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Optimiranje kontinuirnega litja bakrovih zlitin z oblikovnim spominom na osnovi fizikalne in numerične simulacije

Physical and Numerical Simulation Based Optimization in Continuous Casting of Cu SMA Alloys

Povzetek

Kontinuirno litje je pogosto uporabljen in privlačen tehnološki proces v sodobni metalurški industriji. Kljub razširjeni uporabi zaradi zapletenosti fizikalnih procesov v ozadju še vedno ni dobro opisano. Cilj tega prispevka je osnovati model termomehanskega vedenja pri kontinuirnem litju bakrenih zlitin z oblikovnim spominom. Sklopljeno numerično simulacijo toplotnih in mehanskih pojavov v procesu strjevanja smo izvedli z uporabo programske opreme ProCAST, ki omogoča modeliranje procesov v popolnoma neravnovesnih procesnih pogojih. Model je bil uporabljen za izračun porazdelitve temperature in napetosti v odvisnosti od časa med kontinuirnim litjem. Posebna pozornost je bila posvečena vplivu različnih procesnih parametrov na strjevalno fronto (hitrost litja, toplotna prevodnost ob stiku in toplotna učinkovitost vodnega hladilnega sistema). Proučili smo stabilnost morfologije strjevalne fronte in predlagali ustrezne procesne parametre. Rezultati simulacij so primerljivi z eksperimentalnimi vrednostmi, ki kažejo, da je hitrost litja, kot funkcija časa kontinuirnega litja, eden ključnih vplivnih parametrov.

Ključne besede: obdelava materialov, kontinuirno litje, strjevanje, termo mehanika, multifizika

Abstract

The continuous casting process is a widely used attractive technology in modern metal industry. Despite the widespread application due to the inherent complexity from the underlying physics, it is still not well understood. The objective of this paper is to model the thermo-mechanical behavior in continuous casting of Cu based SMA alloys. A coupled thermo-mechanical numerical simulation of solidifying rod is implemented in ProCAST software suite capable of modeling process under full non-equilibrium process conditions. The model is applied to calculate full time dependent temperature and stress distribution during continuous casting. Special focus has been the identification of the solidification front sensitivity on the various process parameters: casting speed, thermal contact conductivity and water cooling system thermal efficiency. The stability of the solidification front profile is examined and typical process parameters are proposed. Results from the simulations compare favorably with experimental experience that one of the key parameters is casting speed full time dependent profile.

Keywords: material processing, continuous casting, solidification, thermo-mechanical, multiphysics

1 Uvod

Zlitine z oblikovnim spominom spadajo med funkcionalne materiale, ki se odlikujejo s sposobnostjo, da si zapomnijo prvotno obliko, kot so jo imeli pred deformacijo, in se po razbremenitvi vanjo tudi povrnejo. Oblikovni spomin materialov je rezultat kristalografske martenzitno-avstenitne reverzibilne brezdifuzijske fazne transformacije. Dosežemo jolahkomehansko (z obremenjevanjem/razbremenjevanjem) ali toplotno (s segrevanjem/ohlajanjem). Zlitine z oblikovnim spominom izkazujejo superelastičnost, če jih v temperaturnem območju stabilnega avstenita, elastično obremenimo do kritične vrednosti in tako omogočimo termoelastično transformacijo avstenita v martenzit. Sprememba kristalne strukture pri tej transformaciji je posledica brezdifuzijskega pomika atomov. Če zunanjo obremenitev odstranimo, deformacija izgine in material se samodejno vrne v prvotno fazo.

Oblikovni spomin so prvič odkrili pri zlitini Au-47,5 at.% Cd leta 1951 in nato še pri zlitini In-Ti leta 1953. Kasneje so ugotovili, da imajo še številne druge zlitine [2-4] oblikovni spomin (Ag-Cd, Au-Cd, Cu-Al-Ni, Cu-Sn, Cu-Zn, Cu-Zn-X, pri čemer je X lahko Si, Sn, Al itn., In-Ti, Ni-Al, Ni-Ti, Fe-Pt, Mn-Cu, Fe-Mn-Si itn.). Izmed teh so najbolj priljubljene polikristalinske zlitine iz sistema Ni-Ti, zlitine na osnovi bakra (Cu-Zn-Al, Cu-Al-Ni, Cu-Al-Mn, Cu-Al-Be itn.) in železove zlitine (Fe-Pt, Fe-Mn-Si itn.) [4]. V tem prispevku smo se osredotočili na bakrove zlitine z oblikovnim spominom.

Uporabnost zlitin z oblikovnim spominom je prvič ugotovil William Buehler leta 1963 za zlitino Ni-Ti. Zlitinam Ni-Ti pogosto pravijo nitinol, kar je kratica za Ni-Ti Naval Ordinance Laboratories, laboratorije, ki so del ameriškega Ministrstva za obrambo. Po odkritju še ni bilo povsem jasno, kateri

1 Introduction

Shape memory alloys (SMAs) are advanced functional materials with special feature of being capable of memorizing and recovering original shape before deformation. Shape memory behavior comes from martensite-austenite reversible diffusionless phase transformation. Such a transformation is obtained by mechanical (loading) or thermal means (cooling/heating). SMA show superelasticity if deformed by critical stress value in the right temperature range (providing thermoelastic martensite formation – collective, diffusionless, movement of atoms that results in a crystal structure change). When the external stress is removed the deformation disappears and the material spontaneously returns to the original phase.

The SMA effect was first discovered in Au-47.5 at.% Cd alloy (in 1951.) and then in In-Ti alloy (1953.). Since then it has been found that numerous alloys [2-4] show shape memory effect (Ag-Cd, Au-Cd, Cu-Al-Ni, Cu-Sn, Cu-Zn, Cu-Zn-X, where X=Si, Sn, Al etc., In-Ti, Ni-Al, Ni-Ti, Fe-Pt, Mn-Cu, Fe-Mn-Si etc.). Among them the three most popular polycrystalline shape memory alloys are: Ni-Ti, Cu-based (Cu-Zn-Al, Cu-Al-Ni, Cu-Al-Mn, Cu-Al-Be etc.) and ferrous alloys (Fe-Pt, Fe-Mn-Si etc.) [4]. In this work we focus our attention to the Cu based SMAs.

Possibility for using the SMA in actual applications was first realized for Ni-Ti alloy in 1963 by its discoverer William Buehler. The Ni-Ti alloys are commonly referred as Nitinol (derived from Ni-Ti Naval Ordinance Laboratories, part of the US Department of Defence). After the discovery it was not quite clear what physical phenomena in these metals is responsible for "remembering" their original shapes. Dr. Frederick E. Wang, an expert in crystal physics, discovered the

fizikalni pojav v teh kovinah je odgovoren za »pomnjenje« njihove prvotne oblike. Dr. Frederick E. Wang, strokovnjak za kristalno fiziko, je odkril strukturne spremembe na ravni atomov, ki smo jih omenili v prejšnjem odstavku [4]. Binarna zlitina Nitinol je kot zlitina z oblikovnim spominom zelo privlačna za uporabo v industriji in medicini zaradi svojega spominskega učinka, psevdoelastičnosti, odpornosti proti rji in biokompatibilnosti. Nitinol zlitine prevladujejo na komercialnem trgu (v biomedicinski, letalski in avtomobilski industriji itn.), vendar pa večino teh zlitin ne moremo uporabljati pri temperaturah nad 100 °C.

Leta 1964 so tudi pri zlitinah na osnovi bakra odkrili, da imajo oblikovni spomin [5]. Glavna prednost bakrovih zlitin z oblikovnim spominom je njihova nizka cena. Veliko bakrovih zlitin z oblikovnim spominom ima boljšo toplotno in električno stabilnost, uporabljamo pa jih lahko tudi pri višjih temperaturah. Izjemno velika anizotropnost v elastičnem področju kot posledica visoke stopnje reda v izhodni fazi in velika kristalna zrna so vzrok za krhkost in slabe mehanske lastnosti. Dodajanje nekaterih zlitinskih elementov (Mn, Fe, Ti, Zr, B idr.) lahko pomembno izboljša žilavost zlitin in druge lastnosti, ki vplivajo na temperature, pri katerih je z njimi mogoče delati.

Bakrove zlitine z oblikovnim spominom so pomembni funkcionalni materiali za uporabo v prožilnih ali senzorskih tehnologijah, zato se zanje uporablja tudi izraz "pametni oz. inteligentni materiali". Najpomembnejše prednosti teh zlitin kot prožilnih mehanizmov so: preprostost (učinki obrabe so zelo majhni), visoko razmerje med močjo in težo (močjo in volumnom), nizka cena itn. Uporaba bakrovih zlitin z oblikovnim spominom pa je tudi omejena zaradi slabe voljnosti in preoblikovalnosti, ki sta posledica grobo zrnate mikrostrukture, velike elastične anizotropije in precipitacije

structural changes at the atomic level we mentioned in the preceding paragraph [4]. Nitinol, as binary SMA, is very attractive for industrial and medical applications due to the important shape memory effect, pseudoelasticity, corrosion resistance and biocompatibility. Nitinol alloys dominate on the commercial market (biomedical, aerospace and automotive industries etc.). However, most Ti-Ni-based alloys cannot be used at temperatures above 100 °C.

On the other hand Cu-based shape memory alloys were found to reveal the shape memory effect in 1964 [5]. The main advantages of Cu-based SMA are their low price compared to other SMAs. Many Cu-based SMAs have a better thermal and electrical stability and a higher operating temperature. Their very high elastic anisotropy and large grain size cause brittle and poor mechanical properties owing to the high degree of order in the parent phase. Adding some alloying elements such as Mn, Fe, Ti, Zr, B etc. to the alloys can significantly improve their ductility and other properties modifying their operating temperatures.

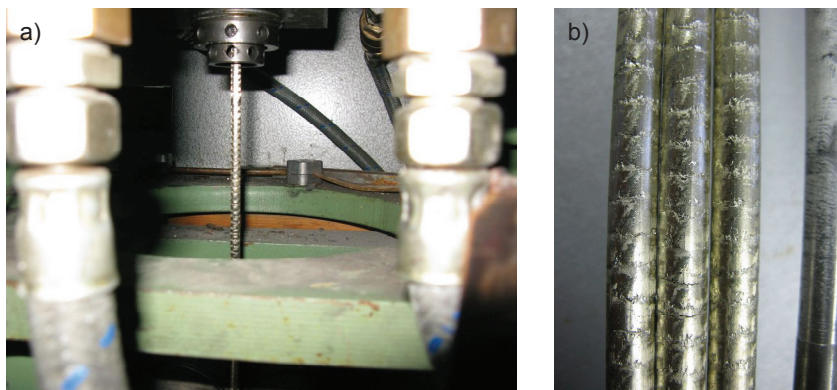
Cu-based SMAs are considered as important functional materials for applications in to actuator or sensor technologies, and are termed as so-called smart or intelligent materials. The most important advantages of these alloys as an actuation mechanism are: simplicity (wear effects are rather small), high power/weight (power/volume) ratios, low price etc. The applications of Cu-based SMAs have limitations due to the poor ductility and workability that is result of the coarse-grained microstructure, the high elastic anisotropy, as well as precipitation of the brittle second-phase particles [6]. In order to overcome this problems the Cu-Al-Ni-Mn and Cu-Al-Mn-Ti(B) were investigated. The Cu-Al-Mn-based shape memory alloys have

krhkih delcev druge faze [6]. Da bi odpravili te težave, so raziskali zlitine Cu-Al-Ni-Mn in Cu-Al-Mn-Ti(B). Zlitine na osnovi Cu-Al-Mn z oblikovnim spominom imajo velik potencial za praktično uporabo v medicinskih, električnih in mikro napravah ter tehnologijah za shranjevanje energije [7].

Tehnologije, ki se uporabljajo pri proizvodnji zlitin z oblikovnim spominom, so: indukcijsko taljenje, elektro oblačno taljenje, hitro strjevanje z litjem na boben, metalurgija prahov, sinteza pri zgorevanju itn. [8, 9]. Izdelki se lahko preoblikujejo v toplem (kovanje, valjanje), ali hladnem (vlečenje žic, valjanje) itn. S temi preoblikovalnimi tehnikami ter s toplotnimi obdelavami lahko dosežemo želene končne lastnosti. Prav tako obstajajo zanimive mikrotehnologije za proizvodnjo zelo tankih zlitin z oblikovnim spominom, ki vključujejo nanos tankih filmov na podlago iz plinske faze, magnetronsko naprševanje itn. Vendar lahko s temi tehnikami običajno izdelamo materiale/zlitine v majhnih količinah. Znano je, da so zlitine z oblikovnim spominom zelo občutljive na odstopanje od ciljne kemijske sestave in na velikost kristalnih zrn, katerih rast je posledica toplotne obdelave. Zaradi grobih zrn (25–100 μm), ki nastajajo med strjevanjem in poznejšo betatizacijo, postanejo bakrove zlitine z oblikovnim spominom krhke in izjemno nagnjene k intergranularnemu širjenju razpok med nadaljno obdelavo. Zlitine Cu-Al-Ni imajo na primer slabo duktilnost zaradi visoke stopnje reda in elastične anizotropije v prvotni β -fazi. Na splošno imajo terneer zlitine z oblikovnim spominom na osnovi bakra zelo velika zrna. To težavo lahko odpravimo z dodajanjem elementov za žilavenje (Ti, B itn.), saj pri tem nastajajo precipitati, ki omejijo velikost in rast zrn, in/ali z uporabo tehnologije hitrega strjevanja. V zadnjih letih je tudi kontinuirno litje zaradi

high potential for practical applications in medical, electrical devices, micromachines and energy-storage technologies [7].

The production technologies of SMAs are induction melting, electro-arc melting, melt-spinning technique, powder metallurgy, combustion synthesis etc. [8,9]. Products can be hot worked (forging, rolling), cold working (wire drawing, rolling), etc. These techniques combined with heat treatments finally lead to the desired properties. Also, there are interesting microtechnologies for the production of very thin shape memory alloys, such as thin film production by vapour deposition, magnetron sputtering etc. But all these techniques generally yield material/alloys in small quantities. It is well known that SMAs are very sensitive to the exact chemical composition and grain size (as a result of the heat treatment). Coarse grains (25–100 μm) formed during solidification and after subsequent betatizing treatment of Cu-based SMAs make them brittle and highly prone for intergranular cracking during working. For example Cu-Al-Ni alloys have poor ductility due to the high degree of order and high elastic anisotropy in the parent β -phase. Generally, ternary Cu-based SMAs show generally a very large grain size. This problem can be solved by addition of adequate refining elements (Ti, B etc.) due to formation precipitates that limit the grain size and grain growth and/or by applying the technology of rapid solidification. In recent years the continuous casting technique is one of the technologies for the production of SMAs, due to the special competitive growth mechanism of crystal and the formation of cast product with a favorable texture [10, 11]. In order to overcome the deleterious effect of coarse grains, the computer modelling of alloy continuous casting process by appropriate technique is a necessity. Here we demonstrate, by numerical calculations, that the complex



Slika 1. Kontinuirno litje: (a) izhod palice iz kristalizatorja in (b) zlitinske palice, ki so bile dejansko proizvedene med poskusom

Figure 1. Continuous casting: (a) rod exit from crystallizer and (b) alloy rods actually produced in experiment

specifičnega "konkurenčnega" mehanizma rasti kristalov postalo ena od tehnologij, ki se uporablja v proizvodnji zlitin z oblikovnim spominom in ulitkov z ugodno teksturo [10, 11]. Za preprečevanje grobozrnate mikrostrukture pri kontinuirnem litju je potrebno računalniško modeliranje procesa litja z ustreznimi tehnikami. V prispevku bomo z numeričnimi izračuni pokazali, da je zapleten pojav prenosa toplote in mase moč opisati s pomočjo našega računskega modela. Razvili smo realistični model, v katerem lahko s programskim paketom ProCAST v celoti simuliramo kontinuirno litje bakrovih zlitin z oblikovnim spomin. Naš livni sistem je shematsko prikazan na sliki 1b, izdelan pa je iz keramičnega lonca, grafitnega kristalizatorja in bakrenega sistema za vodno hlajenje. Kljub na videz preprosti izdelavi fizičnega modela pri tovrstnem livnem procesu naletimo na nekaj teoretskih ovir. V prispevku bomo pojasnili glavne fizikalne lastnosti simulacije, predstavili nekaj numeričnih rezultatov in v zaključku podali sklepne misli ter nekaj smernic za nadaljnje raziskave.

thermal and mass transport phenomena are within the reach of the present computational framework. We have developed a realistic model that simulates a full continuous casting process of Cu-based SMAs using ProCAST software package. Our casting system is depicted schematically on Fig (1b) and is realized with ceramic vessel, graphite crystallizer and water cooling system made from copper. Despite apparent production simplicity, when it comes to physically model, with such a casting process we face several theoretical challenges. This paper is organized as follows: in the second section, we explain main physical features of the simulation, in the third we present some numerical results and in the fourth we provide conclusion remarks as well as some future research directions.

2 Physical Modeling

Purpose of a physical model is to get a better understanding of the different physical phenomena, their interaction and

2 Fizikalno modeliranje

Namen fizikalnega modela je bolje razumeti različne fizikalne pojave, njihovo medsebojno delovanje in vpliv na kontinuirno litje. Pri tem smo uporabili komercialni paket programske opreme ProCAST¹, ki je zasnovan posebej za simulacijo procesov litja. V programski opremi smo zasnovali simulacijo procesa kontinuirnega litja, ki je podobna sistemu v LAB, kot prikazujeta sliki 1a in b. Poznano je, da je razvoj ustreznega fizikalnega modela, ki zajema vse potrebne vplivne veličine, ki nastopijo pri časovno odvisnem neravnotežnem strjevanju, precej zahtevno delo. Nekatere pomembne lastnosti modela so:

1. povečanje volumna, napolnjenega z zlitino (pri tem smo uporabili algoritem Mixed Lagrangian-Eulerian (MiLE) [12] za nestalno modeliranje kontinuirnega litja), je bilo izvedeno s tehniko »harmonike«, ki se začne z dvema volumskima elementoma, napolnjenima z zlitino, eden je statičen (1) in drugi gibljiv (2). Ko se gibljiv volumski element oddaljuje, napolnijo vmesni volumen novi sloji, ki oblikujejo tretji volumski element (3). Novi sloji nastanejo med volumskima elementoma 1 in 3;
2. uporabljeni so bili časovno odvisni robni pogoji med zlitino in kristalizatorjem, pri čemer moramo biti pozorni, da smo vzpostavili nenaključni mrežni stik, ki ga ustvarja relativno gibanje ulitka in kristalizatorja;
3. izjemno zahtevna numerična orodja v pristopu končnih elementov so potrebna, da se upoštevajo zapletenosti roba in različne površinske učinke (kot vidimo na sliki 1b, je v geometriji sistema veliko ostrih robov);
4. uporabljen je bila tudi zrcalna simetrija skozi ploskev XY, tako da je izračunan

the impact on continuous casting process. Here we use a commercial software package ProCAST¹ that is specifically designed for the casting process simulation. Within the software we have designed a continuous casting process simulation that resembles the system in the LAB as shown in Fig. (1a and b). As well known, it is rather complicated to device appropriate physical model that captures all necessary features during nonequilibrium time evolution. Some important characteristics are:

1. enlarging of the space domain filled with alloy (here we use Mixed Lagrangian-Eulerian (MiLE) algorithm [12] for non-steady modelling of continuous casting) is accomplished by "accordion" technique which start with two regions filled with alloy, one is stationary (1) and one is moving (2). As the moving domain goes away, new layers are introduced filling the gap between and forming a third domain (3). New layers are introduced on the interface between region 1 and 3.
2. time dependent boundary conditions between alloy and crystallizer taking care to establish noncoincident mesh contact, caused by relative motion of the casting and crystallizer
3. highly demanding numerical tools within the finite elements (FE) approach are necessary to take into account intricacies of the boundary and various surface effects (as can be seen on Fig 1b, there are plenty of sharp angles in the geometry of the system)
4. we have also utilize mirror symmetry through yx plane, so that computation time is highly reduced

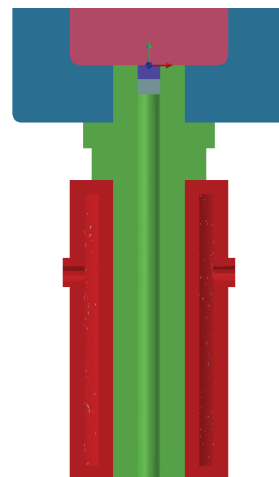
Here we model the system by taking into account chemical, thermal and mechanical properties of the Cu based alloy.

¹ ProCAST je blagovna znamka skupine ESI Group

¹ ProCAST is trademark of ESI Group

Slika 2. Model sistema kontinuirnega litja – deli sistema (zelena: grafitni kristalizator, 145 mm višine; modra: ponovca; vijolična/roza: zlitina; rdeča: vodno hlajen bakreni hladilnik)

Figure 2. Continuous casting system model system parts (green: graphite crystallizer 145 mm height; blue: ladle; violet/rose: alloy; red: copper water cooler)



čas pomembno skrajšan.

Osnovali smo model sistema ob upoštevanju kemijskih, toplotnih in mehanskih lastnosti bakrove zlitine.

Ena od večjih težav pri izvajanju realistične termomehanske simulacije je povezana z upoštevanjem dejanske stične toplotne upornosti. Kot je poznano, je funkcijska odvisnost toplotne upornosti od faze sestave zlitine zelo kompleksna (povečanje upornosti pri nastajanju trdne faze je posledica zmanjšanih stičnih površin). Zaradi pomanjkanja natančnih laboratorijskih podatkov, smo uporabili tipične vrednosti iz literature in upali, da bomo v povprečju dobili prave fizikalne rezultate. Trenutno bi bilo preveč utrudljivo in neobvladljivo, če bi upoštevali množico neuravnoteženih učinkov. Upoštevati pa moramo ločljivost prostora in časa, ki je vključena v končno vrednost časa. Najmanjši končni element smo nastavili na 0,5 mm, čas pa je prilagodljiv (prilagojen z vsakim evolucijskim korakom, vendar se giblje okrog 0,01 s).

3 Rezultati

Poskus kontinuirnega litja smo izvedli s tehniko "go-stop", kjer je znašal poteg (stopnja "go") 5 milimetrov in držanje (stopnja "stop") 0,5–0,7 sekund. Sistem vodnega hlajenja smo nastavili na 6 l/min. Začetna temperatura litja je bila 1250 °C, kar je precej nad temperaturo likvidusa. Pri poskusu in v simulaciji smo sistemu dovolili, da razporeja temperaturna polja, da bi tako

One of the major difficulties in performing realistic thermomechanical simulation is connected to correctly take into account various contact thermal resistance characteristics, because as is well known, they depend in complicated way on the phase of the alloy (increase when solid phase is formed due to reduced contact surfaces). Since we do not have precise experimental values from the experiment, we use typical literature values hoping that we catch right physics on the average. It is tedious and intractable at the moment to take into account myriad nonequilibrium effects. We have to consider space and time resolution that is calculated in finite amount of time. Here we set smallest FE element to 0.5 mm and time is adaptive (readjust with every evolution step but around 0.01 s).

3 Results

In our LAB setting casting speed profile is an essentially regular sequence of 5 mm pulls and 0.5 – 0.7s waiting intervals. Water cooling system was set at 6 l/min. We started at 1250 °C, which is well above the liquidus' temperature. In the experiment and in the simulation we let the system

zmanjšali prehodne začetne učinke, ki nimajo praktične uporabnosti (v simulaciji smo sistemu dovolili, da toplotno stabilizira 30 s brez prenosa mase).

Pri simulaciji so bile uporabljene naslednje toplotne lastnosti materiala: likvidus temperatura (ocenjena - uravnotežena termodinamična fenomenološka vrednost) pri $T_l = 1058\text{ }^{\circ}\text{C}$, solidus pri $T_s = 1020\text{ }^{\circ}\text{C}$, latentna toplota 233 kJ/kg in toplotna prevodnost, gostota, specifična toplota in trdna frakcija pa so podani kot funkcije temperature s tipičnimi oblikami za aluminijeve brone.

Slika 3 prikazuje tipičen rezultat simulacije. Na sliki a je predstavljeno temperaturno polje, ko je postalo že skoraj statično (75 s začetka simulacije oblike), na sliki b pa je prikazana tudi strjena zlitina z obliko meniskusa (mejna površina trdno/tekoče), ki je tipična pri kontinuirnem litju. Iz rezultatov simulacije sklepamo, da je med litjem glavna smer prenosa toplote aksialno, vzdolž same palice, kar je razumljivo, saj je toplotna prevodnost v tej smeri največja. Glavni parameter, ki vpliva na potek strejavanja, je livna hitrost (na sliki 3 je naveden hitrostni profil). Praksa je pokazala, da se najboljši rezultati dosežejo pri kontinuirnem litju s tehniko "go-stop", tako da valji vlečejo lito palico zlitine v ustreznih intervalih in tako omogočijo doseganje lokalnega toplotnega ravnotežja. Podaljšanje časa čakanja je posledica segrevanja grafitnega kristalizatorja med procesom, saj v procesu kontinuirnega litja toplota in material nenehno vstopata v sistem iz talilnega lonca.

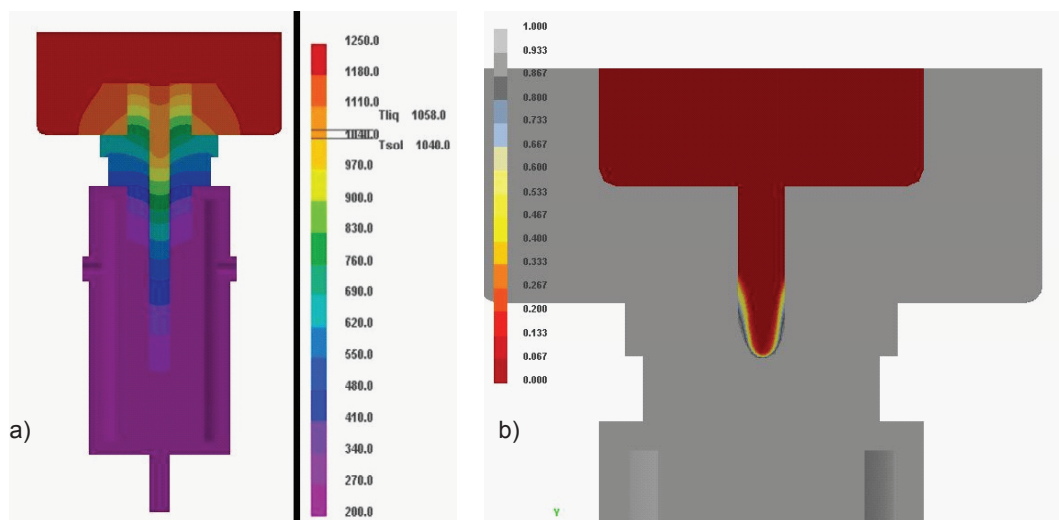
Prenos toplote na kristalizator je težko pravilno modelirati, saj na prenos toplote iz strjenega plašča zlitine na steno kristalizatorja močno vpliva krčenje zlitine pri strjevanju. Oblika meniskusa (na sliki 3b) je rezultat topologije prenosa toplote. Ta geometrija preprečuje večji vpliv zahtevnih

redistribute temperature field in order to minimise transient starting effects, which are of no practical use (in simulation we let the system thermalize for 30 s without mass transport).

Material thermal properties: liquidus is estimated (equilibrium thermodynamic phenomenological value) at $T_l = 1058\text{ }^{\circ}\text{C}$ and solidus $T_s = 1020\text{ }^{\circ}\text{C}$, latent heat 233 kJ/kg and thermal conductivity, density, specific heat, solid fraction are all given as functions of temperature with typical forms for aluminum bronzes.

Fig 3 shows typical simulation result and specifically on (a) we present a temperature field after it became almost stationary (75 s from simulation start) and (b) solid fraction at the same time giving the typical form of the solid liquid interface in continuous casting. From the simulation results we conclude, that during casting the main thermal transport route is through the rod itself, which is easy to understand since the thermal conductivity is highest along this direction. The main control parameter at hand to process adjustment is the casting speed (here speed profile is given in Fig.3). For the best results the best practice turns out to be shift sequencing so that rolls pull alloy rod following appropriate waiting intervals, that enable local thermal equilibration. Waiting time increase is consequence of the graphite crystallizer heating up during the process since in continuous casting process heat and material constantly enter the system from the ladle.

The heat transfer to the crystallizer is critical to model correctly since the heat transfer from the shell is severely affected by shrinkage of the alloy with crystallization. The meniscus shape (see Fig 3b) is the outcome of the heat transfer topology and we make no further assumptions. Present geometry prevents significant impact of



Slika 3. Simulacija po 75 s litja na zrcalni simetrični ploskvi prikaže: (a) toplotno polje na dnu lonca in v kristalizatorju (b) položaj meje trdno/tekoče v kristalizatorju in obliko meniskusa

Figure 3. Simulation results at 75 s on mirror symmetry plane: (a) thermal field (b) solid fraction field depicting meniscus representing solid liquid interface

pretočnih vzorcev, kot so vrtinčialiturbulence. Pravzaprav nas zelo preseneča, da so livarne uspešne pri določanju optimalnih procesnih pogojev brez zapletenih fizikalnih modelov, kot je ta (zlasti jeklarji so zelo pametni pri prilagajanju parametrov v zelo zapletenih fizikalnih pripravah [13]). Povedati je treba, da v teh sistemih šteje prav vse, in fizikalno modeliranje je pravilen način za ustrezno upoštevanje zapletenih medsebojnih delovanj.

4 Sklep in napovedi

- Razvili smo termomehanski model z metodo končnih elementov v programski zbirki ProCAST in ga uporabili za proučevanje vpliva livne hitrosti pri kontinuirnem litju bakrovih zlitin z oblikovnim spominom, pri čemer smo predpostavili nestacionarne pogoje pri litju in upoštevali povprečne vrednosti prenosa toplote. Dobili smo

the complex flow patterns like vortices or turbulences. It is essentially surprising, that foundries are very successful in adjusting optimal set of process conditions without complex physical models like this one (especially steelmakers have been very smart in twiddling parameters in very complex physical set ups [13]). It is fair to say that in these systems everything counts and physical modeling is just a right way to take complex mutual interactions into account properly.

4 Conclusion and Outlook

- A FE thermo-mechanical model was developed in ProCAST software suite and applied to investigate casting speed for continuous casting of Cu based SMA alloys, assuming nonsteady conditions and average values of the transport properties. An accurate thermal and stress model, temperature dependent

natančen toplotni in napetostni model, temperaturnoodvisnelastnostimateriala in temperature neuravnotežene fazne transformacije.

- Visoka hitrost litja ima za posledico višjo temperaturo ulite palice na izhodu iz kristalizatorja in večji delež delno strjenega področja (kašasta faza).
- Učinkovito vodno hlajenje grafitnega kristalizatorja je ključno, saj povišane temperature povzročajo velik padec toplotne prevodnosti in zato povišajo odstotek kašaste faze.
- Zaradi zahteve po nenaključnem toplotnem stiku med zlitino in kristalizatorjem je težko pridobiti zadovoljive volumenske mreže končnih elementov.
- Najboljša praksa za povečanje livne hitrosti je povečanje dolžine kristalizatorja.
- Pri izračunu toplotne obremenitve smo dokazali, da se obremenitve razvijejo v zlitini in kristalizatorju, kar lahko deformira geometrijo in ob stiku povzroči razpoko, s tem pa pomembno povečanje stične toplotne upornosti.
- Trenutni model je mogoče še izboljšati, da bi bil še bolj podoben realnemu livnemu poskusu, ki je bil izveden v laboratoriju. Za to so potrebne še dodatne aktivnosti:
 - o Programsko izračunati stično toplotno upornost za ustrezno upoštevanje različnih okoliščin zlitine med prenosom in strjevanjem.
 - o Izvesti mikrostrukturne simulacije z uporabo izračuna Cellular Automata and Finite Element (CAFE) [14], ki učinkovito deluje na dveh lestvicah (končni elementi in celična mreža avtomata) za modeliranje razvoja nukleacije v mikrostrukturi in rast zrn.

Zahvale: ta prispevek je delno podprla Hrvaška fundacija za znanost v okviru

material properties, and non-equilibrium phase transformation temperatures.

- High casting speed leads to hotter material at the mold exit and may easily contain substantial amount of mushy content
- Efficient water cooling of the graphite crystallizer is essential since elevated temperatures cause severe drop in thermal conductivity and therefore increase percentage of the mushy phase
- Demanding noncoincident thermal contact of the alloy and the crystallizer makes it very difficult to generate satisfactory FE volume mesh
- In order to increase casting speed the best practice is to enlarge crystallizer length
- In thermal-stress calculation it is verified that stresses develop within the alloy and mould which can deform geometry leading to gap creation at the contact resulting in substantial increase in contact thermal resistance
- Several improvements can be made to present a model to improve correspondence to real casting experiment that has been performed in the LAB
 - o programmatically calculate contact thermal resistance to properly take into account various environments of the alloy during transport and solidification
 - o Perform microstructural simulations using Cellular Automata and Finite Element (CAFE) [14] calculation that effectively works on two scales (FE and cellular automata grid) in order to model microstructure development nucleation and growth of the grains.

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