IMK-14 – Istraživanje i razvoj u teškoj mašinogradnji 24(2018)2, SR35-41
UDC 621 ISSN 0354-6829

Integrisan proces proizvodnje abrazivnih reznih elemenata bagera u rudarskoj industriji

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U radu je prikazan integrisan proces proizvodnje reznih elemenata bagera u rudarskoj industriji baziran na primeni savremenih softverskih sistema za optimizaciju i upravljanje parametrima procesa livenja. Koncept obuhvata virtuelnu proizvodnju, praktičnu realizaciju uspostavljenog tehnološkog procesa i konačnu proveru kvaliteta odlivaka tj. reznih elemenata bagera. Primenom prikazane metodologije proizvodnje skraćuje se vreme razvoja novog proizvoda i njegove proizvodnje u odnosu na tradicionalne metode testiranja prototipova.

Ključne reči: Integrisana proizvodnja, Rezni elementi, Softverski sistemi, Optimizacija

1. UVOD

Abrazivno habanje dovodi do preranog otkazivanja mnogih komponenti mehanizacije u rudarstvu uz značajne ekonomske troškove. Bageri kontinualnog dejstva rade pri veoma složenim tehnološkim procesima, pa izbor čelika kao materijala od koga se rade zubi bagera treba da bude uz primenu kriterijuma relativno dobre žilavosti i dovoljne tvrdoće kako bi izdržali dinamička opterećenja i izraženo abrazivno habanje. U takvim slučajevima livenje se može smatrati neprevaziđenim tehnološkim procesom u tehnologiji izrade reznih zuba bagera. Kako su u tehnologiji livenja osobine završnog proizvoda u velikoj meri zavisne od prirode procesa očvršćavanja, to su i faktori koji utiču na transformaciju tečne faze u čvrstu od velikog praktičnog značaja. Najizraženiji uticaji očvršćavanja na osobine i kvalitet proizvoda su kada je livenje završna faza prerade, što je slučaj kod reznih zuba. Razumevanje toka očvršćavanja podrazumeva poznavanje metalnog rastopa, toka materije pri hlađenju u području likvidus-solidus linije, kristalizacijske uslove i ravnotežne dijagrame stanja. Međutim, ovo nije dovoljno, zato je u istraživačkim poduhvatima procesa livenja česta primena savremenih *CAD/CAM* softverskih sistema. Njihov značaj ogleda se u efikasnom dizajnu elemenata sistema livenja i simulaciji samog procesa livenja koja donosi krucijalne zaključke za proizvodni proces, o kvalitetu procesa i proizvoda. *Nimbulkar* i *Dalu* (2016) predstavljaju primenu softvera *AutoCAST-X1* za simulaciju procesa livenja. Naime autori ističu značaj dizajna ulivnog sistema i sistema hranjenja za ispravnost odlivka kroz brojne simulacije u pomenutom softveru [1]. *Jie* i njegovi koautori (2014) koriste softverski paket *ProCAST* u unapređenju livenja legure aluminijuma, i donese zaključak da povećanje temperature liva i brzine livenja rešavaju problem poroznosti [2]. *Dabade* sa svojim saradnicima (2013) koristi softver za simulaciju procesa livenja *MAGMASoft*, za analizu različitih nedostataka u procesu livenja, detektujući njihov uzrok kroz simulacije dimenziono i poziciono različitih varijanti sistema livenja i hranjenja [3].

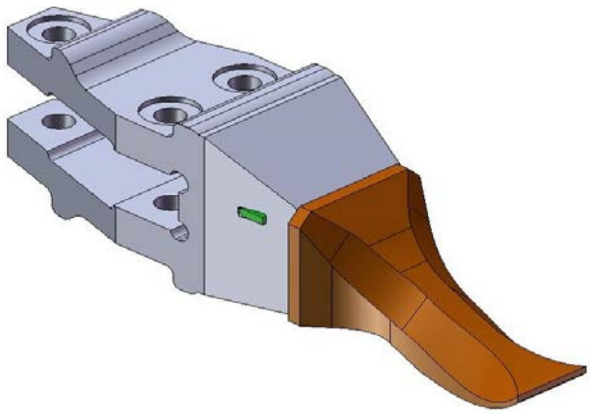
U ovom radu prezentovana je prednost primene softverskog paketa *MAGMASoft* za vizualizaciju i optimizaciju uslova očvršćavanja u cilju dobijanja zahtevane mikrostukture, makro i mikro poroznosti odlivaka koji imaju bitan uticaj na dinamičku izdržljivost i otpornost na abrazivno habanje, kao i metodologija završne ocene kvaliteta materijala reznog elementa.

2. KONCEPCIJA REZNOG ZUBA

Ekonomičnost je važan tehno-ekonomski pokazatelj u procesu proizvodnje uglja. Značajan udeo u troškovima kopanja uglja imaju rezni elementi. Analizom procesa kopanja, evidentirana je maksimalna pohabanost reznog dela do 30% ukupne mase zuba (slika 1).

Slika 1: Pohaban rezni zub

Ekonomski opravdano rešenje za ove uslove kopanja je dvodelni zub, koncepcije prikazane na slici 2, čiji se rezni deo menja nakon pohabanosti, a vezni deo ima višestruku upotrebu.



Slika 2: Koncepcija dvodelnog zuba

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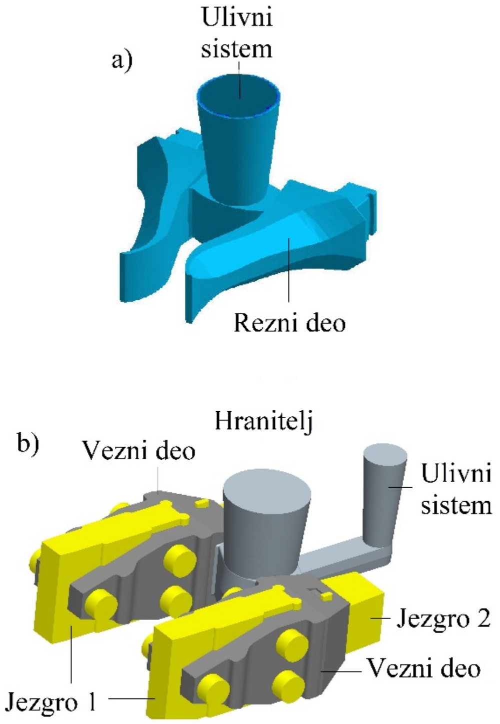
Izborom materijala reznog dela zuba i podešavanjem njegovih tribo-mehaničkih karakteristika procesom livenja i naknadnom termičkom obradom može se uticati na njegove radne karakteristike (otpornost na habanje, žilavost, tvrdoća, dinamička čvrstoća i drugo) prilagođene uslovima radne sredine, čime se povećava efektivno vreme kopanja zuba. Na taj način se značajno smanjuju sredstva uložena u nabavku zuba koji se veznim elementima vezuju za vedricu bagera koja reznim vrhovima izvodi proces kopanja (slika 3).

Slika 3: Bager vedričar sa reznim zubima

3. VIRTUELNA PROIZVODNJA

U ovom slučaju pod virtuelnom proizvodnjom podrazumeva se simulacija procesa livenja reznih zuba primenom savremenih softverskih sistema. U konkretnom primeru korišćen je kompjuterski alat *MAGMASoft* [3] koji omogućava simuliranje procesa livenja i očvršćavanja odlivka. To je vrlo moćan i pouzdan simulacioni softver koji se koristi pri istraživanju parametara poboljšanja i optimizacije procesa livenja. Omogućuje brzo i efikasno testiranje niza mogućnosti i varijanti unutar granica procesa livenja i odabir optimalne kombinacije tehnoloških parametara. Potencijalni problemi se lako otkrivaju i odstranjuju već u fazi projektovanja oblika odlivka, što projektantu/tehnologu omogućava optimizaciju procesa livenja. Rezultati simulacije prikazuju se u 3*D* grafičkom okruženju, gde se rentgenskim pogledom u kalup vidi tok punjenja kalupne šupljine, brzina punjenja kalupa kao i temperaturne oblasti. Presecima kroz odlivak dobija se front očvršćavanja i moguća mesta poroznosti usled očvršćavanja metala. Za simulaciju procesa livenja primenom *MAGMASoft*-a, potrebno je uraditi 3*D CAD* model svih elemenata kalupne šupljine koju popunjava tečni metal, odnosno ulivni sistem (ulivna čaša, sprovodnik, kolektor, razvodnik i ulivnici), odlivak sa jezgrima, hranitelji i odvodnici gasova i dr. Ispravno konstruisan ulivni sistem treba da osigura da se tečni metal uliva u kalupnu šupljinu brzo i bez turbulencija. Turbulentni tok može izazvati ulazak gasova, vazduha i šljake u kalup što je glavni uzročnik nastanka defektnog odlivka. Takođe treba da onemogući unošenje nemetalnih uključaka u kalup, omogući istiskivanje gasova iz kalupne šupljine i osigura dovoljno brzo punjenje kalupne šupljine. Usled zapreminskog skupljanja tečnog metala pri hlađenju, dolazi do smanjenja zapremine odlivka. Ovaj efekat uzrokuje stvaranje unutrašnjih šupljina i mikroporoznosti na mestima koja zadnja očvršćavaju. U takvim slučajevima projektuju se hranitelji sa osnovnom funkcijom da obezbede dovoljno tečnog metala za najmasivnije sekcije odlivka što omogućuje ispravno očvršćavanje. Za optimalno hlađenje potrebno je obezbediti priliv tečnog metala na bazi "usmerenog očvršćavanja", od tanjih ka masivnijim delovima odlivka. Hranitelji se postavljaju na vrh ili sa strane odlivka, tako da poslednji deo tečnog metala treba da očvrsne u samim hraniteljima. Mesto hranitelja uglavnom je limitirano oblikom odlivka (njegov najmasivniji deo). Odvodnici gasova sprečavaju stvaranje vazdušnih džepova u kalupnoj šupljini i postavljaju se na odgovarajućim mestima radi odzračivanja istih. Obavezno se postavljaju na najvišim mestima odlivka. Mesta pojave vazdušnih džepova definišu se na osnovu analize strujanja tečnog metala kroz kalupnu šupljinu. Pored prethodno navedenih 3*D* geometrijskih modela (*STL* standardnog grafičkog formata) za simulaciju su potrebni i parametri tehnologije livenja (temperatura livenja, materijal kalupa, vrsta premaza, materijal odlivka, vrsta livačkog lonca i sl.). Nakon procesiranja livenja daju se preporuke i zaključci. Na osnovu njih, po potrebi izvode se nove simulacije sa promenjenim parametrima. Takođe pri pregledu rezultata simulacije rade se slike kritičnih i zanimljivih detalja, potrebnih korisniku rezultata simulacije. Za koncepcijsko rešenje dva odlivka u jednom kalupu na slici 4 dat je *CAD* model sistema odlivak, ulivni sistem i hranitelj za simulaciju procesa livenja reznog dela (slika 4a) i veznog dela (slika 4b).



Slika 4: CAD elementi dvodelnog zuba: a) rezni deo, b) vezni deo

3.1. Rezultati simulacije

Kao posledica periodičnog ulaska zuba u zahvat kopanja, vezni i rezni elementi zuba izloženi su značajnim dinamičkim opterećenjima. U navedenim uslovima eksploatacije kako kod veznih tako i reznih elemenata mora biti eliminisana mogućnost pojave unutrašnjih šupljina (lunkera) i mikro poroznosti koji su veoma osetljivi na koncentraciju napona i često su uzročnik loma. U ovakvim slučajevima veoma je značajno pre izrade alata potrebnih za oblikovanje kalupa izvršiti simulaciju procesa livenja odnosno izvršiti virtuelni proces livenja na osnovu koga se može proveriti širok spektar tehničko-tehnoloških karakteristika odlivka, [4]. U nizu mogućih kriterijuma za ocenu kvaliteta odlivka, u ovom slučaju daju se rezultati simulacije po kriterijumima "*Solidification*", "*Fstime*", "*Hotspot*" i "*Porosity*" na osnovu kojih se mogu doneti zaključci o eventualnim unutrašnjim greškama u odlivku. Tehnološki parametri potrebni za simulaciju su:

Materijal odlivka: vezni deo- čelik ST50-2 (DIN), rezni deo - čelik X120Mn12 (DIN),

Materijal kalupa: vezni deo - CO_2 pesak, rezni deo - CO_2 pesak.

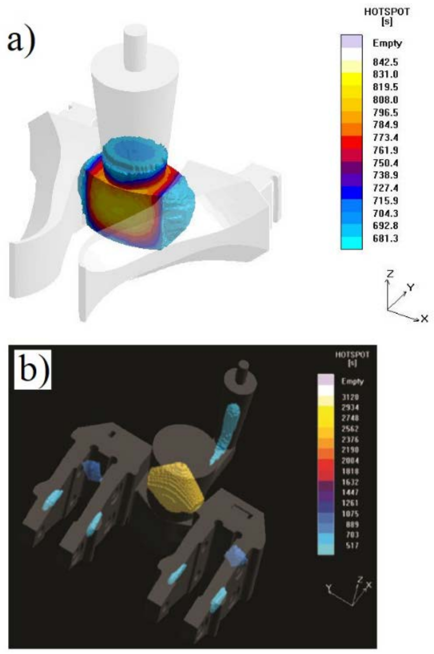
Materijal jezgra: vezni deo - CO_2 pesak.

Temperatura livenja: vezni deo - 1520 °C, rezni deo - (1560-1580) °C.

Vrsta livenja: vezni deo - nagibni lonac, rezni deo-nagibni lonac.

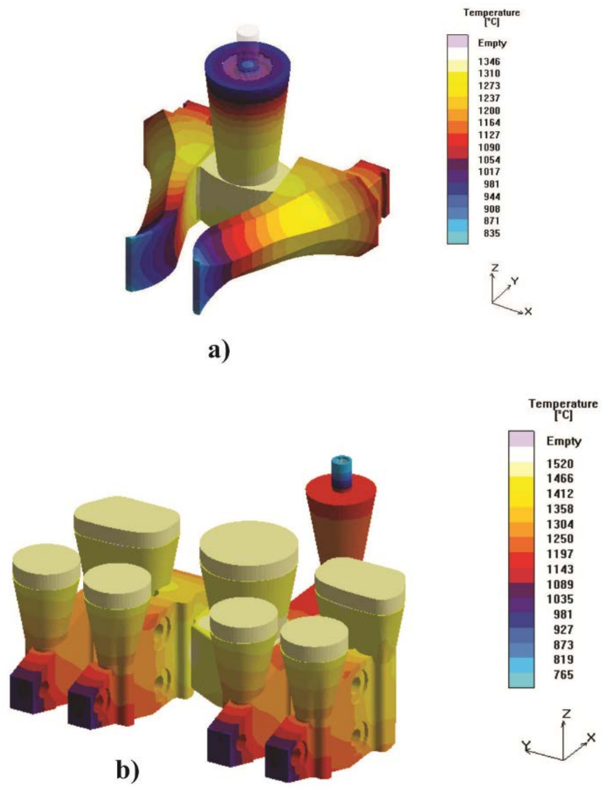
Način livenja: vezni deo - gravitacijsko livenje, rezni deo-gravitacijsko livenje.

Nakon prve simulacije kriterijum "*Hotspot*" pokazao je mesta u odlivku koja poslednja očvršćavaju. Za slučaj reznog dela slika 5a poslednja očvršćava masa liva u ulivniku što obezbeđuje dobro hranjenje odlivka. Međutim pri livenju veznog dela slika 5b vidi se da pored mesta u ulivniku koji poslednji očvršćava postoje mesta koja ne prate usmereno očvršćavanje (na ušicama veznog dela) tako da su ta mesta uzročnici grešaka u odlivku (šupljine). Ova pojava je nametnula izradu novog CAD modela sa dodatnim hraniteljima koji treba da otklone prikazane nedostatke pri ponovljenoj simulaciju procesa livenja.



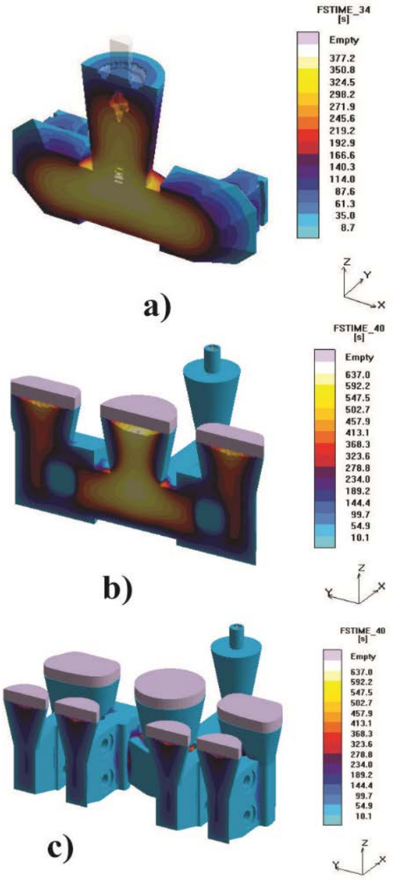
Slika 5: Mesta koja poslednja očvršćavaju u odlivku: a) rezni deo zuba b) vezni deo

Kriterijum "*Solidification*" daje mogućnost prikazivanja faza očvršćavanja sa izotermama temperaturnih polja očvršćavanja, temperaturnih gradijenata, tečnog testastog ili čvrstog stanja. Na slici 6 dati su rezultati očvršćavanja nakon popune kalupa. Sa slike se vidi da odlivak očvršćava od tanjeg ka masovnijem delu, a ulivnik poslednji očvršćava čime je obezbeđeno potrebno hranjenje odlivaka.



Slika 6: Očvršćavanje kalupa nakon procesa livenja: a) rezni deo, b) vezni deo zuba

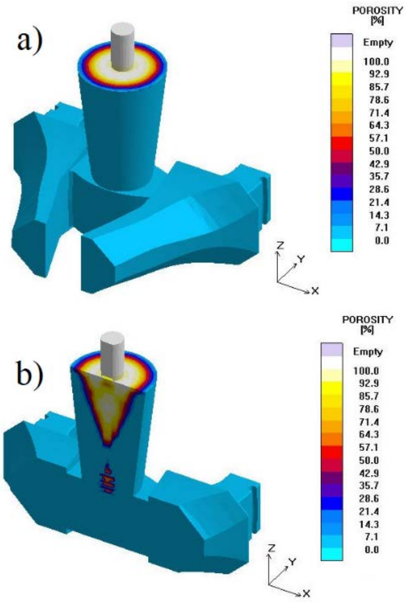
Kriterijum "*Fstime*" prikazuje vreme do kog je moguće makroskopsko hranjenje odlivka pri određenom procentu očvrslog metala (Slika 7).



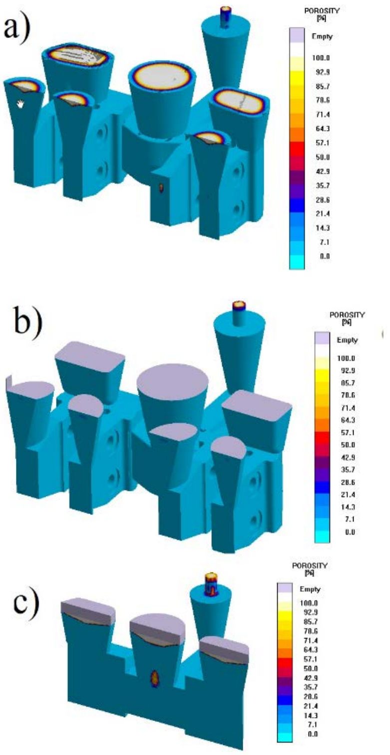
Slika 7: Vreme makroskopskog hranjenja odlivka: a) rezni deo, b) vezni deo zuba

Za slučaj reznog dela pri procentu očvrslog metala 34%, na slici 7a dat je izgled kritičnog preseka kroz hranitelj i ulivnik. Na slici 7b i 7c dat je izgled kritičnih preseka kroz hranitelje 1 i 2, a na slici 7c kroz hranitelje 3. Sa navedenih preseka se vidi da je obezbeđeno ispravno hranjenje odlivaka.

Kriterijum "*Porosity*" omogućuje analizu poroznosti i šupljina u odlivku i dr. Na slici 8 za analizu poroznosti reznog dela dat je izgled preseka kroz vrh i kroz hranitelj i ulivnik. Sa slike se vidi da odlivak nema unutrašnjih grešaka što se moglo zaključiti na osnovu kriterijuma "*Hotspot*" pri prvoj simulaciji.



Slika 8: Poroznost reznog dela: a) presek kroz vrh, b) presek kroz hranitelj

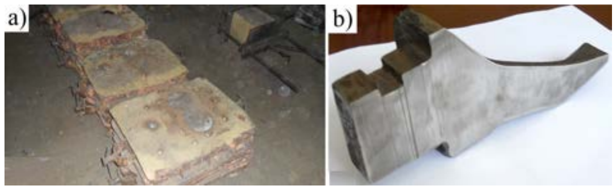


Slika 9: Poroznost veznog dela: a) presek kroz hranitelje 3 (izostavljen jedan hranitelj), b) presek kroz hranitelje 3 (postavljeni svi hranitelji i c) presek kroz hranitelje 1 i 2 i ulivnik

Za vezni deo, na slici 9a, data je simulacija poroznosti na mestu hranitelja 3 za slučaj izostavljanja hranitelja na jednoj ušici. Na tom mestu evidentna je greška u odlivku. Na slici 7b i 7c dati su izgledi preseka odlivaka kroz kompletne hranitelje 3 i kroz hranitelje 1 i 2. Kao što se sa slika vidi, unutrašnje greške su eliminisane.

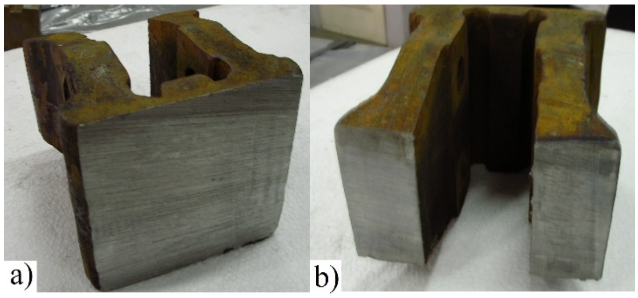
4. STVARNI PROCES LIVENJA

Za rezni deo, prema *CAD* modelu datom na slici 4a urađen je alat za izradu CO_2 kalupa, [5]. Na osnovu tehnoloških parametara datih u toku procesa simulacije u kalupima (slika 10a) odliven je rezni deo, čiji je uzdužni presek prikazan na slici 10b, i kao što se vidi, odlivak nema unutrašnjih grešaka.



Slika 10: Livenje reznog dela: a) kalupi; b) presek reznog dela

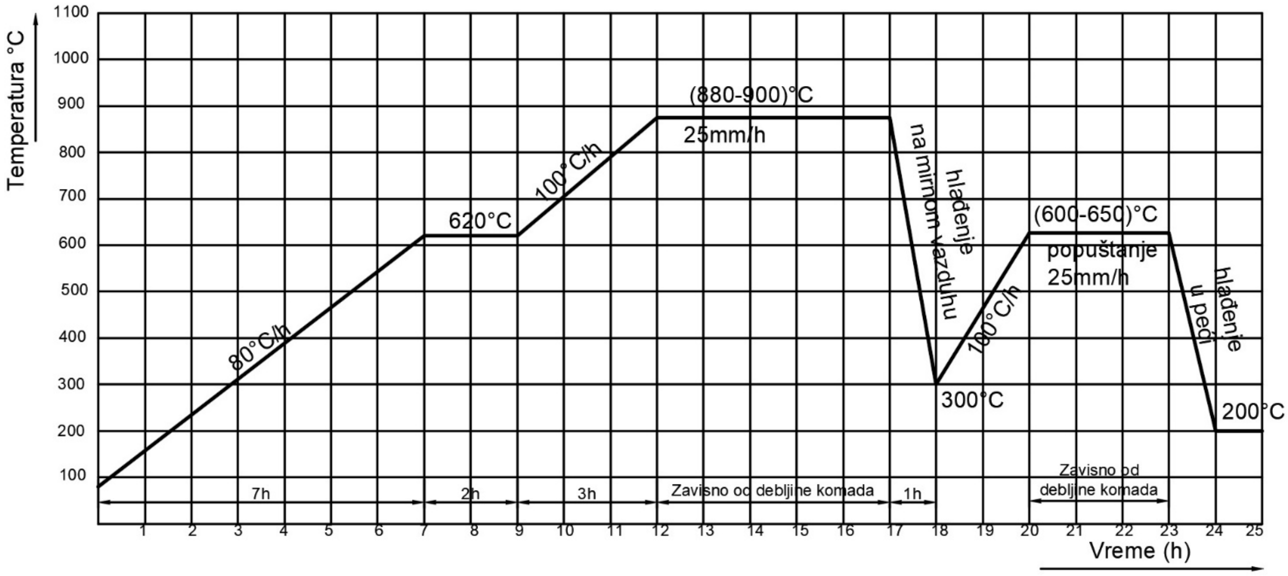
Za vezni deo prema *CAD* modelu u ponovljenoj simulaciji, urađen je CO_2 kalup i u njemu prema prethodno datim tehnološkim parametrima odliven vezni deo. Na slici 11a i 11b dati su preseci veznog dela kroz kritična mesta radi otkrivanja eventualnih grešaka. Kao što se vidi, na ušicama nema unutrašnjih šupljina i tragova poroznosti.



Slika 11: Izgled odlivenog veznog dela: a, b karakteristični preseci

5. VERIFIKACIJA KVALITETA ODLIVKA

Vezni deo dvodelnog zuba radi se livenjem od čelika ST50-2 (DIN) hemijskog sastava C=0.3-0.35%, Si= 0.3-0.6%, $P_{max} \leq 0.05$, $S_{max} \leq 0.05$. Pri livenju od svake šarže ostavlja se uzorak za izradu pločice kojom se verifikuje potreban hemijski sastav odlivka i uzorak od koga se radi standardna epruveta za verifikaciju mehaničkih karakteristika materijala odlivka. Nakon livenja radi otklanjanja unutrašnjih naprezanja u odlivku, odlivci sa uzorcima za izradu epruvete podvrgavaju se procesu normalizacije [6, 7], prema dijagramu na slici 12. Mehaničke karakteristike materijala odlivka posle tehnološkog procesa normalizacije su: zatezna čvrstoća: Rm=600 N/mm^2, izduženje (l=5d_0) %: A=20. Izbor materijala reznog dela zuba zavisi od uslova radne sredine. Za radnu sredinu koja je uglavnom peskovitog ili šljunkovitog karaktera - proces otkopavanja (izrazito abrazivna sredina) kao materijal za izradu reznih delova zuba koristi se tvrdi liv [8], hemijskog sastava: C=2.3–2.6%, Si=0.3–0.5%, Mn=0.5–0.8%, $P_{max} \leq 0.02\%$, $S_{max} \leq 0.02\%$, Cr=13–16%, Ni_{max}=0.6%, Mo= 0.15–0.25%, Cu= 0.4–0.6%, ostali hemijski elementi su u tragovima. Za tvrde livove navedenog hemijskog sastava, dijagram termičke obrade dat je na slici 13. Za identifikaciju kvaliteta materijala reznih elemenata od tvrdog liva, uzorkuje se pločica odgovarajućih dimenzija za ispitivanje hemijskog sastava, tvrdoće i mikrostrukture materijala odlivka. Tvrdoća nakon termičke obrade je 50-52 *HRC*, a mikrostruktura nakon termičke obrade data je na slici 16a. Ako je radna sredina stenovitog karaktera, za livenje reznih delova zuba koristi se čelik X120Mn12 (DIN), odnosno *Hatfield*-ov čelik hemijskog sastava: C=1.1–1.25, Si=0.30–0.50, Mn=11.5–13, Cr_{max}=0.20, $S_{max} \leq 0.02$, $P_{max} \leq 0.035$. U procesu eksploatacije pri kontaktu sa stenskim materijalom dolazi do otvrdnjavanja reznih delova, čime se značajno poboljšavaju radne karakteristike zuba i otežava eventualna mašinska obrada. Pri livenju navedenih elemenata ostavlja se uzorak u obliku pločice odgovarajućih dimenzija za verifikaciju hemijskog sastava, tvrdoće i mikrostrukture materijala odlivka. Odlivci od ovog materijala sa uzorcima za proveru, podvrgavaju se termičkoj obradi gašenja, [9, 10] prema dijagramu datom na slici 14. Za navedeni materijal, mehaničke karakteristike nakon termičke obrade gašenja (zatezna čvrstoća, izduženje i energija udara) se ne daju pošto se materijal u procesu eksploatacije značajno ojačava, tvrdoća je *HB*=210-220, a izgled mikrostrukture materijala je prema slici 16b. Nakon procesa otkrivanja površine, sledi proces kopanja uglja sa reznim elementima livenim od Cr-Ni-Mo (*Hromosil*) čelika, [11,12] hemijskog sastava: C= 0.24–0.30%, Si= 1.4–1.7%, Mn= 1–1.4%, $P_{max} \leq 0.025$, $S_{max} \leq 0.025$, Cr=1.25–1.5%, Ni=0.4–0.6, Mo=0.17–0.22. Kao i u prethodnim slučajevima pri livenju reznih elemenata ostavljaju se isti uzorci za proveru hemijskog sastava odlivka, mehaničkih karakteristika, tvrdoće i mikrostrukture nakon termičke obrade. Za date radne uslove i vrstu materijala predviđena je termička obrada poboljšanje, prema dijagramu na slici 15.



Slika 12: Dijagram procesa normalizacije odlivaka od čelika ST50-2 (DIN)

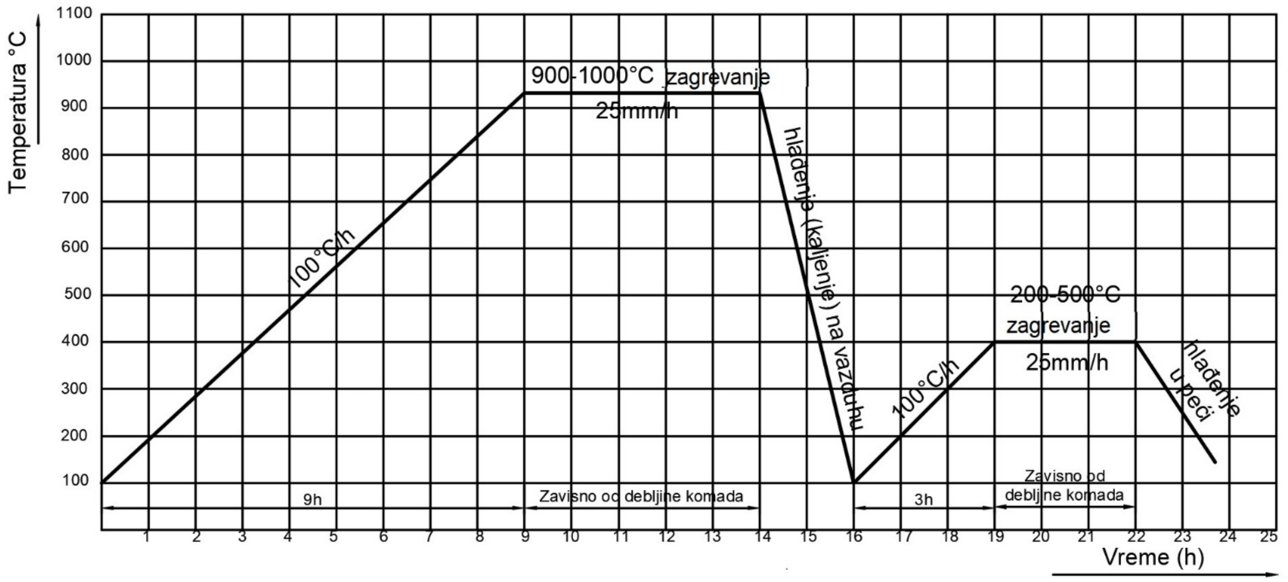


Figure 13: Dijagram termičke obrade poboljšanje za odlivke od tvrdog liva

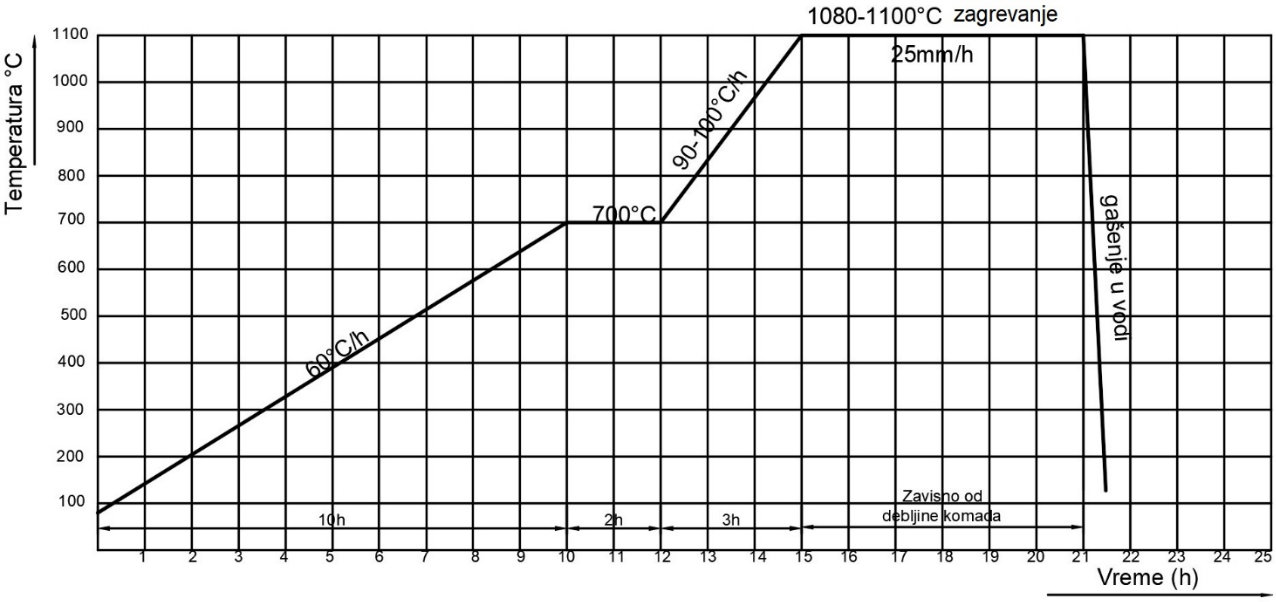


Figure 14: Dijagram termičke obrade gašenje za odlivke od čelika X120Mn12

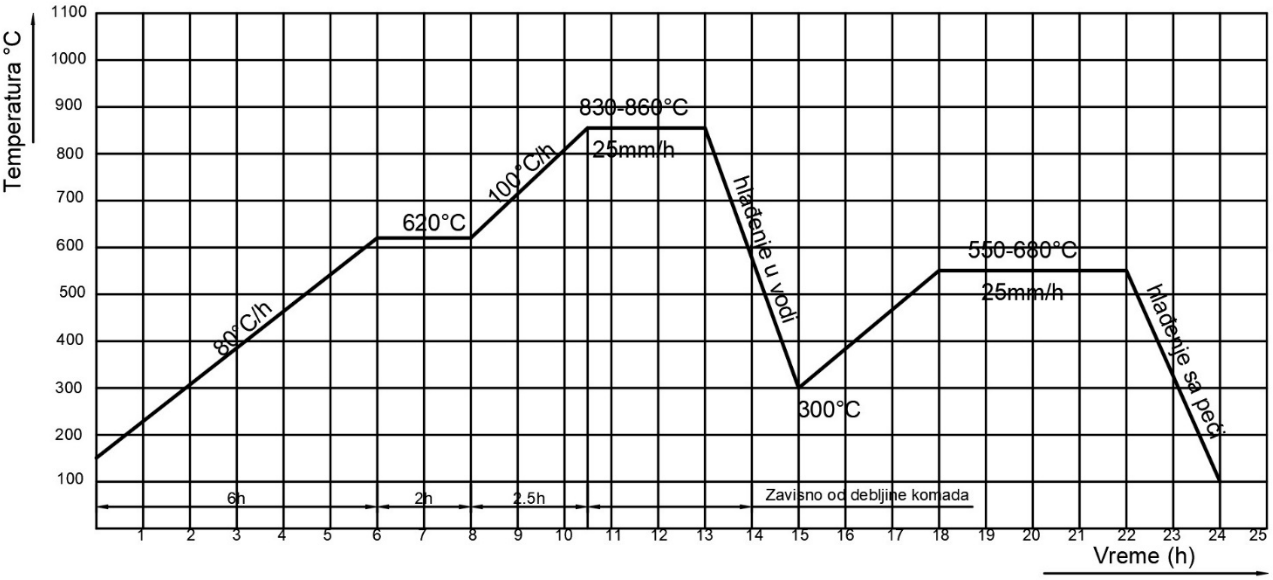
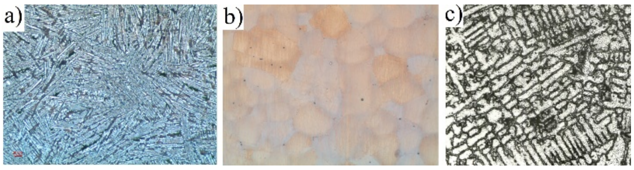


Figure 15: Dijagram termičke obrade poboljšanje za odlivke od čelika Cr-Ni-Mo

Nakon termičke obrade mehaničke karakteristike materijala reznih elemenata su: zatezna čvrstoća: *Rm*=1600 N/mm^2, izduženje (l=5d_0) %: *A*=20, energija udara: *Kv*=25 J, a tvrdoća *HRC*=38-42. Mikrostruktura materijala data je na slici 16c.



Slika 16: Mikrostrukture materijala reznih elemenata zuba: a) tvrdi liv, b) Hatfield-ov čelik c) Hromosil

Sa slike 16b se vidi da kod svih uzoraka od Mn čelika je postignuta austenitna poligonalna i ujednačena struktura po preseku, očekivana za *Hatfield*-ov čelik, koja u eksploataciji pod dejstvom naprezanja treba da se transformiše u martenzit koji čeliku obezbeđuje tvrdoću i otpornost na habanje. Karbidi su sitni i ravnomerno raspoređeni tako da se nigde ne zapaža njihova mreža. Zanemarljivo je i prisustvo nemetalnih uključaka.

Kada je u pitanju tvrdi liv, sa slike 16a se vidi dendritna struktura sa razvijenom inerdendritnom mrežom. Struktura je naizmenično usmerena, takoreći ukrštena što povećava otpornost na habanje i otpornost na udarna opterećenja.

Za čelik *Hromosil* sa slike 16c se vidi martenzitna struktura srednje krupnoće uz prisustvo karbida u relativno manjim količinama. Ovakva mikrostruktura obezbeđuje tvrdoću odlivka i do 45 *HRC* i dobru žilavost preseka što je veoma značajno za ugaljske zube.

6. ZAKLJUČAK

Rezni elementi bagera su odgovorne komponente rudarske mehanizacije i sa aspekta njihove izrade, livenje se može smatrati neprevaziđenim tehnološkim procesom. Kod njih je potrebno ispravno definisati reznu geometriju, materijal i tehnologiju izrade. Rezna geometrija i materijal definiše se tribološki ispravnom konstrukcijom. Kako rezni elementi rade u dinamički i abrazivno veoma teškim uslovima, to zahteva da ne smeju imati unutrašnjih lunkera, makro i mikro poroznosti koji doprinose da odlivak bude veoma osetljiv na dinamička naprezanja koja u tim slučajevima veoma često dovode do loma. Takođe, pored izbora odgovarajućeg materijala za izradu reznih elemenata bagera zavisno od uslova radne sredine, na intenzitet habanja, dinamičku čvrstoću i ostale mehaničke karakteristike veliki uticaj ima mikrostruktura materijala reznih elemenata. Iz tih razloga velika pažnja se poklanja režimima termičke obrade reznih elemenata predviđenim nakon procesa livenja. Pravo rešenje u ovakvim slučajevima je proces virtuelne proizvodnje, odnosno simulacija procesa livenja i termičkih procesa kako u procesu hlađenja odlivka (vrlo često tokom hlađenja odlivka javljaju se unutrašnje pukotine i zaostali naponi) tako i simulacija procesa termičke obrade nakon livenja koji su prikazani u radu.

U poslednjoj deceniji, sa naučnog aspekta simulacija procesa livenja i predviđanje dobijenih osobina materijala doprinela je da se u livarstvu razreše dve ključne nepoznanice:

- kalup kao crna kutija, postao je transparentniji za stručnjake livnica, odnosno omogućeno im je lakše shvatanje uzroka mogućih problema pre završnog procesa livenja, i
- omogućeno je potpuno razumevanje fizičkog, metalurškog i hemijskog stanja tečnog metala.

Za mnoge livnice metala, simulacija procesa livenja postala je standardan alat za projektovanje ulivnog sistema, hranitelja, odvodnika gasova i proučavanje termičkih procesa radi dobijanja željenih karakteristika odlivka. Takođe, simulacija je postala jedan od instrumenata u sistemima obezbeđenja kvaliteta i optimizacije procesa.

ZAHVALNOST

Projekat TR35037: “Razvoj nove konstrukcije kašike bagera kontinualnog dejstva u cilju integrisanja modularnih reznih elemenata”, je finansiran i podržan od strane Ministarstva prosvete, nauke i tehnološkog razvoja Republike Srbije. Autori izražavaju zahvalnost za podršku ovom istraživanju.

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IMK-14 – Research & Development in Heavy Machinery 24(2018)2, EN37-43
UDC 621 ISSN 0354-6829

An Integrated Process for the Production of Abrasive Cutting Elements for Excavators in the Mining Industry

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The paper presents an integrated production process for excavator cutting elements in the mining industry based on modern software systems for the optimization and management of casting process parameters through simulations. The concept involves the virtual manufacture, practical implementation of the established technological process and quality control of final castings i.e. excavator cutting elements. The presented production methodology reduces the time required to develop and manufacture the new product compared to the traditional methods of prototype testing.

Keywords: Integrated production, Cutting elements, Software systems, Optimization

1. INTRODUCTION

Abrasive wear leads to premature failure of many components in mining machines, accompanied by substantial economic loss. Continuous excavators operate under highly complex conditions during the excavation process; therefore, the choice of steel to be used as material for excavator teeth should rely on criteria such as relatively good toughness and sufficient hardness to ensure resistance to severe abrasive wear under dynamic loading. To this end, casting is considered an unsurpassable process in the manufacture of excavator teeth. As properties of the final product in casting technology are largely dependent on the nature of solidification, the factors affecting the liquid to solid transformation are also of great practical importance. The properties and quality of the final product are most strongly affected by solidification in cases when casting is the final processing stage, as in cutting teeth. Understanding the course of solidification entails knowledge of molten metal, its flow during cooling through the liquidus/solidus domain, crystallization conditions and equilibrium phase diagrams. However, as this is not sufficient, research endeavours in casting often use modern *CAD*/*CAM* software systems. Their importance is evidenced by the efficient design of casting system elements and casting process simulation, which results in crucial conclusions on the quality of both the process and the product. *Nimbulkar* and *Dalu* (2016) presented the *AutoCAST-X1* software for casting simulation. The authors stressed the importance of gating/feeding system design for proper casting quality through numerous simulations performed by the software [1]. *Jie* et al. (2014) used the *ProCAST* software to improve the casting of aluminium alloys and determined that the increase in both cast temperature and casting rate solves the porosity problem [2]. *Dabade* et al. (2013) used the *MAGMASoft* casting simulation software to analyse various casting defects by detecting their causes through simulations of dimensionally and positionally different variants of the casting and the feeding systems [3].

This paper presents the advantages of the *MAGMASoft* software for the visualization and optimization of solidification conditions in obtaining the desired microstructure and macro and micro-porosity of castings, which have an important effect on dynamic fatigue strength and abrasive wear resistance. Moreover, a methodology for the final quality assessment of the cutting element material is presented.

2. CUTTING TOOTH CONCEPT

Cost-effectiveness is an important technical and economic indicator in coal production. Cutting elements account for a significant percentage of coal excavation costs. The analysis of the coal excavation process has shown that the maximum wear of the cutting portion of the tooth is up to 30% of total tooth weight (Figure 1).

Figure 1: Worn-out tooth

For given excavation conditions, an economically justifiable engineering solution is offered by the two-piece tooth conceptualized in Figure 2, with the cutting portion replaceable after wear and the holder having multiple uses.

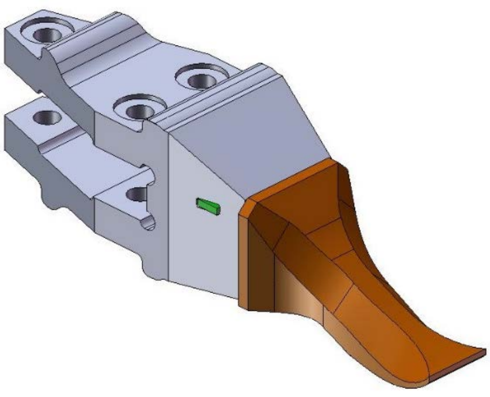

Figure 2: Two-piece tooth design

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The choice of material for the cutting portion of the tooth and adjustment of its tribo-mechanical characteristics by casting and subsequent heat treatment can affect its operating characteristics (wear resistance, toughness, hardness, dynamic strength, etc.) adapted to the working environment, thus increasing the actual excavating time of the tooth. This leads to a significant reduction in the purchase costs of teeth which are attached by the connecting components to the bucket, which performs the excavating operation by cutting tips (Figure 3).

Figure 3: Bucket chain excavator with cutting teeth

3. VIRTUAL MANUFACTURING

In this case, virtual manufacturing involves tooth casting simulation using modern software systems. In this particular example, the *MAGMASoft* computer tool [3] which enables casting simulation and solidification of castings was used. It is a powerful reliable simulation software which can help improve and optimize casting parameters. It provides rapid efficient testing of a range of casting design options and variants and ensures an optimal combination of process parameters. Potential problems are easily detected and eliminated as early as the stage of casting shape design, which allows the designer/engineer to optimize the casting process. Simulation results are presented in a 3*D* graphical environment, with *X-ray* imaging of the mold showing the course of mold cavity filling, mold filling rate and temperature range. Cross-sections through the casting provide the location of the solidification front and possible porosity areas due to metal solidification. The simulation of the casting process using *MAGMASoft* requires 3*D CAD* modelling of all elements of the mold cavity filled with the liquid metal i.e. the gating system (pouring basin, sprue, sprue well, runner and ingates), the casting with cores, feeders, vent holes, etc. A properly designed gating system should ensure that the liquid metal flows into the mold cavity rapidly and without turbulence. Turbulent flow can cause the aspiration of gases, air and slag into the mold, which is the principle cause of defective castings. The system should also prevent non-metallic inclusions from entering the mold, allow gases to be expelled from the mold cavity and ensure sufficiently rapid filling of the mold cavity. Due to the volume shrinkage of the liquid metal during cooling, casting volume is reduced. This effect causes the formation of internal cavities and micro porosity in the last regions of the casting to solidify. In these cases, feeders should supply the liquid metal in sufficient amounts for the thickest sections of the casting, leading to proper solidification. For optimal cooling, the system should allow directional solidification by delivering the liquid metal to thicker areas of the casting. Feeders are placed on the top or at the sides of the casting so as to ensure that the last part of the liquid metal to solidify should be in the feeders. The location of feeders is mostly limited by the shape of the casting (its thickest part). Vent holes prevent the formation of air pockets in the mold cavity and are placed in proper places for their deaeration. They are necessarily placed on the uppermost areas of the casting. Air pocket regions are defined by analysing the flow of the liquid metal through the mold cavity. In addition to 3*D* geometrical models (using the standard *STL* file format), the simulation process also requires casting technology parameters (casting temperature, mold material, type of coating, casting material, type of casting ladle, etc.). Once casting is processed, recommendations and conclusions are made. Based on them, new simulations with a new set of parameters are executed, when necessary. Moreover, images of critical and interesting details which are of importance to users of simulation results are taken. The conceptual design of two castings in a single mold is supported by a *CAD* model (Figure 4) of the system comprising the casting, the gating system and the feeder for simulating the casting of the cutting portion (Figure 4a) and the holder (Figure 4b).

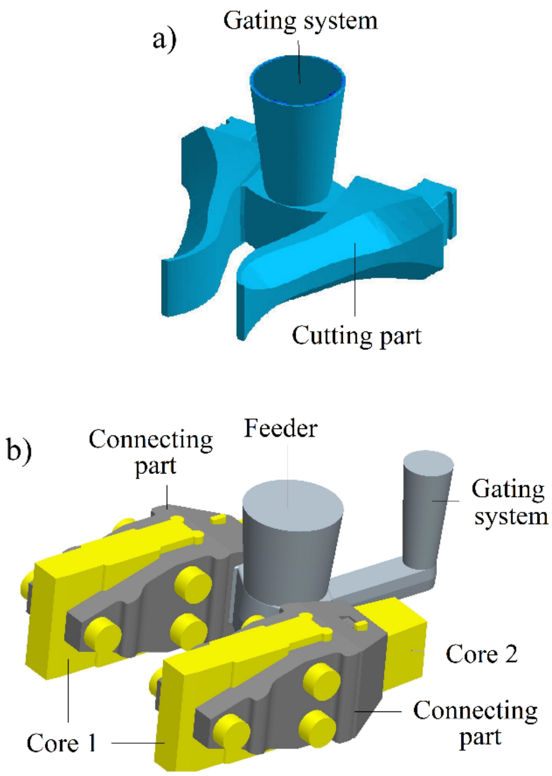

Figure 4: CAD components of the two-piece tooth: a) cutting portion, b) holder

3.1. Simulation results

Due to the periodic engagement of the teeth in the digging operation, both the cutting portion and the holder of the tooth are exposed to significant dynamic loadings. Under the given excavation conditions, in both the cutting portion and the holder, any risk of internal cavities and micro-porosity must be eliminated as they are highly susceptible to stress concentration and are a frequent cause of fracture. In these cases, prior to the design of tools to be used for mold shaping, it is necessary to simulate the casting process i.e. perform virtual casting in order to check the wide spectrum of mechanical and engineering characteristics of the casting, [4]. Among the many potential criteria for quality assessment of castings, simulation results in this case are presented for the "*Solidification*", "*Fstime*", "*Hotspot*" and "*Porosity*" criteria, based on which conclusions on possible internal defects in the casting can be made. The engineering parameters required for simulation are as follows:

Casting material: holder – steel ST50-2 (DIN), cutting portion – steel X120Mn12 (DIN).

Mold material: holder – CO_2 sand, cutting portion – CO_2 sand.

Core material: holder – CO_2 sand.

Casting temperature: holder – 1520 °C, cutting portion – (1560–1580) °C.

Type of casting: holder – tilting ladle, cutting portion – tilting ladle.

Casting method: holder – gravity casting, cutting portion – gravity casting.

Following the first simulation, the "*Hotspot*" criterion showed regions in the casting which were the last to solidify. In the cutting portion (Figure 5a), the regions in the ingates are the last to solidify, which ensures good feeding of the casting. However, the casting of the holder (Figure 5b) reveals that, next to the area in the ingate which is the last to solidify, there are regions where directional solidification does not occur (on the lifting eyes of the holder), which makes them the causal agents of defective casting (cavity). This phenomenon has brought about the design of a new *CAD* model with additional feeders supposed to eliminate the presented deficiencies during the re-simulation of the casting process.

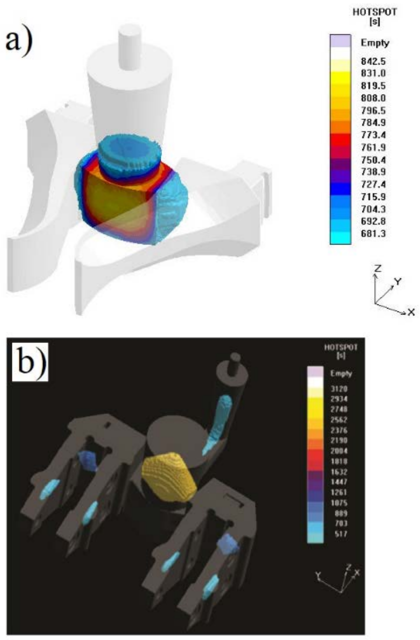

Figure 5: Regions last to solidify in the casting: a) cutting portion, b) holder of the tooth

The *"Solidification"* criterion enables the presentation of solidification stages with the isotherms of the temperature fields, temperature gradients, and liquid, doughy or solid state. Figure 6 illustrates the results of solidification after mold filling. The figure shows that the solidification of the casting progresses from thinner areas to thicker ones, with the ingate last to solidify, thus ensuring feeding of the casting.

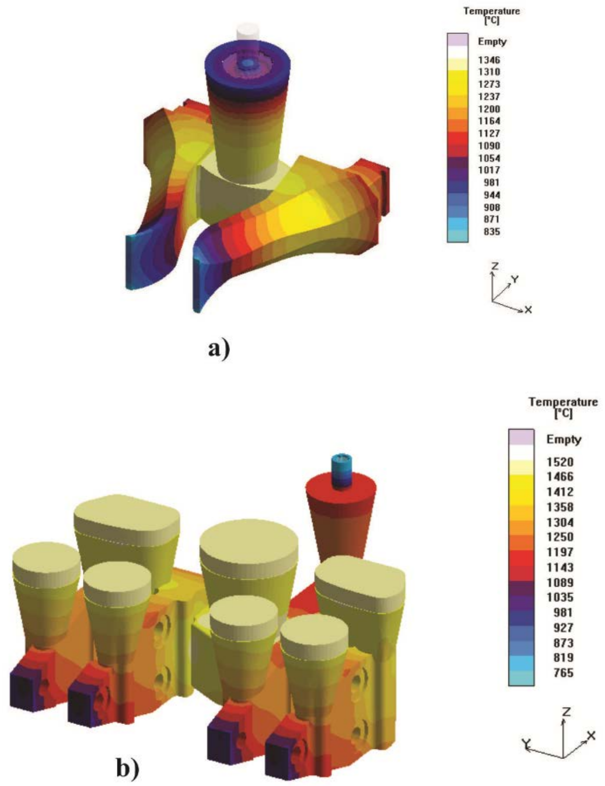

Figure 6: Solidification of the mold after casting: a) cutting portion, b) holder of the tooth

The "*Fstime*" criterion presents the time up to which it is possible to macroscopically feed the casting at a certain solidification percent (Figure 7).

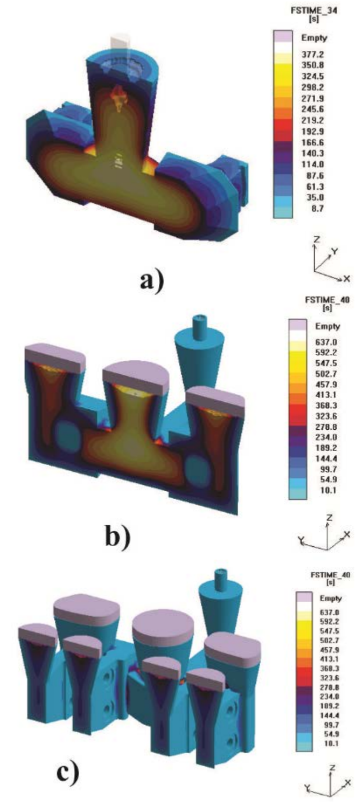

Figure 7: Macroscopic feeding time of the casting: a) cutting portion, b and c) holder

For the cutting portion, at 34% of metal solidification, the critical cross-section through the feeder and the ingate is given in Figure 7a. The critical cross-sections through feeders 1 and 2 (Figures 7b and 7c, respectively) and through feeders 3 (Figure 7c) are presented. The cross-sections show proper feeding of the castings.

The "*Porosity*" criterion enables the analysis of porosity and cavities in the casting. For the purpose of analysis of cutting portion porosity, Figure 8 presents the cross-section through the tip and through the feeder and the ingate. As shown, the casting has no internal defects, which is consistent with the conclusion drawn from using the "*Hotspot*" criterion during the first simulation.

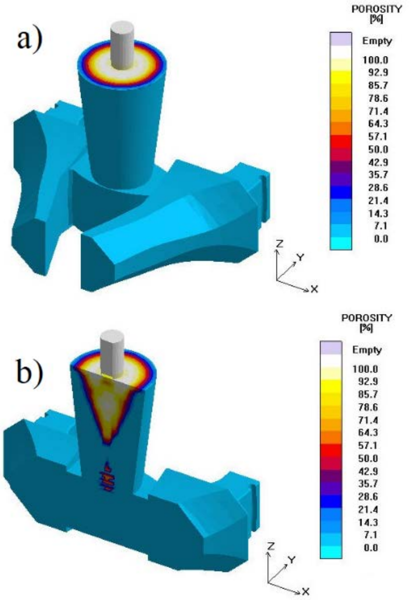

Figure 8: Porosity of the cutting portion: a) cross-section through the tip, b) cross-section through the feeder

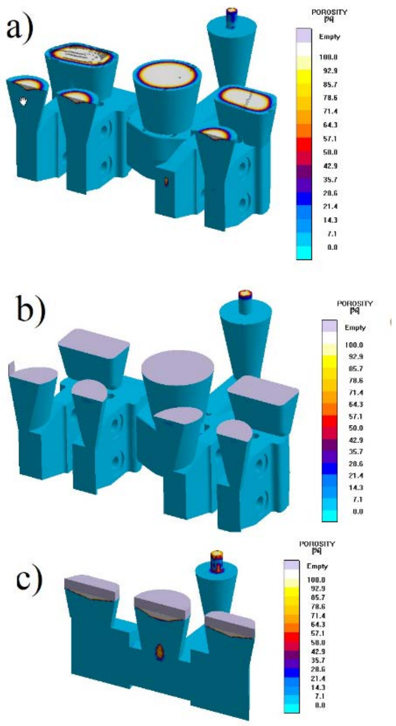

Figure 9: Porosity of the holder: a) cross-section through feeders 3 (one feeder excluded), b) cross-section through feeders 3 (all feeders set) and c) cross-section through feeders 1 and 2 and the ingate

As for the tooth holder, Figure 9a provides the simulation of porosity in the feeders 3 area in case one feeder is excluded. In this area, a defect is observed in the casting. Figures 9b give the cross-sections of the castings through complete feeders 3 and through feeders 1 and 2. As shown, internal defects are eliminated.

4. ACTUAL CASTING

To cast the cutting portion, a CO_2 molding tool was created according to the *CAD* model given in Figure 4a [5]. Based on the casting parameters provided during simulation, the cutting portion was cast in molds (Figure 10a). Its longitudinal section is presented in Figure 10b. As shown, the casting has no internal defects.

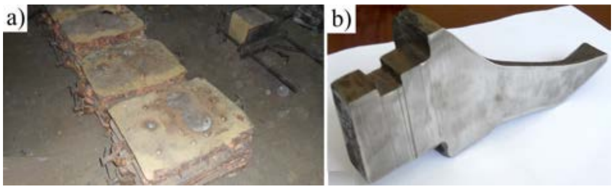

Figure 10: Casting of the cutting portion: a) molds, b) cross-section of the cutting portion

To cast the cutting portion holder, a CO_2 mold was produced according to the *CAD* model in a simulation environment. The holder was cast in the mold using predetermined casting parameters. Figures 11a and 11b present the cross-sections of the holder through critical regions for defect detection. As shown, there are no internal cavities and trace amounts of porosity on the lifting eyes.

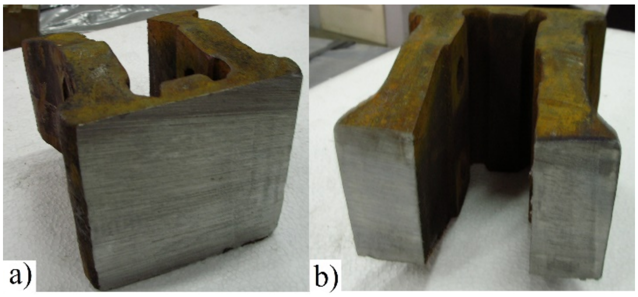

Figure 11: Cast holder: a, b characteristic cross-sections

5. CASTING QUALITY VERIFICATION

The casting material used for the holder of the two-piece tooth is ST50-2 (DIN) steel composed of C=0.3-0.35%, Si= 0.3–0.6%, P_{max}≤0.05, S_{max}≤0.05. During casting, a sample of each production lot is taken to create a test coupon, which is used to verify the chemical composition of the casting, and another sample is taken for the fabrication of a standard test tube for the verification of mechanical characteristics of the casting material. After the casting operation, to eliminate internal strain in the casting, castings and test tube samples are subjected to normalizing [6,7], as shown in Figure 12. The mechanical characteristics of the casting material after normalizing: tensile strength: Rm=600 N/mm^2, elongation (l=5d_0) %: A= 20. The choice of material for the cutting portion of the tooth is dependent on the excavation environment. If the environment is mostly sand or gravel (extremely abrasive environment), the material used for cutting portions is chilled cast iron [8] of the chemical composition: C= 2.3–2.6%, Si=0.3–0.5%, Mn=0.5–0.8%, P_{max} ≤ 0.02%, S_{max}≤ 0.02%, Cr=13–16%, Ni_{max}=0.6%, Mo= 0.15–0.25%, Cu= 0.4–0.6%, and trace amounts of other chemical elements. The chilled cast iron having the above chemical composition is subjected to tempering, as shown in Figure 13. To evaluate the quality of chilled cast iron used as material for the tooth cutting elements, a test coupon having predetermined dimensions is sampled for the analysis of the chemical composition, hardness and microstructure of the casting material. Hardness after heat treatment is 50-52 HRC. The microstructure of the material after heat treatment is given in Figure 16a. For rock environments, the casting material used for the cutting portions of the teeth is X120Mn12 (DIN) steel i.e. the *Hatfield steel* composed of: C=1.1–1.25, Si=0.30–0.50, Mn=11.5–13, Cr_{max}=0.20, S_{max}≤0.02, P_{max}≤0.035. During the excavation, the cutting portions strengthen when they come into contact with the rock material, which leads to a significant improvement in tooth operating characteristics and makes potential machining difficult. When casting these elements, a test coupon having particular dimensions is taken for the verification of the chemical composition, hardness and microstructure of the casting material. *Hatfield steel* castings and test coupons are subjected to quenching, [9,10], as illustrated in Figure 14. The mechanical characteristics (tensile strength, elongation and impact energy) of this material after quenching are not provided as the material significantly strengthens during excavation. Its hardness is about HB=210–220, and its microstructure is presented in Figure 16b. Soil removal is followed by coal mining using cutting elements made of cast Cr-Ni-Mo (*Chromosil*) steel, [11,12] having the chemical composition: C= 0.24–0.30%, Si= 1.4–1.7%, Mn= 1–1.4%, P_{max}≤ 0.025, S_{max}≤ 0.025, Cr=1.25–1.5%, Ni=0.4–0.6, Mo=0.17–0.22. As in the abovementioned cases, when casting the cutting elements, test coupon samples are taken for the verification of the chemical composition, mechanical characteristics, hardness and microstructure of the casting after heat treatment. Under given excavation conditions and for this type of the material, tempering as heat treatment is used, as shown in Figure 15.

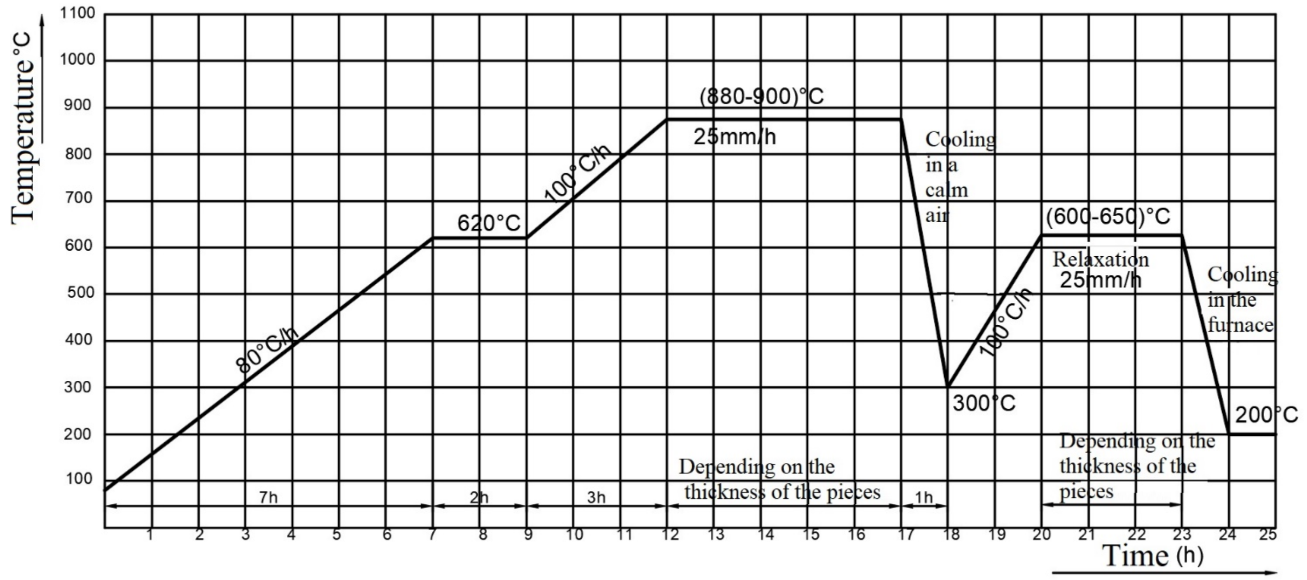

Figure 12: Normalizing of ST50-2 (DIN) steel castings

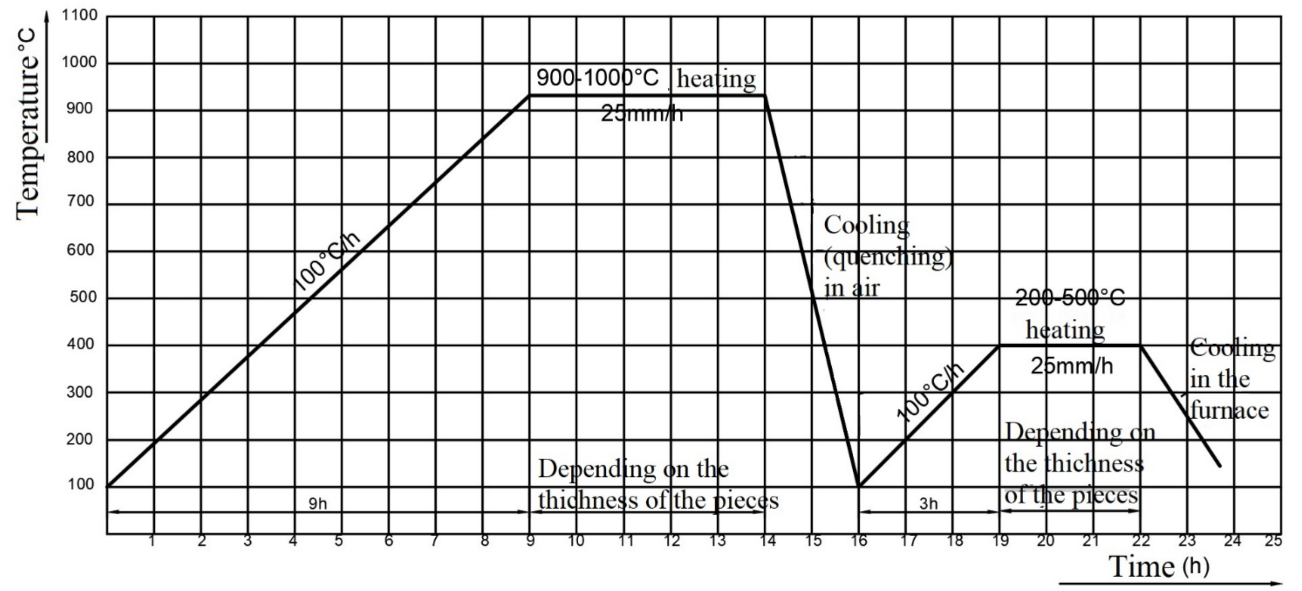

Figure 13: Tempering of chilled cast iron castings

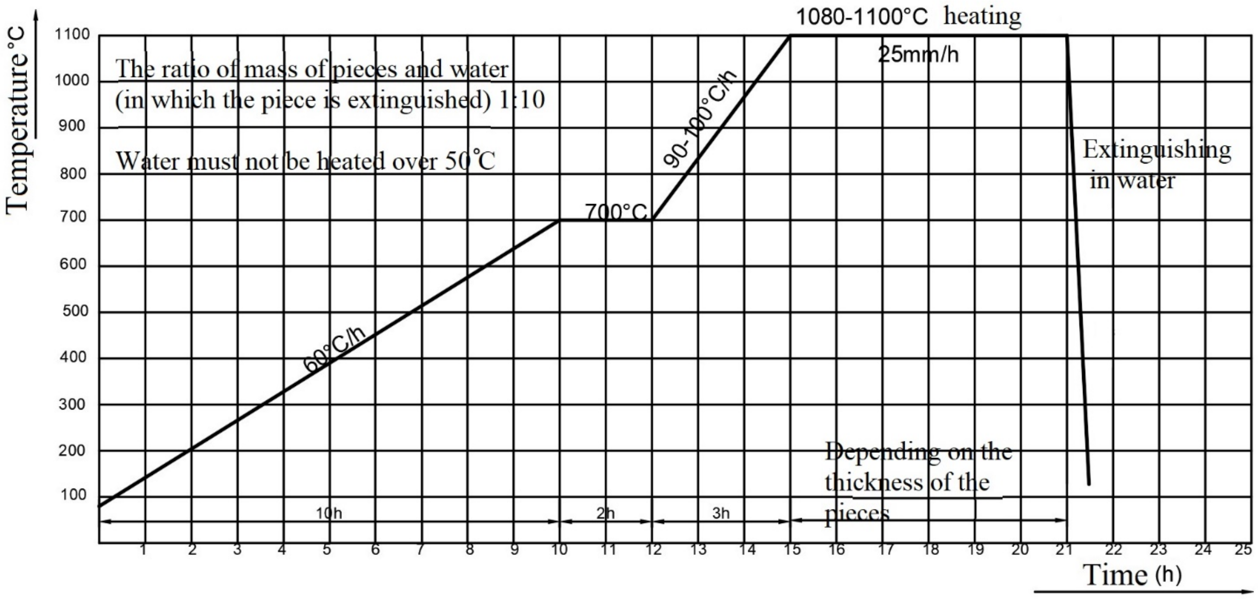

Figure 14: Quenching of X120Mn12 steel castings

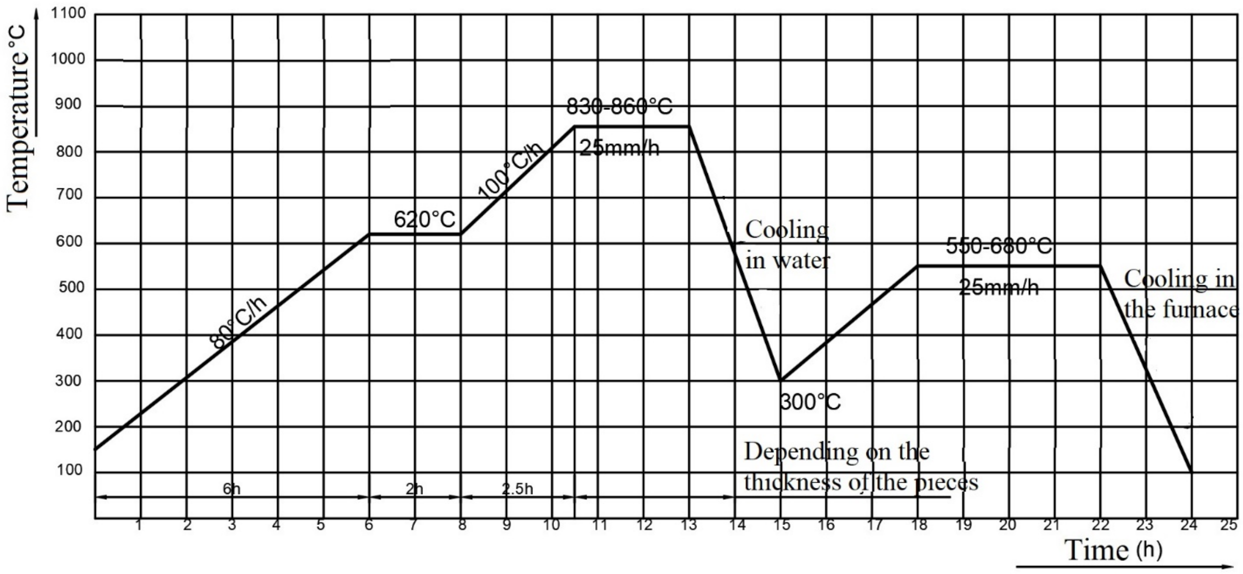

Figure 15: Tempering of Cr-Ni-Mo steel castings

Upon heat treatment, the mechanical characteristics of the material used for cutting elements are as follows: tensile strength: Rm=1600 N/mm^2, elongation (l = 5d_0) %: A=20, impact energy: Kv=25 J, and hardness HRC=38–42. The microstructure of the material is given in Figure 16c.

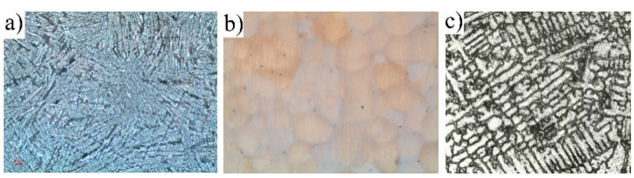

Figure 16: Microstructures of the cutting element material: a) chilled cast iron, b) Hatfield steel, c) Chromosil steel

Figure 16b shows that all Mn steel specimens exhibit a polygonal uniform austenite structure at the cross-section, as expected for the *Hatfield steel*; during excavation, under the effect of strain, the structure is transformed into martensite, which gives steel good hardness and wear resistance. Carbides are fine and evenly distributed, with no mesh observed. The presence of non-metallic inclusions is negligible.

Chilled cast iron (Figure 16a) exhibits a dendritic structure with a well-developed interdendritic mesh. Dendrite orientation is alternating, almost intersecting, which increases wear resistance and impact load resistance.

Chromosil steel (Figure 16c) has a martensitic structure with medium-sized grains and the presence of carbides in relatively small amounts. This microstructure ensures casting hardness of up to 45 HRC and good toughness at the cross-section, which is of high importance for the teeth used in coal excavation.

6. CONCLUSION

Excavator cutting elements play a key role in mining machines. In terms of their fabrication, casting is considered an unsurpassable manufacturing process. Cutting elements require proper cutting geometry, material and production method. Cutting geometry and material are defined by good tribological design. As cutting elements operate under highly dynamic and abrasive conditions, they must not have internal cavities and macro- and micro-porosity, which make the casting highly susceptible to dynamic strain, which very often leads to fracture in these cases. Moreover, in addition to the proper choice of material to be used for excavator cutting elements depending on the excavation environment, the microstructure of the material also has a large influence on wear severity, dynamic strength and other mechanical characteristics. Therefore, great attention is given to heat treatment of cutting elements after casting. In such cases, the real solution is offered by *virtual manufacture* i.e. the simulation of the casting process and heat treatment processes during cooling (internal cracks and residual stresses often occur in the casting during cooling), as well as the simulation of heat treatment processes after casting, which are presented in this paper.

In the last decade, from a scientific standpoint, simulations of the casting process and prediction of material properties have contributed to solving two key unknowns in the foundry industry:

- mold as a black box has become more transparent for foundry experts i.e. causes of problems potentially occurring before the final casting operation have been made easier to understand,
- complete understanding of physical, metallurgical and chemical properties of liquid metals has been made possible.

For many foundries, the simulation of the casting process has become a standard tool for designing the gating system, feeders and vent holes, and investigating thermal processes to obtain desired characteristics of castings. Furthermore, simulation has become an instrument in quality assurance and process optimization systems.

ACKNOWLEDGEMENTS

The project No.TR35037: “Development of new bucket design for continuous excavators due to the installation of modular cutting teeth”, is financed and supported by the Ministry of Science of the Republic of Serbia. The authors would like to acknowledge this contribution.

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