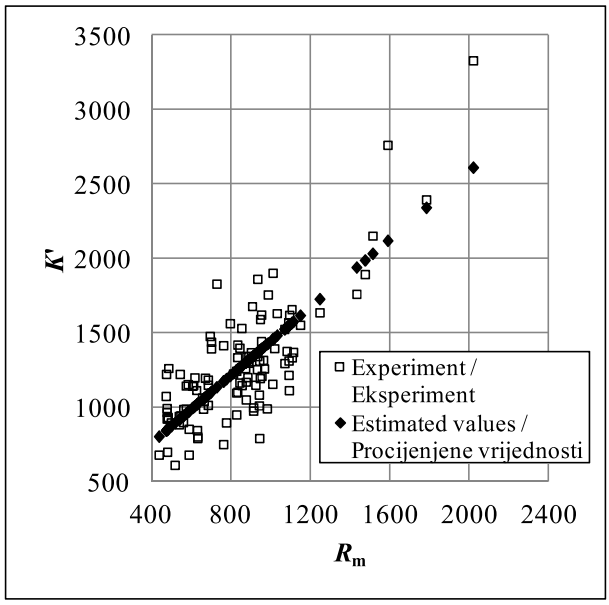

Figure 4. Experimental and estimated results of K' (independent variable: R_m)

Slika 4. Eksperimentalne i procijenjene vrijednosti K' (nezavisna varijabla: R_m)

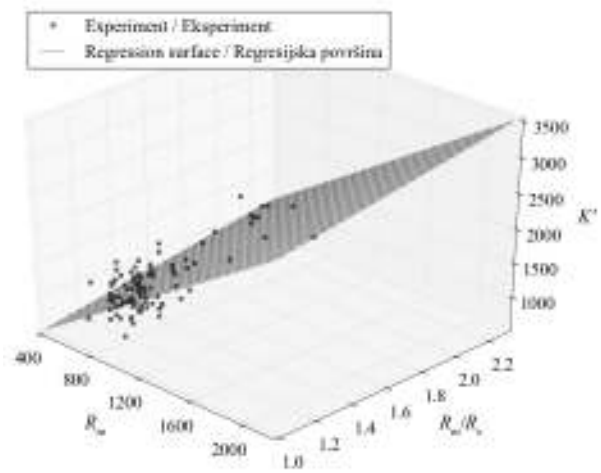

Figure 5. Regression surface (independent variables: R_m and R_m / R_e, dependent variable K')

Slika 5. Regresijska površina (nezavisne varijable: R_m i R_m / R_e, zavisna varijabla K')

4.4. Cyclic strain hardening exponent n'

The regression analyses conducted in this paper confirmed findings from [5] that there is almost no correlation between cyclic strain hardening exponent n' and monotonic properties of LA steels. Coefficients of determination below $R^2 = 0{,}3$ were obtained from simple and multiple regression analyses, with any of the chosen monotonic properties or their combinations as the independent variables. Thus, an average value of all cyclic strain hardening exponent n' values for a group of LA steels ($n' = 0{,}1362$) was used in the evaluation of the obtained results performed in chapter 4.5.

On the other hand, regression analyses conducted for mixed group of steels showed that significant correlation exists only between the ratio R_m / R_e and n', similarly to [7]. Quite good square of correlation coefficient is obtained ($R^2 = 0{,}718$), but the reason for such a good correlation probably lies in a very good correlation of n' and R_m / R_e ratio for a group of high-alloy steels (established in a separate analysis) which then enhances regression results for the whole group of mixed steels.

4.5. Evaluation of the obtained results

Using both the experiment-based and estimated values of K' and n' and "plastic" part of expression (1):

$$\frac{\Delta\varepsilon_p}{2} = \left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}} \qquad (2)$$

preliminary values of stress amplitudes $\Delta\sigma/2$ were calculated for the following values of $\Delta\varepsilon_p/2$: 0,1%, 0,2%, 1% and 2%, for a group of LA steels.
Calculations were made for the estimations of K' from both simple and multiple regression analysis from chapter 4.3, while for n' the constant value of $n' = 0{,}1362$ was taken for both calculations.

To evaluate predictive accuracy of expressions obtained from the regression analyses, the conventional error criterion ([5], [17]) was used. Percentages of the estimation-based stress amplitudes (calculated using estimated cyclic parameters) that deviate less than 10%, between 10 and 20%, between 20 and 30% and more than 30% from their experiment-based counter-parts were determined and given in Figure 6., both for simple and multiple regression analyses. Although certain differences can be noted, the results obtained using both simple and multiple regressions are satisfactory.

5. Conclusion

This paper presents methodology and results of preliminary investigation of the existence of correlation between experimentally determined cyclic parameters: cyclic yield stress R'_e, cyclic strength coefficient K'

and cyclic strain hardening exponent n' with monotonic properties of low-alloy steels.

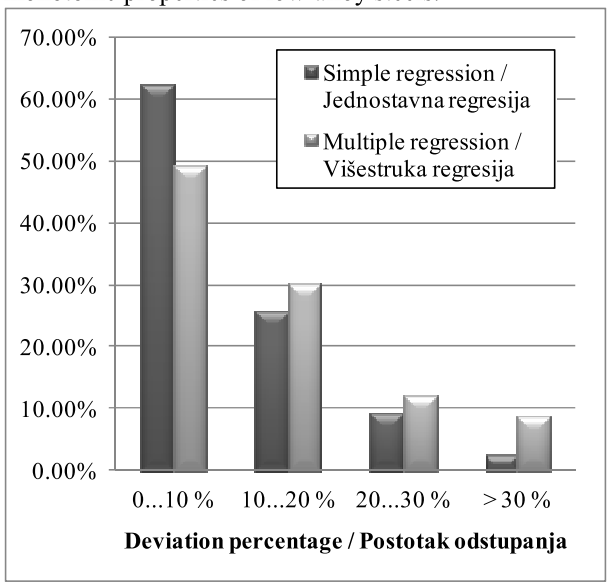

Figure 6. Percentage of estimated values of $\Delta\sigma/2$ that deviate up to 10%, 10 to 20%, 20 to 30% and more than 30% from experiment-based values

Slika 6. Postotak procijenjenih vrijednosti $\Delta\sigma/2$ koje odstupaju od eksperimentalnih vrijednosti do 10%, 10 do 20%, 20 do 30% i više od 30%

Results were compared to those obtained for the mixed group of steels in order to determine if considering different steel groups separately may improve the prediction results.

For both steel groups, good correlations were established between cyclic yield stress R'_e and ultimate strength R_m (somewhat better for low-alloy steels). For a group of low-alloy steels a good correlation was established between cyclic strength coefficient K' and ultimate strength R_m, but also for the combination of two monotonic parameters, ultimate strength R_m and ultimate strength to yield stress ratio R_m/R_e. No relevant correlation could be established between K' and monotonic properties or their combination for the mixed group of steels.

The regression analyses conducted on LA steels for cyclic strain hardening exponent n' showed almost no correlation with the chosen monotonic properties or their combination, while rather good correlation was found to exist between n' and the ultimate strength to yield stress ratio R_m/R_e for the mixed group of steels. This is most probably due to the high correlation found between these parameters of the high-alloy steels.

Consideration of different steel groups separately is shown to improve predictions for cyclic parameters R'_e and especially for K'. As for the estimation of cyclic strain hardening exponent n', some other criteria for grouping steels besides chemical composition should probably be used (e.g. microstructure or heat treatment) or monotonic parameters other than those proposed in this paper should be considered to be used as independent variables. These measures could also improve predictions of R'_e and K'.

Values of stress amplitude calculated using the experiment- and estimation-based values of cyclic parameters of LA steels are in good agreement, which confirms that cyclic parameters can be successfully estimated from the easily obtainable monotonic properties of materials.

It must be noted that, in this paper, estimations were based on linear regressions (both simple and multiple). It is expected that further increase of accuracy of the mentioned estimations can be achieved by performing non-linear analyses and by inclusion of additional monotonic parameters in multiple regressions.

Results obtained in this work will serve as a basis for more detailed analyses of more material groups which, in turn, are to result with methodology and expressions for more accurate estimations of cyclic parameters from monotonic properties of the metallic materials

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Influence of constitutive and process parameters on the cylindrical cup deep drawing predictions for AA2090-T3 sheet

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Keywords

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Constitutive modeling
Yielding asymmetry
Finite element method
Cylindrical cup deep drawing
Earing

Ključne riječi

Ortotropan material
Konstitutivno modeliranje
Asimetrija naprezanja tečenja
Metoda konačnih elemenata
Cilindrično duboko vučenje
Ušičavost

Original scientific article

Abstract: Constitutive modelling of the anisotropic plastic behaviour of the sheet material is of the great importance in the design and analysis of the forming processes intended for these materials. In this article influence of the constitutive parameters, directional dependences of the tensile and compressive yield stresses and Lankford parameters, on the cylindrical cup deep drawing predictions for AA2090-T3 sheet is analyzed. Finite element simulations of the cup drawing process are performed with the finite element program ADINA upgraded with the several orthotropic elasto-plastic constitutive formulations that are adjusted to the different sets of the material data. The analyzed constitutive formulations are based on isotropic hardening, associated or non-associated flow rule and symmetric orthotropic Hill (1948) stress function. In order to evaluate the impact of the strenght diffential effect on the final cup predictions, an investigation is carried out with a recently proposed constitutive formulation based on non-associated flow rule and asymmetric orthotropic yield function derived by extending the original orthotropic Hill (1948) equivalent stress term with a linear combination of the normal stress components. Furthermore, influence of the blankholder force and friction coefficient on the cup earing profile is assessed.

Utjecaj konstitutivnih i procesnih parametara na predviđanja postupka cilindričnog dubokog vučenja legure AA2090-T3

Izvorni znanstveni rad

Sažetak: U postupku planiranja i analize postupaka oblikovanja limova plastičnom deformacijom važno je poznavanje opisa anizotropnog ponašanja materijala. U ovom radu analiziran je utjecaj materijalnih parametara, orijentacijske ovisnosti vlačnih i tlačnih naprezanja tečenja kao i Lankfordova parametra, na predviđanja postupka cilindričnog dubokog vučenja aluminijske legure AA2090-T3. Simulacije postupka dubokog vučenja izvršene su korištenjem programa za analizu metodom konačnih elemenata ADINA nadograđenim s nekoliko ortotropnih konstitutivnih formulacija. Analizirane konstitutivne formulacije temelje se na modelu izotropnog očvršćavanja, pridruženom ili nepridruženom pravilu tečenja i simetričnoj ortotropnoj Hill (1948) funkciji naprezanja. Parametri analiziranih konstitutivnih formulacija određeni su iz različitih skupova materijalnih podataka. S ciljem određivanja utjecaja asimetrije naprezanja tečenja na rezultate predviđanja, analizirana su predviđanja postupka dobivena konstitutivnom formulacijom koja se temelji na nepridruženom pravilu tečenja i asimetričnoj ortotropnoj funkciji tečenja. Analizirana asimetrična funkcija tečenja izvedena je proširivanjem izraza za ekvivalentno naprezanje Hill (1948) funkcije tečenja linearnom kombinacijom normalnih naprezanja. Nadalje, ispitan je utjecaj vrijednosti sile na tlačnom prstenu i faktora trenja na predviđanja ušičavosti u postupku cilindričnog dubokog vučenja.

1. Introduction

In many manufacturing areas the optimization of the sheet metal forming processes is a key factor to reduce product development time and final cost. Considerable research work has been carried out, based on various approaches involving experimental, analytical and computational methods, in an effort to be able to predict material behaviour in these complex processes. Computational methods, especially finite element method, have made significant contribution in this area in last few decades. This contribution is certainly result of the rapid advancement of the computer capabilities but it is also caused by significantly improved knowlege in the constitutive modeling of the anisotropic materials. Since most sheet metals exibit plastic anisotropy, the

Symbols/Oznake

$\mathbf{C}^{e}$	- tensor of elastic moduli - tenzor elastičnosti
$d\boldsymbol{\varepsilon}$	- strain tensor increment - inkrement tenzora deformacije
$d\boldsymbol{\varepsilon}^{e}$	- elastic strain tensor increment - inkrement elastičnog tenzora deformacije
$d\boldsymbol{\varepsilon}^{p}$	- plastic strain tensor increment - inkrement plastičnog tenzora deformacije
$d\bar{\varepsilon}^{p}$	- equivalent plastic strain increment - inkrement ekvivalentne plastične deformacije
$d\lambda$	- plastic multiplier, consistency parameter - plastični množitelj, parametar konzistentnosti
$d\boldsymbol{\sigma}$	- stress tensor increment - inkrement tenzora naprezanja
$F,\ f_y$	- yield function, equivalent stress - funkcija tečenja, ekvivalentno naprezanje
f_p	- plastic potential function - funkcija plastičnog potencijala
r	- Lankford parameter - Lankfordov parametar
$r_0,\ r_{45}, r_{90}$	- Lankford parameter for specimen orientations 0°, 45°, 90° - Lankfordov parametar za uzorke orijentacija 0°, 45°, 90°

Greek letters/Grčka slova

$\delta_1,\ \delta_2$	- asymmetry parameters - parametri asimetrije
$\bar{\varepsilon}^{p}$	- hardening parameter, equivalent plastic strain - parameter očvršćavanja, ekvivalentna plastična deformacija
κ	- hardening function - funkcija očvršćavanja
$\lambda_1, \lambda_2, \nu, \rho$	- anisotropy parameters of Hill (1948) stress function - anizotropni parametri Hill (1948) funkcije naprezanja
$\boldsymbol{\sigma}$	- stress tensor - tenzor naprezanja
σ_b	- equibiaxial yield stress - ujednačeno dvoosno naprezanje tečenja
$\sigma_t,\ \sigma_c$	- tensile, compressive yield stress - vlačno, tlačno naprezanje tečenja
σ_y	- yield stress for referent direction - naprezanje tečenja za referentni pravac
$\sigma_{xx}, \sigma_{yy}, \sigma_{xy}, \sigma_{yx}$	- stress components - komponente naprezanja
$\sigma_0, \sigma_{45}, \sigma_{90}$	- yield stress for specimens orientations 0°, 45°, 90° - naprezanja tečenja za uzorke orijentacija 0°, 45°, 90°

use of an appropriate anisotropic constitutive model in a finite element model of the sheet forming process is important to accurately predict material behaviour.

There are several possibilities to describe plastic anisotropy. The phenomenological plasticity theories based on associated flow rule are most frequently applied for metal materials. A realistic constitutive

model for an anisotropic sheet material based on the associated flow rule requires a yield function with complex functional form and with considerable number of parameters in order to simultaneously describe anisotropy of yielding and anisotropy of plastic flow [1], [2], [3], [4]. Recently, several studies considering aspects of the application of the non-associated flow rule in sheet metal forming have been conducted [5], [6], [7], [8], [9], [10], [11], [12], [13]. It has been shown that non-associated formulations intended for orthotropic materials can result in acceptable predictions of the uniaxial material behaviour and forming processes even if stress functions with a simple functional form and low number of material parameters are utilized as yield function and plastic potential function. Furthermore, in order to describe experimentally observed difference of the tensile and compressive yield stresses, so called strength differential effect, the non-associated formulations for sheet materials based on asymmetric orthotropic yield functions have been developed [10], [11]. These asymmetric orthotropic yield functions have been derived by extending the original orthotropic quadratic Hill (1948) [14] and non-quadratic Karafillis-Boyce (1993) [15] equivalent stress term with a linear combination of the normal stress components.

The objective of the present paper is to further investigate finite element formulations based on associated and non-associated constitutive formulations that utilize simple orthotropic four parametric Hill stress function [9] or its asymmetric modification [10]. Analyzed associated and non-associated formulations might be adjusted to the different sets of the material data obtained in uniaxial tensile and compressive tests. The analyzed formulations are evaluated in predicting the cylindrical cup deep drawing process for AA2090-T3 sheet sample. By comparing the results obtained by the analyzed formulations adjusted to the different sets of material data, impact of the representation of the directional dependences of the tensile yield stresses, compressive yield stresses and Lankford parameter on the final cup predictions is assessed. Furthermore, influence of the blankholder force and friction factor value on the final drawn cup predictions is analyzed.

2. Analyzed anisotropic elasto-plastic constitutive formulations

2.1. Basic equations

Assuming isotropic linear elasticity and additive decomposition of the strain tensor increment $d\boldsymbol{\varepsilon}$ into elastic $d\boldsymbol{\varepsilon}^{\mathrm{e}}$ and plastic part $d\boldsymbol{\varepsilon}^{\mathrm{p}}$, the stress tensor increment $d\boldsymbol{\sigma}$ reads

$$d\boldsymbol{\sigma} = \mathbf{C}^{\mathrm{e}} : d\boldsymbol{\varepsilon}^{\mathrm{e}} = \mathbf{C}^{\mathrm{e}} : (d\boldsymbol{\varepsilon} - d\boldsymbol{\varepsilon}^{\mathrm{p}}) \tag{1}$$

where $\mathbf{C}^{\mathrm{e}}$ is the tensor of elastic moduli. If isotropic hardening is assumed, the yield criterion is defined as

$$F = f_y(\boldsymbol{\sigma}) - \kappa(\bar{\varepsilon}^p) = 0 \tag{2}$$

where $f_y(\boldsymbol{\sigma})$ is a continuously differentiable function called the yield function, scalar $\bar{\varepsilon}^p$ is a hardening parameter and $\kappa(\bar{\varepsilon}^p)$ is a scalar function called hardening function representing a stress-strain relation. According to the plastic potential theory, the plastic part of the strain tensor increment is proportional to the gradient of the stress function $f_p(\boldsymbol{\sigma})$ named plastic potential function

$$d\boldsymbol{\varepsilon}^{\mathrm{p}} = d\lambda \frac{\partial f_p(\boldsymbol{\sigma})}{\partial \boldsymbol{\sigma}} \tag{3}$$

where $d\lambda$ is a non-negative scalar called plastic multiplier or consistency parameter. If plastic potential and yield function are not identical above evolution equation for the plastic strain tensor increment becomes the so-called non-associated flow rule. If the plastic potential and yield function are identical the so-called associated flow rule is reproduced. In the present formulation, hardening parameter is considered as an equivalent plastic strain that obeys the principle of the plastic work equivalence

$$f_y(\boldsymbol{\sigma})\, d\bar{\varepsilon}^p = \boldsymbol{\sigma} : d\boldsymbol{\varepsilon}^{\mathrm{p}} \tag{4}$$

If the plastic potential is a first order homogeneous function that obeys Euler′s identity, by using Eqs. (3) and (4) evolution equation for the hardening parameter reads

$$d\bar{\varepsilon}^p = d\lambda \frac{\boldsymbol{\sigma} : \partial f_p(\boldsymbol{\sigma}) / \partial \boldsymbol{\sigma}}{f_y(\boldsymbol{\sigma})} = d\lambda \frac{f_p(\boldsymbol{\sigma})}{f_y(\boldsymbol{\sigma})} \tag{5}$$

Since, for the elastic processes incremental changes of the internal variables (plastic strain tensor and hardening parameter) vanish and $d\lambda = 0$ applies, for a hardening material plastic multiplier obeys complementary conditions

$$d\lambda \geq 0, \qquad F \leq 0, \qquad d\lambda F = 0 \tag{6}$$

and consistency condition

$$d\lambda dF = 0 \tag{7}$$

Details about the developed computational procedure of the above constitutive description based on the incremental deformation theory and implicit return mapping can be found in [9], [10].

2.2. Hill (1948) stress function

In sheet metal forming it is common practice to assume that the sheet is approximately subjected to plane stress conditions and that material exhibits orthotropic symmetry in plastic properties. Therefore, yield function and plastic potential are considered as functions of the

in-plane stress components, $\sigma_{xx}, \sigma_{yy}, \sigma_{xy}$ and σ_{yx}, where x-axis denotes the original sheet rolling direction and y-axis denotes the direction in sheet plane transverse to the rolling direction. The z-axis denotes the sheet normal direction. Analyzed constitutive formulations utilize yield function and plastic potential with functional form as orthotropic quadratic Hill (1948) yield function [14]. This yield function was originally derived for a three-dimensional anisotropic solid, but it can be written in the following form if expressed in the two-dimensional stress space for a rolled sheet material

$$f_y = \sqrt{\lambda_1 \sigma_{xx}^2 + \lambda_2 \sigma_{yy}^2 - 2\nu \sigma_{xx}\sigma_{yy} + \rho \sigma_{xy}^2 + \rho \sigma_{yx}^2} \quad (8)$$

In the above expression, $\lambda_1, \lambda_2, \nu$ and ρ are anisotropic material parameters. Yielding condition can be stated as $f_y = \sigma_y$ where σ_y is the yield stress for the referent direction. Hill (1948) stress function can be adjusted to the yield stresses or the experimental data indicating plastic flow. If the yield stress for rolling direction is adopted as the referent value, the parameters of Hill (1948) yield function adjusted to yield stresses read

$$\lambda_1 = 1, \quad \lambda_2 = (\sigma_0/\sigma_{90})^2$$
$$\nu = 0.5(1 + (\sigma_0/\sigma_{90})^2 + (\sigma_0/\sigma_b)^2)$$
$$\rho = 2(\sigma_0/\sigma_{45})^2 - 0.5(\sigma_0/\sigma_b)^2 \quad (9)$$

where σ_b is equibiaxial yield stress and σ_0, σ_{45} and σ_{90} are the yield stresses obtained in uniaxial loading of the sheet specimens oriented at 0°, 45° and 90° to the rolling direction. The parameters of the Hill (1948) stress function can be defined in terms of Lankford parameter that reads

$$r = d\varepsilon_{22}^p / d\varepsilon_{33}^p \quad (10)$$

where $d\varepsilon_{22}^p$ and $d\varepsilon_{33}^p$ are width and thickness plastic strain increments obtained in uniaxial loading of the sheet specimen. In calculating parameters of Hill (1948) stress function, three strain ratios, r_0, r_{45} and r_{90}, obtained in uniaxial tension along 0°, 45° and 90° to the rolling direction and the yield stress for the rolling direction can be used. The adopted calibration procedure results in the following expressions for function parameters

$$\lambda_1 = 1, \quad \lambda_2 = \frac{1 + 1/r_{90}}{1 + 1/r_0}$$
$$\nu = \frac{1}{1 + 1/r_0}, \quad \rho = \frac{(1 + 2r_{45})(1/r_0 + 1/r_{90})}{2(1 + 1/r_0)} \quad (11)$$

2.3. Asymmetric orthotropic yield stress function

In the present study, yielding of a sheet material with strength differential effect is described by the yield criterion that was derived by extending the original orthogonal Hill (1948) stress function by the linear combination of the normal stress components [16], [10]. For the plane stress conditions, adopted criterion can be written in the following form

$$f_y = \sqrt{\lambda_1 \sigma_{xx}^2 + \lambda_2 \sigma_{yy}^2 - 2\nu \sigma_{xx}\sigma_{yy} + 2\rho \sigma_{xy}^2} + (\delta_1 \sigma_{xx} + \delta_2 \sigma_{yy}) = \sigma_y \quad (12)$$

where $\lambda_1, \lambda_2, \rho, \nu, \delta_1, \delta_2$ are material parameters to be determined experimentally. Obviously, if $\delta_1 = \delta_2 = 0$ yield function defined by Eq. (8) is reproduced. Furthermore, if $\lambda_1 = \lambda_2 = 1, \rho = 3/2, \nu = 1/2$ and $\delta_1 = \delta_2 \neq 0$ in addition, well-known isotropic Drucker-Prager criterion [17] is obtained. Therefore, the adopted criterion can also be considered as the Drucker-Prager formulation slightly modified by adding anisotropy parameters.

The parameters in Eq. (12) can be defined in terms of selected initial yield stresses in uniaxial tension and compression and equibiaxial tension. If σ_y corresponds to the tensile yield stress for the rolling direction, the adopted calibration procedure results in following expressions for the asymmetry parameters

$$\delta_1 = 0.5(1 - \sigma_{t0}/\sigma_{c0})$$
$$\delta_2 = 0.5(\sigma_{t0}/\sigma_{t90} - \sigma_{t0}/\sigma_{c90}) \quad (13)$$

while parameters of the pressure-insensitive term are defined as

$$\lambda_1 = (1 - \delta_1)^2, \quad \lambda_2 = (\sigma_{t0}/\sigma_{t90} - \delta_2)^2$$
$$\nu = 0.5((\lambda_1 + \lambda_2) - ((\sigma_{t0}/\sigma_b) - (\delta_1 + \delta_2))^2)$$

for σ_{45} in tension:

$$\rho = 0.5((2\sigma_{t0}/\sigma_{45} - \delta_1 - \delta_2)^2 - \lambda_1 - \lambda_2 + 2\nu)$$

for σ_{45} in compression:

$$\rho = 0.5((2\sigma_{t0}/\sigma_{45} + \delta_1 + \delta_2)^2 - \lambda_1 - \lambda_2 + 2\nu) \quad (14)$$

In the present paper, influence of the uniaxial material parameters on the cup drawing predictions is assessed by testing associated and non-associated formulations based on Hill (1948) stress function and adjusted to the different sets of material data. Analyzed associated formulation utilize Hill (1948) stress function adjusted to the yield stresses or Lankford parameters as yield function and plastic potential, while non-associated formulation utilizes Hill (1948) stress function adjusted to the yield stresses as yield function and Hill (1948) stress function adjusted to the Lankford parameters as plastic potential. Furthermore, non-associated formulations based on the presented asymmetric orthotropic yield function adjusted to the tensile and compressive yield stresses are considered.

3. Predictions of planar anisotropy and yielding asymmetry

In this section capabilities of the analyzed associated and non-associated formulations in predicting uniaxial behaviour for AA2090-T3 sheet sample are considered. Descriptions of the directional dependences of the tensile and compressive yield stresses and Lankford parameter obtained by the stress functions used in analyzed formulations are investigated.

In the previous study conducted by authors [9] capabilities of the Hill (1948) stress function adjusted solely to the tensile properties were investigated for the considered material. In the present study, the strength differential effect is considered and predictions of the symmetric Hill (1948) stress function adjusted to the compressive yield stresses are investigated. The parameters of the symmetric Hill (1948) stress functions denoted as Hill-1 and Hill-2 are defined in terms of three directional yield stresses obtained in the uniaxial tension and compression, respectively, of the specimens oriented at 0°, 45° and 90° to the rolling direction and the equibiaxial tensile yield stress according to Eq. (9). Parameters of Hill (1948) stress function denoted as Hill-3 are calculated according to Eq. (11) using three Lankford parameters obtained in uniaxial tensions along 0°, 45° and 90° to the rolling direction. The analyzed asymmetric stress function defined by Eq. (12) contains six adjustable parameters $\lambda_1, \lambda_2, \rho, \nu, \delta_1, \delta_2$ that may be evaluated according to the Eqs. (13) and (14) using tensile and compressive yield stresses along the rolling and the transverse directions, tensile or compressive yield stress at 45° to the rolling direction and the equibiaxial yield stress. In the following, asymmetric yield function adjusted to the tensile yield stress at 45° to the rolling direction is denoted as ASYMM-Hill-1 and yield function adjusted to the compressive yield stress at 45° is denoted as ASYMM-Hill-2. Material data for AA2090-T3 sheet sample are given in Table 1. Table 2 shows calculated anisotropy and asymmetry parameters of the analyzed functions for the considered material.

Table 1. Material data for AA2090-T3 sheet sample [18]

Tablica 1. Materijalni podaci za uzorak lima AA2090-T3 [18]

specimen orientation/ orijentacija uzorka	tensile yield stress σ_t (MPa)/ vlačno naprezanje tečenja σ_t (MPa)	compressive yield stress σ_c (MPa)/ tlačno naprezanje tečenja σ_c (MPa)	Lankford parameter/ Lankfordov parametar
0°	279.6	248.0	0.211
15°	268.7	256.0	0.327
30°	254.4	253.0	0.692
45°	226.8	240.0	1.577
60°	226.4	248.5	1.039
75°	246.6	257.0	0.538
90°	254.4	266.5	0.692
thickness/debljina: 1.60 mm, equibiaxial tensile yield stress/ujednačeno dvoosno naprezanje tečenja: σ_b= 289.4 MPa Young modulus/Youngov modul: 69 000 MPa Poisson ratio/Poissonov koeficijent: 0.33 true stress-strain curve for rolling direction/zakon očvršćavanja za pravac valjanja: $\kappa(\bar{\varepsilon}^p) = 646(0.025 + \bar{\varepsilon}^p)^{0.227}$ MPa			

Table 2. Calculated anisotropy and asymmetry parameters of the analyzed stress functions for AA2090-T3 sheet sample

Tablica 2. Vrijednosti parametara anizotropije i asimetrije analiziranih funkcija naprezanja za uzorak lima AA2090-T3

function label / oznaka funkcije	material data used / korišteni materijalni podaci	λ_1	λ_2	ν	ρ	δ_1	δ_2
Hill-1	$\sigma_{t0}, \sigma_{t45}, \sigma_{t90}, \sigma_b$	1.0000	1.2070	0.6368	2.5729	—	—
Hill-2	$\sigma_{c0}, \sigma_{c45}, \sigma_{c90}, \sigma_b$	1.0000	0.8660	0.5658	1.7684	—	—
Hill-3	$r_0, r_{45}, r_{90}, \sigma_{t0}$	1.0000	0.4251	0.1736	2.2422	—	—
ASYMM -Hill-1	$\sigma_{t0}, \sigma_{t45}, \sigma_{t90}, \sigma_b, \sigma_{c0}, \sigma_{c90}$	1.1315	1.1532	0.6372	2.6313	-0.0637	0.0247
ASYMM- Hill-2	$\sigma_{c0}, \sigma_{c45}, \sigma_{c90}, \sigma_b, \sigma_{t0}, \sigma_{t90}$	1.1315	1.1532	0.6372	2.1193	-0.0637	0.0247

Figs. 1 and 2 show predictions of the uniaxial properties and yield loci obtained by the symmetric Hill (1948) stress functions. It can be observed that functions Hill-1 and Hill-2 adjusted to the yield stresses result in a good description of the directional yield stresses with corresponding sign but poor description of the strain ratios. Function Hill-3 adjusted to the strain ratios results in a reasonable description of directional strain ratios but fails in predicting the yield stresses. These predictions clearly indicate poor capability of the Hill (1948) stress function under associated flow rule in predicting material behaviour even if one type of deformation, tension or compression, prevails. As shown in the previous study [9] some improvements in predicting material behaviour in forming processes can be assessed by using non-associated formulations based on stress function adjusted to tensile yield stresses as yield function and stress function adjusted to Lankford parameter as plastic potential. In this paper non-associated formulations based on symmetric Hill-2 or asymmetric ortotropic yield function adjusted to the compressive yield stresses are considered.

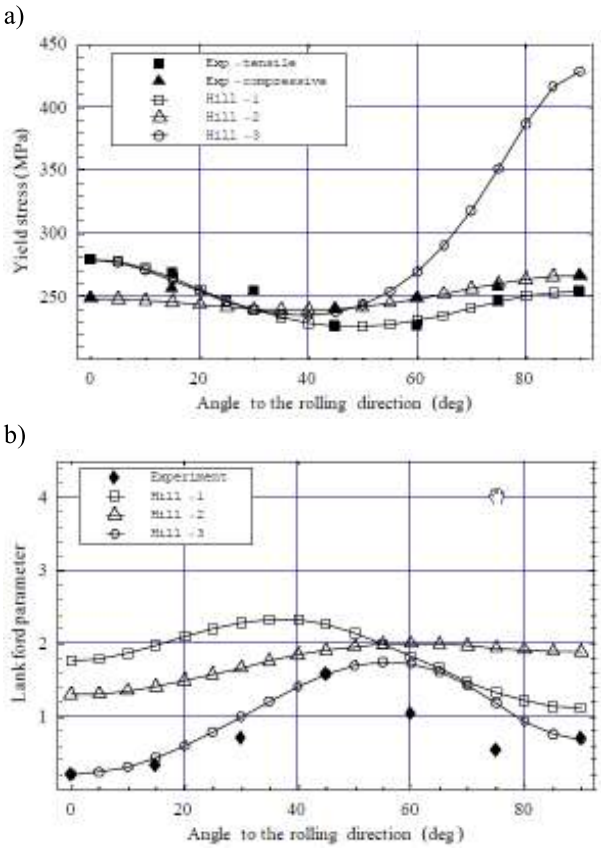


Figure 1. Experimental values and predictions of symmetric Hill stress functions: a) yield stresses; b) Lankford parameters for AA2090-T3

Slika 1. Eksperimentalne vrijednosti i predviđanja simetrične Hill funkcije naprezanja: a) naprezanja tečenja; b) Lankfordovi parametri za AA2090-T3

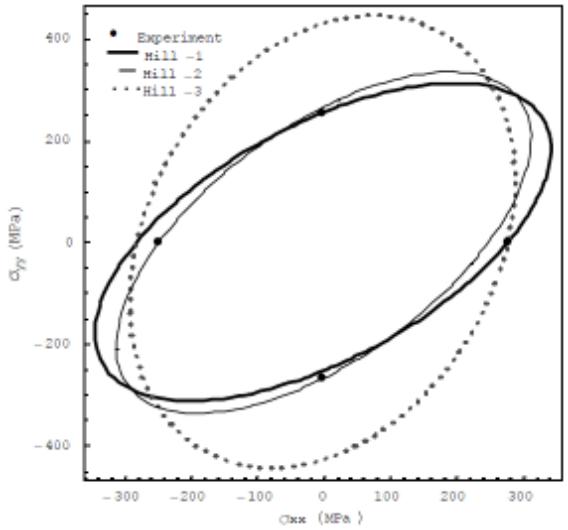


Figure 2. Contours of the symmetric Hill functions for AA2090-T3. Contours correspond to σ_{xy}=0.0

Slika 2. Konture simetrične Hill funkcije za AA2090-T3. Konture odgovaraju vrijednosti σ_{xy}=0.0

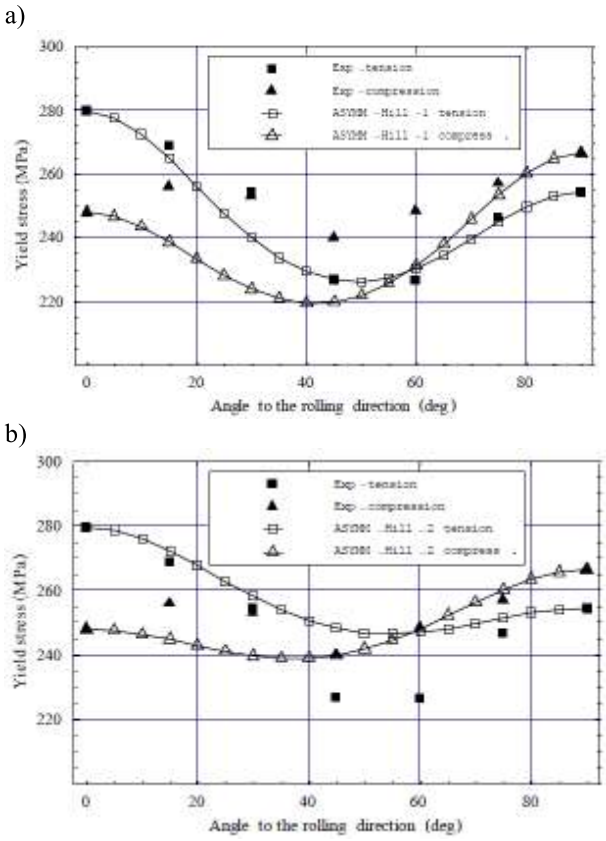
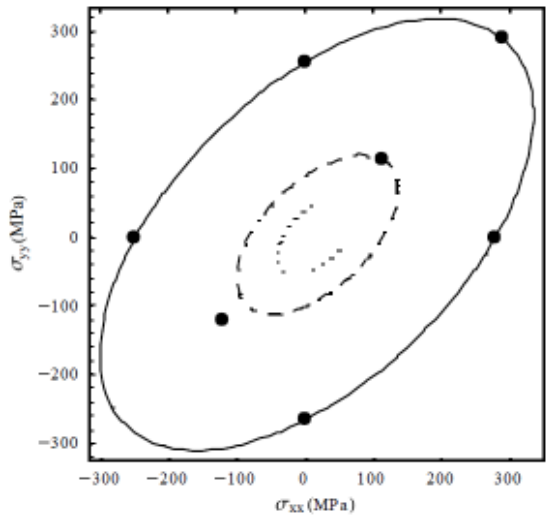


Figure 3. Experimental values and predictions of asymmetric yield functions for AA2090-T3: a) ASYMM-Hill-1; b) ASYMM-Hill-2

Slika 3. Eksperimentalne vrijednosti i predviđanja asimetrične funkcije tečenja za AA2090-T3: a) ASYMM-Hill-1; b) ASYMM-Hill-2

Fig. 3 shows predictions of the uniaxial yield stresses obtained by the asymmetric yield functions. Fig. 4 shows contours of these functions for the zero shear stress and for the shear stress values corresponding to the uniaxial tension/compression of the specimen oriented at 45° to the rolling direction.

a)



b)

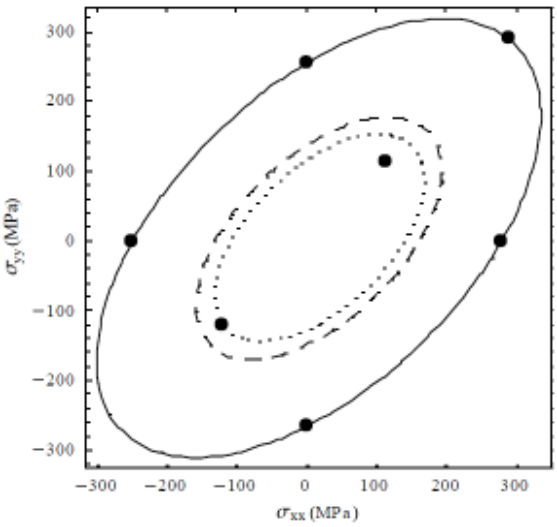


Figure 4. Contours of asymmetric yield functions for AA2090-T3:a)ASYMM-Hill-1; b)ASYMM-Hill-2 –σ_{xy}=0.0, - - σ_{xy}=113.4 MPa, …. σ_{xy}=-120.0 MPa

Slika 4. Konture asimetričnih funkcija tečenja za AA2090-T3:a)ASYMM-Hill-1;b)ASYMM-Hill-2 –σ_{xy}=0.0, - - σ_{xy}=113.4 MPa, …. σ_{xy}=-120.0 MPa

As shown in Fig. 3 directional dependences of tensile and compressive yield stresses cannot be completely captured simultaneously with the analyzed asymmetric yield function. The function ASYMM-Hill-1 with shear parameter adjusted to σ_{45} in tension fails in predicting compressive stress amplitude while the function ASYMM-Hill-2 adjusted to σ_{45} in compression fails in predicting tensile stress amplitude. It can be concluded that two asymmetry parameters involved in the analyzed yield function are insufficient for the accurate uniaxial yield stress representation for the considered material. Nevertheless, it can be expected that by comparing the associated formulations and the non-associated formulations based on symmetric or asymmetric yield function impact of the uniaxial material parameters on the final predictions can be assessed.

4. Cylindrical cup deep drawing for AA2090-T3 sheet sample

In this section, predictions of the associated and non-associated formulations adjusted to the different sets of material data are compared in predicting cylindrical cup deep drawing for AA2090-T3 sheet sample. The simulations are performed with FE code ADINA 8.6 [19] upgraded with the updated Lagrangian formulation of the CBR shell element and the stress integration procedure of the analyzed constitutive formulations based on the incremental deformation theory and implicit return mapping [9], [10]. A schematic view of the cup drawing problem is presented in Fig 5.

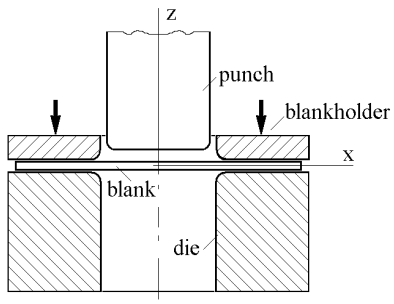


Figure 5. Schematic view of the cylindrical cup deep drawing in *x-z* plane

Slika 5. Shematski prikaz cilindričnog dubokog vučenja u *x-z* ravnini

For the considered cylindrical cup drawing, material and process parameters are those reported in [18]. The initial blank diameter is 158.76 mm with 1.60 mm in thickness. The punch diameter is 97.46 mm with shoulder radius of 12.70 mm. The die opening diameter is 101.48 mm with shoulder radius of 12.70 mm. The blank-holding force is 22.0 kN and the friction factor of 0.1 for blank/punch, blank/die and blank/blank holder contact surfaces is utilized. Due to the shape geometry and material orthotropy, a one-quarter model of the cup is analyzed. One-quarter section of the blank is modeled with 369 4-node CBR shell elements while the blank-

holder, die and punch are modelled as rigid surfaces. For the frictional contact treatment, the constraint function algorithm available in ADINA 8.6 is employed. The classical Coulomb friction law and constant friction factor are used. The isotropic hardening is assumed and power hardening curve, specified in Tab.1, describing the experimental stress-strain data for the rolling direction is utilized.

The contours of drawn cups obtained by the analyzed associated and non-associated formulations are compared with experimental data reported in [18]. The formulations are label according to the utilized yield function and flow rule (AFR for associated and NAFR non-associated flow rule). Full meaning of the labels is presented in Tab. 3.

Table 3. Formulation labels

Tablica 3. Oznake formulacija

formulation label / oznaka formulacije	yield function / funkcija tečenja	potential/ potencijal
AFR-Hill-1	Hill-1	Hill-1
AFR-Hill-2	Hill-2	Hill-2
AFR-Hill-3	Hill-3	Hill-3
NAFR-Hill-1	Hill-1	Hill-3
NAFR-Hill-2	Hill-2	Hill-3
NAFR-ASYMM-Hill-1	ASYMM-Hill-1	Hill-3
NAFR-ASYMM-Hill-2	ASYMM-Hill-2	Hill-3

In the previous study conducted by the authors [9] simulations of the cylindrical cup drawing for AA2090-T3 were performed by the associated and non-associated formulations based on symmetric Hill stress function and adjusted solely to the uniaxial tensile properties (AFR-Hill-1, AFR-Hill-3 and NAFR-Hill-1). Since the analysis of the thickness strain distribution indicated that compressive deformations prevail, in the present study associated and non-associated formulations adjusted to the compressive yield stresses are tested. The experimental earing profiles and simulated profiles obtained by the associated formulations are compared in Fig. 6. By considering Fig. 1 and Fig. 6 it can be concluded that the predicted earing trend (location of peaks and valleys) is the mirror image of the Lankford parameter representation obtained by the material formulation with respect to the transverse direction. The same correlation applies between the experimental earing profile and the experimental strain ratio distribution. As shown in Fig. 6 analyzed associated formulations utilize as plastic potential stress functions Hill-1, Hill-2 and Hill-3 that cannot capture the trend of the experimental strain ratio distribution. Therefore, these models fail in predicting small ears near 0° (and 180°) as well as the location of more pronounce ears near 50°. Also form Fig. 6 it can be seen that the earing amplitude (the maximum and minimum height difference) is best captured by the associated formulation adjusted to the tensile yield stresses.

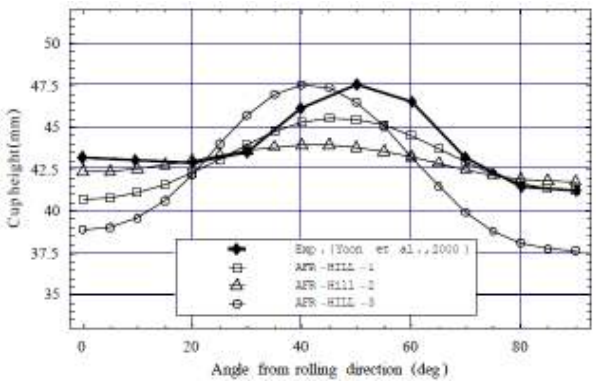


Figure 6. Predictions of the cup heights obtained by the associated formulations based on the symmetric Hill stress function.

Slika 6. Predviđanja visina posudice dobivena formulacijama temeljenim na pridruženom pravilu tečenja i simetričnoj Hill funkciji naprezanja.

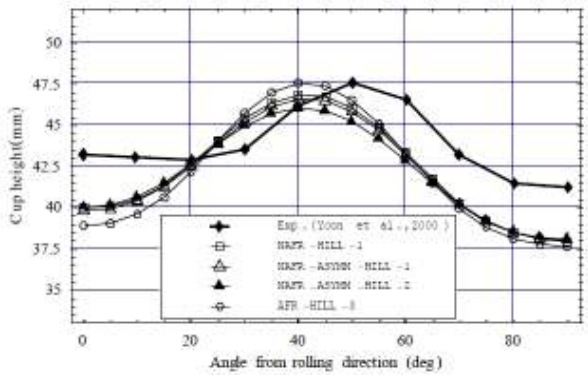


Figure 7. Predictions of the cup heights obtained by the non-associated formulations based on the symmetric or asymmetric yield function.

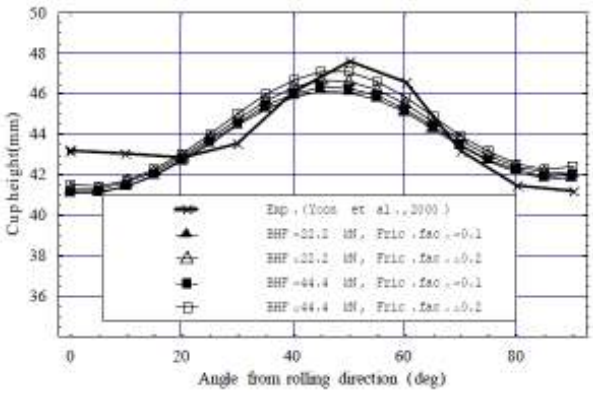
Slika 7. Predviđanja visina posudice dobivena formulacijama temeljenim na nepridruženom pravilu tečenja i simetričnoj ili nesimetričnoj funkciji tečenja.

Fig. 7 shows predictions of the non-associated formulations based on Hill-3 plastic potential and symmetric or asymmetric yield stress function adjusted to the different sets of yield stresses. Predicted cup heights clearly indicate that formulations based on the same plastic potential result in almost identical earing trend and that the difference in the yielding description influences the earing profile amplitude. It can be observed that formulations NAFR-ASYMM-Hill-1 and NAFR-ASYMM-Hill-2 with the improved representation of the orientation dependence of the yield stresses and yielding asymmetry results in improved

predictions of earing amplitude compared to AFR-Hill-3 formulation.

In Fig. 8 influence of the blankholder force and the friction factor on the predicted earing profile for the associated formulations adjusted to the tensile yield stresses or Lankford parameters is presented. The presented results are obtained by the corresponding constitutive formulations available in ADINA 8.6. These ADINA constitutive formulations are marked according to the calibration procedure as the formulations considered in the rest of the paper. Therefore, ADINA associated formulation adjusted to the tensile yield stresses is marked as AFR-Hill-1, while ADINA associated formulation adjusted to the Lankford parameters is marked as AFR-Hill-3. It can be observed that the increase of the blankholder force and friction factor results in increased predicted earing amplitude, i.e. increase of the cup heights near predicted pronounced ears. The increase of the earing amplitude due to increased values of the considered process parameters is more pronounced for the formulation adjusted to the strain ratios, AFR-Hill-3. Also it can be observed that for the associated formulation adjusted to the yield stresses AFR-Hill-1 double increase of the blankholder force and friction factor results in small ears near 0° and 90°.

a)



b)

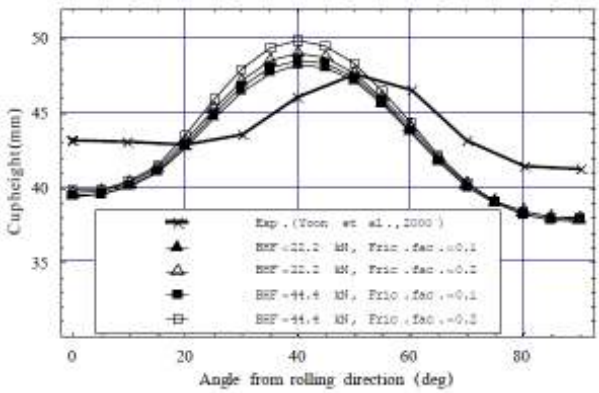


Figure 8. Influence of the blankholder force and friction factor on the predicted cup heights, a) formulation AFR-Hill-1, b) formulation AFR-Hill-3.

Slika 8. Utjecaj sile na tlačnom prstenu i faktora trenja na predviđanja visina posudice, a) formulacija AFR-Hill-1, b) formulacija AFR-Hill-3.

5. Conclusions

In the present paper associated and non-associated constitutive formulations adjusted to the different sets of material data are examined in predicting cylindrical cup drawing process for AA2090-T3 sheet sample. By comparing obtained predictions, influence of the representation of the uniaxial material properties, i.e. directional dependences of the tensile and compressive yield stresses and Lankford parameter on the earing predictions is assessed. It can be concluded that the final predicted earing trend is strongly influenced by the strain ratio representation i.e. by the choice of the plastic potential function. In the non-associated formulations the improved description of the directional dependence of yield stresses and yielding asymmetry results in some improvements of the earing amplitude. Furthermore, by considering predictions obtained with various values of the blankholder force and friction factor it can be concluded that the increase of these processes parameters results in certain increase of the earing amplitude.

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ANNEALING INFLUENCE ON GRAIN SIZE AND MECHANICAL PROPERTIES IN LOW CARBON STEELS

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Keywords

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Ključne riječi

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Mehanička svojstva
Veličina kristalnog zrna

Original scientific paper

In the present study low carbon steel samples were processed by various annealing temperatures and holding times. Annealing temperatures and holding times were chosen in accordance with the central composite design of experiments. Annealing temperatures were chosen within interval 300 to 1000 °C and limits of holding times varied from 60 to 240 minutes. In order to determine the influence of annealing process on the grain size and mechanical properties, after annealing all samples were prepared for metallographic and hardness examination. The results indicated that the grain size increases with increasing annealing temperature and holding time. The opposite was noticed in the hardness behaviour, namely hardness decreases with increasing both annealing temperature and holding time.

Utjecaj žarenja na veličinu zrna i mehanička svojstva kod nisko-ugljičnih čelika

Izvorni znanstveni članak

U ovom su istraživanju uzorci od nisko-ugljičnog čelika žareni na različitim temperaturama i različitim vremenima držanja. Temperature žarenja i vremena držanja odabrani su prema centralno-kompozitnom planu pokusa. Temperature žarenja su izabrane iz intervala 300 do 1000°C, a vremena držanja na temperaturama žarenja varirala su od 60 do 240 minuta. Kako bi se odredio utjecaj žarenja na veličinu kristalnog zrna i mehanička svojstva, nakon žarenja svi su uzorci bili pripremljeni za metalografska ispitivanja i ispitivanja tvrdoće. Rezultati pokazuju da veličina kristalnog zrna raste sa porastom temperature i vremena držanja. Suprotno je primijećeno kod ponašanja tvrdoće, naime tvrdoća se smanjuje i s rastom temperature i s rastom vremena držanja.

1. Introduction

Heat treatment is very important procedure in fabrication of many semi-finished or finished engineering products. Today heat treatment plays an important role in manufacturing due to constant requests for improvement of material properties. A product made of steel may have wide range of properties depending on the heat treatment undergone. Heat treatment offers a low cost way to get the desired combination of material properties. There are numerous various procedures of heat treatment and in this paper the annealing heat treatment is studied. Annealing is always composed of slowly heating to desired temperature and slowly cooling in furnace or still air to room temperature. The most commonly used steels for various constructions are low-carbon steels. These steels are usually made by cold or hot forming technology in the form of plates, strips, sheets, bars and sections. In the case of complex construction these simple semi-finished products may be assembled by welding technology. After the welding there is often a need for the annealing heat treatment [1,2,3]. As a result of thermal cycle during welding, immediately or later on during a lifetime, distortion or residual stress may occur within joined components. These stresses can be as high as the yield stress of weld or base material, so it is necessary to perform stress relief annealing after welding. This is usually carried out at temperatures from 600 to 700 °C [1,2]. Post weld heat treatment is also used to minimize the potential for hydrogen induced cracking. In this case welded construction is heated in the temperature range from 250 to 320°C [3]. Sometimes in order to acquire specific shape, the base metal needs to be cold or hot worked prior to welding. In that case welded components have to be subjected to normalizing heat treatment so as to recover original microstructure and mechanical properties [4]. Normalizing heat treatment is normally performed at temperatures 40 to 50 °C above the A_3 temperature. In the context of the aforementioned there is an obvious need for annealing heat treatment at low

and high temperatures especially in steel welded constructions.

Symbols/Oznake

L_3	- Mean intercept length of grains at magnification 1x, *mm* - Srednja duljina presječenih zrna pri povećanju 1x, *mm*	A	- Annealing temperature, *°C* - Temperatura žarenja, *°C*
L_T	- Total length of test lines, *mm* - Ukupna duljina linija za testiranje, *mm*	B	- Annealing time, *min* - Vrijeme žarenja, *min*
N	- Number of intersections of grain boundaries - Broj presječenih granica zrna	HV	- Vickers hardness of annealed samples - Tvrdoća žarenih uzoraka po Vickersu
M	- Microscopic magnification - Povećanje mikroskopa	d_A	- Average grain diameter, *mm* - Srednja veličina zrna, *mm*
G	- ASTM grain size number - Veličina zrna prema ASTM standardu		

Objective of this paper is to conduct a research on the annealing influence on microstructure and mechanical properties of low carbon steels.

2. Experimental procedure

The goal of this study is to obtain mathematical models that relate annealing temperature and holding time with the hardness and grain size in low carbon steels. In order to get the mathematical models design of experiment (DOE) together with an analysis of variance (ANOVA) and regression analysis (RA) have been used. The DOE was achieved using the face centered central composite design (FCCCD). In the experimental research, modelling and adaptive control of multifactor processes the CCD of experiment, that offers optimization possibility, is very often used [5]. Two factorial FCCCD experiment demand 4 experiments (2 factors on two levels, 2^2), 4 experiments on the central axes and 5 experiments on the average level, that gives total of 13 experiments. The minimal and maximal values of chosen annealing parameters as well as the coded input factors are presented in Table 1. To collect data for ANOVA and RA, software package Design-Expert was used to generate 13 experimental points.

Table 1. Physical and coded values of input factors

Tablica 1. Fizikalne i kodirane vrijednosti ulaznih faktora

Input factors	Coded values of input parameters		
	$x_{-i,min}$	x_{-i0}	$x_{i,max}$
	-1	0	+1
x_1 = annealing temp., °C	300	650	1000
x_2 = holding time, min	60	150	240

The annealing experiments were carried out in the electric furnace capable for heating samples up to 1200°C. The specimens were cut off out of a bar made from steel EN10025-2 S275JR+AR. Chemical composition of the used steel bar is: 0.103% C, 0.222% Si, 0.539% Mn, 0.446% Cu, 0.246% Cr, 0.206% Ni, 0.02% Sn, 0.005% Al, 0.066% Mo, 0.005% Nb, 0.004% V, 0.002% Ti, 0.014% P and 0.012% S. Mechanical properties of the bar are: R_m = 464 MPa, $R_{p0.2}$ = 291 MPa, A = 35% and KV (+20°C) = 91 J. Samples Ø15x30 mm were annealed in as received condition. In accordance with the plan of experiments one specimen at the time was placed in the furnace after the desired temperature had been reached. After achieving the desired holding time at a specific temperature the samples were taken out of the furnace and left to cool in still air.

After the annealing heat treatment the samples underwent a grinding process using a hand grinder with progressively finer grits of sandpaper. Uniform directional wear was achieved after grinding with final 240 grit sandpaper. In order to produce a mirror finish the samples were finely polished using alumina and rotating wheel covered with cloth. Afterwards a Nital 3% (Nitric Acid in alcohol) etchant was used in order to reveal the microstructure of the specimens. Once the specimens were etched digital optical micrographs were taken using a Dino-Lite USB camera attached to Opton Axioskop optical microscope. Average ferrite grain size measurements were conducted manually using the Hyen Intercept Method [6] and software ImageJ.

The first widely used methodology for measuring the average grain size is the Hyen Intercept Method [6]. The Intercept method utilizes randomly positioned lines of a known length that are overlaid on the micrograph. An intersection is a point where a test line is cut by a grain boundary. Once the lines are drawn, a set of rules are utilized to count the intersections of the grain boundaries along the line [7]. By calibrating the software ImageJ with the micrograph's scale bar, the line length can be measured within the program.

Once the intersections along the lines have been counted, the mean intercept length of grains in mm at 1x, L_3, can be determined as:

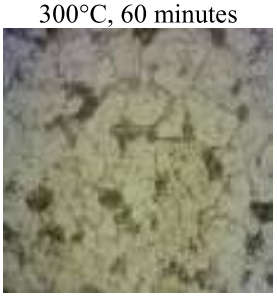
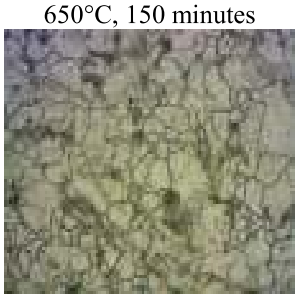
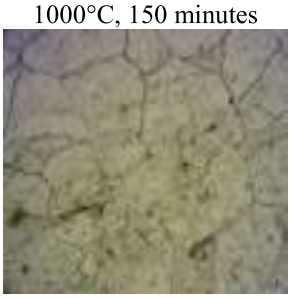
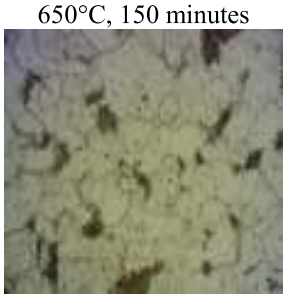
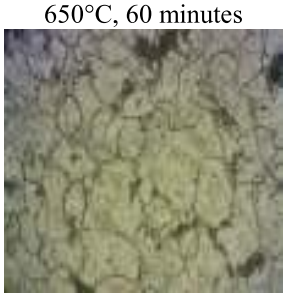
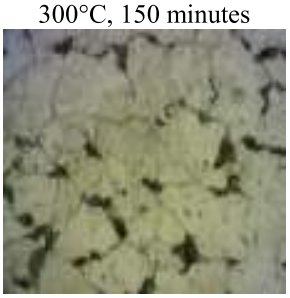
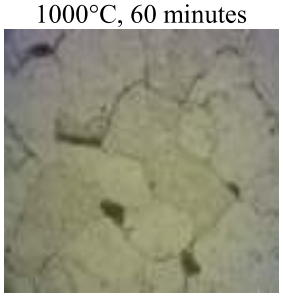
$$L_3 = \frac{L_T}{N \cdot M} \tag{1}$$

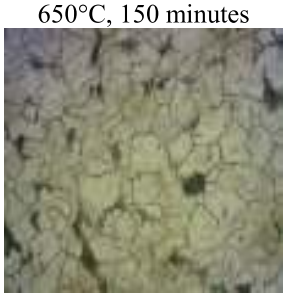
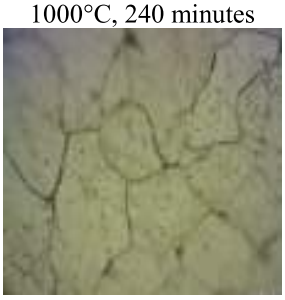
$$G = -6.64385\, log_{10}(L_3) - 3.2877$$

N is the number of counted intersections of grain boundaries cut by test lines of length L_T and M is the magnification used. In this research grain size was determined using micrographs taken at x200 magnification. With the mean intercept length, the ASTM grain size, G, can be determined using equation (1) and further correlated to the average grain diameter using ASTM E112 [8]. Metallographic photos of grinded, polished and etched annealed samples taken by a camera on optical microscope can be seen in table 2. Results of grain size measurement are shown in table 3.

Table 2. Metallographic photos of annealed samples (magnification x500)

Tablica 2. Metalografske slike žarenih uzoraka (povećanje x500)

Original specimen	Specimen 1 650°C, 150 minutes	Specimen 2 650°C, 150minutes	Specimen 3 300°C, 60 minutes 
Specimen 4 650°C, 150 minutes 	Specimen 5 1000°C, 150 minutes 	Specimen 6 650°C, 150 minutes 	Specimen 7 650°C, 240 minutes
Specimen 8 650°C, 60 minutes 	Specimen 9 300°C, 150 minutes 	Specimen 10 300°C, 240 minutes	Specimen 11 1000°C, 60 minutes 

Specimen 12 650°C, 150 minutes	Specimen 13 1000°C, 240 minutes
	

Having determined grain size of the microstructure the samples could be subjected to Vickers hardness testing. Hardness measurement with load of 98.1 N was repeated five times on each sample and average hardness was calculated. The results of hardness and ferrite grain size measurement can be seen in table 3.

Table 3. Results of measurement of hardness and average ferrite grain size diameter on annealed samples

Tablica 3. Rezultati mjerenja tvrdoće i prosječne veličine zrna na žarenim uzorcima

Run	Annealing temperature (°C)	Annealing time (min)	Hardness (HV)	Average grain diameter (mm)
1	650	150	118.0	0.0102
2	650	150	120.0	0.0114
3	300	60	162.0	0.0169
4	650	150	123.0	0.0089
5	1000	150	117.0	0.0354
6	650	150	125.0	0.0124
7	650	240	120.0	0.0154
8	650	60	126.0	0.0139
9	300	150	153.0	0.0204
10	300	240	146.0	0.0167
11	1000	60	119.0	0.0312
12	650	150	121.0	0.0112
13	1000	240	116.0	0.0394

3. ANOVA and regression analysis

The measured values of hardness and grain size on each specimen (Table 3), are input data for the second-order regression models and ANOVA. The ANOVA and regression analysis have been carried out using program package "Design Expert 6". The ANOVA shows which factors and interactions have an important influence on the hardness and grain size in microstructure. Applying the regression analysis the coefficients of regression, multi-regression factors, standard false evaluation and the value of *t*-test were determined and mathematical models were obtained.

3.1. Mathematical model for hardness

Mathematical model for hardness prediction as a function of both annealing temperature and time was obtained as follows:

$$\begin{aligned} HV &= 221.055 - 0.2074 \cdot A - 0.1574 \cdot B \\ &+ 1.0767 \cdot 10^{-4} \cdot A^2 + 1.4687 \cdot 10^{-4} \cdot B^2 \\ &+ 1.0318 \cdot 10^{-4} \cdot A \cdot B \end{aligned} \quad (2)$$

where are:
A - annealing temperature (°C)

B - holding time (minutes)

The coefficients R-Squared, Adjusted R-Squared and Predicted R-Squared were obtained as 0.9878, 0.979, and 0.968 respectively. ANOVA indicates that factor B^2 is not significant.
Graphical representation of the equation (2) is shown on Fig.1.

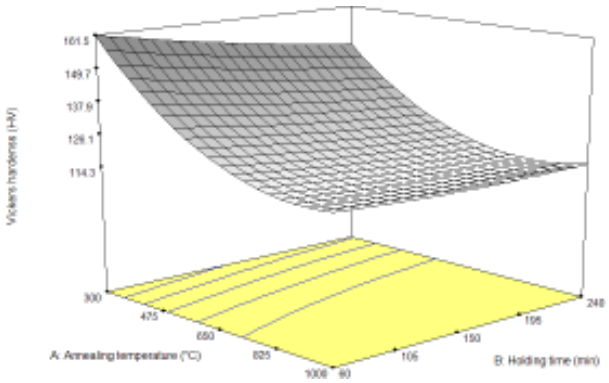


Figure 1. Graphical representation of the influence of annealing temperature and holding time on hardness

Slika 1. Grafički prikaz utjecaja temperature i vremena žarenja na tvrdoću

Surface on the Fig. 1 shows the effect of holding time and temperature on hardness. It may be seen that annealing temperature has a far grater effect on hardness then holding time. No matter which holding time is

taken hardness decreases with increasing annealing temperature. Holding time has almost no effect on hardness at high annealing temperatures, 1000°C for instance. At low annealing temperatures, for example 300°C, hardness decreases with the increment of holding time.

3.2. Mathematical model for ferrite grain size

Utilizing regression analysis module within Design Expert software quadratic mathematical model for grain size prediction was obtained in the following form:

$$d_A = 0.051895 - 1.3770 \cdot 10^{-4} \cdot \mathrm{A} - 6.5216 \cdot 10^{-5} \cdot \mathrm{B} + 1.1724 \cdot 10^{-7} \cdot \mathrm{A}^2 + 1.3106 \cdot 10^{-7} \cdot \mathrm{B}^2 + 6.6825 \cdot 10^{-8} \cdot \mathrm{A} \cdot \mathrm{B} \quad (3)$$

where are:

A - annealing temperature (°C)

B - holding time (minutes)

d_A- average ferrite grain size (mm)

The coefficients R-Squared, Adjusted R-Squared and Predicted R-Squared were obtained as 0.9709, 0.9501, and 0.8147 respectively. ANOVA indicates that factors B^2 and A·B are not significant.

Fig. 2 graphically shows the influence of holding time and annealing temperature on average grain size in microstructure according to equation (3).

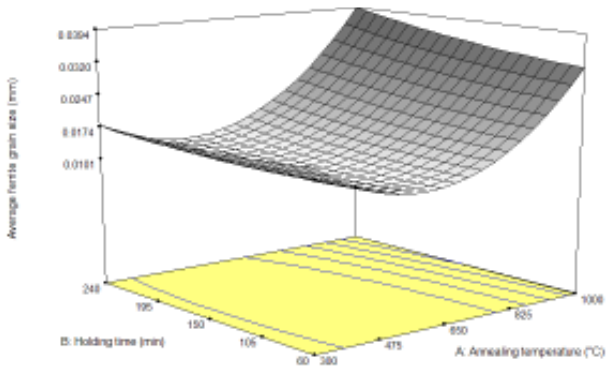


Figure 2. Graphical representation of the influence of annealing temperature and holding time on average ferrite grain size

Slika 2. Grafički prikaz utjecaja temperature i vremena žarenja na prosječnu veličinu feritnog zrna

Fig. 2 shows that annealing temperature has greater effect on the grain size when compared to holding time. Holding time shows significant influence on the grain size only when the annealing at high temperatures is carried out. The average grain size decreases with decreasing annealing temperature but only up to approx. 650°C. Further temperature reduction leads to an increase in grain size. This phenomenon can be noticed for all holding times. Minimal average grain size in the microstructure is achieved when the samples are annealed at temperature of 650°C. An explanation for such behaviour should be finded in the manufacturing process of steel bars. Namely steel bars are manufactured by a process of hot rolling using a series rolling stands. Depending on a rolling speed and bar temperature on the finishing stand various microstructures can occur due to dynamic or static recovery and/or recrystallization. If the strain rate is higher than the recovery or recrystallization rate deformed microstructure usually occurs. When this kind of microstructure is annealed static recrystallization occurs. Effects of such annealing mostly depend on annealing temperature and the magnitude of prior deformation. It appears that samples taken in this research had to some extent deformed microstructure. That particular magnitude of deformation caused the occurrence of minimal grain size at annealing temperature of 650°C.

4. Conclusion

In this work the effect of holding time and annealing temperature on hardness and grain size in a low carbon steel were analysed. Experiments were carried out in accordance with the face centered central composite design of experiments. Utilizing ANOVA and regression analysis quadratic mathematical models for hardness and grain size prediction were obtained. According to obtained models holding time has no significant influence on hardness and grain size. It is especially obvious at low annealing temperatures. When the annealing temperature decreases hardness increases continuously, while grain size decreases up to the temperature of approx. 650°C and increases afterwards. This phenomenon appears to occur due to the magnitude of deformation during manufacturing process of steel bars. In order to obtain minimum average grain size annealing heat treatment should be carried out at temperature of 650°C.

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Tribološki principi i mjere za smanjenje trošenja alata kod obrade odvajanjem čestica

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Ključne riječi
mehanizmi trošenja
alati za obradu odvajanjem čestica
trošenje alata
tribološke mjere

Keywords
mechanisms of wear
cutting tool
tool wear
tribological principles

Pregledni članak
Sažetak: U ovom radu objašnjeni su osnovni tribološki mehanizmi trošenja te tribološki procesi koji se javljaju prilikom obrade odvajanjem čestica u tribosustavu reznog alata i obratka.
S obzirom na veliki utjecaj površinskog trošenja oštrice alata na troškove obrade ali i kvalitetu konačnog proizvoda potrebno je što više smanjiti intenzitet trošenja. Da bi se smanjio intenzitet trošenja potrebno je poznavati procese trošenja koji nastaju unutar tribosustava oštrice alata i obratka i ostale faktore koji utječu na postojanost alata.
U ovom radu navedene su tribološke mjere kojima se postiže manji intenzitet trošenja tj. veća postojanost alata za obradu odvajanjem čestica.

Tribological principles and steps to reduce cutting tool wear
Review article
Abstract: This article explains the basic mechanisms of tribological wear and tribological processes that occur during cutting processes in the tribological system of cutting tool and workpiece.
Due to the large influence on the surface wear of the tool blade on manufacturing costs, and also the same influence on the surface quality of the final product, it is necessary to reduce the wear intensity as much as possible. In order to reduce the intensity of wear it is necessary to understand the processes that occur within the tribo-system of the tool blade and the workpiece, and also the other factors that affect the tool life.
Tribological measures which are used to decrease the intensity of wear are listed in this paper.

1. Uvod

Znanost koja se bavi procesima koji nastaju između dvije površine u relativnom gibanju naziva se tribologija. Zbog normalne sile koja djeluje između površina u dodiru javlja se trenje te dolazi do pretvaranja kinetičke energije u toplinu. Jedna trećina svjetske energije pojavljuje se u obliku trenja na ovaj ili onaj način i uglavnom predstavlja gubitke [1].
Ove pojave obično uključuju odvajanje čestica s jedne ili obje površine. Takav oblik trošenja smatra se normalnim do određenog iznosa. Izvan toga, trošenje može uzrokovati ozbiljnu štetu elemenata u tribosustavu. Oko 70% kvarova mehaničkih komponenti posljedica su triboloških mehanizama [1].
Neželjeno trošenje mehaničkih komponenti obično rezultira smanjenjem preciznosti i učinkovitosti elemenata, većom zračnosti između komponenata, vibracijama, pojačanim trošenjem te ponekad i lomom uslijed zamora materijala. Prema tome, trošenje može predstavljati značajan financijski gubitak. 1976. godine američki stručnjaci na području tribologije proveli su istraživanje kako bi izmjerili troškove uzrokovane prekomjernim trošenjem materijala. Rezultati istraživanja prikazani su Tablici 1.

Tablica 1. Troškovi uzrokovani trošenjem [2].

Table 1. Expenses due to wear [2].

Kategorija	Troškovi
Ratni zrakoplovi	$243.87 po satu leta
Ratni brodovi	$38.92 po satu
Trošenje alata obradom odvajanjem čestica	$9,000,000,000 po godini
Održavanje automobila i troškovi popravka	$40,000,000,000 po godini

Ove troškove moguće je značajno smanjiti razumijevanjem uzroka trošenja i mehanizama trošenja te poduzimajući prikladne tribološke mjere.

2. Mehanizmi i procesi trošenja

Uzrok površinskog trošenja materijala može biti dinamički dodir s površinom drugog krutog tijela, s

tekućinom ili s raznim drugim česticama. Svaki proces trošenja materijala sastoji se od dva ili više osnovnih mehanizma trošenja, ovisno o vrsti tribosustava. Osnovni mehanizmi trošenja su:

- ***abrazija;***

Abrazija je mikro-rezanje na površini materijala s tvrđim materijalom. Primjer abrazijskog trošenja na kućištu ležaja prikazan je na slici 1a.

- ***adhezija***;

Ako su adhezijske sile na dodirnim područjima između površina dvaju materijala jače nego kohezijske sile unutar materijala dolazi do odvajanja čestica na dodirnim mjestima. Na slici 1b prikazan je primjer adhezijskog trošenja matrice od čelika prekrivenog zaštitnim slojem AlCrN nakon 120,000 ciklusa opterećenja.

- ***umor površine;***

Na površini materijala dolazi do odvajanja materijala kao posljedica dugoročnog periodičkog promjenjivog opterećenja. Na slici 1c prikazano je oštećenje bandaže po obodu željezničkog kotača nastalo umorom površine.

- ***tribokorozija***.

Zbog utjecaja okoline tj. oksidacije nastaju reakcijski produkti na površini koji su slabo povezani s površinom te se prilikom dodira sa susjednim površinama lako uklanjaju. Ponavljanje ovog procesa predstavlja štetno korozijsko djelovanje na materijal. Na slici 1d prikazana je površina osovine oštećena tribokorozijom [3].

Slika 1. Osnovni mehanizmi trošenja, a) abrazijsko trošenje [4], b) adhezijsko trošenje [5], c) umor površine [6], d) tribokorozija [7].

Figure 1. Cutting tool wear, a) abrasive wear [4], b) adhesive wear [5], c) surface fatigue [6], d) tribo-corrosion [7].

2.1. Trošenje alata za obradu odvajanjem čestica

Prilikom kontakta s drugim materijalom, alati za obradu odvajanjem čestica izloženi su ekstremnom trenju. Razvijaju se sile visokog iznosa (nekad više od 15 kN) i visoke temperature (do 1000 ˚C). Kao rezultat, trošenje oštrice alata je neizbježno. Trošenje se očituje postupnim gubitkom materijala alata i promjenom oblika alata tijekom procesa obrade odvajanjem čestica što ima za posljedicu promjenu reznih svojstava alata.
Proces rezanja ovisi o nizu ulaznih veličina (materijal alata, geometrija alata i obratka, parametri obrade) koje direktno utječu na izlazne veličine (dimenzije obratka, hrapavost površine, sile rezanja, buka, temperatura, trošenje alata). Alat za obradu odvajanjem čestica izložen je mehaničkim, toplinskim i kemijskim opterećenjima koja razvijaju različite vrste trošenja:

- ***mehaničko trošenje;***

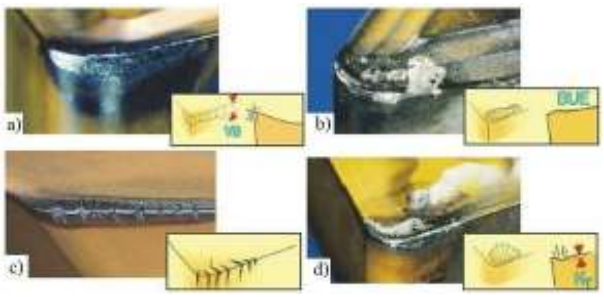
Sastoji se od abrazijskog i adhezijskog trošenja. Abrazijsko trošenje nastupa kada tvrde čestice odvojene s obratka režu površinu alata (slika 2a). Adhezijsko trošenje nastaje zbog adhezijske veze između alata i obratka na prednjoj i stražnjoj površini alata (slika 2b).

- ***termo-mehaničko trošenje;***

Glavni mehanizam je trošenje umorom površine. Dolazi do malih pukotina zbog promjene temperature i periodički promjenjivog naprezanja (slika 2c). Pukotine se šire dok se komadići alata ne odvoje.

- ***termo-kemijsko trošenje;***

Uslijed visokih kontaktnih naprezanja i visokih temperatura dolazi do prelaska atoma iz područja više koncentracije u područja niže koncentracije difuzijom. Brzina difuzije eksponencijalno se povećava s temperaturom. Difuzija atoma s površine alata uzrokuje krhki sloj sa smanjenom čvrstoćom (slika 2d). Mehanizam difuzijskog trošenja prikazan je shematski na slici 3 na primjeru volframovog karbida.



Slika 2. Trošenje alata za obradu odvajanjem čestica, a) abrazijsko trošenje, b) adhezijsko trošenje, c) umor površine, d) difuzijsko trošenje [8].

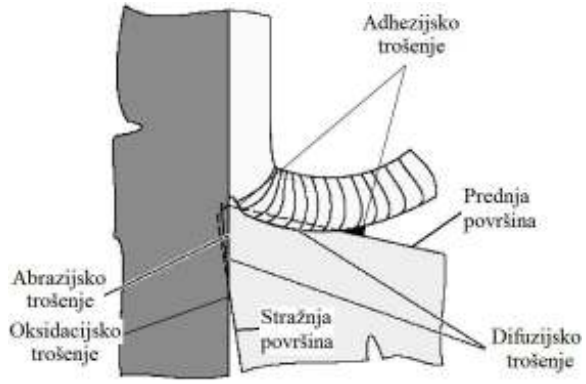
Figure 2. Cutting tool wear, a) abrasive wear, b) adhesive wear, c) surface fatigue, d) diffusion wear [8].

- ***elektrokemijsko trošenje.***

Glavni mehanizam trošenja je tribokorozija. Pod utjecajem visokih temperatura i kisika formira se krhki oksidacijski sloj. Njegovo periodičko formiranje i uništavanje ima za posljedicu trošenje materijala [9]. Karakteristična područja adhezijskog, abrazivnog, difuzijskog i oksidacijskog trošenja alata kod tokarenja prikazana su na slici 4.

Slika 3. Mehanizam difuzijskog trošenja na primjeru alata od volframovog karbida [10].

Figure 3. Diffusion mechanism of wear in the case of tungsten carbide tools [10].

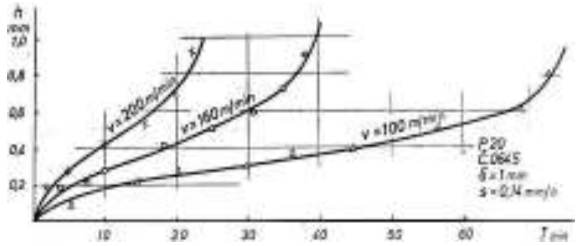


Slika 4. Karakteristična područja trošenja na alatu za tokarenje

Figure 4. Characteristic areas of wear on a lathe tool

Sposobnost obrade alata se najviše smanjuje zbog trošenja stražnje površine pa se širina pojasa trošenja na stražnjoj površini često koristi kao kriterij trošenja. Kada širina pojasa trošenja dosegne određene dimenzije potrebno je zamijeniti alat s novim. Npr. kod obrade tokarenjem potrebno je zamijeniti alat kada pojas trošenja dosegne 0,2 do 1 mm, ovisno o traženoj hrapavosti površine.

Niz faktora utječe na iznos trošenja kao što su parametri obrade, materijal obratka, sredstva za hlađenje i podmazivanje, geometrija alata i materijal alata. Trošenje je intenzivno u početnom periodu obrade odvajanjem čestica. Kada se formira pojas trošenja određene širine, iznos trošenja se naglo smanji. Određen period vremena intenzitet trošenja je nizak sve dok ne počne period trošenja u kojem iznos trošenja jako brzo raste. Ovakav tijek trošenja prikazan je na slici 5 na primjeru alata za tokarenje.



Slika 5. Trošenje stražnje površine alata za tokarenje (h) u ovisnosti o vremenu obrade (T) za različite brzine rezanja [11].

Figure 5. Wear of the lathe tool flank face (h) as a function of processing time (T) for different cutting speeds [11].

Trošenje alata kod većine procesa obrade odvajanjem čestica (tokarenje, bušenje, glodanje itd.) može se opisati krivuljama trošenja prema slici 5. Iznos trošenja u početnom periodu kao funkcija vremena mijenja se približno po zakonu parabole te ovisi najviše o materijalu obratka, materijalu alata, parametrima rezanja i kvaliteti sredstva za hlađenje i podmazivanje. Nakon toga slijedi period u kojem je promjena iznosa trošenja približno konstantna sve do perioda kada se iznos trošenja naglo poveća te je potrebno zamijeniti alat.

3. Tribološke mjere za smanjenje trošenja alata za obradu odvajanjem čestica

Općenito, intenzitet trošenja se može odrediti tijekom procesa obrade mjerljivim veličinama kao što su sila trenja, buka, vibracije i temperatura ili se može mjeriti spektografskom analizom ulja, magnetskim detektorom čestica, radioaktivnim metodama ili ferografijom. Glavne tribološke mjere za smanjenje trošenja su:

- konstrukcijske mjere;
- pravilan izbor materijala tribosustava (izbor materijala ovisno o mehanizmu trošenja);
- zaštita površine materijala (promjena strukture površine da bi se povećala otpornost određenom mehanizmu trošenja);
- period uhodavanja (period prilagođavanja dodirnih površina);
- podmazivanje (smanjivanje trenja i trošenja nanoseći sredstva za podmazivanje) [3].

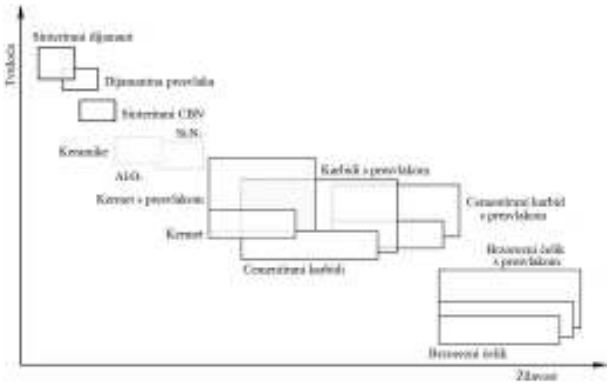
Gore navedene tribološke mjere koriste se kako bi se snizilo trošenje alata za obradu odvajanjem čestica. Faktori koji najviše utječu na vijek trajanja alata su materijal alata, zaštita površine, hlađenje i podmazivanje.

3.1. Materijal alata za obradu odvajanjem čestica

Alati za obradu odvajanjem čestica pod utjecajem su:

- mehaničkih opterećenja (zahtjevi visoke tvrdoće i dobre žilavosti);
- toplinskih opterećenja (zahtjevi temperaturne stabilnosti);
- kemijskih reakcija (što niža sklonost difuziji i oksidaciji).

Otpornost trošenju je proporcionalna tvrdoći materijala. Visoke tvrdoće alata prikladne su kada je otpor rezanja konstantan. Kada postoje udarna opterećenja prilikom obrade potrebna je visoka žilavost materijala. Kako su tvrdoća i žilavost obrnuto proporcionalna svojstva materijala ne postoji idealni materijal za sve vrste obrade odvajanjem čestica. Materijal je potrebno odabrati ovisno o eksploatacijskim uvjetima. Materijali s obzirom na svojstva tvrdoće i žilavosti prikazani su na slici 6.



Slika 6. Tvrdoća i žilavost materijala alata za obradu odvajanjem čestica [12].

Figure 6. Hardness and toughness of cutting tool materials [12].

Brzorezni čelici se koriste kada je potrebna visoka žilavost. Imaju tvrdoću od 65 HR_c ispod temperature od 600 ˚C. Na dodirnom mjestu alata i obratka temperatura je najčešće veća od 600 ˚C pa je potrebno koristiti sredstva za hlađenje i podmazivanje.

Postoji nekoliko vrsta brzoreznih čelika. Razlikuju se prema legirnim elementima. Uobičajeni legirni elementi su:

- volfram (poboljšava temperaturnu stabilnost);
- vanadij (formira tvrde karbide i povoljno djeluje na nastajanje sitno zrnate strukture);
- molibden (povećava žilavost i poboljšava temperaturnu stabilnost);
- i kobalt (poboljšava temperaturnu stabilnost) [13].

Brzorezni čelici često se koriste za obradu odvajanjem čestica u procesima glodanja, bušenja, provlačenja, odvalnog glodanja i urezivanja navoja. U procesima kao što su tokarenje i čeono glodanje obično se koriste tvrdi metali. Tvrdi metali sastoje se od volframovih karbida, titana i kobalta kao vezivnog sredstva. Karbidi imaju visoku tvrdoću prema tome i visoku otpornost prema trošenju. Povećavanjem sadržaja vezivnog materijala povećava se žilavost koja je potrebna prilikom udarnih opterećenja ali se u isto vrijeme smanjuje otpornost na trošenje. Tijekom rezanja na povišenim temperaturama promjena tvrdoće je zanemariva pa se proces često izvodi bez sredstva za hlađenje. U procesu obrade s konstantnim otporom rezanja tvrdi metali sastoje se od oko 95% karbida i 5% vezivnog sredstva. U procesima sa češćim udarnim opterećenjima tvrdi metali imaju više vezivnog materijala, do 30%.

Poboljšanje svojstava materijala može se postići modifikacijom površine ili primjenom zaštitnog sloja na površini [9]. Površinski sloj nanosi se CVD postupkom (kemijsko nanošenje iz parne faze, za brzorezne čelike) ili PVD postupkom (fizikalno nanošenje iz parne faze, za tvrde metale). Najčešće nanošeni slojevi su:

- ***TiN (titanov nitrid);***

Svjetla, zlatna, keramička prevlaka. Ima visoku tvrdoću (oko 2300 HV), mali koeficijent trenja i srednju otpornost oksidaciji. Nanosi se PVD postupkom na rezne alate i alate za obradu deformiranjem te se najčešće koristi.

- ***CrN (kromov nitrid);***

Svjetla srebrno-siva keramička prevlaka koja se nanosi PVD postupkom. Ima veliku tvrdoću (oko 2000 HV), veliku žilavost te veliku otpornost oksidaciji. Otporan na adhezijsko trošenje posebno kod obrade ne-željeznih metala. Kod obrade bakra, aluminija ili titana nadmašuje TiN ali ima veći koeficijent trenja od TiN.

- ***TiCN (titanov karbonitrid);***

Tvrdoće 3000 HV, razvijen za zahtjevnije uvjete (tvrdoća TiN-a je 2500 HV). Nanosi se CVD postupkom na rezne alate za prekidne obrade i za obrade čelika visoke čvrstoće.

- ***TiAlN (titanov aluminij nitrid).***

Plavo-crna keramička prevlaka debljine do 4 μm koja se nanosi PVD postupkom a primjenjuje se kod „suhih" obrada i obrada kaljenih materijala. Velike tvrdoće (oko 3500 HV), malog koeficijenta trenja. Otporna je na oksidaciju do temperature od 800˚C. Prevlaka je glatka i ima izvrsnu otpornost na abrazijsko i adhezijsko trošenje.

Moguće je nanijeti više zaštitnih slojeva ali ukupna debljina je obično oko 10 μm.

3.2. Hlađenje i podmazivanje

Tvrdoća alata se smanjuje na povišenim temperaturama (prikazano na slici 7) što dovodi do bržeg razvoja triboloških procesa i kraćeg vijeka trajanja, što povećava troškove proizvodnje. Glavna svrha sredstava za hlađenje i podmazivanje je odvođenje topline razvijene u zoni rezanja i smanjenje trenja između alata i obratka. Sredstva za podmazivanje smanjuju trenje do 80%. Omogućuju visoke brzine rezanja i malu otpornost rezanju sa zadovoljavajućim vijekom trajanja alata i traženom kvalitetom površine.

Slika 7. Tvrdoća alata za obradu odvajanjem čestica u ovisnosti o temperaturi [14].

Figure 7. Hardness of cutting tool materials as a function of temperature [14].

Sredstva za hlađenje i podmazivanje su svrstana u tri grupe:

- uljne emulzije;
- kemijske smjese;
- čista rezna ulja [11].

Uljne emulzije su mješavine vode, mineralnog ulja i emulgatora. Emulzije s mnogo emulgatora prikladne su za obradu brušenjem gdje je ulje raspoređeno u malim kapljicama. Uljne emulzije obično sadrže EP aditive (extreme pressure tj. ekstremni talkovi) koji sadrže produkte na bazi sumpora, klora i fosfora, koji omogućuju izvrsna podmazujuća svojstva.

Kemijska sredstva su mješavine vode i koncentrata s raznim aditivima odabranim ovisno o uvjetima eksploatacije. Nastala su iz interesa za razvojem sredstava koja ne sadrže mineralna ulja. Ovakvim sredstvima uglavnom se dodaju aditivi kako bi se smanjila površinska napetost vode te se mogu dodati i aditivi na bazi sumpora, klora ili fosfora za poboljšavanje svojstava podmazivanja. Prema namjeni dijele se u dvije grupe:

- ***sintetička sredstva za hlađenje i podmazivanje namijenjena brušenju;***

Sadrže aditive koji pružaju zaštitu od korozije. U slučaju brušenja s velikim presjekom odvojenih čestica koriste se i elementi koji daju i podmazujuća svojstva. Sredstva ostaju prozirna duže vrijeme što olakšava praćenje procesa obrade.

- ***sintetička sredstva namijenjena tokarenju, glodanju, bušenju i sl.***

Imaju široku primjenu. Odnos vode i sintetičkih sredstava ovisi o vrsti proizvodne operacije i o vrsti materijala predmeta obrade (najčešće 20:1 i 40:1).
Postoje i polu kemijska sredstva koja predstavljaju kombinaciju uljnih emulzija i kemijskih sredstava. Ovakva sredstva sadrže manju količinu ulja (10-45%) i veći sadržaj emulgatora sa ciljem smanjenja kapljica i poboljšanja eksploatacijskih karakteristika.
Komponente koje se najčešće dodaju u proizvodnji uljnih emulzija i kemijskih sredstava su:

- emulgatori (omogućuju kvalitetno miješanje vode i ulja);
- antioksidanti i inhibitori korozije (sprječavaju oksidaciju i koroziju metalnih površina);
- antipjenušavci (sprječavaju nastanak pjene tijekom obrade);
- EP aditivi (poboljšanje podmazujućih svojstava);
- baktericidi (sprječavaju nastanak svih mikroorganizama štetnih za zdravlja radnika).

Emulzije i kemijska sredstva za hlađenje i podmazivanje koriste se kod proizvodnih operacija u kojima su brzine rezanja velike a pritisci na kontaktnim površinama mali. Kod ovakvih procesa razvija se velika količina topline te je potrebno brzo odvođenje topline. U proizvodnim operacijama u kojima se javljaju visoki pritisci na kontaktnim površinama između alata i obratka te manja količina topline više se koriste rezna ulja.

Rezna ulja su mineralna ulja sa ili bez aditiva koja ne sadrže vodu. U ovu grupu spadaju:

- ***mineralna ulja,***

Naftni derivati bez aditiva pogodni za obradu mekog čelika, bakra i lakih legura. Mineralna ulja su antikorozivna i stabilna te ako se ne prljaju mogu se koristiti neograničeno. Preporučuju se na radnim mjestima na kojima ulje dolazi u dodir sa kožom radnika.

- ***masna ulja,***

Najčešće sadrže životinjske masti i ulje od repice. Izvrsna podmazujuća svojstva ali su druge karakteristike skromne. Rijetko se upotrebljavaju zbog skupe proizvodnje. Neprijatan miris i stvaranje dima čine ih neupotrebljivim u suvremenoj proizvodnji.

- ***mješavine mineralnih ulja***.

Mješavine mineralnih ulja s masnim uljima poboljšaju kvalitetu obrađenih površina obratka od mekog čelika, bakra, mjedi i aluminija. Posebno su pogodna pri obradi

tvrde bronce. Mineralna ulja se miješaju i sa EP aditivima te se u kombinaciji masnim uljima postižu razna svojstva (uljni film s niskim naprezanjem na smicanje, pogodnost za obradu tvrdih metala, dobra svojstva podmazivanja, dug vijek trajanja alata i sl.).

4. Zaključak

Nakon određenog vremena korištenje alata za obradu odvajanjem čestica više nije ekonomski opravdano. Opada preciznost rezanja, povećava se površinska hrapavost, povećavaju se sile rezanja i temperature te nastaju vibracije. Faktori koji utječu na vijek trajanja alata su parametri rezanja, geometrija alata, mehanička svojstva alata, materijal obratka i vrsta sredstva za hlađenje i podmazivanje.

Potrebno je prilagoditi parametre obrade kako bi se minimaliziralo trošenje alata i u isto vrijeme zadovoljili ekonomski zahtjevi. Geometrija alata i materijal obratka obično su definirani zahtjevima kvalitete obratka.

Mehanička svojstva alata određena su materijalom. Visoka tvrdoća omogućuje višu otpornost na trošenje dok visoka žilavost omogućuje dobru otpornost dinamičkim udarima. Ova svojstva materijala obrnuto su proporcionalna, stoga univerzalni materijal alata za obradu odvajanjem čestica ne postoji već se odabire prema namjeni. Osim tvrdoće i žilavosti jako je bitna stabilnost svojstava materijala na povišenim temperaturama koje se obično razviju prilikom procesa rezanja. Trošenje alata nastaje i zbog difuzije čestica sa površine materijala pa bi materijal alata trebao imati i dobru kemijsku otpornost kako bi se smanjio iznos ovakvog načina trošenja.

Ova svojstva jako mnogo ovise o kemijskom sastavu materijala. Tablica 2 pokazuje svojstva nekih brzoreznih čelika s obzirom na njihov kemijski sastav. Ovo upućuje da bi se daljnjim istraživanjem, promatranjem trošenja alata s obzirom na njegov kemijski sastav, mogla izvesti procjena vijeka trajanja alata s obzirom na kemijski sastav i mikrostrukturu.

Tablica 2. Svojstva tvrdih metala s obzirom na kemijski sastav [15].

Table 2. Hard metal properties according to the chemical composition [15].

Oznaka	Tvrdoća nakon kaljenja (HRC)	Čvrstoća na savijanje (MPa)	Specifični rad loma (MJ/m^2)	Tvrdoća na 600°C (HRC)
W18Cr4V	63-66	3500	0.29	50.5
W6Mo5Cr4V2	63-66	3500-4000	0.30-0.40	47-48
W6Mo5Cr4V3	65-67	3200	0.25	51.7
W9Mo3Cr4V	63-64	4000-4500	0.35-0.40	/
W6Mo5Cr4V2Co5	65-66	3000	0.30	54
W10Mo4Cr4V3Co10	67-69	2350	/	55.5
W2Mo9Cr4V2Co8	66-68	2700-3800	0.23-0.35	55
W7Mo4Cr4V2Co5	66-68	2500-3000	0.23-0.35	54
W12Cr4VCo5	66-68	3000	0.25	54
W6Mo5Cr4V2Al	66-69	3000-4100	0.25-0.30	55-56
110W1.5Mo9.5Cr4VCo8	67-69	2650-3730	0.23-0.29	55.2
W10Mo4Cr4VAl	68-69	3010	0.20	54.2

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CAE modeli u simulaciji proizvodnog procesa

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Keywords

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Material process flow
CAD/CAM

Ključne riječi

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Tok materijala
CAD/CAM

Izvorni znanstveni rad

Sažetak: Od samog početka industrijske proizvodnje teži se povećanju produktivnosti, točnosti obrade i smanjenju vremena izlaska proizvoda na tržište. Težnja da se složeni proizvodi izrade brže, kvalitetnije i efikasnije dovela je do intenzivnog razvoja i primjene novih metoda u razvoju industrijske proizvodnje. U ovom radu prikazan je postupak optimizacije proizvodnog procesa koji stvara opipljiv proizvod odnosno robu. Za simulaciju i optimizaciju proizvodnih procesa korišten je Tecnomatix Plant Simulation tvrtke Siemens PLM software, koji se koristi na Zavodu za industrijsko inženjerstvo i management. Ulazne varijable za pokretanje simulacijskog modela su definirani tehnološki procesi obrade, postojećeg proizvodnog sustava. Sustav se sastoji od tri proizvoda sa definiranim vremenima obrade i strojevima za njihovu obradu. Nakon pokretanja i analize početnog simulacijskog modela, potrebno je doći do ideje i prijedloga kako provest optimizaciju tog proizvodnog sustava. Na temelju tih prijedloga potrebno je napraviti nekoliko modela, te dati detaljnu analizu svakog od njih. Na kraju rada, kao rezultat optimizacije odabran je jedan od tih modela, koji predstavlja optimalno rješenje za ovaj slučaj.

CAE models in the simulation of the production process

Original scientific paper

Abstract: From the beginning of industrial production, tends to increase productivity, accuracy and reduce processing time-to-market are present. Faster, better and more efficiently requisites for complex products has led to intense development and application of new methods in the development of industrial production. This paper presents a concept for the optimization of the manufacturing process that produces a tangible product or goods. A Tecnomatix Plant Simulation Siemens PLM software for the simulation and optimization of production processes has been used. This software has been used in the Department of Industrial Engineering and Management. Input variables for running the simulation model are defined technological processes of manufacturing of the existing production system. The system consists of three products with defined processing times and machines for processing them. After the launch and initial analysis of the simulation model, we need to come up with ideas and suggestions on how to design the production system. On the basis of these results it is necessary to make several models, and provide a detailed analysis of each of them. In the end, as a result of the optimization was chosen one of given models, which was the optimal solution for observed case.

Symbols/Oznake

CAE	- Computer aided engineering - računalom podržano inženjerstvo	*CIM*	- computer integrated manufacturing - računalom integrirana proizvodnja
CAD	- computer aided design - računalnom podržano konstruiranje	*MPP*	- material requirements planning - planiranje potreba materijala
CAM	- computer aided manufacturing - računalnom podržana proizvodnja	*CAPP*	- computer aided process planning - računalom podržano planiranje procesa
CAA	- computer aided analysis - računalom podržana analiza	*NC*	- numerical control - numeričko upravljanje

1. Uvod

Povećanje produktivnosti, točnosti obrade i smanjenje vremena izlaska proizvoda na tržište težnja je svake proizvodnje. Izrada računalnih CAE modela doprinijela je tome da se kvalitetnije i efikasnije može simulirati i analizirati intenzivni razvoj novih proizvoda. Ovim je pristupom omogućena i primjena novih metoda u razvoju industrijske proizvodnje.

No, proizvod u suvremenom svijetu računalnih CAE simulacija može biti nešto vrlo neopipljivo kao što je računalni softver, nečije znanje, algoritam, formula ili neka usluga. Pri tome je bitno naglasiti kako korišteni modeli moraju biti što jednostavniji, a ipak ispravni za svrhu za koju su namijenjeni [1][2]. U tom smislu, računalni modeli omogućuju opis kompleksnih fenomena, njihovo bolje razumijevanje, komunikaciju onih koji rješavaju problem i samo rješavanje problema. U radu je dat prikaz optimizacije proizvodnog procesa koji stvara opipljiv proizvod šire strojarske tehnologije odnosno robu. Polazišno računalno rješenje pri tome jest CAE odnosno Tecnomatix Plant Simulation tvrtke Siemens PLM software. Uz pomoć navedenog programskog rješenja moguće je izvršiti simulaciju proizvodnog procesa s unaprijed definiranim ulaznim parametrima te izvršiti analizu dobivenih rezultata. Dobiveni rezultati kasnije mogu poslužiti kao temelj optimizacije postojećeg proizvodnog procesa.

U radu je dat prikaz simulacije proizvodnog procesa koji je analiziran kroz modele 1 – 4. Temeljem dobivenih rezultata dane su zaključne smjernice za optimizaciju postojećeg proizvodnog procesa.

2. Digitalna proizvodnja

2.1. Osnovni pojmovi digitalne proizvodnje

Digitalna proizvodnja predstavlja korištenje integriranog računalnog baziranog sustava koji se sastoji od: *simulacije*, *3D vizualizacije*, *analitičkih i ranih statističkih alata* za stvaranje i razvoj proizvoda i proizvodnog procesa te izrade izvještaja (slika 1). Digitalna proizvodnja nastala je iz inicijativa kao što su DFM (engl. Design for manufacturability), CIM, fleksibilna proizvodnja (engl. Flexible manufacturing), LEAN (engl. LEAN manufacturing) i drugih koji ističu potrebu za više zajedničkih proizvoda i proizvodnih procesa. Mnoge od dugoročnih koristi PLM-a ne može se postići bez cjelovite digitalne strategije [3, 4, 5].

Digitalna proizvodnja je ključna točka integracije između PLM-a i različitih proizvodnih aplikacija, strojeva i razmjenu informacija između proizvodnje i dizajna. To omogućuje tvrtkama da postignu bolja vremena isporuke proizvoda, te da ostvare uštede kroz smanjenje vremena uhodavanja pri startanju proizvodnje i naknadnih promjena. Pri tome bitnu ulogu imaju CAx i PDM alati.

2.2. Važnost izrade računalnog modela

Simulacija kompletnog toka materijala u proizvodnji uključujući sve relevantne proizvodne, skladišne i transportne aktivnosti ključni je dio virtualnih tvornica koje se danas široko koriste u procesu planiranja proizvodnih procesa. Smanjenjem zaliha i smanjenjem vremena procesa za 20 % do 60 % u mogućnosti smo povećati produktivnost stvarnih proizvodnih procesa za 15 % do 20 % [6].

Potreba za provođenje simulacije može ovisit o strateškim ili tehnološkim ciljevima. Može se zasnivati na postojećem strojnom parku i njegovoj optimizaciji ili biti zasnovana na temelju novih tehnoloških procesa na novim strojevima.

Sa strateškog gledišta korisnik dobiva odgovore na pitanja gdje je najbolje izraditi tvornicu za novi proizvod, ovisno o faktorima kao što su logistika, radna snaga, troškovi proizvodnje i skladištenja i sl. Zbog pritiska na povećanje učinkovitosti proizvodnih procesa, kako je navedeno u uvodnom dijelu, nastala je potreba za računalnim aplikacijama koji imaju mogućnost prikaza i simuliranja virtualnih tvornica odnosno izrade digitalne proizvodnje. Navedene aplikacije imaju mogućnost upravljati ciklusom proizvodnog okruženja, sakupljanja podataka o toku proizvodnje i omogućuju optimizaciju procesa proizvodnje određenog proizvoda [7].

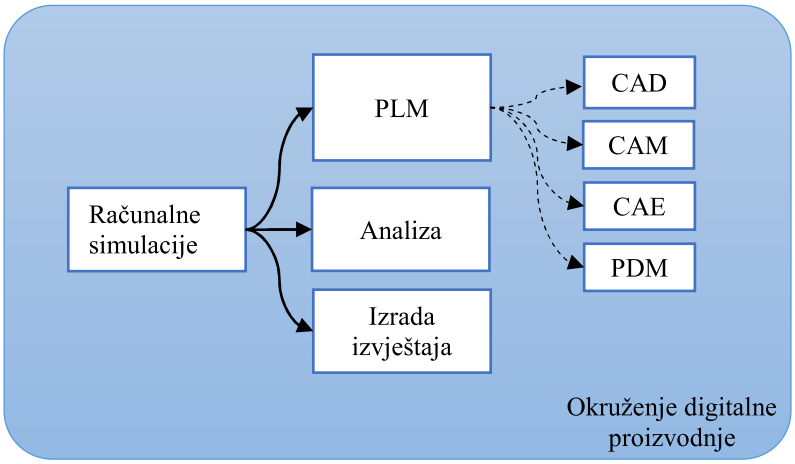

Figure 1. Schematic presentation of computer simulation in the digital production environment
Slika 1. Shematski prikaz računalnih simulacija unutar digitalnog proizvodnog okruženja

2.3. Računalni model

Analizirani su postojeći proizvodni kapaciteti na način da se pomoću četiri simulacije s realističnim ulaznim podacima kako bi se usporedila efikasnost dosadašnjeg proizvodnog procesa. U tu je svrhu korišten računalni simulacijski paket Tecnomatix Plant Simulation čije je sučelje prikazano na slici 2. On sadrži niz alata za analizu proizvodnih modela pomoću stohastičkih algoritma za računanje i upravljanje eksperimentima, te za utvrđivanje parametara za optimizaciju proizvodnog procesa. Plant Simulation stvara sve potrebne funkcionalnosti modela, analize i održava velike i kompleksne proizvodne procese na efikasan način. U usporedbi sa ostalim simulacijskim softverima Plant Simulation pruža vrlo fleksibilan način upravljanja sa modelom, npr. mijenjanje parametara modela za vrijeme izvršavanja simulacije.

U simulaciji su definirani priprema, izvođenje i evaluacija te su pažljivo usmjereni ka traženju optimalnog rješenja u sklopu projektiranog simulacijskog modela. Simulacija proizvodnih procesa izvršena je pomoću sljedećih koraka:

- procjena i sakupljanje podataka iz realnih proizvodnih procesa koji su neophodni za projektiranje simulacijskog modela,
- određivanje cilja simulacijske studije i stvaranje simulacije u skladu sa definiranim ciljevima,
- pokretanje eksperimenta za izvođenje simulacije u sklopu modela, što daje određeni broj rezultata,
- interpretacija podataka simulacije proizvodnog modela.

U procesu definiranja zadatka i ciljeva simulacijskog modela postavljena su sljedeća pitanja:

- koju propusnost i kakav rezultat se može očekivati?
- koji je optimalni broj resursa (strojeva, radnika, alata)?
- gdje su potrebna i veličina međuskladišta?
- kolika je optimalna količina proizvoda za obradu?
- koja strategija obrade je optimalna za model?

Nakon toga definirani su dijelovi proizvodnje obuhvaćeni simulacijom poput ulaza materijala, obrada, dostava, skladište, itd. Simulacija se izvršava na osnovu početnog modela, te se kasnije promatraju nedostaci. Sanacijom i poboljšanjem nedostataka te dodavanjem novih elemenata modelu razvijamo i optimiziramo proizvodni proces.

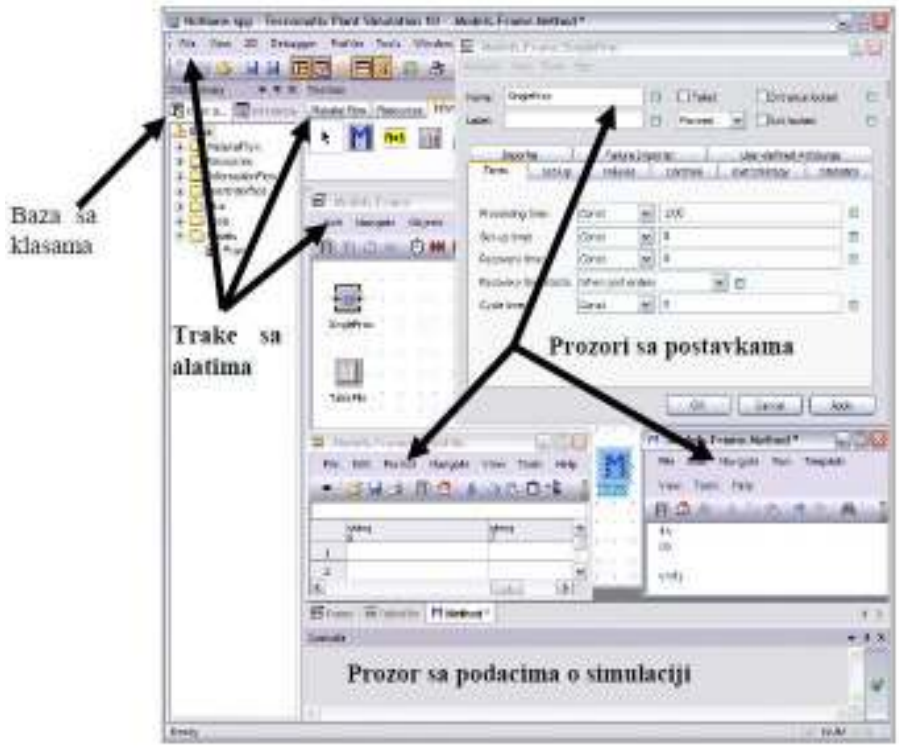

Figure 2. Plant Simulation environment
Slika 2. Sučelje Plant Simulation aplikacije

2.4. Definiranje proizvodnje

Na postojećem proizvodnom sustavu razvijeno je nekoliko različito koncipiranih simulacijskih modela proizvodnog procesa. Proizvodni proces potrebno je izraditi u skladu sa zahtjevima izloženim u radu. Simuliranje obrade ograničit na tjedan dana (5 dana dvije smjene 7:00 h – 23:00 h). Odabrati optimalni. Rezultat simulacije prikazati na godišnjoj razini za optimalni proizvodni proces. Za simulacijski model izabran je postojeći proizvodni proces sa tri proizvoda: *vratilo, osovina sa zupčanikom te kućište.*

U skladu s pripadnim podacima, za proizvode vratilo, osovina sa zupčanikom i kućište dodijeljene su i oznake u simulacijskom modelu PR_A, PR_B i PR_C. Za PR_A (PR_B i PR_C) definiran je tehnološki proces, a u tablici 1 (Tablica2, Tablica3) dana su vremena obrade i strojevi za obradu pojedine tehnološke operacije. U tablici 4 prikazan je redoslijed postupaka obrade za postojeći proizvodni proces. Modeliranje simulacijskog modela izvršeno je u skladu sa prikazanim podacima.

Table 1. Production data for PR_A product
Tablica 1. Podaci za obradu proizvoda PR_A

Operation number/ Broj operacije	Processing name/ Naziv obrade	Machine name/ Naziv stroja za obradu	Machining time [h]/ Vrijeme obrade [h]
10	Turning/ Tokarenje	CNC turning machine/ CNC tokarilica	0,136
20	Induction hardening/ Indukcijsko kaljenje	Induction hardening machine/ Stroj za indukcijsko kaljenje	0,02
30	Grinding/ Brušenje	Grinding machine/ Brusilica	0,09

Podaci obrade procesa izrade PR_B dati su u tablici 2.

Table 2. Production data for PR_B product
Tablica 2. Podaci za obradu proizvoda PR_B

Operation number/ Broj operacije	Processing name/ Naziv obrade	Machine name/ Naziv stroja za obradu	Machining time [h]/ Vrijeme obrade [h]
10	Turning/ Tokarenje	CNC turning machine/ CNC tokarilica	0,037
20	Milling/ Glodanje	CNC milling machine/ CNC glodalica	0,01
30	Induction hardening/ Indukcijsko kaljenje	Induction hardening machine/ Stroj za indukcijsko kaljenje	0,018
40	Grinding/ Brušenje	Grinding machine/ Brusilica	0,01

Detaljni podaci obrade procesa izrade PR_C prikazani su u tablici 3.

Table 3. Production data for PR_C product
Tablica 3. Podaci za obradu proizvoda PR_C

Operation number/ Broj operacije	Processing name/ Naziv obrade	Machine name/ Naziv stroja za obradu	Machining time [h]/ Vrijeme obrade [h]
10	Turning/ Tokarenje	CNC turning machine/ CNC tokarilica	0,025
20	Grinding/ Brušenje	Grinding machine/ Brusilica	0,017
30	Milling/ Glodanje	CNC milling machine/ CNC glodalica	0,016
40	Grinding/ Brušenje	Grinding machine/ Brusilica	0,025

Table 4. Process workflow
Tablica 4. Hodogram obrade

Nr/ Rb	Activity/ Aktivnost	Equipment/Oprema	Product/Proizvod			Time (h)/Vrijeme (h)		
		Label/ Oznaka	A	B	C	t_A	t_B	t_C
1.	Buffer/ Skladištenje	ULAZ				--	--	--
2.	Turning/ Tokarenje	TOK_1 TOK_2	10	10	10	0,136	0,037	0,025
3.	Inductionhardening/ Indukcijsko kaljenje	IK	20	30		0,02	0,018	--
4.	Milling/ Glodanje	GLO_1 GLO_2		20	30	--	0,01	0,16
5.	Grinding/ Brušenje	BRUS_1 BRUS_2 BRUS_3	30	40		0,09	0,1	--
6.	Drilling/ Bušenje	SB			20 40	--	--	0,017 0,025
7.	Buffer/ Skladištenje	IZLAZ_A IZLAZ_B IZLAZ_C				--	--	--

3. Usporedba modela 1 – 4

3.1. Model 1

Model temeljen na postojećem proizvodnom procesu sastoji se od 9 strojeva i 6 međuskladišta. Proizvodi ulaze u proces obrade u serijama od 100 komada uzastopno, što je definirano tabelom *Grupe_proizvoda* (slika 3). Za upravljanje vremenom simulacije modela koristi se *EventController*, odnosno putanja materijala kroz process. Model uključuje i dvanaest *Method objekata*, pomoću kojih se na nekim strojevima upravlja i sa vremenom obrade. Pomoću objekta *Kalendar* definiran je radni tjedan (smjene, pauze i radni dani). Pomoću objekta *Chart* dostupna je statistika obrade koja je temelj za postupke vezane uz optimizaciju proizvodnog procesa. Optimizacija procesa provodi se kroz optimizaciju veličine međuskladišta. Pomoću objekta *ExperimentManager* generirano je 5184 eksperimenata i odabrano je rješenje dobiveno u 84. eksperimentu. Rezultat eksperimenta definira optimalnu veličinu međuskladišta za ponuđene ulazne varijable. U ovom slučaju promatrana su četiri međuskladišta (R_Stol_4, R_Stol_5, R_Stol_2, RStol_C), a dobivene veličine su R_Stol_4 = 20 kom, R_Stol_5 = 5 kom., R_Stol_2 = 35 kom. i RStol_C = 60 kom.

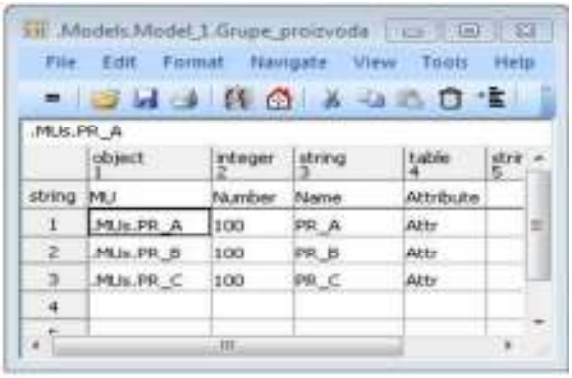

Figure 3. Defining the quantity of products
Slika 3. Definiranje količine proizvoda

Dijagram opterećenja strojeva u *modelu 1* (slika 4).

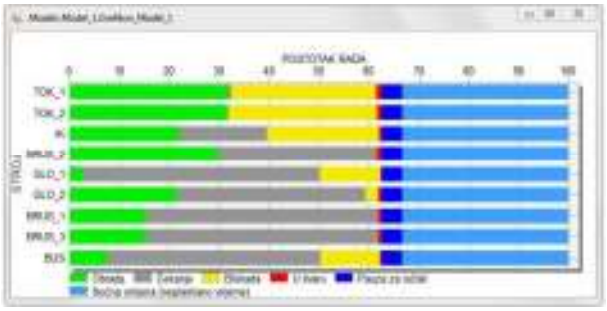

Figure 4. Diagram of machines' occupancy (Model 1)
Slika 4. Dijagram opterećenja strojeva (Model 1)

Simulacijom modela 1 dolazimo do zaključaka da obrada u serijama ne zadovoljava, odnosno da je serija od 100 komada prevelika za ovaj proizvodni proces. Stoga se nakon provedene analize kreira idući model 2.

Simulacijom modela 1 pokazano je da obrada u serijama ne zadovoljava, odnosno da je serija od 100 komada prevelika za ovaj proizvodni proces. Stoga se u modelu 2 smanjuje serija proizvoda metodom pokušaja i pogrešaka sve do 20 komada po seriji, što se pokazalo kao najbolja veličina serije za ovaj model. Dalje se može zaključiti da se treća operacija proizvoda C može obrađivati na dva stroja paralelno.

To su strojevi GLO_1 i GLO_2, te se na temelju toga vrši promjena putanje proizvoda C kroz proizvodni proces. Model 2 sadrži jednaki broj strojeva i međuskladišta kao i model 1. Model 2 proizvodnog procesa prikazan je na slici 5.

Radi lakšeg praćenja toka određenog proizvoda kroz proizvodni proces u svim modelima u toku modeliranja koriste se objekti *SankeyDiagram* nazvan prema vrsti obradaka koji prati. Tako su definirani objekti Putanja_PR_A, Putanja_PR_B i Putanja_PR_C, koji pokazuju putanju tih obradaka kroz proces. Svaki objekt prikazuje drugu boju tako da se može aktivirat sve objekte istodobno i razlikovat putanju pojedinog proizvoda. Slika 6 prikazuje dijagram opterećenja strojeva za model 2.

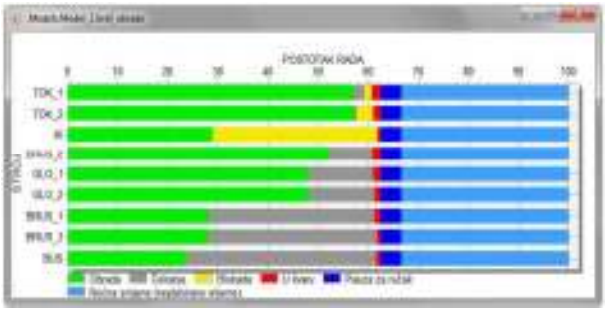

Figure 6. Diagram of machines' occupancy (Model 2)
Slika 6. Dijagram opterećenja strojeva (Model 2)

3.2. Model 2

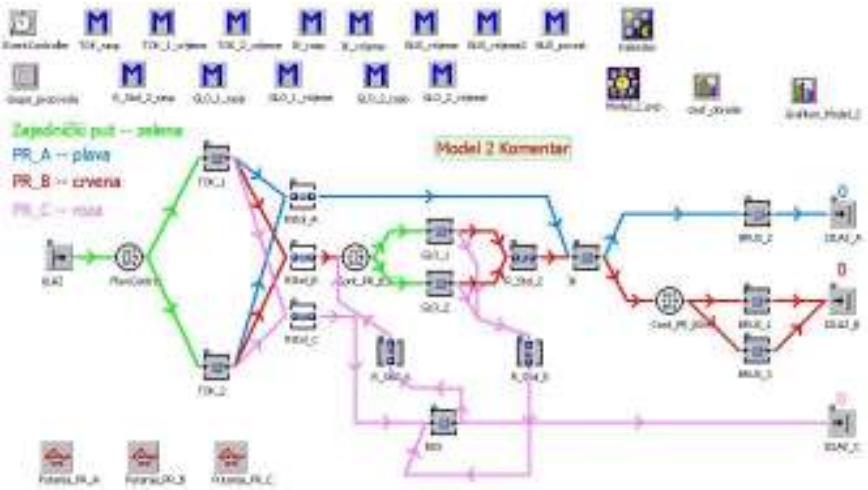

Figure 5. Model 2 of production process
Slika 5. Model 2 proizvodnog procesa

3.3. Model 3

Ovaj model izrađen je na temelju rezultata dobivenih iz prva dva modela. Analizom opterećenja strojeva u modelu 2 može se zaključiti da su strojevi BRUS_1 i BRUS_3 slabije opterećeni, odnosno da su veći dio vremena u stanju čekanja na obradu, te je putanja proizvoda A preusmjerena na ova dva stroja za brušenje (BRUS_1 i BRUS_3). Također, ovaj model sadrži i jedno međuskladište više. To međuskladište nazvano R_Stol_3. Dodano je iz razloga što je analizom opterećenja strojeva utvrđeno da je stroj za indukcijsko kaljenje (IK) preko 30 % vremena u stanju blokade, te nije moguće vršiti obradu na njemu. Međuskladište R_Stol_3 postavlja se u proizvodni proces na poziciju izlaza dijelova iz stroja za indukcijsko kaljenje, te time postižemo smanjenje vremena blokade tog stroja. Slika 7 prikazuje opterećenja strojeva u modelu 3.

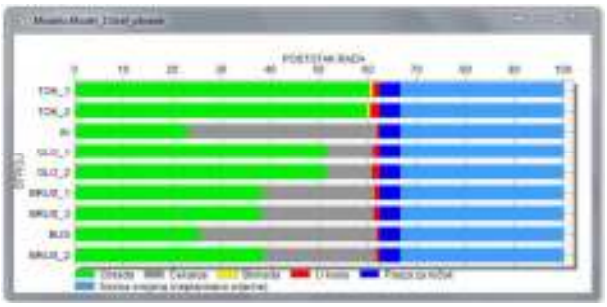

Figure 7. Diagram of machines' occupancy (Model 3)
Slika 7. Dijagram opterećenja strojeva (Model 3)

Iz dijagrama opterećenja strojeva (Slika 7) vidi se kako promjena putanje obradaka utječe na postotak vremena obrade strojeva BRUS_1 i BRUS_3. Usporedbom rezultata modela 3 sa modelom 2 dolazimo do zaključaka da se produktivnost proizvodnog procesa modela 3 povećala za: *proizvod A*: 20 proizvoda, odnosno 2,8 % povećana produktivnost, *proizvod B*: 54 proizvoda, odnosno 7,9 % povećana produktivnost, *proizvod C*: 42 proizvoda, odnosno 5,1 % povećana produktivnost. Kada se količine proizvoda dobivene simulacijom modela 3 pomnože sa 52 tjedna u godini može se zaključiti da je proizvodni proces zadovoljio zadane kriterije za proizvod A (37.440kom./god.) i proizvod C (37.648 kom./god.), ali ne zadovoljava kriterij za proizvod B. Ovaj model (Model 3) godišnje isporuči 38 324 proizvoda B što je 11 676 komada manje od zahtijevane količine tog proizvoda.

3.4. Model 4

Kroz treći model postignuto je najbolje iskorištenje proizvodnog procesa, sa proizvodnjom gotovo bez blokada strojeva. Pregledom rezultata modela 3 može se zaključiti da je povećana proizvodnja proizvoda A za 7440 kom. i proizvoda C za 17648 kom., dok je količina proizvoda D manja za 11676 kom. Model 4 se u odnosu na model 3 ne razlikuje u niti jednom segmentu osim veličinama serije ulaska materijala u proces obrade. U modelu 3 proizvodi su ulazili u proizvodni proces u serijama od 20 komada. Kroz model 4 prikazati će se kako promjena veličine serije i rasporeda ulaza proizvoda utječu na krajnji rezultat količine obrađenih proizvoda. Na slici 8 prikazan je objekt (tabela) *Grupe_proizvoda* pomoću kojega se definira kojim će redoslijedom i u kojim količinama će proizvodi ulaziti u proizvodni proces. Na prvo mjesto postavljen je proizvod B kao prioritet pošto je za ostala dva proizvoda postignuta zadovoljavajuća količina.

Figure 8. Diagram of machines' occupancy (Model 4)
Slika 8. Dijagram opterećenja strojeva (Model 4)

4. Rezultati

Nakon završetka izrade i prikupljanja podataka vezanih za simulaciju modela dolazi se do odabira najpovoljnijeg proizvodnog procesa. Uvidom u dobivene rezultate može se zaključiti da je model 4 ujedno i najbolje rješenje proizvodnog procesa. Najpovoljniji je iz razloga što sadrži obrade na strojevima bez velikih zastoja i blokada. Model 4 također ima i najveće proizvodne kapacitete za čak 44 % više ukupno proizvedenih proizvoda u odnosu na model 1. Usporedbom modela 4 i modela 3 može se zaključiti kako veličina ulazne serije proizvoda utječe na količinu proizvoda koje će biti proizvedena u proizvodnom procesu. To znači da ukoliko postoji zahtjev za nekim proizvodom u većoj količini nego što je planirano, promjenom ulaznih serija može se doći do zadovoljavajućih količina proizvedenih proizvoda. Kako je za simulaciju modela korišteno vrijeme od pet radnih dana u dvije smjene, treća smjena ostaje neiskorištena. U slučaju povećanja potražnje za proizvodima postoji dodatni prostor za popunjenje kapaciteta treće smjene. Slika 9 prikazuje statističke podatke izlaza proizvoda iz proizvodnog procesa za proizvode: A (PR_A), B (PR_B), te proizvod C (PR_C) u modelu sa uključenom trećom smjenom, dok je na

slici 10 prikazan dijagram opterećenja strojeva u modelu 4 sa uključenom trećom smjenom.

Proizvod A/ Product A

Working:	74.18%	Average lifespan:	27:40.6091
Delayed:	18.98%	Average exit interval:	6:53.9551
Setup:	0.00%	Total throughput:	966
Failed:	1.45%	Throughput per hour:	10.38
Paused:	5.39%	Throughput per day:	204.33

Proizvod B/ Product B

Working:	77.89%	Average lifespan:	34:07.5218
Delayed:	14.95%	Average exit interval:	4:25.0342
Setup:	0.00%	Total throughput:	1530
Failed:	0.95%	Throughput per hour:	15.16
Paused:	6.21%	Throughput per day:	326.67

Proizvod C/ Product C

Working:	78.15%	Average lifespan:	37:26.3395
Delayed:	16.68%	Average exit interval:	9:40.8933
Setup:	0.00%	Total throughput:	690
Failed:	0.87%	Throughput per hour:	6.87
Paused:	4.30%	Throughput per day:	146.33

Figure 9. Results output products A, B, C from the manufacturing process model 3 with included third shift

Slika 9. Rezultati izlaza proizvoda A, B, C iz proizvodnog procesa modela 3 s uključenom trećom smjenom

Figure 10. Diagram of buffer's occupancy - model 3 with included third shift

Slika 10. Dijagram opterećenja međuskladišta u modelu 3 sa uključenom trećom smjenom

Zaključno u tablici 5 prikazane su proizvodne mogućnosti modela 4 proizvodnog procesa kao optimalnog proizvodnog procesa za proizvod A, proizvod B i proizvod C.

5. ZAKLJUČAK

U ovom radu dat je prikaz planiranja i simulacije proizvodnih procesa. Oni predstavljaju bitnu stavku pri pokretanju nove proizvodnje ili pri unaprjeđivanju postojeće. Da bi se izbjegli troškovi uhodavanja i razne probleme prilikom startanja ili unaprjeđivanja proizvodnje uz pomoć računalne aplikacije Tecnomatix Plant Simulation može se izraditi više modela proizvodnog procesa i odabrati najefikasnijeg. Ti virtualni modeli sadrže sve značajke pravih proizvodnih procesa npr. mogućnost programiranja smjena proizvodnje, vremena potrebnog za redovno održavanje strojeva, prikaz međuskladišta, strojeva i radnika. Danas kada je potrebno reagirati brzo i efikasno na zahtjeve tržišta ova aplikacija za simulaciju proizvodnih procesa dolazi do velikog izražaja i uvelike smanjuje vrijeme i troškove potrebne za startanje proizvodnje.

Korištenjem aplikacije Tecnomatix Plant Simulation u ovom radu razvijeno je četiri modela proizvodnog procesa gdje se vidi kako loše isplaniran proizvodni proces može davati vrlo loše proizvodne rezultate. U modelu 1 nisu postignute zadovoljavajuće količine te se pristupilo izradi modela 2 u kojem nisu postignuti zadovoljavajući rezultati količina proizvoda B. Slična stvar uz određeno poboljšanje rezultata dobivena je u modelu 3. Optimalni rezultat proizvodnje svih proizvoda dobiven je u modelu 4. Vidljivo je da se pravilnim odabirom veličine ulazne serije proizvoda može znatno utjecati na krajnju količinu proizvoda proizvedenih u istom proizvodnom sustavu. To znači da ukoliko postoji zahtjev za nekim proizvodom u većoj ili manjoj količini nego što je planirano, promjenom ulaznih serija može se doći do zadovoljavajućih količina proizvedenih proizvoda.

Table 5. Summary of the results of production parts process
Tablica 5. Rezime rezultata proizvodnje dijelova

	Product A (pcs/year)/ Proizvod A (kom/tjedan)	**Product B (pcs/year)/Proizvod B (kom/god)**	**Product C (pcs/year)/ Proizvod C (kom/god)**	**Total (pcs/year)/ Ukupno (kom/god)**
Quantity/ Količina	30 000	50 000	20 000	100 000
Model 1	29 484	26 000	25 428	80 912
Model 2	37 440	35 516	35 464	108 420
Model 3	37 440	38 324	37 648	113 412
Model 4	35 204	56 628	25 480	117 312

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Elements of investment projects for hydropower plant refurbishment

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ekonomsko financijska analza

Professional paper
Abstract: In this paper are presented the theoretical analysis of the basic elements of the investment project and the analysis of the specific investment project in the case of Refurbirshment Project Zakučac HPP. Special attention is devoted to the economic - financial analysis because the most important part of the project for a decision on further investment in project.

Elementi investicijskih ulaganja kod revitalizacije hidroelektrane

Stručni rad
Sažetak: U ovom radu dana je teorijska raščlamba osnovnih elemenata investicijskog projekta i analiza konkretnog investicijskog projekta na primjeru Projekta revitalizacije HE Zakučac. Posebna pozornost je posvećena ekonomsko – financijskoj analizi jer je taj dio projekta najvažniji za odluku o daljnjim ulaganjima u projekt.

1. Uvod

Glavna misija projektnog menadžmenta je planiranje, koordiniranje i kontrola aktivnosti projekta. Na tragu spomenutog, svi projekti dijele jednu zajedničku karakteristiku tj. pretakanje ideja i djelatnosti u nove tvorevine. Uvijek prisutan element rizika i nesigurnosti govori da gotovo nikad događaji i aktivnosti unutar jedne cjeline (projekta) ne mogu biti predviđeni s apsolutnom sigurnošću.

Znači, temeljna misija upravljanja projektima je predvidjeti što je više moguće opasnosti i problema, te planirati, organizirati i kontrolirati aktivnosti da projekt bude što uspješnije izveden usprkos svim rizicima. U cilju što boljeg upravljanja projektima vrše se simulacije projekata i optimiziraju zadani parametri [1].

U ovom radu dan je primjer Projekta revitalizacije HE Zakučac (terminološki: obnova i zamjena, rekonstrukcija ovisno o definiciji Zakona o prostornom uređenju i gradnji). Naime, za Hrvatsku elektroprivredu su projekti revitalizacija i gradnje novih hidroenergetskih objekata prioritetnog karaktera kako zbog financijskih interesa ove nacionalne tvrtke tako i zbog šireg interesa Republike Hrvatske.

U današnjem svijetu globalizacije vremenu recesije, potrošnja električne energije raste proporcionalno sa zahtjevima kako privatnih domaćinstava tako i gospodarskih aktivnosti, uviđa se koliko je potrebno osigurati kvalitetnu i dostatnu opskrbu električnom energijom.

2. Osnovni elementi investicijskog projekta

2.1 Pojmovno određenje

Postoji nekoliko osnovnih projektnih pojmova koje je potrebno definirati kako slijedi:

Projekt u užem smislu. Projekt je svaki zaokružen, cjelovit, složen pothvat čije se karakteristike i cilj mogu definirati, a koji se mora ostvariti u određenom vremenu, te zahtijeva koordinirane napore nekoliko službi odnosno zaposlenih radnik u tim službama [2].

Projektni zadaci. Projektni zadaci su sve aktivnosti potrebne za realizaciju unaprijed definiranih projektnih rezultata [3]. Oni su specifični za svaki projekt međutim mogu se razlikovati zadaci planiranja od zadataka realizacije projekta. Zadaci realizacije projekta se dijele na zadatke pribavljanja i korištenja resursa (npr. kadrova za jednu projektnu fazu) i na zadatke koji su neposredno usmjereni na realizaciju projektnog cilja (npr. rješenje projektnog problema).

Projektni zadatak tima HE Zakučac je revitalizacija postojećeg postrojenja na način da se izvrši zamjena i obnova dotrajale elektro i strojarske opreme kojoj je istekao životni vijek.

Koordinacija i izvođenje projekta. Pojam koordinacija projektom odnosi se na sve one nositelje projektnih zadataka koji su nadležni za osiguranje i korištenje projektnih resursa i za koordinaciju projektnih aktivnosti. I kod individualne i kod čiste projektne organizacije postoji voditelj projekta koji rukovodi i koordinira projektom odnosno zadaje zadatke projektnom timu i koordinira njihov rad kako bi projekt bio ostvaren u predviđenom vremenu i uz minimalne troškove. Vodstvo Projekta revitalizacije HE Zakučac je stručni tim ljudi na čelu s voditeljem cjelokupnog projekta.

Izvođenjem projekta upravljaju projektni suradnici koji izvršavaju projektne zadatke uz korištenje raspoloživih resursa, a pritom oni nemaju pravo izdavanja uputa . Izvođači Projekta revitalizacije HE Zakučac su djelatnici HEP-a i vanjski suradnici i izvođači radova.

Projektna obilježja i projektne vrste. U načelu osnovna projektna obilježja su: jednokratnost, vremenska određenost odnosno ograničeno trajanje, cjelovitost međusobno povezanih aktivnosti, rješavanje zadataka koncentracijom sredstava i kadrova (korištenje zadanih resursa), posebna organiziranost, a kod hidroelektrana je posebno obilježje kontinuirani rad hidroelektrane odnosno rad bez zastoja.

U literaturi se nailazi na različite vrste projekata i na njihove brojne klasifikacije prema više kriterija (predmet projekta, problemi koje projekt rješava, tip organizacije, učestalost pojavljivanja projekata i drugo) prema kojima se mogu razvrstavati projekti.

Primjerice *Frese* [3] iznosi tri temeljne kriterija kod određivanja projektnih vrsta: (1) objekt projektiranja, (2) utjecaj okoline na projekt, (3)stupanj projektne novosti. U prvu skupinu autor uvrštava projekte prema njihovoj usmjerenosti. te razlikuje projekte koji su orijentirani prema materijalnom cilju i procesno orijentirane projekte. Projektima koji su orijentirani prema materijalnom cilju ostvaruju se promjene proizvodnog programa i programa plasmana neke proizvodne organizacije. Među procesno orijentiranim projektima razlikuju se procesi učinaka (postupci u ostvarivanju ponajprije nabave, proizvodnje i plasmana) od procesa upravljanja (informacijski procesi potrebni za koordiniranje procesa učinaka).

U drugoj se skupini dioba projekata zasniva na utjecaju okoline - postoje projekti na koje se utječe izvana i projekti na koje takvog utjecaja nema. U trećoj skupini *Freseovih* projekata diobeno stajalište je stupanj suvremenosti prema kojemu autor razlikuje projekte s visokim stupnjem suvremenosti od projekata s malim stupnjem suvremenosti. Utjecaj okoline na projekt uvijek postoji, međutim taj utjecaj varira od projekta do projekt. Utjecaj okoline je to veći što je projekt veći, a manji kad je projekt manji npr. kad se radi o preinaci nekog stroja.

Što se tiče projektnih vrsta na području hidroelektrana u HEP-u postoje dvije projektne vrste: revitalizacija postojećih hidroenergetskih postrojenja (HE Peuća, HE Zakučac, HE Dubrovnik, HE Dubrava) i izgradnja novih hidroelektrana (HE Lešće).

Životni vijek projekta. Projekt se odvija kroz određeni vremenski period tijekom kojega se mijenjaju razine napora potrebne u pojedinoj fazi projekta. Životni vijek projekta se može podijeliti na dva temeljna perioda: prije i poslije prihvaćanja financijskog plana . Slika 1. prikazuje krivulju životnog vijeka projekta.

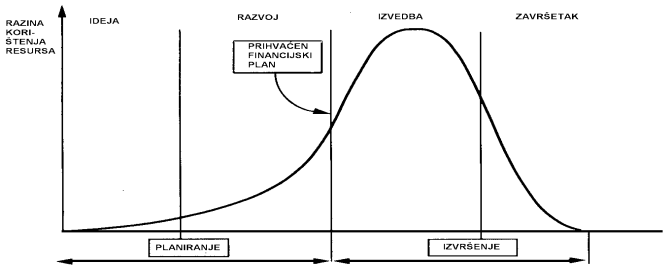

Figure 1. Project life [4]
Slika 1. Životni vijek projekta [4]

Različiti autori različito definiraju faze kroz koje se provodi projekt. Ovisno o vrsti projekta, ali i samom autoru javljaju se razlike u pojmovnim i klasifikacijskim detaljima definiranja projektnih faza. Ipak, sve se spomenute faze mogu svesti na četiri osnovne faze:
(1) projektna ideja, (2) planiranje projekta (razvoj), (3) realiziranje projekta (izvedba), (4) provjeravanje/primjena projekta (završetak):

I. Projektna ideja je prva projektna faza pa u njoj nastaje ideja i potreba za pokretanjem nekog projekta. U ovoj se fazi kroz prethodna istraživanja ili studije, analizom situacije i definiranjem problema te kritičkim razmišljanjima o problemu otkriva i definira problem. Dakle, projektna ideja kao prva projektna faza ima ulogu otkrivanja i definiranja problema koji bi se kroz ostale faze projekta trebao riješiti.

II. Planiranje projekta kao druga projektna faza ima zadatak definirati strategiju i načine rješavanja problema definiranog u prethodnoj fazi, ali i detaljno razraditi i opisati projekt. Različiti autori različito dijele ovu fazu na podfaze, no u općem smislu mogu se podijeliti na dvije podfaze: (1) osnovna studija i (2) studija detalja. Osnovna studija ima zadataka razmotriti problem na općoj razini, razraditi i podijeliti problem na podprobleme, definirati strategiju za rješavanje problema, odrediti vrijeme potrebno za realizaciju projekta, okvirno utvrditi troškove projekta, itd. Nakon svih razmatranja u podfazi osnovne studije potrebno je donijeti zaključak o isplativosti projekta. Ako je projekt isplativ prelazi se na drugu podfazu planiranja projekta, tj. studiju detalja. Studija detalja ima zadatak detaljno razraditi i definirati cjelokupni projekt, njegovo vrijeme trajanja te njegove troškove.

III. Realiziranje projekta je treća projektna faza, a može se podijeliti u dvije podfaze: (1) izvođenje ili realizacija projekta i (2) uvođenje projekta. U podfazi izvođenja ili realizacije projekta projekt se realizira i provodi prema u prethodnoj fazi utvrđenim pravilima, poštuju se dogovoreni rokovi i troškovi. Prilikom realizacije projekta može doći i do određenih odstupanja od zacrtanog projekta iz prethodne faze. Do tih odstupanja obično dolazi zbog promjene uvjeta u kojima se projekt realizira, ali i često i zbog neadekvatnog i lošeg plana projekta iz prethodne faze. Druga podfaza realiziranja projekta je uvođenje rezultata dobivenih projektom u postojeći sustav.

IV. Provjeravanje i primjena projekta je završna projektna faza u kojoj se prate rezultati dobiveni projektom, ali i njegovim uvođenjem u sustav kako bi se uklonili eventualni nedostaci nastali ili nepažnjom kroz prethodne tri faze ili zastarijevanjem projekta. U ovoj fazi projekt "živi" pa se neprestano prate njegovi učinci i po potrebi ispravljaju greške ili se pokreće novi projekt ako se zaključi da je stari zastario.

Prema N. Kuvačiću ove 4 faze mogu se svrstati u tri karakteristična razdoblja: aktivizacijsko razdoblje (projektna ideja + planiranje projekta odnosno razvoj), eksploatacijsko razdoblje (realiziranje projekta odnosno izvedba) i pokusno razdoblje (primjena projekta) [5].

2.2 Sadržaj investicijskog projekta

Polazeći od zahtjeva poduzetničkog projekta te prakse zemalja razvijena tržišnog gospodarstva svaki bi poduzetnički projekt trebao sadržavati [5]:

Naslovnica projekta – treba biti grafički prikladno oblikovana, sadržavati informacije o nazivu poduzetničke ideje; zatim o nazivu, djelatnosti, adresi, telefonu, osnivačima ili vlasnicima tvrtke; o autorima projekta i primatelju projekta.

Kazalo ili sadržaj projekta – daje temeljni uvid u to što se nalazi u projektu te na kojim stranicama počinju i završavaju pojedine stranice projekta.

Operativni sažetak projekta – piše se tek nakon projektne elaboracije cijelog pothvata. Neki ga autori stavljaju na početak, a neki u prilogu projekta. Sažetak se piše zato da bi svaki čitatelj mogao na brzinu iščitati glavne performanse projekta. Operativni sažetak mora sadržavati sve bitne podatke o poduzetničkom projektu.

Opis poduzetničke ideje – prvo ili uvodno poglavlje projekta, a trebalo bi sadržavati sve relevantne informacije o autorima i evoluciji – povijesti poduzetničke ideje na kojoj se pothvat temelji, zatim opis proizvoda, robe ili usluga koji su predmetom poduzetničkog pothvata, poduzetničke i profesionalne referencije autora i nositelja pothvata i sl.

Tržišni podaci projekta - su jedno od ključnih poglavlja projekta. Ono mora ponuditi informacije o tržišnim prednostima i pogodnostima proizvoda, robe ili usluga, zatim o ciljnim tržištima – potencijalnim potrošačima, o konkurenciji i mogućem tržišnom udjelu, o realnim mogućnostima tržišne ekspanzije, o nabavi inputa projekta (oprema, sirovine, energenti, kapital, radna snaga i dr.).

Tehničko-tehnološki opis projekta – ovo poglavlje obvezatno treba sadržavati informacije glede makrolokacije i mikrolokacije, tehnološkog rješenja, kapaciteta i radnog procesa, potrebna zemljišta i prostora, potrebne opreme, materijalnih inputa i drugih tehničko-tehnoloških odrednica.

Menadžment projekta – u ovom poglavlju valja ponuditi informacije o pravno-vlasničkom obliku organiziranja pothvata, zatim popis i reference glavnih partnera i dioničara, informacije o pravima vlasnika tvrtke, informacije o broju, strukturi i zadaćama zaposlenika-izvršitelja, zadaćama i ovlastima menadžerske ekipe.

Marketing projekta – osim tržišnih podataka, sve marketinške aspekte pothvata u samom projektu valja

predočiti u obliku sažetka marketinškog programa i to kroz kratke informacije glede praćenja i istraživanja tržišta, razvoja proizvoda i usluga, određivanja i politike cijene, kanala nabave i prodaje, fizičke distribucije i svih drugih odrednica marketinške orijentacije tvrtke tijekom eksploatacije poduzetničkog pothvat.

Financijski podaci projekta - ovo poglavlje treba sadržavati niz tabličnih prikaza i njima primjerenih objašnjenja od kojih su neizostavni projekcija potrebnih ulaganja u stalna trajna i obrtna sredstva, projekcija izvora kapitala, terminski plan ulaganja, projekcija otplate zajmova ili kredita, projekciju amortizacije i ostatka vrijednosti projekta; dinamičku projekciju prihoda i rashoda; dinamičku projekciju računa dobiti-gubitka te druge relevantne financijske projekcije.

Ocjena učinkovitosti projekta – ovdje valja predočiti pokazatelje buduće učinkovitosti projekta prema statičkim i dinamičkim metodama ocjene.

Dodaci i prilozi projektu – projektu se dodaju različiti prilozi i dokumentacija koja se odnosi na pojedine dijelove i poglavlja ili pak dopunjuje temeljni tekst, kao što su različite fotografije, slike, tablice, skice, prospekti i katalozi.

Pismo primatelju – uz projekt svakom primatelju valja napisati originalno prigodno i sasvim kratko animirajuće pismo na temelju kojeg će on steći prvi dojam o projektu.

2.3 Namjena projekta

Iako većina poduzetnika temeljne konture svog posla nose u glavi ili pak za specifične dijelove angažiraju menadžere, dobro je sve ideje imati na papiru te pokazati onima koje će to zanimati ili kojima treba pokazati. Najčešći korisnici i područja namjene poduzetničkog projekta su:

Poduzetnici-investitori. Poduzetnici u projektu nalaze stožerne smjernice za pokretanja, financiranje, organiziranje, vođenje, razvijanje i kontrolu poduzetničkog projekta tijekom njegova životnog vijeka.

Potencijalni dioničari. Potencijalni dioničari iz projekta mogu vidjeti zašto im se i koliko isplati ulagati svoj kapital u dotični projekt, odnosno kupovati dionice baš te tvrtke, odnosno dioničkog društva.

Financijeri i kreditori. Financijerima (bankama) i kreditorima (kupcima i dobavljačima) projekt služi kao podloga za ocjenu financijskog zdravlja, ali i kredibiliteta poduzetnika kojeg kane financirati.

Distributeri, dobavljači, kupci. Projekt je glavno polazište i poduzetnikova referenca za pregovore s budućim kupcima, dobavljačima, distributerima, kooperantima i drugima radi sklapanja ugovara i uspostavljanja poslovnih veza.

Partneri suulagači. Projekt je dobra referenca za traženje partnera zbog zajedničkih ulaganja, različitih oblika udruživanja, širenja i razvoja postojeće djelatnosti.

Menadžeri i zaposlenici. Budući da svaki projekt pretpostavlja određen broj menadžera i zaposlenika, nijedan od njih se neće moći angažirati bez prethodnog uvida u projekt.

Državna uprava. Država, odnosno državna uprava, također je zainteresirana za poduzetnički projekt, posebno ako njegova djelatnost može značajnije utjecati na društveno-gospodarski razvitak ili okoliš.

Državni fondovi. Projekt je i ključni dokument na temelju kojega mala tvrtka sklapa poslovne ugovore za tzv. državne narudžbe te se uključuje u različite državne fondove za poticanje i razvoj malog poduzetništva. Kao i svaki drugi projekt tako i Projekt revitalizacije HE Zakučac ima svoju namjenu a financira se isključivo sredstvima HEP-a.

2.4 Pisanje projekta

Svako područje stručnog, znanstvenog ili sasvim slobodnoga pisanja ima svoja pravila, pa tako i pisanje poduzetničkog/investicijskog projekta. Zato bi se prigodom njegova pisanja i konačnog oblikovanja valjalo pridržavati nekih usvojenih grafičko-oblikovnih, jezičnih i drugih pravila kako bi se što manje lutalo i gubilo vrijeme i novac. Kako nema još pravila za pisanje poduzetničkog projekta, postoje neke općeprihvaćene konvencije za pisanje poduzetničkog projekta od kojih su neki: pisanje na srednje – finom 80- gramskom papiru, formata A4; svaki primjerak projekta mora izgledati kao original; temeljni tekst projekta ne bi trebao biti opsežniji od 50 autorskih kartica s potrebnim brojem tablica, shema, slika i grafikona; projekt ne treba pretrpavati nepotrebnim informacijama, podacima, pokazateljima, slikama, a posebice ne onim što se može priložiti u dodacima; sadržajem, obujmom, formom, načinom izlaganja ne dovodit čitatelja u iskušenje da do kraja ne pregleda projekt; riječju projekt treba tako strukturirati da animira čitatelje da ga pročitaju u jednom dahu.

2.5 Prezentacija projekta

Potencijalni ulagači, dioničari, zajmodavci i financijeri, osim osobnog uvida u projekt, često zahtijevaju i njegovu skupnu ili ekskluzivnu prezentaciju. Za prezentaciju se koriste i tehnička pomagala od kojih su najčešći računalo i različiti oblici tzv. multimedijske prezentacije. Prvi dio prezentacije obično traje 15 do 20 minuta, a zatim slijedi diskusija s pitanjima od oko pola sata. Valja imati na umu da slušatelji (gledatelji) obično žele čuti koliko se i u čemu dotični proizvod ili usluga razlikuju od konkurencijskih, jesu li oni i kako zaštićeni od prodora konkurenata, tko su njihovi potencijalni kupci ili potrošači i kakve su mogućnosti plasmana, što su glavne odrednice marketinškog i promocijskog spleta, kada će se vratiti uloženi novac i

kolika će biti zarada. Dakle, treba pokušati efektno, uvjerljivo i argumentirano govoriti o svemu što bi publiku trebalo zanimati, intrigirati i provocirati na kasniju diskusiju i pitanja.
Osim mnoštva kriterija procjene i sasvim individualnih dojmova nazočni će pozorno promatrati izgled prezentanta, stil izlaganja, jezik i dikciju, cjelovitost i konzistentnost projekta, ozbiljnost i argumentiranost tržišnih istraživanja, financijskih podataka i pokazatelje profitne učinkovitosti projekta, sposobnost prezentanta da sve potrebito obavi u za to predviđenom vremenu. Nikada ne treba smetnuti s uma da su publika iskusni ulagači koji sumnjaju u sve prije nego u nešto povjeruju.

3. Anatomija projekta na primjeru Projekta revitalizacije HE Zakučac

3.1 Opći prikaz

Svaki znanstveni ili stručni rad ima svoju uobičajenu strukturu koja pretpostavlja odgovore na temeljna znanstveno-istraživačka ili stručna pitanja, što se u slučaju poduzetničkoga projekta svodi na nekoliko glavnih pitanja, i to: što, zašto, komu, koliko, kada, gdje i kako proizvoditi, tražiti ili usluživati. Sadržaj projekta nije za sve slučajeve jednak. Stručnjaci (teoretičari i praktičari) veoma različito formalno i suštinski strukturiraju projekt što ponajviše ovisi o devet čimbenika:

1. Teorijska i praktična uporišta autora projekta,
2. Namjena, odnosno pretpostavljeni korisnici projekta,
3. Područje djelatnosti koje se u projektu elaborira,
4. Tehničko-tehnološke značajke proizvoda ili usluga,
5. Tražene specifičnosti dotičnog proizvoda ili usluge,
6. Vremensko razdoblje za koje se projekt elaborira,
7. Struktura i red veličina pothvatom postavljenih ciljeva,
8. Veličina poduzetničkog pothvata koji se projektom elaborira,
9. Značenje poduzetničkoga pothvata koji se projektom elaborira.

Spomenuti i drugi čimbenici umnogome određuju anatomiju svakoga projekta glede stupnja obuhvata i detaljiziranja pojedinih dijelova njegove sadržajne strukture te određuju razinu, dubinu i širinu istraživačkoga postupka koji prethodi projektnome osmišljavanju ideje koja je predmetom njegove elaboracije.
Teoretičari i praktičari koji se bave različitim aspektima poduzetničkoga projektiranja uglavnom su suglasni da je, osim korektne formalne strukture, zapravo, najbitniji suštinski sadržaj projekta što je kod projekata HE Zakučac i postignuto.

3.2 Naslovnica i kazalo projekta

Posredstvom naslovnice čitatelji ostvaruju prvi dodir s poduzetničkim projektom, zbog čega ona, osim što treba biti grafički prikladno oblikovana, obično sadrži informacije predočene u Tablici 1. Glede upozorenja o zaštiti autorskih prava, na naslovnicama poduzetničkih projekata često se nalazi i upozorenje o vlasničkome pravu, uz molbu da se projekt ne reproducira te da se povrati vlasniku ako primatelja projekt ne zanima

Table 1. Information on the cover of the project
Tablica 1. Informacije na naslovnici projekta

Naziv, djelatnost, adresa i telefon tvrtke
Središnje i istaknuto otisnut naslov Poduzetnički projekt ili Biznis-plan
Predmet elaboracije (naziv poduzetničke ideje)
Najnužniji podaci o osnivačima i/ili vlasnicima tvrtke
Podaci o autorima, redaktorima i recenzentima projekta
Podaci o osobi za vezu tvrtke pošiljatelja
Podaci o primatelju projekta
Podaci o rednom broju primjerka koji se upućuje dotičnome primatelju
Podaci o mjestu i vremenu izrade projekta
Upozorenje o zaštiti autorskih/vlasničkih prava

Odmah iza naslovnice poduzetničkog projekta nalazi se stranica ili stranice s ispisanim *kazalom sadržaja projekta* u kojem se predočavaju naslovi dijelova, poglavlja, glava itd. projekta. Iz sadržaja *kazala* čitatelji mogu dobiti preliminarni uvid u to što se sve nalazi u projektu te na kojim stranicama počinju i završavaju pojedini dijelovi. Hijerarhijska dubina predočavanja sadržaja projekta u kazalu ponajviše ovisi o stavovima samih autora, pa nema nekih uobičajenih pravila s tim u svezi. Ne ulazeći u različite mogućnosti hijerarhijske dubine sadržaja stožerni se zahtjevi mogu svesti na potrebu maksimalno moguće preglednosti i informativnosti kazala projekta (upotreba rimskih brojeva, velikih tiskanih slova, malih pisanih slova).
Sadržaj Projekta revitalizacije HE Zakučac dan je u Tablici 2.

Table 2. Contain of Refurbishment Zakucac HPP Project
Tablica 2. Sadržaj Projekta revitalizacije HE Zakučac

1. Uvod
2. Ciljevi investicijskog poduhvata
3. Stanje postojeće opreme i građevinskih objekata
3.1 Stanje postojeće opreme
3.2 Stanje građevinskih objekata
4. Provedene aktivnosti na realizaciji projekta revitalizacije HE Zakučac do konca 2002. godine
4.1 Izrada tehničke dokumentacije
4.2 Dozvole
4.3 Izvršeni radovi na projektu revitalizacije HE Zakučac do konca 2003. godine
5. Sažetak projekta
6. Tehnički prikaz Projekta revitalizacije HE Zakučac od 2004. do 2010. godine
6.1 Kratki opis objekta
6.2 Uloga HE Zakučac u elektroenergetskom sustavu
6.3 Hidrološke podloge
6.4 Moguća proizvodnja HE Zakučac
6.5 Dokumentacija
6.6 Revitalizacija elektro i strojarske opreme i građevinski radovi
7.Organizacija i način izvođenja projekta revitalizacije HE Zakučac
7.1. Organizacija i vođenje Projekta revitalizacije HE Zakučac
7.2 Organizacija radova na Projektu revitalizacije HE Zakučac
7.3. Vremenski planovi Projekta revitalizacije HE Zakučac
8.Struktura ulaganja
8.1 Obrazloženje troškova ulaganjau
8.2 Struktura troškova Projekta revitalizacije HE Zakučac
9. Ekonomska analiza Projekta revitalizacije HE Zakučac
9.1 Ulaganja
9.2 Proizvodnja električne energije
9.3 Realizacija projekta
9.4 Metoda ekonomske analize
9.5 Ulaganja i financiranje ulaganja
10.Zaključak
prilog br. 1: Vremenski plan Projekta revitalizacije HE Zakučac
prilog br. 2: Analitičke tablice proračuna cijene proizvodnje

3.3 Sažetak projekta

Operativni se sažetak obično predočava na tri do četiri stranice teksta i oblikuje se tek nakon izrade kompletnoga projekta. Neki ga utori stavljaju na početak, a neki na kraju projekta. Piše se zato da bi svaki zainteresirani čitatelj (za pet minuta i na jednom mjestu) mogao iščitati stožerne tehničko-tehnološke, tržišne, organizacijske, financijske i druge performanse poduzetničke ideje koja je potanko elaborirana u projektu. Obujam i struktura operativnog sažetka ovise o veličini i značenju poduzetničkoga pothvata, vrsti djelatnosti, namjeni projekta. Prema N. Kuvačiću operativni sažetak bi morao sadržavati dostatnu količinu sažetih informacija, i to prema skupinama istaknutim u Tablici 3.

Table 3. Chapters of operative project
Tablica 3. Sadržaj poglavlja operativnoga sažetka projekta

Stožerni podaci o tvrtki investitora
Asortiman proizvoda, robe ili usluga
Tržišni podaci i konkurencijske prednosti
Tehničko-tehnološki podaci
Struktura i izvori potrebnoga kapitala
Potrebni menadžeri i novi zaposlenici
Aktivizacijsko razdoblje – tijek izvedbe
Mjere zaštite okoliša i zaposlenika
Pokazatelji učinkovitosti projekta

U operativni sažetak može se staviti i znatno više informacija, zapravo, onoliko koliko poduzetnik misli da će biti na prvi pogled zanimljivo potencijalnim primateljima projekta. U svakom slučaju ne valja pretjerivati i već na početku čitatelje zatrpavati mnoštvom često i suvišnih podataka i informacija. Iz operativnog sažetka projekta revitalizacije HE Zakučac se iščitavaju najbitnije informacije vezana uz ovaj projekt (Tablica 4).

Table 4. Operative summary - Example of Refurbishment Zakucac HPP
Tablica 4. Operativni sažetak na primjeru Projekta revitalizacije HE Zakučac

1.Investitor:HEP Proizvodnja d.o.o
2.Naziv projekta: Revitalizacija (Zamjena i obnova) HE Zakučac
3.Lokacija:HE Zakučac je smješten u Splitsko-dalmatinskoj županiji na ušću rijeke Cetine u more, udaljena cca 2 km od Omiša
4. Instalirana snaga HE: postojeće stanje - 486 MW (540 MVA) nakon revitalizacije - 538 MW (680 MVA)
5. Prosječna godišnja proizvodnja: postojeće stanje - 1404 GWH (niz od 1981-2003.) nakon revitalizacije - 1462 GWH
6. Prethodni troškovi: 128.536.000,00 kn
7.Troškovi investicije:--- 697.000.000,00 kn
8. Financiranje: vlastita sredstva

3.4 Opis poduzetničke ideje i tržišni podaci projekta

Opis poduzetničke ideje. Na samom početku projekta novoga pothvata (onoga koji će se realizirati u sklopu novoosnovane- nove tvrtke) valja opisati sve glavne odrednice poduzetničke ideje, odnosno programa ulaganja kojim je predviđena njezina realizacija. Ideju za pokretanje novoga ili unapređenje i razvoj postojećega biznisa valja elaborirati (u ovom dijeli opisati) tako da se

vidi tko su autori i kako su došli do ideje, koje su specifičnosti i pogodnosti odabrane ideje
(proizvoda, roba ili usluga) te na čemu se temelje poduzetničke i druge podobnosti osnivača ili budućih vlasnika tvrtke.
Kada je riječ o već djelatno-aktivnoj tvrtki, onda ovo poglavlje neizostavno mora sadržavati i poseban dio (analiza investitora) u kojem se predočava dostatan obujam informacija i pokazatelja o dosadašnjemu poslovanju tvrtke, a prema izboru samog projektanta, s tim da predočene informacije svim zainteresiranima nude realnu sliku tržišnoga položaja i financijskoga zdravlja tvrtke investitora.
Čitatelji s osobitom pozornošću čitaju i analiziraju ovaj dio projekta, jer se u njemu nalaze sve animirajuće informacije za daljnje praćenje projekta tj. njegov slijed od ideje do realizacije. Kada je riječ o projektu koji tek nastaje, opis poduzetničke ideje bi trebalo strukturirati u tri karakteristična dijela: (1) Autori i evolucija ideje, (2) Opis proizvoda i usluga, (3) Poduzetničke referencije.
Sva tri dijela trebaju sadržavati najbitnije informacije vezane za poduzetnički projekt.
Tržišni podaci projekta. Istraživanje prodajnoga i nabavnoga tržišta, odnosno outputa i inputa poduzetničkoga projekta glavna je predpoduzetnička aktivnost i informacijska podloga svakog poduzetničkog pothvata, pa joj valja pristupiti s osobitom pažnjom i visokim stupnjem umijeća i istraživačkog strpljenja. Istraživanje prodajnog tržišta poduzetniku omogućava relativno pouzdane odgovore na pitanja o tome tko su potencijalni kupci njegova proizvoda, robe ili usluga, odnosno kakav proizvod, robu ili uslugu potencijalni kupci žele kupiti, zatim zašto oni kupuju, kako kupuju, koliko kupuju, kada kupuju i po kojim cijenama žele kupovati.
Na razini konkretnog projekta, valja identificirati segmente potencijalnih potrošača na ciljnom tržištu, procijeniti potrošačke financijske potencijale identificiranih segmenata te prepoznati najkraći put za plasman proizvoda, roba ili usluga do pojedinih skupina potrošača.
Tržište je mjesto susreta ponuda i potražnje, pa stoga uspjeh novoosnovanih tvrtki i asortimana proizvoda, roba i usluga koje nude ovisi o tome kako su predvidjeli i istražili potrebe potencijalnih kupaca i u kojoj su ih mjeri spremni zadovoljiti.
Hrvatska elektroprivreda kao jedino veliko poduzeće koje proizvodi električnu energiju u RH nema potrebu ulagati velika sredstva u ispitivanje tržišta jer ne postoji poduzeće koje bi onemogućilo njegov relativni monopol na tržištu RH. Električna energija koja je postala neophodna za svakodnevni život daje HEP-u mogućnost stvaranja i realiziranja novih projekata bez značajnog uplitanja javnosti. Ovdje su naravno iznimka projekti koji direktno utječu na okoliš i njegovo zaštitu. Kada se radi o takvim projektima od iznimne je važnosti napraviti istraživanje tržišta i poduzeti sve mjere kako bi se okoliš na najbolji način zaštitio od negativnih posljedica takvih projekata (npr. izgradnja TE). Važno je uzeti u obzir, prilikom planiranja novih projekata ili investicija, i energetsku krizu u svijetu koja je postala još izraženija s početkom rata u Iraku. Energetska kriza je dovela do povećanja cijene nafte što direktno utječe na sve segmente gospodarstva, kako svjetskog tako i Hrvatskog (porast cijena energije, pad BDP-a, povećanje troškova proizvodnje i dr.).

3.5 Tehničko-tehnološki opis projekta

Uz informacije o tržišnim podacima, informacije iz tehničko-tehnološkoga opisa glavne su odrednice objektivnosti svakog projekta. U ovom poglavlju valja predočiti nužne informacije dostatne za odgovore na pitanja gdje, kako, i s čime proizvodit, tržit ili usluživati. To nužno pretpostavlja informacije glede izbora makrolokacije i mikrolokacije, potrebne opreme i njezina kapaciteta, potrebnih stalnih kapaciteta, materijalnih inputa, potrebnih zaposlenika, nužnih zaštitnih mjera. Posebnu pozornost valja obratiti na mjere zaštite na radu i ekološke aspekte. Poglavlje tehničko-tehnološkog opisa treba strukturirati prema slijedećim dijelovima: (1) Lokacija projekta, (2) Tehnologija, oprema, kapacitet projekta, (3) Potrebna stalna sredstva, (4) Potrebni materijalni inputi, (5) Projekcija zaposlenika, (6) Zaštitne mjere, (7) Razdoblje izvedbe.
Važnost ovog poglavlja u području tehničkih djelatnosti je velika. Za primjer naveden je dio tehničko-tehnološkog opisa iz investicijskog programa o nastavku revitalizacije HE Zakučac[6]. Kako je ovo projekt revitalizacije on sadrži cjelokupan popis postojeće opreme (turbine i turbinska oprema, hidromehanička oprema, pomoćni pogoni, stanje elektroopreme) i popis stanja građevinskih objekata.
Za HE Zakučac u tehničko-tehnološkom opisu je važan opis hidrološke podloge jer hidroelektrana Zakučac je dio višenamjenskog sustava za uređenje i korištenje voda i zemljišta sliva rijeke Cetine, koji se prostire kroz dvije države. Širi sliv rijeke Cetine uzvodno od zahvata HE Zakučac, ima površinu 3 800 km2 i obuhvaća krška polja na više nadmorskih horizonata sa stalnim i povremenim vodotocima. Osnovno uređenje dotoka za HE Zakučac postiže se daljinskim akumulacijama Peruća i Buško Blato, a osnovni hidrološki podaci dani su u Tablici 5.

Table 5. Basic hidrological dana- Zakucac HPP
Tablica 5. Osnovni hidrološki podatci – HE Zakučac

Osnovni podatci	**Prije revitalizacije**	**Poslije revitalizacije**
Meteorološko-klimatološki podatci: srednja godišnja oborina	1400 m	Bez promjene
Hidrološka svojstva: - slivna površina - srednji protok Cetine kod Trilja - Velika voda Cetine – vjerojatnosti 0.01 - projektna velika voda Cetine kod Prančevića	3800 km^2 107,5 m^3/s 800 m^3/s 1200 m^3/s	Bez promjene

U Tablici 6 dane su tehničke karakteristike postojeće i nove opreme za HE Zakučac

Table 6. Technical characteristics of existing and new equipment – Zakucac HPP
Tablica 6. Tehničke karakteristike postojeće i nove opreme HE Zakučac

Opis	Postojeće stanje	Nakon revitalizacije
Tehničke karakteristike turbina A i B		
tip turbine	Francis vertikalna	Francis vertikalna
proizvođač	Voith Austrija	Voith Austrija
snaga turbine	119.9 MW	146 MW
broj okretaja	300 min^{-1}	333 min^{-1}
instalirani protok	50 m^3/s	60 m^3/s
Tehničke karakteristike turbina C i D		
tip turbine	Francis vertikalna	Francis vertikalna
proizvođač	Litostroj, Ljubljana,	
snaga turbine	145 MW	147 MW
brzina vrtnje	333min^{-1}	333 min^{-1}
instalirani protok	60 m^3/s	60 m^3/s
Tehničke karakteristike generatora A i B		
tip	sinkroni	sinkroni
nazivna snaga	120 MVA	170 MVA
faktor snage	0.9	0.85
nazivni napon	16 kV+10%- 5%	16 kV ±7.5%
nazivni broj okretaja	300 min^{-1}	333 min^{-1}
Tehničke karakteristike generatora C i D		
tip	sinkroni	sinkroni
nazivna snaga	150 MVA	170 MVA
faktor snage	0.9	0.85
nazivni napon	16kV+10%-5%	16kV ±7,5%
nazivni broj okretaja	333 min^{-1}	333 min^{-1}
Tehničke karakteristike transformatora A		
tip	3xjednofazni -uljni	trofazni-uljni
nazivna snaga	50MVA	170MVA
napon više naponske strane	121/√3kV	242 kV
napon niže naponske strane	16 kV	16kV
vrsta hlađenja	OFWF	OFWF
Tehničke karakteristike transformatora B		
tip	3xjednofazni -uljni	trofazni-uljni
nazivna snaga	40MVA	170 MVA
napon više naponske strane	242/√3kV	242 kV
napon niže naponske strane	16 kV	16kV
vrsta hlađenja	OFWF	OFWF
Tehničke karakteristike transformatora C		
tip	3xjednofazni -uljni	trofazni-uljni
nazivna snaga	50MVA	170 MVA
napon više naponske strane	242/√3kV	242 kV
napon niže naponske strane	16 kV	16kV
vrsta hlađenja	OFWF	OFWF
Tehničke karakteristike transformatora D		
tip	3xjednofazni -uljni	trofazni-uljni
nazivna snaga	50MVA	170 MVA
napon više naponske strane	121/√3kV	242 kV
napon niže naponske strane	16 kV	16kV
vrsta hlađenja	OFWF	OFWF

3.6 Menadžment i marketing projekta

Menadžment projekta. Menadžment promatran s različitih stajališta može se uzimati kao sinonim za upravljački tim stručnjaka. Management je proces rada s drugima i pomoću drugih na ostvarivanju organizacijskih ciljeva u promjenjivome okruženju uz efektivnu i efikasnu uporabu ograničenih resursa. U teoriji se najčešće govori o pet glavnih funkcija menadžmenta: (1) Planiranje poduzetničke djelatnosti, (2) Organiziranje proizvodnje, trženja ili usluživanja, (3) Kadroviranje ili upravljanje ljudskim resursima, (4) Vođenje ili upravljanje ljudskim resursima, (5) Kontroliranje izvršenja planiranih aktivnosti

Marketing projekta. Marketing je poslovna filozofija, koncepcija, sustav i funkcija koja u središte pozornosti stavlja potrošače, istražuje njihove potrebe i na tržištu im nudi proizvode, robu ili usluge koji će primjereno zadovoljiti njihova očekivanja glede količina, vrsnoće, asortimana, zatim uporabnih, tehničkih, estetskih i drugih obilježja, i to sve na određenom mjestu, u željeno vrijeme i po prihvatljivim cijenama. Što se tiče marketinga, tu je riječ o specifičnoj poslovnoj strategiji, taktici i politici u svrhu kvalitetnijega zadovoljenja potrošačkih potreba koje se na tržištu pojavljuju kao platno manifestna ili potencijalno moguća potražnja te maksimiranja profitnih učinaka poduzetničke aktivnosti. P. Kotler, marketinški stručnjak, konstatira da se prema markentiškoj koncepciji ključ postizanja ciljeva sastoji u određivanju potreba i želja ciljnih tržišta i – u odnosu prema konkurenciji – uspješnijem i djelotvornijem transferu željenih zadovoljstava. U projektu treba posebnu pozornost posvetiti *marketinškom miksu*, tzv. 4 P – product, price, place, promotion (proizvod, cijena, prodaja, promocija). Kombinacija marketinškog miksa postaje realan izraz sveukupne politike tvrtke. Marketing u poslovanju HEP-a ne zauzima značajnu poziciju jer nije potrebna reklama za korištenje el.energije, a ne postoji ni konkurencija zbog koje bi HEP trebao ulagati u promidžbu. Jedini oblici marketinga vidljivi na Hrvatskom tržištu koje provodi HEP su pozivanje na racionalnije korištenje el. energije zbog zaštite okoliša i čestitke upućene građanima putem medija za blagdane.

3.7 Financijski podaci projekta

Ovo poglavlje obično sadržavati mnoštvo tabličnih prikaza i njima primjerenih tekstualnih objašnjena od kojih neizostavno treba sadržavati projekciju potrebnih ulaganja u stalna i trajna obrtna sredstva, projekciju izvora i strukture sredstava i kapitala, projekciju terminskog financiranja prema stavkama sredstava, projekciju terminskog financiranja prema izvorima kapitala, projekciju potrebnih ulaganja i izvora sredstava i izvora kapitala, projekciju otplate financijskih zajmova, projekciju godišnje amortizacije i ostatka vrijednosti projekta, dinamičku projekciju prihoda i rashoda, dinamičku projekciju dobiti-gubitaka, dinamičke projekcije ekonomskih tijekova dinamičku projekciju bilance i ostale projekcije koje poduzetnički projekt zahtijeva. U ovom radu su prikazani osnovni financijski podaci HE Zakučac.

Ekonomsko-financijska analiza projekta revitalizacije HE Zakučac. U osnovnim financijskim podacima *HE Zakučac* navedeni su svi troškovi i ekonomska analiza Projekta revitalizacije HE Zakučac. U financijskom dijelu *struktura ulaganja* navodi se kako će se investicija nastavka projekta revitalizacije HE Zakučac financirati iz vlastitih sredstava HEP-Proizvodnja d.o.o. Na temelju idejnog projekta, informativnih ponuda i zadnjih ponuda za slične radove na objektima HEP-Proizvodnja d.o.o. procijenjena je ukupna investicija **697.000.000,00** kuna, odnosno **9.560.000,00** €. Navedene su i sve ostale stavke koje financijski dio projekta zahtijeva, a sve je najbolje vidljivo iz Tablice 7.

Table 7. Structure of the total cost of Refurbishment Project Zakucac HPP

Tablica 7. Struktura ukupnih troškova Projekta revitalizacije HE Zakučac

Opis pozicije	Ulaganje kn
Tehnička dokumentacija i konzalting	25.000.000,00
Oprema (ukupno)	581.000.000,00
Građevinski radovi (ukupno)	78.000.000,00
Ostali troškovi (ukupno)	13.000.000,00
SVEUKUPNO	697.000.000,00

Nakon svih izračuna troškova i potrebnih ulaganja slijedi ekonomska analiza kojoj je svrha utvrditi ekonomsku opravdanost projekta, a u ovom primjeru ekonomsku opravdanost Projekta revitalizacije HE Zakučac. Temeljno polazište ekonomskog vrednovanja je u činjenici da se HE Zakučac obnavlja iz razloga dotrajalosti elektro i strojarske opreme (turbina, generator, pomoćna oprema). Ako se zbog dotrajalosti pojedinih komponenata opreme, te komponente ne obnove, mogu se očekivati veće havarije (lom regulacijskih lopatica, lom rotorskih lopatica, oštećenja ležajeva, havarije na regulacijskom sustavu i sl.) i prestanak rada tih jedinica. Povećanje pouzdanosti opreme se procjenjuje na osnovi robusnosti sustava (što je sustav robusniji pouzdanost je veća), temperature ležajeva (što je temperatura manja to je pouzdanost veća), kavitacijskih karakteristika sustava (što je kavitacija manja sustav je pouzdaniji), vibracija u sustavu (manje vibracije - veća pouzdanost) i drugih tehničkih elemenata.

Temeljem spomenutog proizlazi da se ekonomskom analizom ne vrednuje samo dodatna proizvodnja kao rezultat projekta revitalizacije (projektom revitalizacije

se povećava prosječna godišnja proizvodnja s 1404 GWh na 1462 GWh, povećava se snaga HE s 486 MW na 538 MW, smanjuje se prosječna cijena proizvodnje električne energije s 6.21 lipa/kWh na 5.10 lipa/kWh), nego cjelokupna proizvodnja nakon revitalizacije . Na taj način temelj za ekonomsku analizu su proizvodnja HE Zakučac nakon revitalizacije investicije u Projekt revitalizacije. Financiranje ulaganja je iz vlastitih sredstava HEP Proizvodnja d.o.o. Izvori financiranja utječu na cijenu električne energije na način da je troškove korištenja izvora financiranja potrebno uključiti u cijenu električne energije. U ekonomskom smislu svoju cijenu korištenja jednako imaju vlastita i tuđa sredstva.
(u Tablici 8 je prikazan rezultat proračuna dviju cijena električne energije-nominalne i diskontirane).

Na Slici 2 prikazana je proizvodnja električne energije prije i nakon revitalizacije.

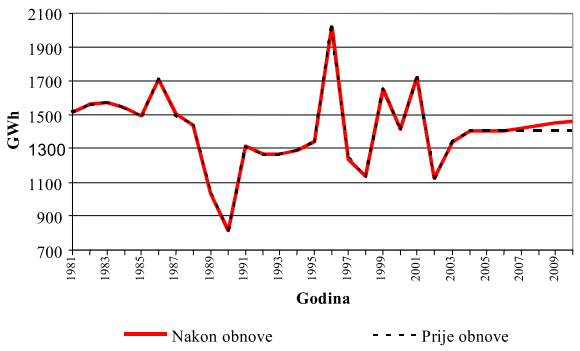

Figure 2. Production of Zakucac HPP
Slika 2. Proizvodnja HE Zakučac

Uzimajući u obzir i cijenu električne energije i uspoređujući je s cijenom električne energije iz alternativnih izvora (slobodni kapaciteti termoelektrana u HEP-u, uvoz električne energije ili izgradnja novih objekata)-Tablica 9, proizlazi zaključak da je cijena električne energije u HE Zakučac nakon revitalizacije (72.2 kn/MWh tj. 9.90 €/MWh) znatno manja od cijene električne energije u alternativnim izvorima. Ova činjenica upućuje na to da je Projekt revitalizacije HE Zakučac ekonomski opravdan i nužan

Table 8. Zakucac HPP- Price of electricity production after refurbishment
Tablica 8 Cijena električne energije nakon revitalizacija HE Zakučac

Godina	GWh	Cijena električne energije			
		Nominalna		Diskontirana	
		lipa/kWh	€ centi/kWh	lipa/kWh	€ centi/kWh
2004	1.404,043	4,97	0,66	7,38	0,98
2005	1.404,043	4,97	0,66	7,38	0,98
2006	1.406,543	5,00	0,66	7,37	0,97
2007	1.420,543	5,40	0,71	7,30	0,96
2008	1.433,043	5,77	0,76	7,22	0,95
2009	1.433,043	6,20	0,82	7,15	0,94
2010	1.433,043	6,56	0,87	7,09	0,94
2011	1.433,043	6,56	0,87	7,09	0,94
2012	1.433,043	5,92	0,78	7,09	0,94
2013	1.433,043	5,33	0,70	7,09	0,94
2014	1.433,043	5,29	0,70	7,09	0,94
2015	1.433,043	5,25	0,69	7,09	0,94
2016	1.433,043	5,25	0,69	7,09	0,94
2017	1.433,043	5,20	0,69	7,09	0,94
2018	1.433,043	5,15	0,68	7,09	0,94
2019	1.433,043	5,15	0,68	7,09	0,94
2020	1.433,043	5,15	0,68	7,09	0,94
2021	1.433,043	5,15	0,68	7,09	0,94
2022	1.433,043	5,07	0,67	7,09	0,94
2023	1.433,043	4,67	0,62	7,09	0,94
2024	1.433,043	4,64	0,61	7,09	0,94
2025	1.433,043	4,64	0,61	7,09	0,94
2026	1.433,043	4,64	0,61	7,09	0,94
2027	1.433,043	4,63	0,61	7,09	0,94
2028	1.433,043	4,63	0,61	7,09	0,94
2029	1.433,043	4,63	0,61	7,09	0,94
2030	1.433,043	4,63	0,61	7,09	0,94
2031	1.433,043	4,56	0,60	7,09	0,94
2032	1.433,043	4,16	0,55	7,09	0,94
2033	1.433,043	3,73	0,49	7,09	0,94
Prosjek 2004-2033.		5,10	0,67	7,18	0,95

Nominalna cijena je knjigovodstvena cijena, cijena bez cijene korištenja izvora financiranja.
Diskontirana cijena je ekonomska cijena s uključenom cijenom korištenja izvora financiranja 8%.

Table 9. Price of alternative electricity production
Tablica 9. Cijena proizvodnje električne energije alternativnih izvora

Termoelektrana	Promjenljivi trošak* Kn/MWh	Cijena u €/MWh
Plomin 1	127.9	16.83
Plomin 2	111.5	14.67
Rijeka	279.8	36.82
Sisak	317.4	41.77
Jertovec	428.3	56,.35
Uvoz-nova TE	Ukupna cijena KN/MWh	Ukupna cijena €/MWh
Uvoz Kn/MWh** (s ino prijenosom)	243.20-266.00 (temeljna) 380.00-418.00 (vršna)	32.00-35.00 50.00-55.00
Nova TE Kn/MWh*** (ugljen, plin)	212.80-273.60	28.00-36.00

**Troškovi i cijena proizvodnje u 2003. (HEP-Proizvodnja)*
***Burza električne energije u Njemačkoj (EEX)*
****Institut za elektroprivredu i energetiku ("Razina cijene", 2002.)*

U kratkom pregledu osnovnih ekonomsko-financijskih podataka HE Zakučac vidljivo je da je projekt revitalizacije HE Zakučac isplativ.

4. Zaključak

U ovom radu je dan teorijski osvrt na investicijske projekte s naglaskom na anatomiju projekta i financijsku analizu kao i tehno ekonomsku analizu investicijskih projekata na primjeru Projekta revitalizacije HE Zakučac. Investicijski projekti ovakvog tipa su dugoročno isplativi što je i vidljivo iz analize projekta: manja je cijena električne energije iz obnovljivih izvora u odnosu na alternativne izvore električne energije, dobiva se dodatna godišnja proizvodnja električne energije, rasterećuju se postojeće HE, dugoročno se povećava dobit HEP-a. Isto tako, značajan je i ekološki aspekt ovog energetskog sektora: kod revitalizacija postojećih elektrana dobivaju se novi MW električne energije bez novog zadiranja u okoliš i bez skupih građevinskih radova a male HE ulaze u program *Zelene energije* koja će posebno biti subvencionirana na tržištu električne energije.
Važno je napomenuti da na temelju izvršenih analiza i izračuna projekti ovakvog tipa, uzimajući za primjer Projekt revitalizacije HE Zakučac, spadaju u red učinkovitih projekata niske razine rizika što daje poticaj za daljnja ulaganja u iste.

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Analysis of investments in small hydropower plants

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investicija
projekt
ocjena projekta

Early information
Abstract: This paper gives an overview of investments in small hydropower plants. Economic - financial analysis was made in the case of project small hdyro powerplant Peruća that would use water of biological minimum existing HPP Peruća Dam. Investment is profitable when viewed from the economic-financial, technological and environmental aspects. The value of the investment is € 2.000.000,00 an average annual production of Peruća SHPP is 3778, 94 MWh, and the expected return on investment after 16 years.

Analiza investiranja u male hidroelektrane

Prethodno priopćenje
Sažetak: U ovom radu dan je prikaz isplativosti ulaganja u male hidroelektrane. Ekonomsko – financijska analiza napravljena je na primjeru izgradnje MHE Peruća koja bi koristila vode biološkog minimuma postojeće pribranske HE Peruća. Ulaganje je isplativo gledano s ekonomsko- financijskog, tehnološkog i ekološkog aspekta. Vrijednost investicije je 2.000.000,00 EUR, prosječna godišnja proizvodnja MHE Peruća iznosi 3778, 94 MWh, a očekivani povrat ulaganja je nakon 16 godina.

1. Uvod

Energija vode (hidroenergija) najznačajniji obnovljivi izvor energije, a ujedno i jedini koji je ekonomski konkurentan fosilnim gorivima i nuklearnoj energiji, [1].

Hidroenergija zauzima prvo mjesto u svijetu na popisu obnovljivih izvora energije i to će još dugo biti tako. Danas je tržište za male i srednje hidroelektrane atraktivnije nego ikad. Liberalizacija tržišta u Europi otvara veliki ekonomski potencijal koji zahtijeva strategiju velikih tvrtki, [2].

Korištenje hidroenergije ima svoja ograničenja. Ne može se koristiti posvuda jer podrazumijeva obilje brzo tekuće vode, a poželjno je i da je ima dovoljno cijele godine, jer se električna struja ne može jeftino uskladištiti. Da bi se poništio utjecaj oscilacija vodostaja grade se brane i akumulacijska jezera. To znatno diže cijenu cijele elektrane, a i diže se razina podzemnih voda u okolici akumulacije. Razina podzemnih voda ima dosta utjecaja na biljni i životinjski svijet, pa prema tome hidroenergija nije sasvim bezopasna za okoliš, [4].

Problemi vezani za projektiranje i puštanje u rad male hidroelektrane, općenito, leže u ekonomskim i zakonodavnim izvorima. Gradnja male hidroelektrane je ekonomski zahtjevan projekt i danas je u Republici Hrvatskoj glavni problem nezainteresiranost mjerodavnih tijela za ulaganja u obnovljive izvore energije, što isključuje i potrebno djelovanje državnih organa usmjereno na banke da se otvore ka ulaganju, jer tržišni interes banaka izostaje zbog niskih kamata za ovakve investicije (u svakom slučaju nižih kamata nego za ostale tržišne aktivnosti).

U ovom radu će radu biti predstavljen investicijski projekt za izgradnju male hidroelektrane konkretno za izgradnju male hidroelektrane Peruća, uključujući potrebnu opremu, pogon, proizvodnju te održavanje. S ovim projektom je, bez obzira na isplativost, teško krenuti u realizaciju jer je tržište električne energije u Hrvatskoj prilično limitirano. Jedan od važnijih razloga za izgradnju male hidroelektrane Peruća leži u problemu biološkog minimuma. Izgradnjom hidroelektrane Peruća nije bio odgovarajuće riješen način ispuštanja biološkog minimuma iz akumulacije za vrijeme stajanja glavnih agregata, što je obveza prema vodoprivrednoj suglasnosti i važećem Pravilniku o korištenju akumulacije Peruća. Predviđene količine biološkog minimuma ispuštaju se kroz temeljni ispust korištenjem regulacijskog zatvarača na izlazu temeljnog ispusta.

Ovakav način ispuštanja biološkog minimuma neprikladan je jer zahtjeva podizanje table zatvarača svega nekoliko centimetara, a regulacijski zatvarač nije konstruiran za takav režim rada (velike brzine vode i česte manipulacije) što se negativno odražavalo na njegovu tehničku ispravnost. HE Peruća nema tehničko

rješenje za kontrolirano ispuštanje malih količina vode. Ispuštanje biološkog minimuma temeljnim ispustom pokazalo se jako nepovoljnim sa strane održavanja jer dolazi do velikih troškova održavanja opreme koja nije predviđena za doziranje takvih ispusta, [3].

Symbols/Oznake

g	- gravitacija (m^2/s)	Q	- protok (m^3/s)
H_n	- neto pad (m)	t_g	- broj sati MHE u godini
η	- iskoristivost (%)	W_g^{MHE}	- dio godišnje proizvodnje MHE (kWh)
η_{bt}	- iskoristivost blok transformetora (%)	W_g	- ukupna godišnja proizvodnja MHE (kWh)
η_g	- iskoristivost genaeratora (%)	W_i	- mjesečna proizvodnja MHE u i-tom mjesecu (kWh)
η_t	- iskoristivost turbine (%)		

2. Analiza ulaganja

2.1. Analiza tržišta

Temeljem Zakona o energiji i Zakona o tržištu električne energije u Republici Hrvatskoj stvorene su temeljne pretpostavke za rad tržišta električne energije. Izradom i donošenjem Pravila djelovanja tržišta električne energije i ostalih potrebnih podzakonskih akata ostvareni su uvjeti za početak rada i postupno otvaranje tržišta električne energije.

U Hrvatskoj postoji samo jedno tržište električne energije. U početnoj fazi rada tržišta odabran je model bilateralnog tržišta u kojem se trgovanje električnom energijom provodi temeljem bilateralnih ugovora. Bilateralni ugovori sklapaju se između sudionika na tržištu električne energije. Na području jugoistočne Europe već se dugo realiziraju bilateralne razmjene električne energije.

Povlašteni proizvođač je energetski subjekt koji u pojedinačnom proizvodnom objektu istodobno proizvodi električnu i toplinsku energiju, koristi otpad ili obnovljive izvore energije na gospodarski primjeren način koji je usklađen sa zaštitom okoliša.

HEP-Operator prijenosnog sustava i HEP-Operator distribucijskog sustava dužni su od povlaštenog proizvođača preuzeti njegovu ukupno proizvedenu električnu energiju, dok je svaki opskrbljivač dužan, prema propisanim uvjetima, preuzeti minimalni udjel električne energije koju su proizveli povlašteni proizvođači u sustavu poticanja.

Status povlaštenog proizvođača električne energije stječe se rješenjem Hrvatske energetske regulatorne agencije, u skladu s uvjetima koje Pravilnikom o stjecanju statusa povlaštenog proizvođača električne energije propisuje ministar gospodarstva, rada i poduzetništva.

Zakonska energetska regulativa u Hrvatskoj u kojoj se pravno regulira poticanje korištenja obnovljivih izvora energije (OIE) i kogeneracijskih postrojenja te način isplate poticaja povlaštenim proizvođačima koji u svojim energetskim postrojenjima proizvode električnu energiju i istu isporučuju u elektroenergetsku mrežu, izrađena je na temelju smjernica europskog zakonodavstva i energetskih zakona u Hrvatskoj.

Povlašteni proizvođač, osim hidroelektrana snage veće od 10 MW, može steći pravo na poticajnu cijenu iz Tarifnog sustava za proizvodnju električne energije iz obnovljivih izvora energije i kogeneracije.

Nakon što je energetski subjekt ishodio rješenje o prethodnom statusu povlašteni proizvođač sklapa Ugovor o otkupu električne energije s Hrvatskim operatorom tržišta energije (HROTE). Povlašteni proizvođač ima pravo na poticajnu cijenu primjenom Tarifnog sustava za proizvodnju električne energije iz obnovljivih izvora energije i kogeneracije. Na taj se način stječu i potrebna jamstva za kreditiranje, ukoliko je neophodno investitoru za gradnju postrojenja. Otkup proizvedene električne energije iz postrojenja reguliran je preko HROTE-a. HROTE sklapa poseban ugovor sa svim energetskim subjektima za opskrbu električne energije, kako bi naplatio sva potraživanja za otkup električne energije. Način i elementi utvrđivanja poticajne cijene, odnosno poticajna cijena utvrđena Tarifnim sustavom za proizvodnju električne energije iz obnovljivih izvora energije i kogeneracije, važećim u trenutku sklapanja ugovora o otkupu električne energije, neće se mijenjati tijekom razdoblja trajanja ugovora. Tarifnim sustavom je utvrđena visina tarifne stavke u kn/kWh, a za malu hidroelektranu (1-10 MW) iznosi 0,69 kn/kWh, [16].

U Hrvatskoj postoje dvije kategorije kupaca: povlašteni i tarifni kupci. Temeljem Uredbe o naknadama za poticanje proizvodnje električne energije iz obnovljivih izvora energije i kogeneracije povlašteni i tarifni kupci električne energije dužni su plaćati naknadu za poticanje proizvodnje električne energije iz obnovljivih izvora energije i kogeneracije. Naknada će biti posebno iskazana u računu za električnu energiju, uz sve ostale naknade čije je plaćanje definirano Zakonom o energiji.

Kupci stječu status povlaštenog kupca temeljem Zakona o tržištu električne energije. Na dan stupanja na snagu ovoga Zakona svi kupci s godišnjom potrošnjom većom od 20 GWh i svi kupci koji su priključeni izravno na prijenosnu mrežu stječu status povlaštenog kupca. S 1. srpnjem 2007. godine svi poduzetnici stekli su status povlaštenog kupca.

Zakonom je propisana postupna dinamika otvaranja tržišta električne energije u Republici Hrvatskoj. Tržište je potpuno otvoreno od 1. srpnja 2008. Godine, [7], [8].

Status povlaštenog kupca znači da kupac prema vlastitom izboru odabire svog opskrbljivača. Mali kupci (u smislu članka 2, Zakona o tržištu električne energije) koji ne žele koristiti stečeno pravo, mogu ostati tarifni kupci.

U Hrvatskoj je velika većina proizvodnje HEP Proizvodnja d.o.o. Za gradnju novih kapaciteta proizvodnje električne energije odabrana je tenderska (natječajna) procedura.

Izgradnja objekta za proizvodnju električne energije za povlaštene kupce je slobodna odluka energetskog subjekta koji ima dozvolu za obavljanje djelatnosti proizvodnje električne energije. Energetski subjekt može graditi objekte za proizvodnju električne energije za tarifnog kupca na temelju provedenog natječaja i odobrenja kojeg izdaje Vijeće za regulaciju

U Hrvatskoj su do sada licencirane tri tvrtke za proizvodnju električne energije: HEP Proizvodnja d.o.o, TE Plomin d.o.o. i INA d.d.. Najveća od njih, HEP Proizvodnja (ovisno društvo u sastavu HEP d.d.) je društvo s ograničenom odgovornošću s dozvolama za obavljanje dvaju energetskih djelatnosti: proizvodnju električne energije za tarifne kupce i proizvodnju električne energije za tržište (iz eventualno neangažiranih postojećih proizvodnih i novih kapaciteta). Prema Zakonu o tržištu električne energije, ključna djelatnost će biti proizvodnja električne energije za tarifne kupce i pružanje usluga sustava. Na Slici 1. vidi se odnos u ostvarenoj proizvodnji hidroelektrana i termoelektrana na godišnjoj osnovi.

Figure 1. Achieved annual production of electricity in Croatia, [2]

Slika 1. Ostvarena godišnja proizvodnja električne energije u RH, [2]

U strukturi elektroenergetskog sustava Hrvatske, više od polovice izvora čine hidroelektrane. Zbog toga Hrvatska spada među vodeće zemlje u proizvodnji energije iz obnovljivih izvora. Razvoj energetskog korištenja vodnih snaga u Hrvatskoj započinje još 1895. godine s prvom hidroelektranom izgrađenom na Skradinskom buku na rijeci Krki - današnjom HE Jaruga.

Sve hidroelektrane HEP-a dobile su Zeleni certifikat za proizvodnju električne energije iz obnovljivih izvora. Temeljno obilježje hidroelektrana hrvatskog elektroenergetskog sustava je dugogodišnji rad i starost postrojenja.

Male hidroelektrane predstavljaju kombinaciju prednosti proizvodnje električne energije iz energije hidropotencijala i decentralizirane proizvodnje električne energije, dok istovremeno ne pokazuju negativan utjecaj na okoliš kao velike hidroelektrane, [6].

Sa saznanjem o toj činjenici i o mogućem maksimalnom angažmanu koji je prikazan u Tablici 1. ovaj projekt izgleda kao dobra poduzetnička ideja.

Table 1. Initial and maximum engagement on Cetina river, [12]

Tablica 1. Angažman HE na Cetini u inicijalnom stanju i maksimalnom angažmanu, [12]

HE	Angažman (MW)		
	Inicijalno	**Maksimalno (2003.)**	**Maksimalno (2010.)**
Peruća	35	41,6	61,2
Orlovac	210	237	237
Zakučac	430	486	540
Kraljevac	17	41,6	41,6
Đale	35	40,8	40,8
Ukupno	727	847	920,6

Male hidroelektrane u Hrvatskoj. Iako se energija rijeka i potoka u Hrvatskoj koristila tisućama godina (za pogon mlinova i sl.), sustavna istraživanja mogućnosti za njezino iskorištavanje u hidroenergetske svrhe u malim hidroelektranama na području Hrvatske započela su tek 1980. godine. Jedan od tih vodotokova na kojem postoje brojne mogućnosti za izgradnju malih hidroelektrana pregradnjom postojećih ili napuštenih mlinova (vodenica) je rijeka Mrežnica.

„Postojeći modeli i programi za planiranje i izgradnju EES-a podcjenjuju ulogu malih hidroelektrana u sustavu i gospodarstvu prvenstveno zbog toga što njihovu ulogu vrednuju prvenstveno kroz snagu objekta. Postojeća metodologija planiranja izgradnje MHE pokazala se neosjetljivom na suvremene zahtjeve za zaštitom prirode i okoliša te kulturne baštine. Važeća zakonska regulativa ne prepoznaje objekte MHE na adekvatan

način, pa su procedure za dobivanje dozvola i suglasnosti dugotrajne i složene, kao da se radi o znatno većim i opsežnijim projektima. U našoj zemlji vrlo mali broj MHE je u pogonu, pogotovo ako se vrši usporedba sa susjednim zemljama (Slovenija, Austrija, ...)", [5].

Istraživanje potencijalnih lokacija za MHE u Hrvatskoj uključuje: mjerenje protoka tijekom godina (u suradnji s Državnim hidrometeorološkim zavodom), određivanje krivulje trajanja protoka, ispitivanje izvedivosti i cijene projekta, princip diskvalificiranja lokacije uz minimiziranje ulaganja, hidrologija, ekologija, prostorni planovi, utjecaj na kulturnu baštinu i život, [9], [13], [18].

U Hrvatskoj trenutno postoji 15 malih hidroelektrana, većinom u vlasništvu Hrvatske elektroprivrede d.d. (HEP), dok su 3 u privatnom vlasništvu, a 2 u vlasništvu industrije. Od 77 proučavanih lokacija isključene su 52 lokacije. 33 zbog prostorno-planskih ograničenja, 18 zbog zaštite okoliša i kulturne baštine, dok su dvije lokacije spojene u jednu novim rješenjem. Preostalo je 25 lokacija. Najveći interes za izgradnju hidroelektrana bilježi se na području Splitsko-dalmatinske, Karlovačke, Zadarske i Požeško-slavonske županije (Slika 2.).

Figure 2. Pilot projects of small hydropower plants in Croatia, [5]

Slika 2. Pilot projekti malih hidroelektrana u RH, [5]

Smatra s da dosadašnji iskorišteni hidropotencijal u Hrvatskoj iznosi 6,6 milijardi kWh godišnje, a preostali tehnički iskoristivi još 6,1 milijardi kWh. Od preostalog tehnički iskoristivog hidropotencijala 2,93 milijardi kWh Hrvatska može koristiti samostalno. Međutim ova se količina umanjuje jer se slivno područje Cetine dijeli sa Bosnom i Hercegovinom. Svega potencijalnih 1,56 milijardi kWh planirano je proizvesti u objektima isključivo energetskog korištenja, a to je 25% ukupnog tehnički iskoristivog potencijala u konvencionalnim hidroelektranama. Zbog toga što je najveći dio hidropotencijala predviđeno koristiti višenamjenskim objektima u kojima je osim proizvodnje električne energije važna i: zaštita od poplava i regulacija rijeka; vodoopskrba pučanstva i gospodarstva; navodnjavanje, nužno je projekte hidroelektrana rješavati zajednički sa svim korisnicima voda, [11],[14].

2.2. Proračun moguće proizvodnje MHE Peruća

Cilj ovog poglavlja je utvrđivanje moguće proizvodnje agregata za biološki minimum MHE Peruća uz optimalno korištenje hidropotencijala vode koja se ispušta iz akumulacije Peruća kao biološki minimum u periodima kad su oba agregata u HE Peruća izvan pogona. Stvarna proizvodnja MHE normalno je niža od moguće proizvodnje uglavnom zbog promjene potražnje potrošača, odnosno u nekim razdobljima godine i dana, veće mogućnosti proizvodnje od potražnje potrošača. U uvjetima kada nema agregata za biološki minimum, taj hidropotencijal je nepovratno izgubljen na padu akumulacije Peruća.

Potrebno je provesti proračun moguće proizvodnje za dva slučaja: (1) ispuštanje biološkog minimuma uz pretpostavku da nema dodatnih zahtjeva za navodnjavanjem; (2) ispuštanje biološkog minimuma uz zadovoljenje dodatnih potreba navodnjavanja za konačnu etapu razvoja natapnog sistema sinjskog polja.

Moguća godišnja proizvodnja električne energije u MHE Peruća uvjetovana je sljedećim utjecajnim faktorima:

- stupanj korisnosti turbine, generatora i blok transformatora
- zatečena kota akumulacije Peruća koja definira bruto pad i gubici u dovodu preko kojih se dobiva neto pad
- režim rada HE Peruća, u prvom redu pretpostavljeno vrijeme u kojem ne radi ni jedan agregat HE Peruća, kada je potrebno ispuštati vodu biološkog minimuma koju bi trebala iskorištavati MHE Peruća
- propisani protok biološkog minimuma mjeren na hidrološkoj postaji Šilovka

Proračun moguće godišnje proizvodnje MHE Peruća bit će napravljen prema sljedećem modelu:

$$W_g = 9{,}81 \cdot Q \cdot H_n \cdot \eta_t \cdot \eta_g \cdot \eta_{bt} \cdot t_g \qquad (1)$$

Moguća proizvodnja MHE Peruća za slučaj bez dodatnog navodnjavanja

$$W_g = 9{,}81 \cdot 4 \cdot 47{,}14 \cdot 0{,}9 \cdot 0{,}95 \cdot 0{,}95 \cdot 3316 = 4982{,}21 MWh \qquad (2)$$

Dio godišnje proizvodnje MHE Peruća iz potrebnog protoka biološkog minimuma na hidrološkoj postaji Šilovka, koja je osnova za kasniju ekonomsku valorizaciju izgradnje MHE Peruća, iznosi:

$$W_g^{MHE} = W_g \cdot \frac{Q_{MHE_Per}}{Q_{inst}} = 4982{,}21 \cdot \frac{1{,}93}{4} = 2403{,}92\ MWh \qquad (3)$$

Moguća proizvodnja MHE Peruća za slučaj sa dodatnim količinama vode za navodnjavanje

$$W_g = 9{,}81 \cdot 5 \cdot 46{,}95 \cdot 0{,}92 \cdot 0{,}95 \cdot 0{,}95 \cdot 3316 = 6340{,}51\ MWh \qquad (4)$$

Dio godišnje proizvodnje MHE Peruća iz potrebnog protoka biološkog minimuma na hidrološkoj postaji Šilovka:

$$W_g^{MHE} = W_g \cdot \frac{Q_{MHE_Per}}{Q_{inst}} = 6340{,}51 \cdot \frac{2{,}98}{5} = 3778{,}94 MWh \quad (5)$$

2.3. Ekonomsko financijsko parametriranje

Analiza ulaganja. Ukupno potrebita ulaganja u poduzetnički pothvat dijele se na: (1) ulaganja u stalna sredstva (dugotrajnu imovinu ili osnovna sredstva); (2) ulaganja u obrtna sredstva (kratkotrajnu imovinu ili obrtna sredstva). Po iskustvu već napravljenih studija mogu se približno odrediti udjeli nabrojanih stavki u investicijskim troškovima: (1) prethodni radovi, dokumentacija i ostalo: oko 10%; (2) građevinski objekti: oko 30%; (3) oprema: oko 60%. Projekcija ulaganja u stalna i obrtna sredstva dana je u Tablici.2.

Table 2. Investment in fixed and current – Peruća SHPP,[20]
Tablica 2. Ulaganje u stalna i obrtna sredstva – MHE Peruća, [20]

Redni broj	Stavke stalnih i obrtnih sredstava	Iznos (EUR)
I.	**Stalna sredstva - ukupno**	**1.980.000**
1.	Nematerijalna ulaganja	170.000
2.	Izgradnja i uređenje objekta	700.000
3.	Postrojenja i oprema	1.100.000
4.	Pribor, alati i slično	10.000
II.	**Obrtna sredstva - ukupno**	**14.600**
5.	Godišnje plaće	9.600
6.	Izvanredni troškovi	5.000
III.	**Ukupno potrebna sredstva**	**1.994.600**

Ukupna potrebna sredstva će se zaokružiti na 2.000.000 € radi jednostavnijeg računanja.

Izvori kapitala i način financiranja. Poduzetnički se pothvat može započeti realizirati s relativno skromnijim novčanim sredstvima, ali zato se treba napraviti uskladba potrebitih ulaganja i realnih izvora, tzv. realno moguću konstrukciju financiranja projekta koja predstavlja kvantificiranu i vremensku projekciju.
Pod izvorima financiranja podrazumijevaju se financijska sredstva, koja vlasnik sredstava (banka, poduzeće, samostalni poduzetnik, država,...) stavlja pod određenim uvjetima na korištenje korisniku – investitoru.
Izvori financiranja se dijele na vlastita i tuđa sredstva. Za razliku od tuđih, za vlastita sredstva kao izvor financiranja se ne obračunavaju izravni troškovi korištenja, kao što su npr. kamata i dio dobiti partneru u zajedničkom investicijskom pothvatu. Pod vlastitim sredstvima podrazumijeva se i kapital ulagača
Bankarski kredit bi bio uzet kod HBOR-a, Hrvatske banke za obnovu i razvitak, u sklopu njihovog „Programa kreditiranja projekata zaštite okoliša, energetske učinkovitosti i obnovljivih izvora energije", [10]. Krediti se odobravaju u svrhu ulaganja u osnovna sredstva (osnivačka ulaganja, zemljište, građevinski objekt, oprema i uređaji) i trajna obrtna sredstva. HBOR u pravilu kreditira do 75% predračunske vrijednosti investicije bez PDV-a. Krediti se odobravaju u kunama s valutnom klauzulom. Poček je do 2 godine uz kamatnu stopu od 4%. Rok otplate je do 12 godina, uključujući i poček, [15]. Izvori financiranja su prikazani u Tablici 3.

Table 3. Sources of financing - Peruća SHPP, [20]
Tablica 3. Izvori financiranja - MHE Peruća, [20]

Redni broj	Stavke izvora sredstava - kapitala (vlastiti i tuđi izvori)	Iznos (EUR)	Struktura	
			(%)	(%)
I.	**Vlastita sredstva**	**800 000**	**40**	100
1.	Vlasnički kapital	100 000	5	12,5
2.	Kapital ulagača	700 000	35	87,5
II.	**Tuđa sredstva**	**1.200.000**	**60**	100
3.	Bankarski kredit	1.200.000	60	50
III.	**Ukupno**	**2.000.000**	**100**	-

Poslovna simulacija rada MHE Peruća. Primjena navedenih teorijskih postavki ekonomsko – financijske analize će biti prikazana na primjerima simulacije odabranog scenarija, [21]. Oni će svojim rezultatima prikazati isplativost ovog projekta u njegovoj implementaciji. Sve vrijednosti ulaganja će biti prikazane kao, otprilike, 30 % stvarne vrijednosti (izvori sredstava, vrijednost opreme, zgrade). Vijek trajanja projekta procijenjen je na 30 god., ali će se radi preglednosti tablica to prikazati kroz vijek projekta od 12 god. Na taj način će se dobiti realan omjer ulaganja i vijeka trajanja, a time i vjerni rezultati.
Vrijednosti pojedinih radova su detaljno analizirani u [20], a zbog opsega ovdje se iznose samo sumarne vrijednosti. Znači, strojarnica će biti izgrađena i za građevinske radove bit će potrebno 700.000 €, oprema će biti cijela financirana iz tuđih sredstava, kredita koji iznosi 1.200.000 €. Vlastita sredstva su podijeljena na vlasnički kapital (100.000 €) te kapital ulagača (700.000 €), njegova dividenda je 20 %. Kao što je već objašnjeno, u simulaciji su navedene vrijednosti prikazane kao trećina.

Ocjena učinkovitosti projekta.
Račun dobiti i gubitka - financijsko izvješće (račun) koja predočava poslovne aktivnosti tijekom određenog vremenskog razdoblja, odnosno prihode i rashode, kamatne i porezne efekte te čistu i zadržanu dobit. Riječ je, dakle, o računu koji najizravnije preslikava poslovne aktivnosti, pa se može reći da je to zorna slika učinkovitosti poslovanja u promatranom vremenskom razdoblju [17], [19].

Ta projekcija ujedno i predstavlja raspodjelu ukupnog prihoda, kojim se iskazuju sva izdvajanja iz ukupnog prihoda, i to za: pokriće uloženih činitelja (kapital, materijal i rad), pokriće troškova vanjskih izvora financiranja (kamate i ostali troškovi), opću potrošnju (porezi), za vlasnike poduzeća (dividende ili udio u dobiti, rezerve i zadržanu dobit).

Iz Tablice 4 se vidi da projekt ostvaruje dobit tijekom cijelog projektnog vijeka, dobit u 3. god nešto manja zbog toga što se počeo otplaćivati kredit i financijski rashodi su time veći.

Table 4. Profit and loss account, [20]
Tablica 4. Račun dobiti i gubitaka, [20]

godina/ year->Demo3	1	2	3	4	5	6	7	8	9	10	11	12
1.UKUP. PRIHODI / TOTAL INCOME	256	259	261	264	266	269	272	275	277	280	283	286
2.UKUP. RASHODI / TOTAL COSTS	109,086	108,786	128,092	126,65	119,991	116,432	116,811	118,125	116,371	116,547	110,99	110,018
2.1.Rashod proizv / product.costs	109	108,7	110,7	110,7	105,6	103,6	105,6	108,6	108,6	110,6	106,9	107,9
2.1.1.Mater.trošk / mater.expense	34,3	34	36	36	38	38	40	42	42	44	45	46
2.1.2.Amortizacija / depreciation	65,7	65,7	65,7	65,7	57,6	55,6	55,6	55,6	55,6	55,6	49,9	49,9
2.1.3.Bruto place / gross wages	9	9	9	9	10	10	10	11	11	11	12	12
2.2.Financ.rashodi / financ.costs	0	0	17,3	15,8	14,3	12,8	11,1	9,4	7,7	5,9	4	2
3.BRUTO DOBIT / GROSS PROFIT	146,9	150,2	132,9	137,3	146	152,5	155,1	156,8	160,6	163,4	172	175,9
4.Porez na dobit / profit tax	51,4	52,5	46,5	48	51,1	53,3	54,3	54,9	56,2	57,2	60,2	61,5
5.NETO DOBIT / NET PROFIT	95,4	97,6	86,3	89,2	94,9	99,1	100,8	101,9	104,4	106,2	111,8	114,3
5.1.Rezerve / reserves	4,7	4,8	4,3	4,4	4,7	4,9	5	5	5,2	5,3	5,5	5,7
5.2.Ukup.dividende / tot. dividends	19	19,5	17,2	17,8	18,9	19,8	20,1	20,3	20,8	21,2	22,3	22,8
5.2.1.Obic.divid / common dividends	19	19,5	17,2	17,8	18,9	19,8	20,1	20,3	20,8	21,2	22,3	22,8
5.2.2.Povl.divid. / preferred divid.	0	0	0	0	0	0	0	0	0	0	0	0
6.ZADRZ. DOBIT / RETAINED	71,6	73,2	64,7	66,9	71,1	74,3	75,6	76,4	78,3	79,6	83,8	85,7

Statička ocjena projekta. U Tablici 5 i na Slici 3 prikazana je statička ocjene projekta iz koje se mogu iščitati sve vrijednosti kao pozitivne, u višoj ili manjoj mjeri. Dobiveni podaci su očekivani s obzirom na sve tablice koje su dosad prikazane, jer se već moglo primijetiti da ovaj projekt izgleda kao pogodan projekt za realizaciju.

Na primjeru prve godine tijeka projekta će se objasniti dobiveni pokazatelji. Rentabilnost ukupnih poslovnih sredstava je omjer između neto dobiti i ukupnih poslovnih sredstava, tj. osnovnih i obrtnih sredstava. Sve veličine su iz reprezentativne godine projekta, što znači da je to godišnja neto dobit, a vrijednost osnovnih sredstava njihova je neamortizirana vrijednost na kraju reprezentativne godine, a obrtna sredstva jednaka su njihovoj vrijednosti u toj godini. Projekt je prihvatljiviji, što je vrijednost pokazatelja veća, dok je njegova granično prihvatljiva vrijednost jednaka nuli. U ovom slučaju iznosi 0,123 što znači da se akumulacija realizira u visini od 12,3%.

Rentabilnost prometa predstavlja omjer neto dobiti i ukupnih prihoda, tj. učešće neto dobiti u prihodima. U prvoj godini iznosi 0,373 što znači da prihodi generiraju neto dobit od 37,3%. Rentabilnost financijskih izvora iznosi 0,123 što znači da prinos na uloženi kapital iznosi 12,3%. Obrtaj poslovnih sredstava, koji predstavlja omjer ukupnih prihoda i ukupnih sredstava, iznosi 0,332, a to znači da se ukupnom imovinom realiziraju 0,332 puta veći prihodi tijekom godine, udjel tuđeg financiranja je 0,561 što pokazuje koliki se dio imovine financira iz tuđih izvora koji je u ovom slučaju 56,1%, te reprodukcijska sposobnost (odnos između neto dobiti uvećane za amortizaciju i poslovnih sredstava) iznosi 0,209 što znači da se proširena reprodukcija akumulira u visini od 20,9%.

Table 5. Static project rating, [20]
Tablica 5. Statičke ocjene projekta, [20]

godina / year ->Demo3	1	2	3	4	5	6	7	8	9	10	11	12
s1) Rentabilnost poslovnih sredstava / profitability of assets	0,123	0,115	0,098	0,098	0,1	0,101	0,099	0,097	0,097	0,096	0,097	0,097
s2) Rentabilnost prometa / profitability of sales	0,373	0,376	0,33	0,338	0,356	0,368	0,37	0,37	0,376	0,379	0,395	0,399
s3) Rentabilnost financijskih izvora / profitab.of financ.sources	0,123	0,115	0,118	0,116	0,116	0,114	0,111	0,107	0,104	0,101	0,101	0,099
s4) Obrtaj poslovnih sredstava / turnover of assets	0,332	0,306	0,299	0,292	0,282	0,275	0,269	0,264	0,257	0,253	0,248	0,243
s5) Udjel tudeg financiranja / debt ratio	0,561	0,512	0,454	0,398	0,34	0,286	0,235	0,185	0,137	0,09	0,044	-0,001
s6) Reprodukcijska sposobnost / reproductive capability	0,209	0,193	0,174	0,171	0,162	0,158	0,155	0,151	0,148	0,146	0,141	0,139

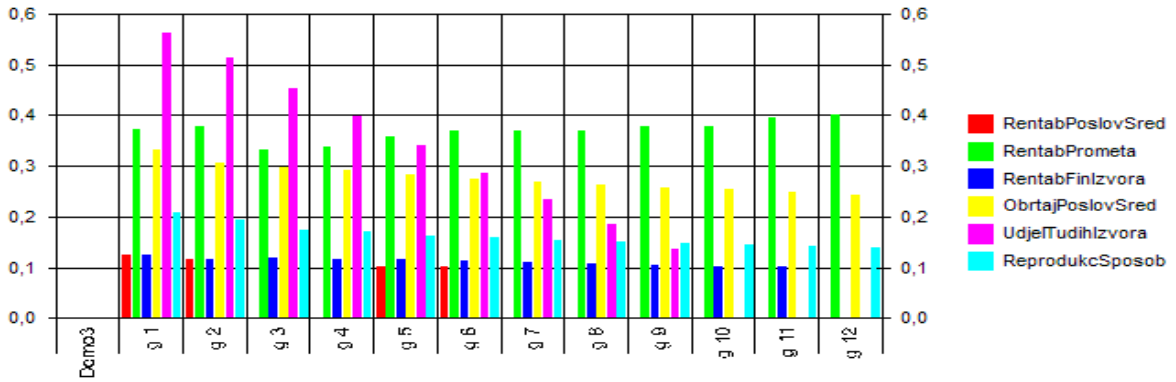

Figure 3. Static project rating, [20]
Slika 3. Statička ocjena projekta, [20]

Dinamička ocjena projekta- metoda razdoblja povrata investicije. Kao što se vidi iz Tablice 6, projekt počinje pozitivno poslovati između 4. i 5. godine aktivizacijskog razdoblja. To bi značilo da se ulaganja povrate otprilike na polovici životnog vijeka. Treba napomenuti da je početni vijek zapravo 30. god. pa se povrat ulaganja očekuje između 15. i 16. god. projekta.
Temeljna prednost te metode je u tome da ona daje značajan naglasak na brz povrat uloženog kapitala, te tako pridonosi povećanoj likvidnosti projekta. Logika ove metode lako je razumljiva, te zbog toga njena primjena ne zahtjeva prethodna stručna znanja.
Metoda razdoblja povrata investicija ima nekoliko nedostataka. Pretjerani naglasak na likvidnost ne mora biti jedini cilj razvojne strategije, jer se ponekad naglašena likvidnost može žrtvovati radi postizanja veće rentabilnosti

Table 6. Dynamic project rating, [20]

Tablica 6. Dinamička ocjene projekta – metoda razdoblja povrata investicije, [20]

godina / year ->Demo3	0	1	2	3	4	5	6	7	8	9	10	11	12
Godišnja investicija / annual investment	888,1	0	0,2	0	0,1	0,1	1,8	1	1,2	0,7	1,1	4,4	0,6
Kumulativna investicija / cummulative investment	888,1	888,1	888,4	888,4	887,1	872,8	874,7	875,8	877	877,8	878,9	883,4	884,0
Godišnji ak.prenos / annual accm.inflows	0	166,5	158,6	172,2	166,4	162,1	162,6	162,6	161,9	162,9	162,4	160,2	323,6
Kumulativni prenos/ cummul.accm.inflows	0	166,5	325,4	498,6	665	824,2	986,8	1149,5	1311,5	1474	1636,5	1796,7	2020,3
NEPOVRAĆENA INVEST./UNRETURNED INVE	-888,2	-888,4	-241,1	-173,8	-6,1	151,3	312,1	473,8	634,4	796,2	957,8	1113,3	1336,6

3. Zaključak

Projekt MHE Peruća počinje poslovati pozitivno negdje između 4 i 5. godine aktivizacijskog razdoblja. Znači, povrat ostvaruje negdje na pola životnog vijeka tj. za 16 godina.
Također, izgradnjom MHE Peruća oslobađa se zatvarač temeljnog ispusta od nenamjenskog korištenja za često ispuštanje malih protoka vode biološkog minimuma, što će rezultirati dodatnim koristima u smanjenju troškova održavanja i produljenju životnog vijeka, kao i pozitivni ekološki efekt na floru u faunu nizvodno od elektrane. Takvi parametri u analizi nisu ekonomski kvantificirani budući da ih je vrlo teško procijeniti, ali se može zaključiti kako doprinose pozitivnom rezultatu ukupne analize.
Na temelju svih korištenih metoda slijedi da je projekt ekonomski isplativ. Stoga je ovaj projekt preporučljiv za realizaciju jer se radi o projektu koji spada u red učinkovitih projekata relativno niske razine rizika. U toku životnog vijeka projekt pokazuje dobre performanse s aspekta likvidnosti, te učinkovitost s motrišta vlasnika osiguravajući povrat viši od minimalno traženog.
Iz svega rečenog se može zaključiti da je ovo područje u kojem je svijetla budućnost jer potrebe za električnom energijom iz obnovljivih izvora svakodnevno rastu, a uz državne poticaje je moguće krenuti u realizaciju. Zna se da su početna ulaganja jako velika, veća nego kod klasičnih načina proizvodnje električne energije, ali ovakvi projekti su dugoročni i samo je pitanje trenutka kada će se isplatiti. Naravno, očekuje se i daljnja potpora i inicijativa države jer, kako je već i prikazano, u Hrvatskoj ima još veliki broj lokacija koje se mogu iskoristiti za izgradnju malih hidroelektrana. Mogu se istaknuti i prednosti kao što je njihova ekološka prihvatljivost, pa ta da njihovom proizvodnjom električne energije nema emisije ugljičnog-dioksida u

okoliš što je izrazito važno, smanjuje se potrošnja fosilnih goriva, sigurnija i pouzdanija opskrba električnom energijom, stupanj djelovanja do 90%, mali pogonski troškovi, radni vijek je vrlo dug, praktično neograničen.
Sve navedeno govori da su MHE budućnost u proizvodnji energije iz obnovljivih izvora.

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Mediteranski temperament povremeno je dobro malo ohladiti.

Vrući dalmatinski temperament zaslužuje da ga se stalno drži na idealnoj temperaturi, a to je lako uz zemni plin. Hlađenje i grijanje vašeg doma ili ureda postaje jednostavno, ugodno i dostupno, a temperatura uvijek idealna neovisno o godišnjem dobu. Odaberite zemni plin i učinit ćete veliku uslugu sebi, svom kućnom budžetu i okolišu.
Kontaktirajte nas i rado ćemo vam dati detaljne informacije o instaliranju zemnog plina u vaš dom.

PRIKLJUČITE SE!

Saznajte više o plinofikaciji Dalmacije na:
www.evn.hr, info@evn.hr ili na besplatnom info telefonu 0800 820 820.

ZEMNI PLIN USKORO U VAŠEM DOMU

Za udobniji život.

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