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Simulacija nagibnega litja

The Simulation of Tilt Casting Process

Izvleček

Ulivanje je del proizvodnega procesa, med katerim na ulitku nastane največ napak. Rešitve nagibnega litja za gravitacijsko ulivanje lahko opišemo kot urjenje v omejevanju škode. V našem primeru smo za simulacijo nagibnega litja bakrenega ulitka pipe uporabili model nadzornih prostornin. Cilj poskusov je bil prepoznati kritične parametre procesa in vzpostaviti simulacijski protokol s pomočjo več procesov nagibnega litja ter tako osnovati modele in proučiti geometrije.
Ključne besede: simulacija, metoda nadzornih prostornin, nagibno litje, pipa

Abstract

The filling process is the point in manufacture when most of the defects are introduced into the cast part. Tilt casting solutions for gravity pouring could be described as damage limitation exercises. Here a Control Volume model is used to simulate the tilt casting process of a copper based faucet casting. The target of the experiments were to identify the critical process parameters and build a simulation protocol by the help of which several tilt casting processes and geometries can be modelled and examined.
Key-words: simulation, control volume method, tilt casting, faucet

1 Nadzorovano nagibno litje

Najpogostejša oblika nagibnega litja je proces, ki ima edinstveno lastnost, saj lahko tekočo kovino v formo prenesemo s preprostim mehanskim načinom ob pomoči gravitacije, vendar brez površinske turbulence (Durvillov postopek). Zato lahko z njim potencialno proizvedemo visoko kakovostne ulitke. Različne metode prenosa tekoče kovine so shematsko prikazane na slikah 1 in 2.

Pri Durvillovem postopku sta talilni lonček in forma pritrjena drug nasproti drugega na vrtljivi ploščadi. Povezana sta s kratkim kanalom. Lonček se segreva, napolni s kovino, s katere poberejo peno, pri tem pa se ploščad vrti.

1 Controlled Tilt Casting

The most common form of tilt casting is a process with the unique feature that liquid metal can be transferred into a mould by simple mechanical means under the action of gravity, but without surface turbulence (Durville process). It therefore has the potential to produce very high-quality castings. The various methods of liquid metal transfer are schematically illustrated in Figure 1-2.

In the Durville process a melting crucible and a mould are fixed opposite of each other on a rotatable platform. A short channel section connects the two. The crucible is heated, charged with metal, and

Pri tem procesu se kovina stopi v lončku, ki je pritrjen na nagibni livni stroj. Ni razlivanja zaradi gravitacije. Med procesom prenosa nadzor zagotavlja, da se kovina premika s kotaljenjem v svoji oksidni kožici, kožica pa se ne naguba zaradi motenj, kot je valovanje. Najpomembnejši del prenosa je kot nagiba, ki je najbližji vodoravnemu položaju. V tem položaju sprednja stran taline napreduje tako, da se njena oksidna kožica širi, medtem ko njena vrhnja površina vselej ostane v vodoravnem in mirnem položaju. Na tej ključni stopnji pretoka kovine mora biti hitrost vrtenja minimalna. Če ta stopnja ni dobro izvedena, se kovina v formo prelije v obliki vala, pljuskne navzgor proti zadnji strani forme, med padcem pa jo poškodujejo ujeti oksidi.

Če za nagibno litje obstaja razdelilni sistem, ta ne upošteva nujno pravil zasnove za gravitacijsko litje, saj ima gravitacija v tem postopku zgolj minimalen vpliv. Na hitrost polnjenja litine vpliva hitrosti nagiba polnilnega sistema in ne nujno kanali. Ko je forma napolnjena, se lahko polnilni kanali uporabijo kot dovodni kanali, zato morajo biti ustrezne velikosti.

Koncept nagibnega litja se uporablja tudi za ulivanje aluminijevih zlitin v oblikovane trajne forme. Pregledali smo zasnove dovodnih kanalov in prednosti nagibnega ulivanja pred gravitacijskim ulivanjem [1–3]. Prednosti so naslednje:

Nadzorovanje hitrosti polnjenja pomaga preprečevati nastanek obrobkov. To je posledica dejstva, da je hitrost povečevanja tlaka zaradi padca kovine nizka, začne se pri nič, kar je v nasprotju z običajnimi gravitacijskimi ulitki, za katere so značilni visoki dinamični tlaki in visoka hitrost doseganja polnega hidrostatičnega tlaka. Zmanjšana količina obrobkov je pomembna za odlitke, kot so rešetke in žari, ki jih je sicer težko prevleči.

skimmed clear of dross, and the platform is rotated.

In this process the metal is melted in the crucible fixed in the tilt machine. No pouring under gravity takes place at all. During the whole process of the transfer, careful control ensured that the melt progressed by rolling in its skin of oxide avoiding any folding of its skin by disturbances such as waves. The most sensitive part of the transfer is at the tilt angle close to the horizontal. In this condition the melt front progresses by expanding its skin of oxide, whilst its top surface at all times remains horizontal and tranquil. At this critical stage of metal flow the rate of rotation must be a minimum. If this stage is not kept under good control, the metal surges into the mould as a wave, splashes upwards against the rear face of the mold, and is damaged during its fall by entraining oxides.

The running system for tilt castings, if any, does not necessarily follow the design rules for gravity casting, since gravity is only marginally influential in this process. The filling rate of the casting is under the control of the tilt rate , not necessarily the channels of the filling system. Furthermore, after the mould is filled the filling channels can be used as feeding channels, and thus be sized appropriately.

The concept of tilt pouring is also popularized for pouring aluminum alloys into shaped permanent molds. The gating designs and the advantages of tilt pouring over gravity top pouring have been reviewed [1-3]. The benefits are the following:

The control over the rate of filling helps to control flash. This is because the rate of increase of pressure due to the head of metal is rather slow, starting from zero, in contrast to normal gravity-poured castings, where there are high dynamic pressures and a high rate of attaining the full hydrostatic pressure. The reduced flash is important for

Avtomatizirano litje lahko vzpostavimo razmeroma preprosto, zagotavlja pa dosledne rezultate.

Zelo velike odlitke lahko z lahkoto proizvede en livar. To je edinstvena prednost nagibnega litja, ki je v primerjavi z običajnimi gravitacijskimi odlitki bistveno bolj ekonomična.

Nastavitev jeder je prilagodljiva, tako da jih lahko izvedemo vodoravno ali navpično ali celo v nekaterih osrednjih položajih, odvisno od zahtev za jedra.

Pri izmetu odlitka ima upravljavec podobno možnost vodoravnega ali navpičnega izmeta.

Priprava za nagib z dovodnim kanalom na spodnji strani in rešitev s stranskim dovodnim kanalom sta prikazana na sliki 1. Lijak je tukaj v spodnjem delu forme, preostanek razdelilnega kanala in dovajalni sistem ter livna votlina pa so v zgornjem delu forme. Z nagibno kokilo je treba ravnati previdno, da zagotovimo prosto odzračevanje zračnih žepkov v ozračje. Prav tako mora imeti stranica kokile, ki drži ulitek, izmetače, če so ti potrebni.

Kokila s stranskimi kanali je zasnovana tako, da omogoča padec taline v livno votlino. Sistemu za nagibno litje bi ustrezala livna votlina predvsem v zgornji polovici kokile, castings such as gratings and grills that are otherwise difficult to dress.

Automated casting can be arranged relatively easily, with the benefit of consistent results.

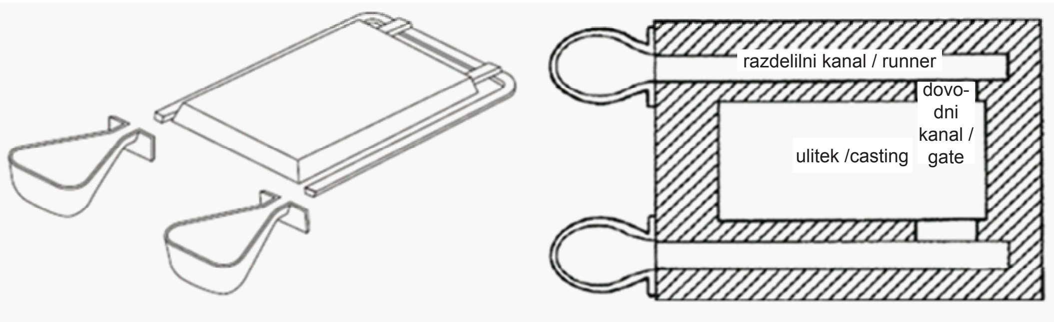
Very large castings can be easily produced by one caster. This seems to be a unique benefit for tilt casting, making for considerable economies compared to normal gravity-poured molds.

The setting of cores has the flexibility of being carried out in either the horizontal or vertical attitude, or even in some intermediate position, depending on the requirements of the cores.

For the ejection of the casting the operator similarly has the option of carrying this out vertically or horizontally.

A bottom-gated tilt arrangement and a side gated solution are shown in Figure 1. Here the sprue is in the drag, and the remainder of the running and gating system, and the mold cavity, is in the cope. Care needs to be taken with a tilt die to ensure that the remaining pockets of air in the die can vent freely to atmosphere. Also, the die side that retains the casting has to contain the ejectors if they are needed.

The die with side gates is arranged so as to allow the melt to fall inside the mould cavity. Tilt pour system that would have



Slika 1. Dvojna nagibna kokila in kokila s stranskim ulivnim sistemom

Figure 1. Twin-poured tilting die and die with side gates

kar bi preprečilo padec kovine iz dovodnega kanala. Potrebni bi bili oddušniki.

Občasno se kovina uliva neposredno v livno votlino, s čimer se v celoti odpravi potreba po razdelilnih kanalih ter zagotavlja najugodnejšo spremembo temperature, vendar najslabše polnjenje. Pot pretoka zarisujejo oksidne sledi. Te značilnosti lahko predstavljajo težavo, saj nakazujejo prisotnost cevi, kar lahko predstavlja resne napake.

Da bi bolje razumeli postopek, smo simulirali vodne modele pretoka tekočine [4] in izvedli računalniške simulacije nagibnega litja [5]. Ugotovili smo, da na pretok zaradi nagiba vplivajo gravitacijska, centrifugalna in vztrajnostna sila. Vendar pri nizkih hitrostih vrtenja, ki se uporabljajo pri večini procesov nagibnega litja, centrifugalna in vztrajnostna sila prispevata manj kot 10 % skupnega učinka zaradi gravitacijske sile in se ju zato lahko običajno zanemari. Kotna hitrost vrteče forme je prav tako nekoliko prispevala k linearni hitrosti sprednjega dela tekočine, vendar je bilo to ponovno zanemarljivo, saj os vrtenja običajno ni bila zelo oddaljena od središča forme.

Prvo podrobno študijo nagibnega litja z uporabo tukaj predstavljenih konceptov kritične hitrosti in površinske turbulence so izvedli v Univerzitetnem tehnološkem centru Rolls-Royce [6]. Uporabili smo računalniško nadzorovano programabilno livno kolo, na katero se lahko pritrdijo peščene forme za proizvodnjo odlitkov iz aluminijeve zlitine. Pretok kovine med polnjenjem forme smo beležili z uporabo rentgenske radiografije. Ugotovili smo, da pri nizkih hitrostih vrtenja ne moremo zanemariti mehanskega učinka površinske napetosti in/ali površinskih filmov na meniskusu tekočine. V vseh začetnih pogojih pri nizkih hitrostih nagiba na pretok pomembno vpliva površinska napetost. Zato se pod hitrostjo vrtenja približno 7° na sekundo hitrost taline, ki prihaja proti

benefited from the mould cavity mainly in the upper half of the die, avoiding the fall of metal from the gate. Vents would then have been necessary.

Occasionally the metal will be poured directly into the mould cavity, eliminating runners entirely and giving the best temperature gradient but poorest filling. The appearance of the flow path is outlined by streaks of oxide. Such features are a concern since they indicate the presence of flow tubes, thus possibly constituting serious defects.

In an effort to understand the process in some depth, water models of liquid flow were simulated [4], and computer simulations of the tilt casting process carried out [5]. It was detected that a combination of gravity, centrifugal, and inertia forces governs tilt-driven flow. However, for the slow rates of rotation such as they are used in most tilt casting operations, centrifugal and inertia effects contribute less than 10% of the effects due to gravitational forces, and could therefore normally be neglected. The angular velocity of the rotating mould also made some contribution to the linear velocity of the liquid front, but this again was usually negligible because the axis of rotation was often not far from the center of the mould.

The first detailed study of tilt casting using the recently introduced concepts of critical velocity and surface turbulence was carried out in the Rolls-Royce University Technology Centre [6]. A computer-controlled, programmable casting wheel was used onto which sand moulds could be fixed to produce castings in an aluminium based alloy. The flow of the metal during the filling of the mould was recorded using X-ray radiography. It is worked out that at the slow rotation speeds the mechanical effect of surface tension and/or surface films on the liquid meniscus could not be neglected.

koncu razdelilnega kanala, zmanjšuje zelo nepredvidljivo. Gravitacija prevzame nadzor šele po nagibu prek zadosti velikega kota.

Tako kot pri drugih procesih litja, če jih izvedemo prepočasi, lahko zaradi prezgodnjega zmrzovanja nastanejo nepravilni ulitki. Pri višjih hitrostih se lahko prezgodnjemu zmrzovanju izognemo, vendar se poveča nevarnost površinske turbulence.

Poskusi so pokazali, da je lahko pretok tekoče kovine v formo med nagibnim litjem miren ali kaotičen, odvisno do nagiba forme ob začetku litja in nagibne hitrosti. Kakovost ulitkov je neposredno povezana s kakovostjo pretoka v formo.

Napredovanju taline med nagibnim litjem lahko sledimo. Najprej se napolni livarski lonec ob ustju razdelilnega kanala. Samo takrat je nagib forme aktiviran [7]. Oblikovali smo naslednje trditve:

Če proces začnemo, ko je forma že nagnjena navzdol, postane ta nestabilna, takoj ko kovina vstopi v lijak in steče navzdol. Hitrost napredovanja taline se zaradi gravitacije pospešuje in talina doseže skrajni konec razdelilnega kanala pri hitrosti, ki povzroča pljuskanje. Pljuskanje prehaja po površini taline. Rezultat so ulitki slabe zanesljivosti.

Če pa proces začnemo, ko je forma v vodoravnem položaju, livarski lonec s kovino običajno ni napolnjen do roba in se zato kovina ne preliva prek roba lonca, v dovajalni kanal pa vstopi šele, ko doseže zadosten kot nagiba. Na tej stopnji je razlika navpičnega padca med začetnim in skrajnim koncem razdelilnega kanala najverjetneje večja od kritične razlike padca. Čeprav je mogoče izdelati nekoliko boljše ulitke, nevarnost slabe zanesljivosti ostaja. Ta nezadovoljiv način prenosa je značilen za veliko priprav za nagibno litje, kot lahko vidimo na sliki 2.

For all starting conditions, the flow at low tilt speeds is significantly affected by surface tension. Thus below a speed of rotation of approximately 7° per second the speed of the melt arriving at the end of the runner is reduced in a rather erratic way. Gravity only takes control after tilting through a sufficiently large angle.

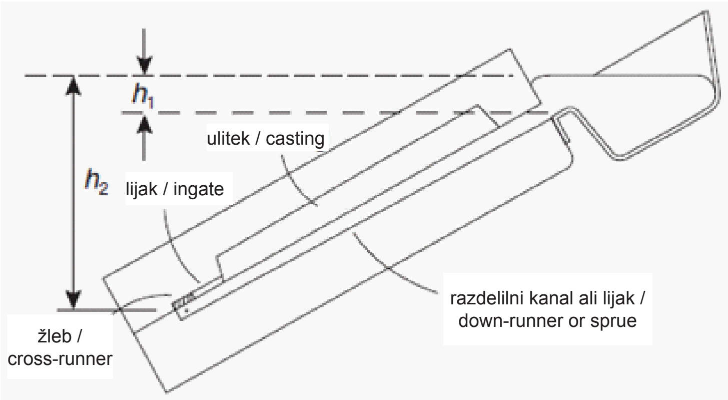
As with all casting processes, if carried out too slowly, premature freezing will lead to misrun castings. At higher speeds, however, although premature freezing could be avoided, the considerable danger of surface turbulence increased.

The experiments revealed that the molten metal could exhibit tranquil or chaotic flow into the mold during tilt casting, depending on the angle of the mold's tilt at the beginning of the casting and the tilting speed. The quality of the castings could be linked directly to the quality of the flow into the mould.

The progress of the melt during the tilt casting process can be followed. Initially, the pouring basin at the mouth of the runner is filled. Only then is the tilting of the mold activated [7]. The following statements were determined:

If the mold starts from some position in which it is already tilted downward, once the metal enters the sprue it is immediately unstable, and runs downhill. The melt accelerates under gravity, hitting the far end of the runner at a speed sufficient to cause splashing. The splash action entrains the melt surface. Castings of poor reliability are the result.

If the mold starts from a horizontal position, the metal in the basin is not usually filled to the brim, and therefore does not start to overflow the brim of the basin and enter the runner until a significant tilt angle has been reached. At this stage, the vertical fall distance between the start and the far end of the runner is likely to be greater than the



Slika 2. Metoda nagibnega litja

Figure 2. Tilt casting method

Če pa je na začetku procesa forma med polnjenjem posode nagnjena nekoliko navzgor, obstaja verjetnost, da bo do takrat, ko bo sprememba kota zadostovala za začetek prelivanja taline iz posode, kot razdelilnega kanala še vedno nekoliko nad vodoravnim položajem. Ob začetku polnjenja razdelilnega kanala se meniskus dejansko dviga po nekoliko dvignjenem naklonu. Tako je njegovo napredovanje povsem stabilno, saj njegovo gibanje naprej nadzoruje dodaten nagib.

Edinstvena značilnost prenosa, če se ta začne nad vodoravnim položajem, je, da je površina tekoče kovine ves čas prenosa v skoraj vodoravnem položaju. Zato v nasprotju z vsemi drugimi vrstami gravitacijskega ulivanja tovrstno nagibno litje ne vključuje prostega navpičnega padca.

Zaključki glede nagibnega litja so naslednji:

Če se postopek nagibnega litja začne v nagnjenem položaju ali položaju, ki je nižji od vodoravnega, tekoča kovina po razdelilnem kanalu pospešuje navzdol s hitrostjo, ki je upravljavec ne more nadzorovati. Kovina teče v obliki ozkega curka in oblikuje vztrajno oksidno cev. Prav tako hitrost tekočine na skrajnem koncu razdelilnega kanala skoraj zagotovo preseže kritični

critical fall distance. Thus although slightly better castings can be made, the danger of poor reliability remains. This unsatisfactory mode of transfer typifies many tilt casting arrangements as seen in Figure 2.

If, however, the mould is initially tilted slightly uphill during the filling of the basin, there is a chance that by the time the change of angle becomes sufficient to start the overflow of melt from the basin, the angle of the runner is still somewhat above the horizontal. When the filling of the runner starts the meniscus is effectively climbing a slight upward slope. Thus its progress is totally stable, its forward motion being controlled by additional tilt.

The unique feature of the transfer when started above the horizontal in this way is that the surface of the liquid metal is close to horizontal at all times during the transfer process. Thus in contrast to all other types of gravity pouring, this condition of tilt casting does not involve a free vertical fall at all.

In summary, the conclusions for tilt casting are:

If tilt casting is initiated from a tilt orientation at, or below, the horizontal, during the priming of the runner the liquid metal accelerates downhill at a rate out of the operator's control. The metal runs as a narrow jet, forming a persistent oxide flow pogoj za površinsko turbulenco. Če je forma že na začetku nagnjena za več kot 10° pod vodoravnim položajem, zanesljiva proizvodnja ulitkov z nagibnim litjem ni več mogoča.

Velika prednost nagibnega litja je uporaba zadosti pozitivnega začetnega kota, tako da talina napreduje po navzgor nagnjenem razdelilnem kanalu. Tako je njeno napredovanje stabilno in nadzorovano. Za ta način polnjenja je značilen vodoraven prenos tekoče kovine, ki ustvarja pogoje za polnjenje forme brez površinske turbulence.

Polnjenje forme naj bo v začetnih stopnjah počasno, da se izognemo visokim hitrostim na skrajnem koncu razdelilnega sistema. Ko pa tekoča kovina steče po razdelilnem kanalu, pomaga pospeševanje hitrosti vrtenja forme preprečevati vsakršno posledično nepolnjenje ulitkov.

2 Poskusi

Tehnološki koraki simuliranega nagibnega litja so razvidni s slike 3.

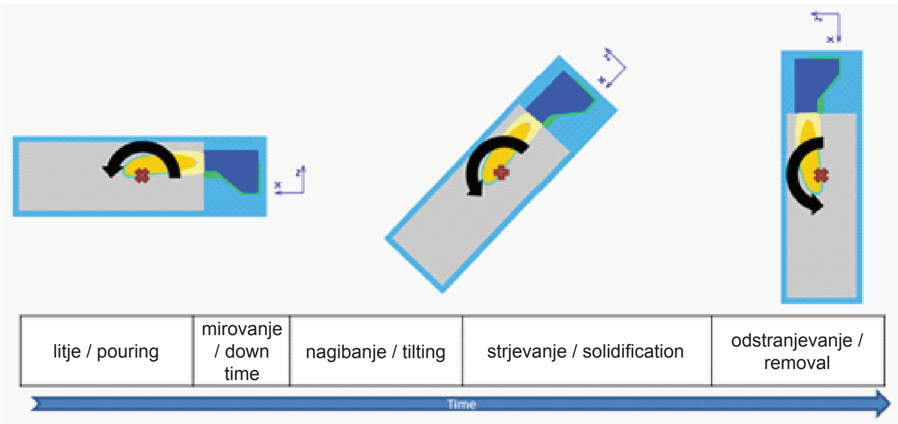
tube. In addition, the velocity of the liquid at the far end of the runner is almost certain to exceed the critical condition for surface turbulence. Once the mold is initially inclined by more than 10° below the horizontal at the initiation of flow, it is no longer possible to produce reliable castings by the tilt casting process.

Tilt casting operations benefit from using a sufficiently positive starting angle that the melt advances into an upward sloping runner. In this way its advance is stable and controlled. This mode of filling is characterized by horizontal liquid metal transfer, promoting a mold filling condition free from surface turbulence.

Tilt filling is preferably slow at the early stages of filling to avoid the high velocities at the far end of the running system. However, after the running system is primed, speeding up the rate of rotation of the mould greatly helps to prevent any consequential non-filling of the castings.

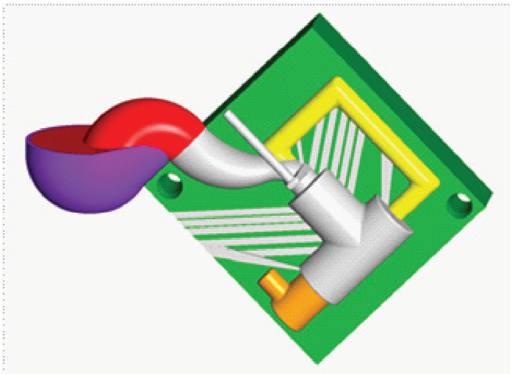
2 Experiments

The technological steps of the simulated tilt casting process can be seen on Figure 3.



Slika 3. Tehnološki koraki procesa

Figure 3. Technological steps of the process



Slika 4. Poenostavljena priprava za nagibno litje (ulivni sistem, odzračniki, jedra, kokilni del)

Figure 4. Simplified tilt casting assembly (gating, vents, cores, die part)

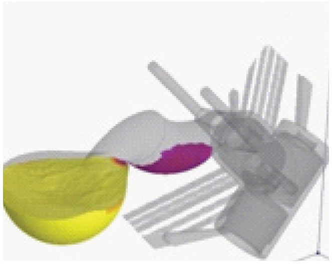
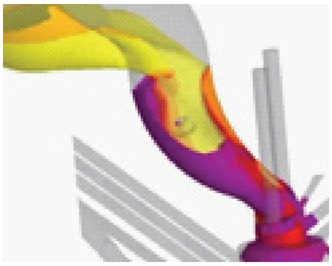
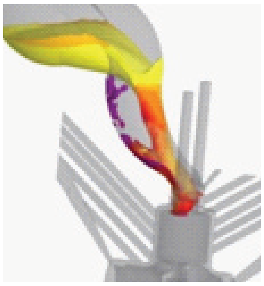
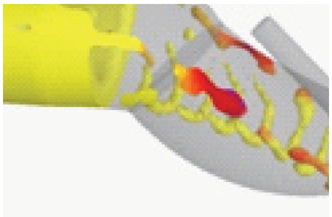
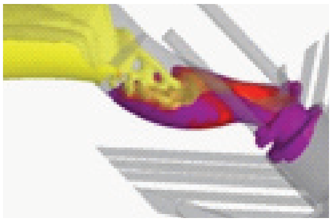
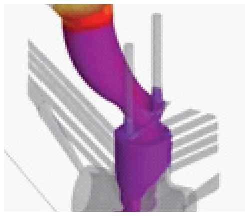
The complete tilt casting assembly must be simplified and the pouring basin has to be enlarged to avoid over pour and it must be modelled separately. The examined casting part is a faucet, which is shown on Figure 4 by the accessories.

Initial parameters for the Control Volume calculations are: CuZn39Pb1AlB_B copper base alloy poured into zirconium bronze mold with the application of furan resin coated sand cores. For the determination of pouring conditions foundry shop experiments were examined and the following parameters were defined: quantity of poured metal (consideration of liquid contraction), pouring temperature, die and core temperature, material and temperature of the basin, gating section of metal, flow

Vrednosti / Values		Nagib_01 / Tilt_01	Nagib_02 / Tilt_02	Nagib_03 / Tilt_03	Nagib_04 / Tilt_04	Nagib_06 / Tilt_06	Nagib_07 / Tilt_07
Lita kovina / Poured metal	kg	3,16	4,35	4,35	4,60	4,28	4,28
Livna temperatura / Pouring temp.	°C	1000	1000	1100	1100	1100	1100
Kokilna temperatura / Die temp.	°C	250	250	250	250	250	250
Temperatura jedra / Core temp.	°C	30	30	30	30	30	30
Material posode / Basin material	-	jeklo / steel	jeklo / steel	jeklo / steel	jeklo / steel	jeklo / steel	jeklo / steel
Temperatura posode / Basin temp.	°C	950	950	950	950	950	950
Polmer dovajalnega kanala / Gating radius	mm	50	45	45	45	44	40
Višina tlak / Pressure height	mm	5	5	4	4	4	60
Hitrost pretoka / Flow rate	kg/s	6,06	3,47	2,70	2,97	2,97	9,5
Čas nagiba / Time of tilt	s	2,4	2,5	1	1	1	1
Vrednosti / Values		Nagib_10 / Tilt_10	Nagib_11 / Tilt_11	Nagib_12 / Tilt_12	Nagib_14 / Tilt_14	Nagib_15 / Tilt_15	Nagib_16 / Tilt_16
Lita kovina / Poured metal	kg	5,95	4,598	4,598	5,95	5,95	5,95
Livna temperatura / Pouring temp.	°C	1100	1100	1200	1100	1200	1300
Kokilna temperatura / Die temp.	°C	250	250	300	250	250	300
Temperatura jedra / Core temp.	°C	30	30	30	30	30	30
Material posode / Basin material	-	keramika / ceramic	keramika / ceramic	keramika / ceramic	keramika / ceramic	keramika / ceramic	keramika / ceramic
Temperatura posode / Basin temp.	°C	950	950	950	950	950	1000
Polmer dovajalnega kanala / Gating radius	mm	40	44	44	45	45	60
Višina tlak / Pressure height	mm	30	5	5	40	40	50
Hitrost pretoka / Flow rate	kg/s	6,72	3,32	3,32	9,82	9,82	19,53
Čas nagiba / Time of tilt	s	2	2	2	2	2	4

Preglednica 1. Preizkusna matrika

Table 1. Experimental matrix

		
Med polnjenjem livarskega lonca talina vstopi v livno votlino / During basin filling the melt enters to the cavity	Hlajenje taline med nagibom / Melt cooling during tilting	Neustrezni pogoji pretoka v ulivnem sistemu / Improper flow conditions in the gating system
		
Nerealna razpršenost taline / Unrealistic spatter of the melt	Hlajenje taline med nagibom / Melt cooling during tilting	Nenapolnjena livna votlina / Unfilled cavity

Preglednica 2. Učinki napak

Table 2. Error effects

Celotno pripravo za nagibno litje je treba poenostaviti in livarski lonec povečati ter tako preprečiti prelivanje, modelirati pa ga je treba posebej. Ulitek, ki smo ga proučevali, je bil pipa na sliki 4 z dodatki.

Začetni parametri za izračun Bakrova zlitina CuZn39Pb1AlB_B, ulita v cirkonij-bronasto formo, z dodajanjem peščenih jeder, prevlečenih s furanovo smolo. Da bi določili pogoje ulivanja, smo proučili livarske poskuse in določili naslednje parametre: količina lite kovine (ob upoštevanju krčenja tekočine), livna temperatura, temperatura kokile in jedra, temperatura materiala in lonca, dovodni del kovine, pretočni del in loputa med loncem in dovajalnim sistemom ter pogoji nagiba, kot so rotacijski vektor, os, kot in čas. Preizkusna matrika je razvidna v preglednici 1. Nagib_01 – Nagib_16 so znaki poskusov [8].

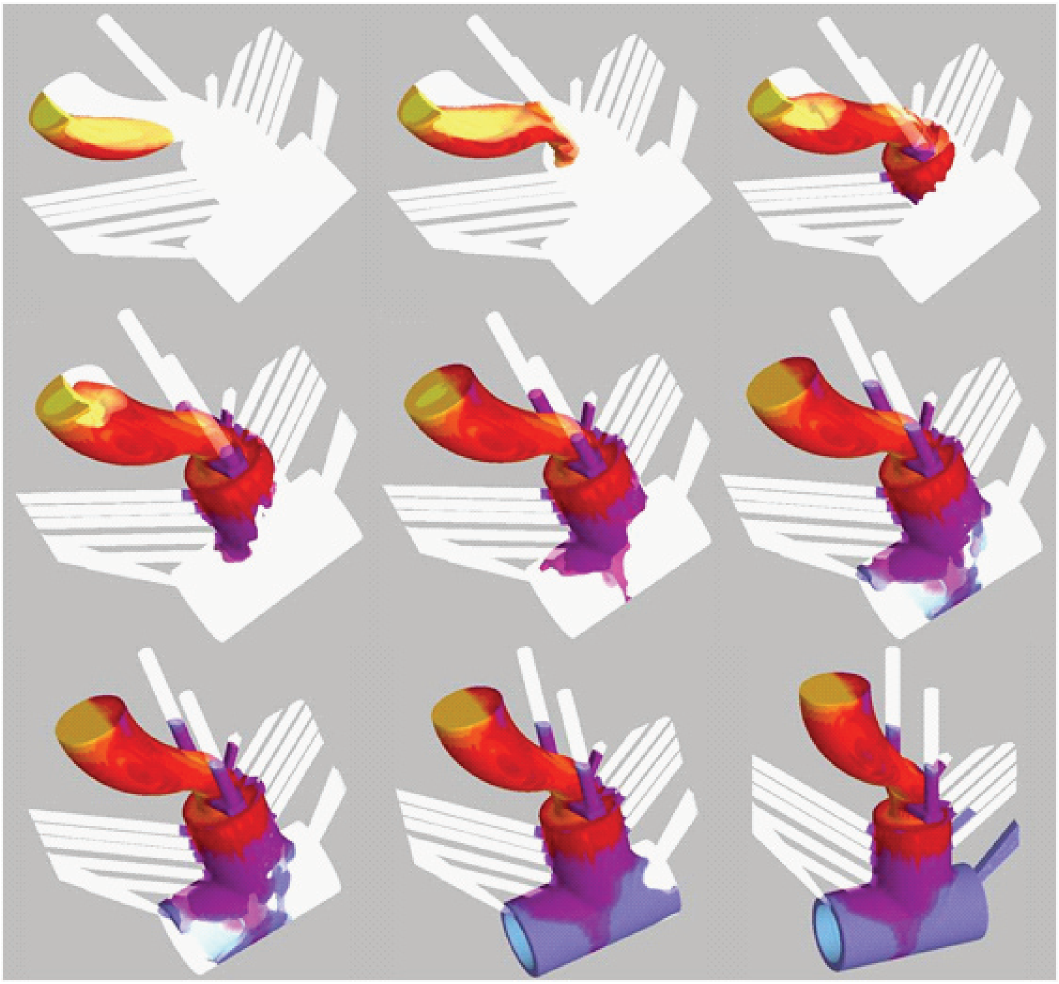
section and choke between basin and gating system and tilting conditions such as rotation vector, axis, angle and time. The experimental matrix can be seen on Table 1. Tilt_01 – Tilt_16 are the signs of the experiments [8].

The characteristic error effects can be seen on Table 2.

The filling process can be seen on figure 6.

3 Summary

Regarding the adequacy of simulation the following factors played the main rules: titling parameters, temperature values and die materials. The most important results of simulation, besides of the determination of technological parameters,



Slika 6. Polnjenje livne votline

Figure 6. Filling of the cavity

Značilni učinki napak so razvidni iz preglednice 2.

Postopek polnjenja je razviden s slike 6.

3 Povzetek

Z vidika ustreznosti simulacije so glavne vloge odigrali naslednji dejavniki: parametri

are the identification of the critical process parameters:

- Geometrical adequacy: height of basin, cross-section of the basin's nose, geometry of the flow channel between the basin and the gating system.
- Pouring conditions: consideration of liquid contraction, cross-section of the melt stream, definition of pressure height to avoid splashing.

nagiba, temperaturne vrednosti in kokilni materiali. Najpomembnejši rezultat simulacije je poleg določanja tehnoloških parametrov določanje parametrov kritičnega procesa:

- Geometrijska ustreznost: višina lonca, prerez nosa lonca, geometrija pretočnega kanala med loncem in dovajalnim sistemom.
- Livni pogoji: upoštevanje krčenja tekočine, prerez toka taline, opredelitev višine tlaka za preprečevanje pljuskanja.
- Opredelitev materiala in temperature lonca, nanos refraktornih premazov za preprečevanje hlajenja taline.
- Pogoji nagiba: merila za zaustavitev polnjenja, možnosti vrtenja, čas prekinitve po polnjenju, čas nagiba, kot nagiba.

- Definition of the material and the temperature of the basin, application of refractory coatings to avoid melt cooling.
- Tilt conditions: filling stop criteria, rotation options, downtime after filling, time of tilt, tilt angle.

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Sistem usposabljanja na osnovi sheme kompetenc inženirjev

Trainig System Based on Engineers Competence Star

Izvleček

Na livarstvo se še vedno gleda kot na eno najpomembnejših metod proizvodnje kovinskih elementov. V zadnjih nekaj letih so v tem sektorju razvili veliko novih rešitev in tehnologij, z naraščajočim povpraševanjem po ulitkih pa se je razširil tudi obseg njihove uporabe.

Livarne se vedno pogosteje soočajo z izzivom prilagajanja proizvodne strukture nenehno spreminjajočim se zahtevam trgov, ki pa je dosegljiv z zagotavljanjem potrebnih materialov, strojev, naprav in človeških virov [1].

V moderni dobi so človeški viri v podjetjih postali vedno pomembnejši in se običajno obravnavajo kot ključni dejavnik za pridobivanje konkurenčne prednosti. Zato se v obdobju gospodarstva, ki temelji na znanju, vedno več pozornosti posveča upravljanju s kadri, zlasti z vidika kompetenc. Zavedanje, da so kompetence kadrov (spretnosti, znanje, izkušnje, sposobnosti) ključni dejavnik za uspeh podjetja, je družbe prisililo v iskanje in uporabo inovativnih orodij za njihovo upravljanje. Upravljanje s človeškimi viri na osnovi kompetenc se je izkazalo za uporabno v vseh postopkih, ki vključujejo kadre – tj. v pridobivanju novih kadrov, izbiri, ocenjevanju zaposlenih, snovanju kariernih poti in zlasti pri prepoznavanju potreb zaposlenih po usposabljanju. Ob upoštevanju potrebe po nenehnem strokovnem razvoju kadrov smo izdelali modul usposabljanja na osnovi elementov sistema upravljanja kompetenc. Namenjen je delavcem v livarnah, zlasti inženirjem na področju livarstva.

Abstract

Casting is still perceived as one of the most significant methods of manufacturing metal elements. Over the last several years many new solutions and technologies have been developed in this sector which, along with the ever growing demand for casts, have extended the range of their application.

More and more frequently, foundries have to face the challenge of adapting their production structure to constantly changing demands of markets, which is feasible by providing the necessary materials, machinery, devices and human resources [1].

In modern times, it is the human resources of the corporation that has grown more and more significant and is commonly regarded as the crucial factor in gaining the competitive advantage. Therefore, in the era of economy based on knowledge, increasing attention has been paid to the staff management, especially in the case of competency. The perception of staff competency (skills, knowledge, experience, abilities) as a key factor for company's success has compelled corporations to search and implement innovative tools to manage them. Competency-based human resources management has been found useful in all staff-related processes - recruitment, selection, employee evaluation, establishing career paths and especially in identifying training needs of employees. With regard to the necessity of constant staff development, a training module based on the elements of competency

management system has been devised. It is dedicated to foundry workers, especially casting engineers.

V obdobju gospodarstva, ki temelji na znanju, je človeški kapital eden izmed najpomembnejših virov vsakega podjetja. Zaposleni, zlasti njegove kompetence, je postal najpomembnejši vir konkurenčne prednosti. Raziskava, ki jo je Izobraževalni in raziskovalni inštitut (Educational Research Institute) izvedel v 941 poljskih podjetjih, je potrdila ta pristop. Glede na anketirana podjetja je najpomembnejši vir za podjetnike zgoraj omenjeni človeški kapital (47 %), kompetence pa so bile izpostavljene kot njegova najpomembnejša lastnost (72,2 %), sledijo kvalifikacije (49,6 %) in formalna izobrazba (39,3 %).

Izraz »kompetenca« je v okviru upravljanja s človeškimi viri opredeljen kot »znanje, spretnosti, sposobnosti, slogi delovanja, osebnost, načela, zanimanja in druge lastnosti, ki se uporabljajo in razvijajo med delom in vodijo v dosežke, skladne s strateškimi cilji družbe« [2]. To pomeni, da se kompetenca kaže v rezultatih namenskega delovanja kadrov, ki prinese učinkovito uresničevanje dodeljenih nalog [3].

Najpomembnejše lastnosti kompetenc so skladnost z nalogami, spremenljivost in merljivost [4].

Skladnost z nalogami pomeni sposobnost zaznavanja in prepoznavanja kompetenc med opravljanjem določenih nalog. Za izvrševanje številnih nalog se lahko uporabljajo določene spretnosti ali sposobnosti, hkrati pa lahko nekatere naloge zahtevajo več različnih spretnosti. Za opravljanje ene naloge je lahko potrebna tudi zgolj ena spretnost.

Spremenljivost kompetenc kaže na možnost njihovega razvoja. Ta lastnost je zelo pomembna v postopku upravljanja s kompetencami v smislu usklajevanja

In the era of economy based on knowledge human capital is one of the most significant resources of every corporation. An employee, especially his competency, have become the main source of competitive advantage. A survey conducted by the Educational Research Institute based on 941 polish companies has confirmed the validity of this approach. According to the surveyed companies, the most important resource for entrepreneurs is the above mentioned human capital (47%), and the competency was pointed as most significant among its features (72,2%), followed by qualifications (49,6%) and formal education (39,3%).

The term “competency” in the scope of human resources management is defined as “knowledge, skills, abilities, styles of action, personality, principles, interests and other features that are used and developed in the course of work and lead to achievements consistent with strategic goals of the corporation” [2]. This means that competency is revealed in the result of intentional actions performed by the staff, which facilitate effective realisation of conferred tasks [3].

The most important features of competency are compliance with tasks, variability and measurability [4].

Compliance with tasks stands for the ability to observe and identify the competency during the performance of particular tasks. A certain skill or ability may by used to fulfill a number of tasks, and at the same time some tasks may require several different skills. It is also possible that a single skill is required to carry out a single task.

Variability of competency indicates the possibility of its development. This kompetenc kadrov s sedanjimi in prihodnjimi potrebami organizacije.

Merljivost je enako pomembna lastnost. Omogoča merjenje stopnje kompetence in določanje želene stopnje na osnovi prevzetih lestvic razvoja kompetenc.

Temelj novega trenda v upravljanju s kadri, tj. upravljanje s človeškimi viri na osnovi kompetenc, predstavlja izraz »kompetenca«. Predstavlja alternativo tradicionalnemu pristopu k upravljanju s kadri, izkazalo pa se je, da je neizpodbitno učinkovitejši v spremenljivih okoljih. Omogoča optimalno porazdelitev človeškega kapitala in usklajevanje njegovih kompetenc z zadanimi nalogami, povezan pa je z nenehnim razvojem novih tehnik in tehnologij ter z vedno višjimi zahtevami strank glede kakovosti.

Izvajanje sistema upravljanja s človeškimi viri na osnovi kompetenc zahteva uporabo ustreznih orodij in postopkov. Njegova osnova so kompetenčni model in kompetenčni profili posameznih zaposlenih. Za mnogo podjetnikov je ta pristop še vedno novost in vzbuja številne skrbi. Omejitve pri izvajanju pristopa na osnovi kompetenc so izjemno visoki stroški priprave in uvedbe kompetenčnega modela, dolgotrajnost projekta in oklevanje kadrov, ki jih skrbijo nepredvidljive posledice sprememb v podjetju.

Zaradi vedno večjih interesov glede kompetenc in njihove uporabe v postopkih, ki vključujejo kadre, smo na podlagi te lastnosti (strokovne usposobljenosti) razvili modul Smart Foundry (Pametna livarna). V modulu smo uporabili tehnike razvrščanja in merjenja kompetenc.

Upravljanje kompetenc vključuje nekaj ključnih postopkov – prepoznavanje, razvrščanje in merjenje kompetenc. V pripravljenem modulu usposabljanja smo uporabili elemente razvrščanja in merjenja kompetenc.

feature is of a great importance in the process of competency management in terms of matching the staff competency to both present and future needs of the organisation.

Measurability is an equally significant feature. It allows to measure the level of competency and to determine the desired level based on the adopted scales of competency development.

A new trend of staff management, that being the Competency-Based Human Resources Management, is based on the term “competency”. It is an alternative for the traditional approach to staff management, although it has proven to be undeniably more effective in a changing environment. It allows for the optimal distribution of the human capital, matching its competency to undertaken assignments connected with the constant development of new techniques and technologies and with the increasingly higher quality requirements of customers.

The implementation of competency-based human resources management system requires the use of appropriate tools and procedures. Its basis consists of a competency model and competency profiles of particular employees.

To many entrepreneurs this approach is still an innovation and raises numerous concerns. The limitations of implementing the competency-related approach are excessively high costs of preparing and introducing the competency model, time-consuming nature of the project and the reluctance of staff concerned about the unforeseeable consequences of changes in the company.

In regard to the growing interest in the aspect of competency and its application in staff processes, the training module of Smart Foundry system has been developed based on this very feature – professional competency.

Vsak del kompetence, ki se nanaša na določeno prepoznano in ovrednoteno delovno mesto, mora biti predstavljen na lestvici. Namen je s stopnjami na lestvici določiti, kako uspešno je bila kompetenca pridobljena.

V literaturi na to temo najdemo različne primere lestvic pridobivanja kompetenc, od preprostih, dvostopenjskih lestvic, ki označujejo posedovanje ali pomanjkanje določene kompetence, do večstopenjskih lestvic. Najpogosteje uporabljena je petstopenjska lestvica.

Za izdelavo individualne lestvice pridobivanja kompetenc potrebujemo opise posameznih stopenj njihovega pridobivanja z nedvoumnimi značilnimi vedenji, ki se imenujejo vedenjski kazalniki, enako število stopenj pa moramo uporabiti za vsak posamezni del kompetence.

Uporaba enotnih lestvic pridobivanja kompetenc zagotavlja jasen grafični prikaz, kako dobro je zaposleni pridobil kompetenco, želeno stopnjo te pridobitve, kot tudi vpogled v primanjkljaje in presežke kompetenc.

Merjenje kompetence pomeni, da zaposleni označi trenutno stopnjo pridobljene kompetence v primerjavi z želeno stopnjo. Neposredni nadrejeni ocenjevanega zaposlenega ima ključno vlogo v tem postopku, zlasti v smislu višje ocene kompetence.

Ne glede na uporabljeno metodo je merjenje kompetence oblika ocenjevanja zaposlenega, ki zagotavlja povratno informacijo. Primarni cilj te metode je povečanje motiviranosti in spodbujanje zaposlenih k večji učinkovitosti pri opravljanju njihovih dolžnosti. Način, kako zaposleni prejme povratno informacijo, ima velik vpliv na njegovo delovno učinkovitost.

Techniques of competency scaling and measuring have been applied in this component.

Competency management includes a few key processes – identification, scaling and measurement of the competency. Elements of competency scaling and measuring have been applied in the prepared training module.

Each piece of competency referring to a particular work station that has been identified and undergoes evaluation has to be represented on a scale. This serves the purpose of defining how well the competency has been acquired with levels on an adopted scale.

The literature of the subjects gives various examples of competency scales, ranging from a simple, two-level scale showing the possession or a lack of a certain competency to a multi-level scales. The most commonly used is a five-level scale.

Creating an individual competency scale requires descriptions of particular levels of its acquisition with unambiguous characteristic behaviours, which are called behavioural indicators and application of the same number of levels to each piece of competency.

The use of uniform competency scales provides a clear graphic presentation of how well an employee has acquired the competency, a desired level of this acquisition and a view of competency gaps and surpluses.

Competency measurement consists in indicating the current level of competency acquisition by the employee in reference to the desired level. A direct supervisor of the evaluated employee plays a vital role in this process, especially in regard to the increase of competency assessment.

Regardless of the method adopted, the competency measurement process is a form

Uporaba kompetenc pri strokovnem razvoju zaposlenega

Proces strokovnega razvoja zaposlenega se začne z analizo potreb po usposabljanju, pri kateri se uporabijo informacije, pridobljene s kompetenčnim profilom posameznih delovnih postaj. Njegov končni učinek je določanje neskladij med trenutnimi kompetencami zaposlenega in kompetencami, ki so potrebne za ustrezno učinkovitost pri opravljanju dodeljenih nalog. Na tej stopnji vsebuje povratna informacija podatke o primanjkljajih in presežkih kompetenc, ki so običajno predstavljeni v grafični obliki.

Na podlagi prepoznanih primanjkljajev kompetenc lahko kadrovska služba začne z izvajanjem ustreznih programov razvoja. Postopek se začne, če lahko prepoznana neskladja nadomestimo z ustreznimi usposabljanji [5].

Poleg različnih metod usposabljanja se lahko postopek razvoja strokovne usposobljenosti izvaja na podlagi prenosov znanj, promocij, učenja od izkušenejših zaposlenih in različnih oblik »coachinga« in mentorstva. Njegov namen je pripraviti zaposlenega na to, da bo opravljal vedno zahtevnejše naloge in prevzel več odgovornejših delovnih mest [6].

Pristop livarskih družb k upravljanju s človeškimi viri

Specifična narava livarstva zahteva sodelovanje več kvalificiranih zaposlenih, vključno s konstruktorji in tehnološkimi inženirji. Raziskava, ki so jo opravili v poljskih livarnah, je pokazala, da imajo v konstruktorskih (tehnoloških) pisarnah potrebe po naslednjih kadrih: tehnološki inženir, strukturni inženir, vodja metalurg in vodja tehnološkega oddelka.

of evaluation of the employee that yields feedback. Its primary goal is to increase motivation and encourage employees to enhance the performance of their duties. The manner in which the feedback is communicated to the employee has a major impact on its effectiveness.

Use of Competency in Employee Professional Development

The process of employee development starts with an analysis of training needs that employs the information given in the competency profiles of particular work stations. Its final effect is the identification of discrepancies between current competency of the employee and competency needed for proper performance of conferred assignments. In this stage, feedback contains information on competency gaps and surpluses, usually presented in a graphical form.

The identified competency gaps urge the Human Resources department to start adequate development programs. The process is commenced if the revealed discrepancies can be compensated with appropriate trainings [5].

Apart from various training methods, the process of competency development can be conducted based on transfers, promotions, learning from a more experienced employee and different forms of coaching and mentoring. Its purpose is to prepare the employee to carry out more and more complex tasks and take more responsible positions [6].

Casting Corporation’s Approach to HRM

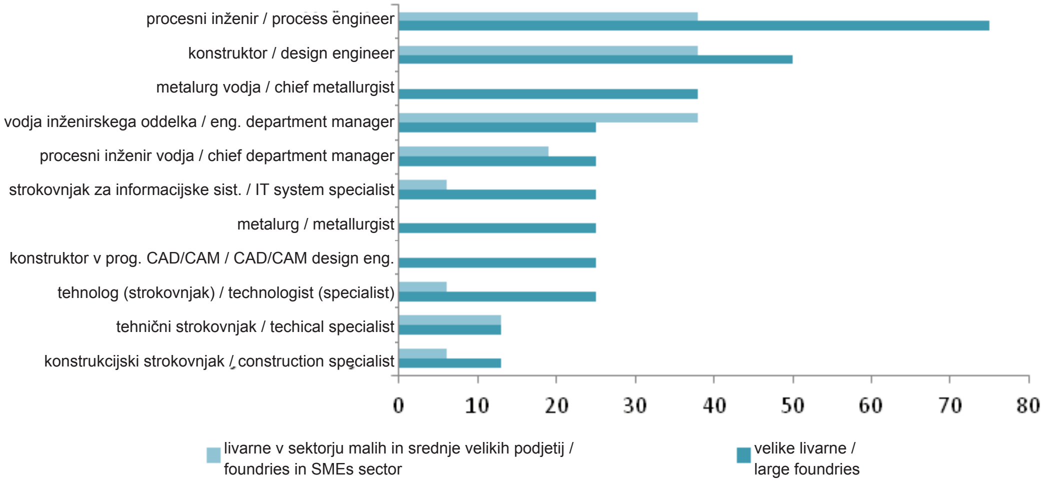
The specific nature of casting requires involvement of numerous qualified employees, including designers and technology engineers.

A survey conducted on a group of Polish foundries has shown that within the

V velikih livarnah je tehnološka ekipa sestavljena iz številnih strokovnjakov, ki so odgovorni za posamezne naloge, medtem ko v malih in srednje velikih podjetjih ekipe sestavljajo predvsem tehnološki in strukturni inženirji. Te razlike nastajajo zaradi

design (technological) office there is a need for positions such as: technology engineer, structural engineer, chief metallurgist and head of technology department.

In major foundries technology team consists of numerous specialists responsible



Slika 1. Kadri v inženirskem oddelku v livarni

Figure 1. Positions in engineering department in foundry

Slika 2. Osnovne kompetence, ki se pričakujejo od kandidatov za delovna mesta

Figure 2. Basic competencies expected from job candidate

zahtevnosti proizvodnega procesa, obsega in narave proizvodnje ter finančnega ozadja družb.

Kljub vedno večji potrebi po strokovnjakih na področju livarstva že leta opažamo pomanjkanje ustrezno kvalificiranih kadrov. Razlog je zlasti omejena izobrazba na tem področju in manjša priljubljenost livarskega poklica.

Pomanjkanje ustrezno kvalificiranih delavcev in omejene zmogljivosti na tem področju so razlogi za uvedbo sistema upravljanja s človeškimi viri na osnovi kompetenc [1].

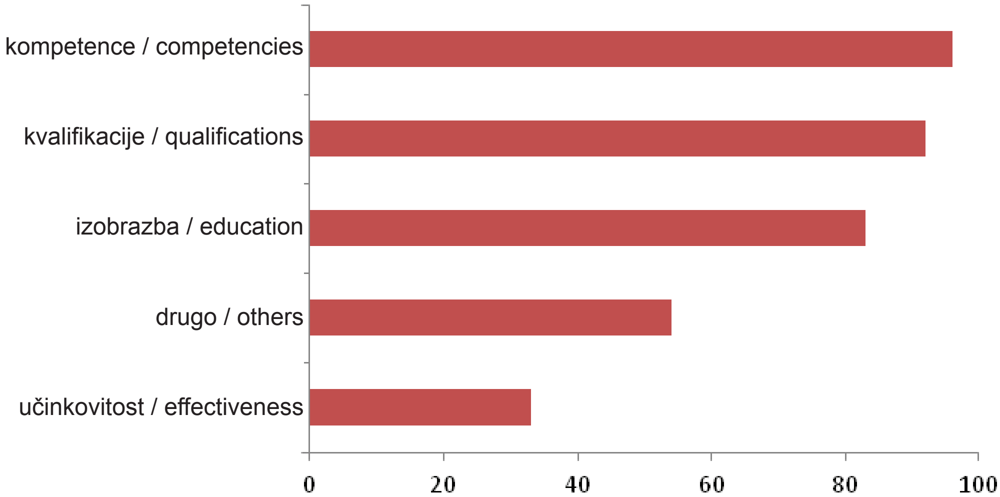
Ta koncept vedno pogosteje uporabljajo družbe v livarski industriji. Študija, ki smo jo izvedli, je pokazala, da se je 67 % anketiranih livarn strinjalo z izvajanjem pristopa upravljanja s človeškimi viri na osnovi kompetenc, kar nakazuje, da so kompetence zaposlenih po njihovem mnenju eden ključnih virov. Opisi delovnih mest se v livarskih družbah uporabljajo pogosto, medtem ko je redno ocenjevanje zaposlenih redka praksa. 96 % anketiranih

for particular tasks, whereas in small and medium-sized foundries teams are based mainly on the technology and structural engineers. Those differences are caused by the the production process complexity, capacity and nature of production as well as the corporation's financial background.

Despite the growing demand for specialists in the field of casting, the lack of appropriately qualified staff has been observed for years. It is caused mainly by limited education in this scope and the decrease in the popularity of foundry worker profession.

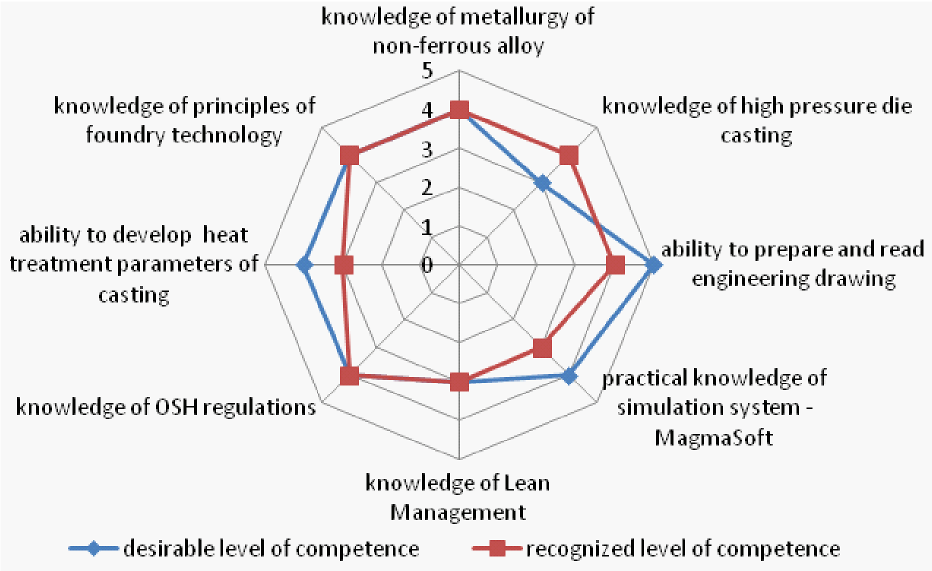
Shortage of properly qualified employees and limited capability in this area stimulate the implementation of competency-based human resource management system [1].

This concept is more and more often employed by corporations operating in the casting industry. A self study has shown that as much as 67% of surveyed foundries declare competency-based approach to HRM which indicates that employees'



Slika 3. Ključni profili v postopku pridobivanja novih delavcev v livarnah

Figure 3. Key profiles in recruitment process in foundries



Slika 4. Primer sheme kompetenc

Figure 4. Example of competency star

družb se zaveda potrebe po strokovnem razvoju svojih kadrov in izvaja različne ukrepe, povezane z razvojem, med katerimi sta najpogostejša mentorstvo in interno usposabljanje.

Modul usposabljanja Smart Foundry

Modul usposabljanja Smart Foundry smo razvili na osnovi analize strukture kadrov, ki smo jo izvedli za potrebe livarske industrije, in priljubljenosti kompetenčnega pristopa (oziroma njegovih elementov) v livarskih družbah. V modulu so uporabljena orodja sistema upravljanja s človeškimi viri na osnovi kompetenc, namenjen pa je inženirskim kadrom, zaposlenim na različnih oddelkih livarskih družb. Glavni namen tega modula je prepoznati primanjkljaje kompetenc zaposlenih in določiti predmete usposabljanja za odpravljanje teh primanjkljajev.

competency is regarded as one of the key resources. Work station descriptions are commonly used in casting corporations, whereas periodic evaluation of employees is a rare practice. In the scope of professional development of employees as much as 96% respondents are conscious of the need for the development of their staff and take various development-related steps, mentoring and internal training being the most common.

Smart Foundry - Training Module

The Smart Foundry training module has been developed on the basis of staff structure analysis carried out for the needs of casting industry and the popularity of the competency-based approach (or its elements) in casting corporations. The module uses tools of the competency-based human resource management system

Na podlagi ankete smo sestavili seznam glavnih nalog, ki se dodeljujejo procesnim inženirjem (livarskim tehnologom, metalurškim tehnologom, tehnologom za litje v pesek) in ki jih ti opravljajo v različnih celicah livarne, ter kompetenc, ki so uporabne pri njihovem izvajanju. Stopnjo pridobivanja kompetenc smo opisali s pomočjo petstopenjske lestvice, pri čemer stopnja 1(A) pomeni pomanjkanje kompetence, 5(E) pa pomeni strokovnjaka na določenem področju.

Oseba, ki upravlja z modulom – uporabnik, mora najprej s pomočjo preverjanja označiti ključne kompetence, ki so potrebne za določeno delovno mesto in se uporabljajo za opravljanje nalog, dodeljenih temu delovnemu mestu. Vsota vseh označenih delov kompetence mora biti med 8 in 12, zato je treba označiti samo ključne spretnosti, sposobnosti itn., ki so najpomembnejše za neko delovno mesto in pripadajoče naloge.

Profil ocenjevanega zaposlenega mora sovpadati s kompetenčnim profilom tega zaposlenega v podjetju, ki se poslužuje modula. Ta bo pozneje omogočal ustrezno dodeljevanje želene kompetence in njenih stopenj ter vmesno ocenjevanje trenutno prepoznanih stopenj kompetence.

V naslednjem koraku je treba zbrati podrobne opise stopenj pridobivanja posameznih delov kompetenc skladno s prevzeto petstopenjsko lestvico. Natančni in točni opisi posameznih stopenj pomenijo zanesljive ter točne povratne informacije glede potrebnega usposabljanja.

Modul zahteva tudi vnos želenih delov kompetenc in rezultatov preverjanj zaposlenih (diagnosticirane stopnje) v sistem.

Vneseni podatki so nato predstavljeni na shemi kompetenc, ki jasno prikazuje prepoznane primanjkljaje in presežke kompetenc. Najpomembnejši končni podatki and is dedicated to the engineering staff employed in various departments of the casting corporation. The main purpose of this component is to identify the employees' competency gaps and determine the subjects of trainings to address them properly.

Based on a survey, a list of main tasks assigned to process engineers (casting technologist, metallurgy technologist, molding sand technologist) has been compiled, which are performed in different cells of the foundry and competency useful in their realisation. The competency acquisition level has been described with a five-level scale, where 1(A) level stands for the lack of competency and 5(E) – indicates an expert in the particular field.

A person handling the module – a user must first indicate the key pieces of competency required for a particular (undergoing a verification) position, employed for the performance of tasks assigned to that position. The sum of all indicated pieces of competency should be between 8 and 12, therefore only key skills, abilities, etc. should be indicated, which are those of the greatest significance in regard to the position and tasks assigned to it.

The profile of the evaluated employee should coincide with the competency profile of that very employee in the company employing the module. It will later allow to properly allocate the desired competency and its levels and use the interim evaluation to indicate currently identified competency levels.

Next stage comprises in compiling thorough, detailed descriptions of acquisition levels for specific pieces of competency in accordance with the adopted 5-level scale. Preciseness and accuracy of the descriptions of particular levels results in reliable and accurate feedback concerning necessary trainings.

modula usposabljanja so informacije o področjih, ki jih morajo usposabljanja pokriti, in o predmetu takšnih usposabljanj.

Informacije o presežkih kompetenc se lahko uporabijo za imenovanje »coachev« za notranja usposabljanja na področju zanimanja, kjer se pojavljajo presežki.

V primeru družb, ki s človeškimi viri upravljajo po tradicionalnih postopkih, lahko modul usposabljanja Smart Foundry služi kot orodje za opise delovnih postaj na osnovi kompetenc in za izvajanje rednih ocenjevanj zaposlenih, vključno s kompetenčnim vidikom.

Izvajanje tega modula poteka v dveh korakih:

Korak 1 – oblikovanje kompetenčnega modela, tako imenovana knjiga kompetenc, ki je sestavljena iz določanja delov kompetenc, ki so ključne za podjetje, in izvajanja diagnoz zaposlenih, ki so kompetenčno ustrezni za celotno organizacijo.

Korak 2 – oblikovanje kompetenčnih profilov, t. i. opisi delovnih mest z deli kompetenc, zbranimi v knjigi [7].

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Subsequently, the module requires that the given desired pieces of competency and results of the verified employee evaluation (the diagnosed levels) are entered to the system. The entered data is presented on a radar chart (a so-called competency star) that clearly shows the identified gaps and surpluses of competency. The ultimate outcome data of the training module is the information about the areas that need to be covered with trainings and about the subject of such trainings.

The information on the competency surpluses can be used to designate the coaches for internal trainings in the area of interest to which the surpluses apply.

In case of corporations employing traditional human resources management processes, the training module of Smart Foundry system may serve as a tool for creating competency-based descriptions of work stations and for conducting periodical evaluations of employees that include the competency aspect.

The course of this module can be presented with two stages:

Stage 1 - creation of competency model, the so-called competency book, that comprises in determining the pieces of competency that are pivotal for the company and conducting a diagnosis of employee competency appropriate for the whole organisation.

Stage 2 - creation of competency profiles, i.e. descriptions of work stations with the pieces of competency compiled in the book [7].

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Načini izboljšanja mehanskih lastnosti recikliranih aluminijevih zlitin

Ways to Improve Mechanical Properties of Recycled Aluminium Alloys

Izvleček

Poraba aluminija in aluminijevih zlitin po svetu narašča, ti materiali pa se uporabljajo na vedno nove načine. Aluminij se lahko proizvaja iz surovine, imenovane boksit, ali z recikliranjem odpadnega aluminija. Pri recikliranju aluminija je trdnost materiala odvisna od kakovosti staljene kovine ter legirnih elementov in elementov v sledeh v odpadnem aluminiju. Od trdnosti materiala litih izdelkov se veliko pričakuje in trg nenehno povprašuje po materialu, ki ima pravo in zanesljivo kakovost.

V tem prispevku smo želeli raziskati načine za izboljšanje mehanskih lastnosti recikliranih aluminijevih zlitin, osnova katerih je zlitinski sistem Al-Si. Proučili smo vpliv vsebnosti vodika na notranjo poroznost materiala in učinek legirnega elementa silicija (Si) na mehanske lastnosti materiala.

Vsebnost vodika smo med procesom recikliranja na določenih mestih merili z indeksom gostote (v talilnici) in z različnimi razplinjevalnimi metodami. Indeks gostote je merilo za merjenje in primerjavo vzorcev ob upoštevanju notranje poroznosti. Ker zrak vsebuje vlago, to vpliva na topnost vodika v talini in temperaturo taline. Rezultati nateznih preizkusov in mikroskopske raziskave jasno razkrivajo, da razlike v vsebnosti zlitinskih elementov vodijo v izjemne razlike v mehanskih lastnostih.

Ključne besede: aluminij, recikliranje, legirni elementi, litje, strjevanje, vodik, mehanske lastnosti, mikrosturktura

Abstract

The aluminium and aluminium alloys consumption in the world is increasing and continues to find new applications. Aluminium can be produced from the raw material bauxite or by recycling aluminium scrap. When aluminium is being recycled the material strength is depending on the molten metal quality as well as the alloying and trace elements in the aluminium scrap. High demands are put on the material strength of cast products and the market is continuously asking for a material with the right and reliable quality.

This paper aims to investigate ways to improve the mechanical properties of recycled aluminium alloys based upon the Al-Si alloy system. The influence of hydrogen content on internal porosity and the sole effect of the alloying element Si on the mechanical properties have been studied.

The hydrogen content has been measured by Density Index at specific locations in the recycling process (at the smelter) and with different degassing methods. Density Index is a

measure for measuring and comparing the samples with respect to the internal porosity. As the air contains moisture, along with the melt temperature, the solubility of hydrogen in the melt is affected. Furthermore, the tensile test results and microscopic investigations reveal clearly that the variations within the alloying element range lead to remarkable differences in the mechanical properties.
Keywords: Aluminium, recycling, alloying elements, casting, solidification, hydrogen, mechanical properties, microstructure

1 Uvod

V zadnjih letih se je število različnih vrst uporabe aluminijevih ulitkov povečalo zaradi njihove lahkosti, visoke trdnosti glede na težo, prožnosti in izjemne vsestranskosti. Toda ena lastnost je še posebej cenjena. Aluminij lahko recikliramo v nedogled. Ne glede na to, kolikokrat ga obdelamo in uporabimo, ostane tako rekoč nespremenjen. Zato je aluminij material s trajnimi lastnostmi, material, ki ni potrošen, ampak ga lahko uporabljamo vedno znova brez izgube njegovih najpomembnejših lastnosti. Za pretaljevanje aluminija potrebujemo malo energije: v procesu recikliranja je potrebne le 5 % energije, ki je potrebna za proizvodnjo primarne kovine [1–3].

Zahteve glede kakovosti aluminijevih zlitin pri pretaljevanju opredeljuje evropski standard EN 1676:2010. Ta standard razvršča in določa te lastnosti, proizvodne pogoje, njihove lastnosti in identifikacijske oznake [4]. Standard določa omejitve glede kemijske sestave aluminijevih zlitin za litje in mehanske lastnosti posameznih poskusnih litih vzorcev teh zlitin [5]. Ti standardi predstavljajo referenčne smernice za sektor, ki se ukvarja z litjem aluminijevih zlitin in s proizvodnjo ulitkov.

Kakovost aluminijevih ulitkov je v veliki meri odvisna od procesa litja in parametrov, kot so hitrost strjevanja, vendar pa tudi kemijska sestava pomembno vpliva na njihove mehanske lastnosti [6].

1 Introduction

The use of aluminium cast components in so many different applications has increased in recent years thanks to their light weight, high strength to weight aspect ratio, flexible and very versatile. But there’s one quality that is particularly most valuable. Aluminium is infinitely recyclable. It remains essentially unchanged no matter how many times it is processed and used. Therefore, aluminium be considered as a material with permanent characteristics, one that is not consumed, but used over and over again, without the loss of its essential properties. The remelting of aluminium requires little energy: no more than 5 % of the energy required to produce the primary metal initially is needed in the recycling process [1-3].

The quality requisites of aluminium alloys intended for remelting is defined by European Standard EN 1676:2010. This standard specifies the classification and designation that apply to these qualities, manufacturing conditions, their features and identification markings [4]. The standard specifics the chemical composition limits of aluminium alloys for casting and the mechanical features of the separate casting test specimens for said alloys [5]. These standards are reference guidelines in the world of foundry aluminium alloys and casting manufacturing.

The quality of aluminium components mainly depends on casting process and parameters, such as solidification rate, Ena od največjih težav, povezanih z litjem aluminijevih zlitin, je mikroporoznost. O soodvisnosti poroznosti in mehanskih lastnosti litih aluminijevih zlitin je pisalo veliko avtorjev [7–10]. Za določanje te soodvisnosti v večini študij uporabljajo parameter globalne volumetrične poroznosti. Med procesom litja in strjevanja nastajajo plini, ki povzročajo mikroporoznost. Plini so lahko posledica reakcije med formo iz peska in kovino ali pa se med strjevanjem sproščajo plini, raztopljeni v tekoči kovini. Najpomembnejši plin, ki je precej topen v aluminiju in njegovih zlitinah, je vodik. Topnost vodika v aluminiju se spreminja neposredno s temperaturo in kvadratnim korenom tlaka – topnost hitro narašča z naraščanjem temperature nad likvidusom. Škodljive učinke poroznosti na mehanskih lastnosti litih aluminijevih zlitin je veliko avtorjev proučevalo več let [11–17].

Izvedli so veliko študij, v katerih so raziskovali učinek posameznih spremenljivk na lastnosti litih zlitin Al-Si-Mg in predvsem vsebnost bakra (Cu), magnezija (Mg) in železa (Fe). V nekaterih študijah [18, 19] poudarjajo, da je zaradi trojne evtektične reakcije pri približno 525 °C vsebnost bakra v evtektični talini visoka, kar poveča volumetrično krčenje med strjevanjem in poroznost ter tako zmanjša trdnost izdelkov. Druge študije [20, 21] kažejo, da se trdnost teh zlitin izboljšuje z dodajanjem bakra do 5 %.

Učinek legirnih elementov silicija, bakra, magnezija, mangana in železa na mehanske lastnosti reciklirane aluminijeve zlitine EN AB-46000 je proučeval Dugic in sod. [22] s proizvajanjem usmerjeno strjenih vzorcev z malo napakami. V tej študiji rezultati nateznih preizkusov in mikroskopskih raziskav jasno odkrivajo, da razlike v količini zlitinskih elementov vodijo v izjemne razlike v mehanskih lastnostih, ki znašajo do 73 MPa v natezni trdnosti

but also chemical composition, obviously, significantly affects the mechanical properties [6].

One of the most serious problems associated with the casting of aluminium alloys is the micro porosity. The correlation between the porosity and mechanical properties of cast aluminium alloys have been discussed by many authors [7-10]. Most of these studies use the parameter of global volumetric porosity to determine this correlation. During the casting and solidification process, the evolutions of gases cause the micro porosity. The gases may be the result of a reaction between the casting sand mould and the metal, or they may result from the evolution of gases dissolved in the liquid metal during solidification. The most important gas that is appreciably soluble in aluminium and its alloys is hydrogen. The solubility of hydrogen in aluminium varies directly with temperature and the square root of pressure; solubility increases rapidly with increasing temperature above the liquidus. The detrimental effects of porosity on the mechanical properties of cast aluminium alloys have been studied for many years and by many authors [11-17].

Many studies have been carried out in order to investigate the effect of single variables on the properties of cast Al-Si-Mg alloys and especially the Cu, Mg and Fe content. Some studies [18,19] emphasize that due to ternary eutectic reaction at about 525°C, the Cu content in the eutectic melt is high which increases volumetric shrinkage during solidification and porosity and thus decreasing the strength of components. Other studies [20,21] reveal that the strength of these alloys are improved as Cu is added up to level of 5%.

The sole effect of the alloying element range of Si, Cu, Mg, Mn and Fe on the mechanical properties of the recycled in 49 MPa v meji plastičnosti. Raztezek do razpoke je prav tako posledica legirnih elementov, in sicer zaradi večje vsebnosti intermetalnih spojin.

Cilj tega prispevka je proučiti vpliv vsebnosti vodika na nastajanje notranje poroznosti in učinek legirnega elementa silicija, brez vpliva bakra, železa ali drugih sestavin, ki jih najdemo v sekundarnih zlitinah, na mehanske lastnosti zlitin na osnovi Al-Si.

2 Materiali in metode

Za proučevanje vsebnosti vodika in razplinjevanja smo izbrali dve različni vrsti zlitin (EN AB-46000 in EN AB-43400) skladno z evropskim standardom EN 1676:2010. Sestavi obeh zlitin sta navedeni v preglednici A.1 v dodatku A. Vsebnost vodika smo na določenih mestih v različnih stopnjah procesa ocenjevali z indeksom gostote, kakovost taline pa smo spreminjali z različnimi metodami razplinjevanja. Indeks gostote je merilo za merjenje in primerjavo vzorcev ob upoštevanju njihove notranje poroznosti. V merjenje smo vključili dva vzorca. Prvi vzorec iz vsake skupine smo postavili v vakuumski stroj, kjer se je strdil v vakuumu (označen z V). Stroj je nastavljen tako, da deluje štiri minute pri znižanem tlaku 80 mbar. Drugi vzorec se je strdil na zraku pod atmosferskim tlakom (označen z A). Indeks gostote smo izračunali po enačbi 1.

$$DI = \frac{D_A - D_V}{D_A} \times 100 \ [\%] \qquad (1)$$

DI = indeks gostote, [%]
D_A = gostota vzorca, ki se je strdil pod atmosferskim tlakom, [kg/dm^3]
D_V = gostota vzorca, ki se je strdil v vakuumu, [kg/dm^3].

aluminium alloy EN AB-46000 by producing directional solidified samples with low defect levels have been investigated by Dugic et al [22]. In this study the tensile test results and microscopic investigations reveal clearly that the variations within the alloying element range lead to remarkable differences in the mechanical properties, that can be quantified to 73 MPa in tensile strength and 49 MPa in yield strength. The elongation to failure was also affected as a function of the alloying elements which is due to increased levels of intermetallics.

The aim of this paper is to discuss the influence of hydrogen content on the internal porosity formation and the sole effect of the alloying element Si, without any interaction from Cu, Fe and other constituents found in secondary alloys, on the mechanical properties of Al-Si based alloys.

2 Materials and Methods

Two different types of alloys (EN AB-46000 and EN AB-43400) regarding to the European Standard EN 1676:2010 were selected for the investigations of the hydrogen content and degassing. The compositions of the both alloys are given in Appendix A, table A.1. The hydrogen content was evaluated by Density Index (DI) at specific locations, at different stages in the process and the melt quality has been been varied with different degassing methods. DI is a measure for measuring and comparing the samples with respect to the internal porosity. A measurement includes two samplings. The first sample in each group is placed in a vacuum machine, where it solidifies during vacuum (labelled with V). The machine is set to run at 80 mbar reduced pressure for four minutes. The second sample solidifies free in air, during

Pri procesu razplinjevanja v livarni uporabljajo tradicionalno mešanico dušika in klora. Danes so na trgu zelo razširjene soli klorovih in fluorovih spojin, ki se v livarnah uporabljajo zelo pogosto. Za merjenje učinkovitosti te soli v procesu razplinjevanja smo po običajnem procesu razplinjevanja uporabili še razplinjevalno sol na osnovi klora ($MgCl_2$). Sol proizvaja družba Hoersch GmbH pod trgovskim imenom Dursalite.

Da bi proučili učinek silicija na mehanske lastnosti zlitin Al-Si brez neposrednega vpliva poroznosti, oksidov in/ali intermetalnih spojin, smo uporabili tehniko usmerjenega strjevanja. Osnovni material za to študijo je bil Al-7%Si-0,4%Mg, pri čemer smo ulili šest zlitin z različnimi koncentracijami silicija, modificiranimi s približno 100–150 ppm Sr. Kemijsko sestavo posamezne zlitine smo določili z uporabo optične emisijske spektometrije SPECTROMAXx in je prikazana v preglednici 1.

Preglednica 1: Kemijska sestava

Table 1: Chemical composition

Element	Si	Mg	Fe	Sr	Ti	Al
AIA	6,55	0,40	0,1	0,0150	0,13	Bal.
AIB	10,09	0,40	0,2	0,0104	0,13	Bal.
AIC	11,40	0,39	0,2	0,0100	0,13	Bal.
AID	12,50	0,39	0,2	0,0140	0,12	Bal.
AIE	13,03	0,39	0,2	0,0090	0,12	Bal.
S	14,46	0,38	0,2	0,0117	0,12	Bal.

Vzorce, cilindrične palice (dolžina 20 cm, premer 1 cm), smo ulili v stalno bakreno formo. Lite palice smo nato pretalili in segreli do 710 °C za 30 minut v argonski atmosferi (Ar) s tehniko postopnega strjevanja (slika 1) v Bridgmanovi peči ter usmerjeno strjevali, tako da smo dobili vzorce z mikrostrukturo, ki je enaka kot pri tlačnem litju, s širino sekundarnih dendritnih vej (SDAS) 8–10 µm. Povprečno vrednost SDAS iz 10 meritev z

atmospheric pressure (labelled with A). The DI was calculated according to eq 1.

$$DI = \frac{D_A - D_V}{D_A} \times 100 \ [\%] \qquad (1)$$

DI = Density Index, [%]

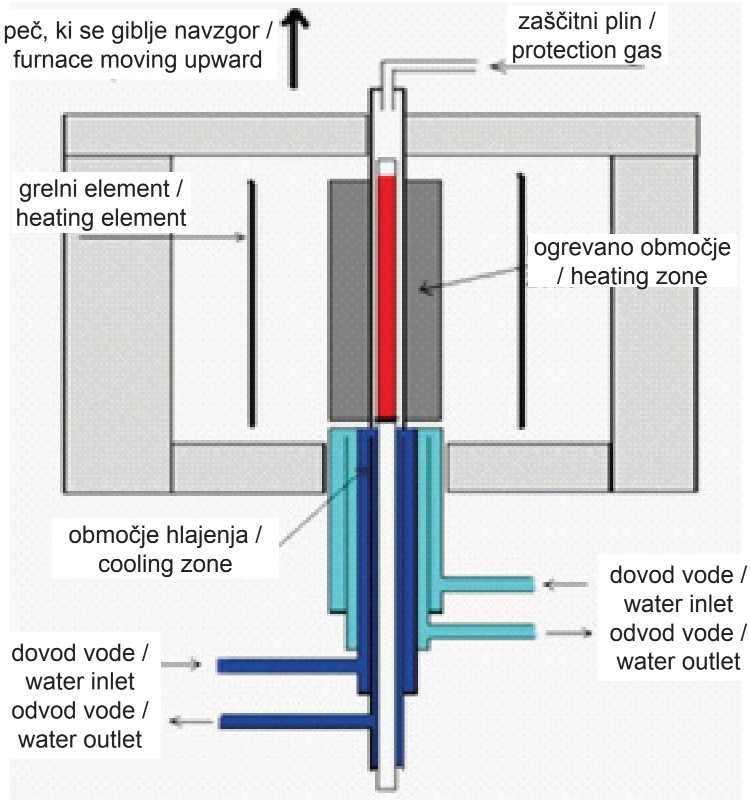
D_A = the density of the sample which solidified during atmospheric pressure, [kg/dm^3]

D_V = the density of the sample which solidified during vacuum pressure, [kg/dm^3].

The degassing process used in the cast house is a traditional gas blend of nitrogen and chlorine gas. In the market today salt of chlorine and fluorine compounds are widely spread and is the one commonly used among cast houses. In order to measure the efficiency of such salt in the degassing process, chlorine based degassing salt ($MgCl_2$) was carried out after the normal degassing process. The salt is manufactured as Dursalite from Hoersch GmbH.

In order to investigate the sole effect of Si on the mechanical performance of Al-Si alloys without any direct impact of porosity, oxides and/or intermetallics, the directional solidification technique has been employed. The base material for this study was Al-7%Si-0.4%Mg where six alloys with variation of Si concentration were cast, modified with approximately 100-150 ppm Sr. The chemical composition of each alloy were obtained using SPECTROMAXx optical emission spectroscopy, see table 1.

Samples, initial cylindrical rods (length 20 cm, diameter 1 cm) were cast in a permanent copper mold. The cast rods were then re-melted remelted and heated to 710°C for 30 minutes under Ar-atmosphere in the gradient solidification technique, see figure 1, using a Bridgman



Slika 1. Shema peči za usmerjeno strjevanje

Figure 1. A scheme of the directional solidification furnace

usmerjenim strjevanjem smo izvedli v vseh pogojih.

3 Rezultati in razprava

3.1 Meritve indeksa gostote taline v rotacijski peči

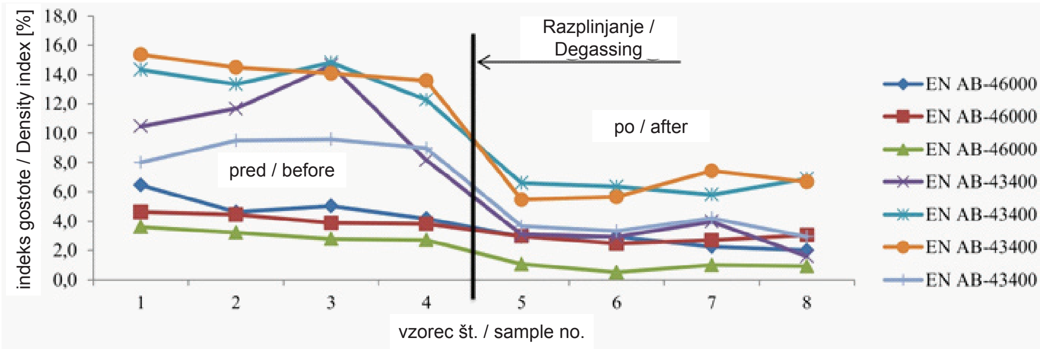
Indeks gostote pred procesom razplinjevanja in po njem je osvetljen na sliki 2. Različne krivulje predstavljajo tri različne ulitke zlitine EN AB-46000, poimenovane C1–C3, in štiri različne ulitke (C1–C4) zlitine EN AB-43400.

furnace and directionally solidified in a way to produce samples with microstructures corresponding to high pressure die cast ones with a secondary dendrite arm spacings (SDAS) of 8-10 μm. An average SDAS offrom 10 measurements offrom the directional solidification direction has been carried out in all conditions.

3 Results and Discussion

3.1 The Density Index Measurements from the Melt in The Rotary Furnace

The density index before and after the degassing process are highlighted in figure 2. The various curves illustrate three



Slika 2: Povprečne vrednosti indeksa gostote iz štirih preizkusnih serij pred razplinjevanjem sedmih različnih posameznih šarž in po njem

Figure 2: The average density index values from four test series before and four after degassing of seven individual charges of metal

Kot lahko vidimo, zlitina EN AB 46000 izkazuje povprečno nižji indeks gostote kot EN AB 43400. Višji indeks gostote je lahko posledica višje prvotne vsebnosti vodika, višje ravni vključkov in/ali oksidov. Rezultati razplinjevanja jasno kažejo na učinkovitost tega procesa. Indeks gostote se je po razplinjevanju s 16 % znižal na 6–8 % za zlitino EN AB 43400 in s 7 % na 1–2 % za zlitino EN AB 46000. V tem primeru lahko talilnica do neke mere zagotovi visoko kakovost taline v ingotih po ustreznem razplinjevanju.

Glavne razlike v kemijski sestavi med zlitinama EN AB-43400 in EN AB-46000 so 2,5 % Cu, 0,8 % Zn, 0,6 % Si, 0,1 % Mg, 0,1 % Fe, 0,08 % Mn, vendar so razlike tudi v drugih elementih, ki so različno uravnavani. Silicij je edini zgoraj omenjen element, za katerega je znano, da niža topnost vodika v aluminijevih zlitinah. Drugih pet omenjenih elementov poveča topnost vodika in najverjetneje predstavlja dejavnik, zaradi katerega se razlikuje topnost med obema vrstama zlitin.

Baker je zlitinski element, katerega delež se med sestavama (2,5 wt. %) obeh zlitin najbolj razlikuje, kar v največji meri

different charges of an EN AB-46000 type of alloy, named C1-C3 and four different charges (C1-C4) of EN AB-43400.

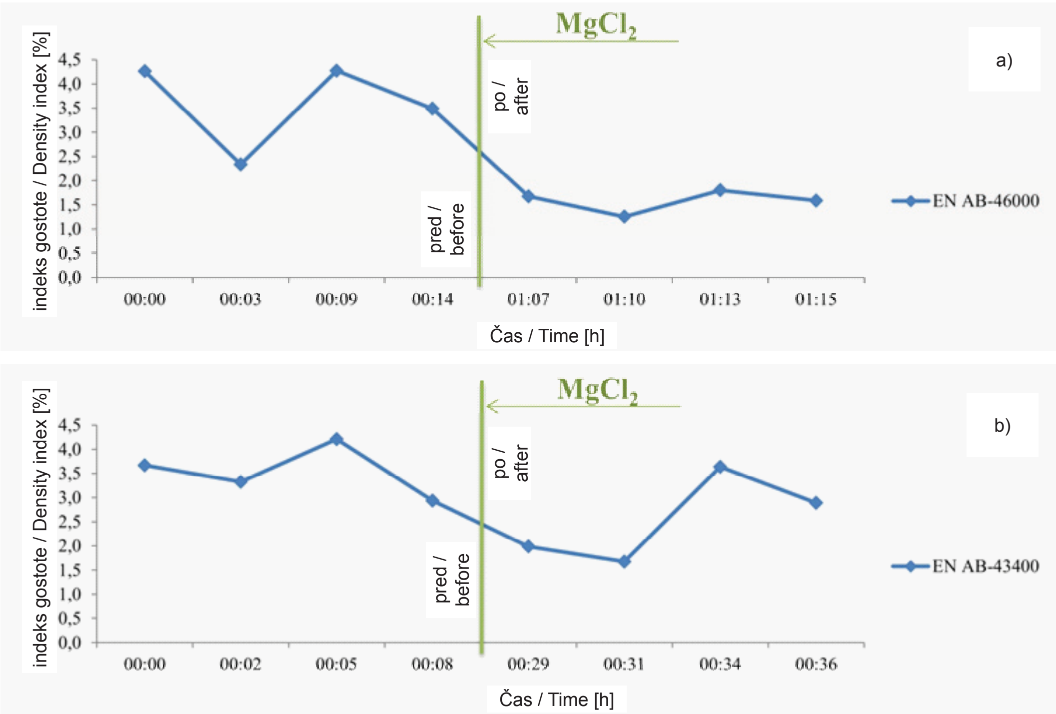
As can be observed, the EN AB 46000 alloy exhibits generally lower DI than the EN AB 43400 alloy. The higher DI could be due to higher initial hydrogen content, higher level of inclusions and/or oxides. The degassing however clearly demonstrates its effectiveness; the DI after the degassing operation drops from approximately 16% down to 6-8 % for the EN AB 43400 alloy and from approximately 7 % down to 1-2 % for EN AB 46000. Hereby the smelter can in this case to some extent guarantee a high level of melt quality in the ingots after a proper degassing.

The main differences in the chemical composition between alloys EN AB-43400 and EN AB-46000 are 2.5 % Cu, 0.8 % Zn, 0.6 % Si, 0.1 % Mg, 0.1 % Fe, 0.08 % Mn, but also the other elements that are regulated differently. Corresponding to the hydrogen solubility [17], Si is the only element mentioned above, that is known to decrease the solubility of Hydrogen in aluminium alloys. The other five mentioned elements increase the hydrogen solubility prispeva k zmanjšanju topnosti vodika v zlitini EN AB-46000. Obdelava aluminijevih zlitin v livarnah je danes pogosto standardizirana, ne glede na vrsto zlitine ali druge dejavnike, kot je vlažnost. Likvidus temperature je v veliki meri odvisen od vsebnosti silicija v aluminijevi zlitini, topnost vodika pa je odvisna tudi od koncentracij drugih elementov. Ta prispevek potrjuje teorijo o topnosti vodika in daje predloge za različne načine obdelave aluminijevih zlitin v odvisnosti od dejavnikov, ki vplivajo na vsebnost vodika.

Po tradicionalnem postopku razplinjevanja in s pridobljenimi rezultati, ki so razvidni iz slike 2, smo izvedli dodatno obdelavo, da bi ugotovili, ali je mogoče

and are likely the factor that differ the solubility between the two types of alloy.

Between the two alloys, Cu is the alloying element that has the greatest difference in percentage between the compositions (2.5 wt %), which contributes the most to the decrease of the hydrogen solubility for the EN AB-46000 alloy. The metal treatment of aluminium alloys in a cast house are today often standardized no mater of the type of alloy or other factors as the humidity. The liquidus temperature is much dependent of the Si content in an aluminium alloy, but the hydrogen solubility is also depending on other element concentrations. This article sates the theory of the hydrogen solubility and gives suggestions on how to work with



Slika 3. Izhodni podatek meritve indeksa gostote za vrsto zlitine EN AB-46000 je prikazan na sliki a), na sliki b) pa indeks gostote za zlitino EN AB 43400

Figure 3. The output from the DI measurement for the EN AB-46000 type of alloy in a) while b) demonstrates the DI for the EN AB 43400 alloy

indeks gostote še nekoliko znižati. Uporabili smo razplinjevalno sol $MgCl_2$ in rezultate predstavili na sliki 3 za obe vrsti zlitine (EN AB-46000 in EN AB-43400) posebej. Rezultati na slikah 3 a in b prikazujejo štiri meritve po prvem postopku razplinjevanja in štiri meritve po obdelavi s soljo $MgCl_2$.

3.2 Spreminjanje indeksa gostote kot dejavnika prenosa kovine

Slika 4 prikazuje spremembe indeksa (slika 2 na desni strani) gostote od razplinjevalne postaje do zadrževalne peči tik pred litjem ingotov. V talilni peči smo po razplinjevanju kot prvi postaji izvedli tri merilne postaje. Po prvi postaji smo kovino izpustili v naslednji vsebnik in nato v zadrževalno peč, preden smo jo končno ulili v ingote. Diagram na sliki 4 prikazuje šest krivulj, ki predstavljajo tri zlitine vrste EN AB-46000 in tri zlitine vrste EN AB-43400.

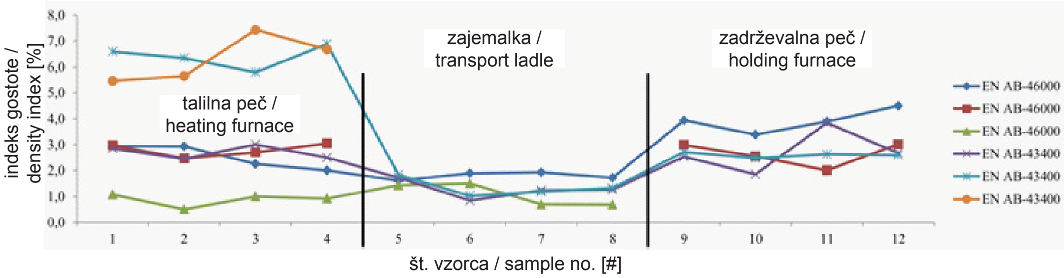
Ker je indeks gostote povezan z nastajanjem notranje poroznosti, proces nastajanja poroznosti pa je povezan z vsebnostjo vodika in oksidov, ki služijo kot nukleacijska mesta za poroznost, jasno opažamo, da se indeks gostote po večkratnem izpustu taline poveča. Izpuščanje taline in čas pospešita proces

aluminium alloys differently depending on factors that affect the hydrogen content.

After traditional degassing and the outcomes declared in figure 2, an additional treatment was performed to investigate whether it is possible or not to reduce the DI further. The use of $MgCl_2$ degassing salt after the traditional degassing process was performed and is presented in figure 3 for the EN AB-46000 and EN AB-43400 type of alloy respectively. The results shown in figure 3 a and b, correspond to four measurements before the second degassing process and four with the $MgCl_2$ treatment.

3.2 Variation of the Density Index as a Function of Metal Transport

Figure 4 shows the changes in DI from the degassing station, reported in figure 2 (right hand side), to holding furnace, just prior to casting of ingots. Three measurement stations were carried out with the heating furnace after degassing as the first station. After the first station the metal was tapped to the next container and after a second tap in the holding furnace before the final casting into ingots. The diagram in figure 4 shows six curves representing three alloys



Slika 4: Sprememba v indeksu gostote med razplinjevalno postajo (postaja 1), transportnim loncem (postaja 2) in zadrževalno pečjo (postaja 3)

Figure 4: The change in density index from the degassing station (station 1), the transport container (station 2) and the holding furnace (station 3)

nastajanja vodika v talini in oksidov/ oksidnih filmov zaradi izpuščanja; celo oksidi sčasoma postanejo grobi.

3.3 Vpliv silicija na mikrostrukturo in mehanske lastnosti

Mikrostruktura

Po [17] silicijevi dodatki ne bi smeli povzročati dodatne poroznosti, saj silicij pravzaprav pomeni zmanjšano topnost vodika v talinah zlitin na osnovi Al-Si. Edina večja sprememba v mikrostrukturi, ki se pojavi, ko se vsebnost silicija približuje 14 %, je v deležu primarnih aluminijevih dendritov, ki je skoraj nič. Pri skoraj 7 wt. % silicija mikrostrukturo sestavljajo α-dendriti in spremenjena evtektična zlitina Al-Si, kot na sliki 5. Če vsebnost silicija povečamo do 11 wt. %, se delež α-dendritov in evtektična zlitina Al-Si pomembno spremenita. Mikrostrukturo z vsebnostjo silicija 12,5 wt. % izkazuje predvsem evtektična zlitina Al-Si z nekaj α-dendriti manjše velikosti. V primerjavi z zlitino s 13,0 wt. % silicija, za katero je značilna povsem evtektična struktura Al-Si, iz katere raste dendritska struktura, v mikrostrukturi nismo našli α-dendritov. Vzrok za ta prehod je najverjetneje dejstvo, da je rast evtektične strukture Al-Si v sklopljenem območju hitrejša od rasti α-dendritov. Dodajanje več silicija pa povzroči spremembo mikrostrukture. V evtektični zlitini Al-Si se je dendritska rast spremenila v stebričasto rast. Zaradi nastajanja dolgotrajnega mejnega sloja pred trdnim strjevanjem robovi okoli evtektične zlitine Al-Si vsebujejo intermetalne spojine in grob silicij. Pri uporabi usmerjenega strjevanja v hiperevtektičnih zlitinah presenetljivo nismo opazili primarnega silicija.

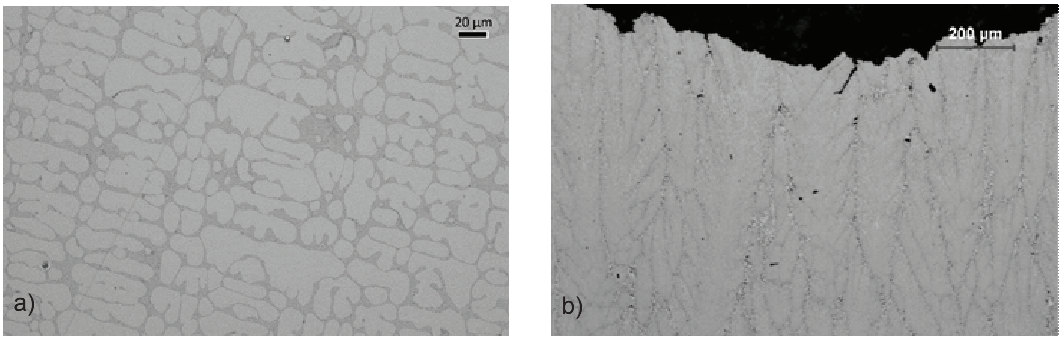
of the EN AB-46000 type of alloy and three the EN AB-43400.

Since DI is linked to internal porosity formation, and the formation process of porosity is linked to the hydrogen level and oxides that serve as nucleation sites for porosity, it is clearly observed that the DI is increasing after tapping a couple of times. Melt tapping and time accelerate the hydrogen pick-up process in the melt as well as oxides/oxide films formations due to the tapping; even the oxides are getting coarser with time.

3.3 The Influence of Si on the Microstructure and Mechanical Properties

Microstructure

According to [17], the Si additions should not lead to any further porosity formations since the Si actually leads to reduced solubility of hydrogen in the molten Al-Si based alloys. The only remarkable change in the microstructure, when approaching 14% of Si, is the fraction of primary aluminium dendrites that is nearly zero. At around 7 wt. % Si the microstructure is composed of α-dendrites and modified Al-Si eutectic, see figure 5. Increasing the Si level up to 11 wt. % the fractions of α-dendrites and Al-Si eutectic are remarkably changed. The microstructure of the alloy with Si level of 12.5 wt. % exhibit mostly Al-Si eutectic with few and smaller size of the α-dendrites. Compared to the alloy with Si of 13.0 wt. % that is characterized by a fully Al-Si eutectic structure growing with a dendritic structure; no α-dendrites however is is found in the microstructure. This transition is probably due to the fact that the Al-Si eutectic growth in the coupled zone is more rapid then α-dendrites growth. Adding more Si lead to change in the microstructure; the Al-Si eutectic changed from dendritic

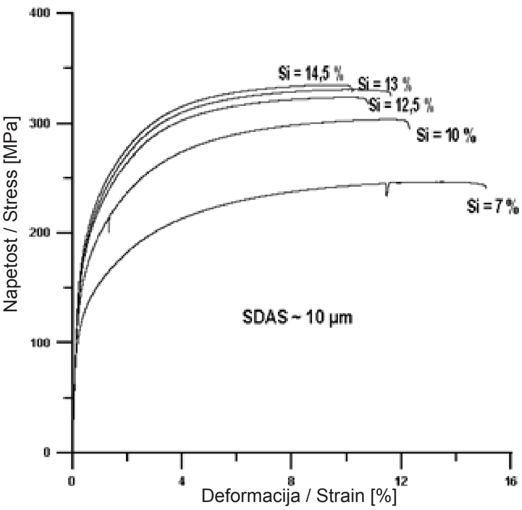


Slika 5. Slika a) prikazuje zlitino s 7 % silicija, b) pa prikazuje zlitino s 14,5 % silicija

Figure 5. While a) is illustrating the alloy with 7% Si, b) illustrates the alloy with 14.5 % Si

Mehanske lastnosti

Na mehanske lastnosti zlitin na osnovi Al-Si neposredno vplivajo dejavniki, kot so hitrost strjevanja, napake in zlitinski elementi. Da bi se izognili vsem drugim vplivom na vsebnost silicija, smo izdelali usmerjeno strjene vzorce. Kot je razvidno s slike 6, imajo silicijevi dodatki pomemben vpliv na mejo plastičnosti in končno natezno trdnost zaradi disperzijskega utrjanja. Vendar lahko opazimo majhen padec raztezka do razpoke, ki znaša približno 10 % za zlitino, ki vsebuje 14,5 % silicija. Razlog za takšno



growth to columnar growth. Due to long range boundary layer build up ahead of solid interface the boarders around the A-Si eutectic contains intermetallics as well as coarser Si. Surprisingly no primary Si in the hyper eutectic alloys was observed when employing directional solidification.

Mechanical properties

Several factors such as solidification rate, defects and alloying elements impart directly on the mechanical performance of Al-Si based alloys. In order to avoid any other impacts than the Si level, directionally solidified samples were produced. As observed in figure 6, the additions of Si have a significant influence on yield strength and ultimate tensile strength due to dispersion hardening. However, a small drop in elongation to failure may be observed but the drop is from a high level and maintained at around 10 % for the alloy containing 14.5% Si. The reasons for that retained high level

Slika 6. Vpliv silicijevih dodatkov na natezno trdnost litih zlitin Al-Si

Figure 6. The influence of Si additions on the tensile behaviour of Al-Si cast alloys

ohranitev visoke ravni voljnosti je lahko poleg spreminjanja morfologije silicija, ki je zlasti vlaknasta, proizvodna metoda. Z usmerjenim strjevanjem običajno dobimo dobro napolnjene vzorce, ki vsebujejo malo napak.

4 Sklepi

Z ocenjevanjem rezultatov smo pokazali, da so vrednosti indeksa gostote odvisne od vrste zlitin. Sestava zlitine pomembno vpliva na absorpcijo vodika v talino ali njegovo izločanje. Baker je zlitinski element, katerega delež se med sestavama (2,5 wt %) zlitin EN AB-43400 in 46000 najbolj razlikuje, kar v največji meri prispeva k zmanjšanju topnosti vodika v zlitini EN AB-46000.

Količine silicija, ki smo jih povečali s 7 na 14 %, so povsem spremenile mikrostrukturo – od aluminijevih dendritov in evtektične strukture Al-Si do povsem evtektične strukture Al-Si. Evtektična struktura Al-Si je prispevala k pomembnemu izboljšanju trdnosti na račun voljnosti, ki je padla z že tako visokih vrednosti – s 16 % pri vsebnosti silicija 7 % na 10 % za zlitine s 14 % silicija.

4.1 Zahvale

Avtorji se zahvaljujejo Oddelku za strojništvo Fakultete za tehnologijo Univerze Linnaeus v Växjö na Švedskem in Oddelku za materiale in proizvodnjo na Šoli za inženirstvo v Univerzi v Jönköpingu v Jönköpingu na Švedskem.

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of ductility behaviour may be, besides the modification of Si morphology being mostly fibrous, the production method; directional solidification that usually produces well fed samples that contain low amount of defects.

4 Conclusions

The evaluation of the results shows that the Density Index values are depending upon the type of alloy. The alloy composition has great significance on the hydrogen absorption of the melt or removal from the melt. Between the alloys EN AB-43400 and 46000, Cu is the alloying element that has the greatest difference in percentage between the compositions (2.5 wt %), which contributes the most to the decrease of the hydrogen solubility for the EN AB-46000 alloy.

The additions of Si from approximatley 7% to 14% changed the microstructure fully; from Al-dendrites and Al-Si eutectic to a fully Al-Si eutectic. The Al-Si eutectic structure contributed to a significant strength improvment on the expense of ductility that drops from already high values; around 16% at Si content of 7% down to around 10% for alloys with 14% Si.

4.1 Acknowledgements

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Dodatek A / Appendix A

Preglednica A.1. Kemijska sestava merjenih šarž kovine. Izračunali smo srednje vrednosti za vsako vrsto zlitine (Mv) in razlike v povprečnih koncentracijah med obema vrstama zlitine (ΔMv).

Table A.1. The chemical composition of the measured charges of metal. The mean values for each type of alloy are calculated (Mv) as well as the difference in the average concentrations between the two types of alloy (ΔMv).

EN AB 43400	Alloy Composition [wt.%]											
	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Pb	Sn	Ti	Na
1	9,885	0,821	0,059	0,343	0,350	0,010	0,006	0,049	0,005	0,001	0,036	0,000
2	9,055	0,799	0,056	0,338	0,359	0,007	0,007	0,051	0,006	0,005	0,038	0,000
3	9,370	0,826	0,055	0,325	0,375	0,009	0,006	0,085	0,010	0,002	0,036	0,000
4	9,555	0,863	0,059	0,369	0,352	0,008	0,006	0,061	0,006	0,001	0,033	0,000
5	9,802	0,536	0,060	0,142	0,325	0,007	0,006	0,069	0,009	0,002	0,039	0,000
M_v	9,533	0,769	0,058	0,303	0,352	0,008	0,006	0,063	0,007	0,002	0,037	0,000
EN AB 46000	Alloy Composition [wt.%]											
	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Pb	Sn	Ti	Na
1	8,720	0,878	2,954	0,296	0,258	0,020	0,023	0,860	0,050	0,039	0,025	0,000
2	8,711	0,958	2,972	0,306	0,290	0,028	0,028	0,767	0,040	0,039	0,022	0,000
3	8,205	0,660	2,233	0,221	0,225	0,020	0,026	0,857	0,048	0,028	0,030	0,000
4	8,791	1,064	2,196	0,327	0,273	0,038	0,040	0,910	0,067	0,060	0,026	0,000
5	8,768	0,844	2,379	0,223	0,165	0,034	0,017	0,810	0,045	0,022	0,021	0,000
6	9,617	1,050	2,619	0,230	0,218	0,038	0,031	0,764	0,053	0,048	0,027	0,000
7	9,079	1,097	2,667	0,273	0,220	0,049	0,040	0,835	0,088	0,060	0,019	0,000
M_v	8,841	0,936	2,574	0,268	0,236	0,033	0,029	0,829	0,056	0,042	0,024	0,000
ΔM_v	-0,69	0,17	2,52	-0,04	-0,12	0,02	0,02	0,77	0,05	0,04	-0,01	0,00

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Nastanek zlatih nanodelcev pri ultrazvočni razpršilni pirolizi

Formation of Gold Nanoparticles with Ultrasonic Spray Pyrolysis

Povzetek

Ultrazvočna razpršilna piroliza (USP) je poznana metoda za sintezo različnih finih prahov. V prejšnjem raziskovalnem delu smo z USP uspeli sintetizirali različne zlate nanodelce (AuNPs) brez natančnega poznavanja mehanizmov nastanka. Zato, da bi identificirali te mehanizme in imeli večji nadzor nad sintezo AuNPs, smo modificirali USP z ločenim območjem za izhlapevanje kapljic aerosola in z uvedbo reducirnega plina neposredno v reakcijsko peč. V takšnem sistemu smo z 2,5 MHz ultrazvočnim generatorjem ustvarili kapljice aerosola iz raztopine z $HAuCl_4$, kjer so bile koncentracije raztopljenega zlata med 0,5 in 5 g/l. Nosilni plin dušik (s pretokom med 1,5 do 4,5 l/min) je transportiral kapljice v cono izhlapevanja, kjer so bile testirane temperature med 50 in 100°C. Za redukcijo zlatega klorida v AuNPs smo uporabili plin vodik (s pretokom med 1.0 in 2.0 l/min). V reakcijski peči so bile testirane temperature med 300 in 400°C. Ugotovljeno je bilo, da AuNPs nastanejo s kombinacijo mehanizmov pretvorbe kapljic v delec (t.i. DTP mehanizem) in plina v delec (t.i. GTP mehanizem). Eksperimentalno smo potrdili, da so parametri, ki najbolj vplivajo na razmerje med tema mehanizmoma: koncentracija zlata v začetni raztopini in pretoka plinov. Ustrezno izbrani parametri sinteze so minimizirali nastanek AuNPs z DTP mehanizmom in omogočili prevladujočo sintezo z GTP mehanizmom, kar je posledično ustvarilo enotne oblike AuNPs, ki jih pred tem ni bilo možno doseči.

Ključne besede: ultrazvočna razpršilna piroliza (USP), zlati nanodelci (AuNPs), DTP in GTP mehanizem nastanka, presevna elektronska mikroskopija (TEM)

Abstract

Ultrasonic Spray Pyrolysis (USP) is a known method for synthesis of various fine powders. In our previous research work we synthesized different gold nanoparticles (AuNPs) with limited success, as the formation mechanisms were not known for AuNP synthesis with the USP. In order to identify the formation mechanisms and provide greater control over AuNP synthesis, we have modified the USP with a separate aerosol droplet evaporation zone and an introduction of the reduction gas directly into the reaction furnace. A 2.5 MHz ultrasound was used to create aerosol droplets of a solution with $HAuCl_4$, with gold concentrations from 0.5 to 5 g/l. Nitrogen was used as the carrier gas for droplet transportation into the heating zone (gas flow from 1.5 to 4.5 l/min). Hydrogen gas was used for reduction of the gold chloride into AuNPs (gas flow from 1.0 to 2.0 l/min). Heating temperatures were 50-100°C for the evaporation zone and 300-400°C for the reaction furnace. It was identified that the AuNPs are formed from a combination of the Droplet-to-Particle mechanism, DTP and the Gas-to-Particle mechanism, GTP. The most influential parameters for affecting the ratio between these two formation mechanisms were determined: Gold concentration in the precursor solution and gas flows. Appropriate synthesis parameters have decreased the formation by the DTP mechanism; synthesizing AuNPs mainly by the GTP mechanism and producing more uniform AuNPs, which were not obtained previously.

Keywords: Ultrasonic Spray Pyrolysis (USP), gold nanoparticles, DTP and GTP formation mechanisms, Transmission Electron Microscopy (TEM)

Nastanek zlatih nanodelcev pri ultrazvočni razpršilni pirolizi

Nanomateriali (nanodelci, nanocevke, nanopiramide, itd., materiali z vsaj eno dimenzijo pod 100 nm) imajo različne lastnosti v primerjavi z materiali običajnih dimenzij. Njihove spremenjene fizikalne in kemijske lastnosti izhajajo iz velikega razmerja med površino in prostornino ter visoke površinske aktivnosti. Zaradi tega so uporabni na različnih področjih (elektronika, kemija, biotehnologija, medicina) [1]. Zlasti zanimivi so zlati nanodelci (AuNP), saj imajo dodatno lastnost, imenovano površinska plazmonska resonanca (Surface Plasmon Resonance – SPR) [2]. Ta s pomočjo vpadne svetlobe povzroča nihanje prevodnih elektronov na površini nanodelcev. AuNP imajo dobre fizikalne, kemične in optične lastnosti zaradi plazmonske resonance [3-5]. Običajno so AuNP biološko nereaktivni in so zato primerni za biomedicinsko slikanje in terapijo [6,7]. Takšni AuNP se lahko konjugirajo in funkcionalizirajo s peptidi in se tako lahko uporabljajo za diagnozo in zdravljenje raka [8-10]. Iz naših raziskav je bilo razvidno, da so sferični AuNP z velikostjo 50 nm najbolj primerni za biomedicinske aplikacije [11]. Zato je bil cilj naše raziskave sinteza sferičnih AuNP z ozko velikostno porazdelitvijo okoli 50 nm (70% vseh AuNP), z visoko vsebnostjo Au (vsaj 99,99 mas.% Au).

Znane so različne proizvodne metode za nanodelce; delijo se na pristop izdelave,

Formation of gold nanoparticles with Ultrasonic Spray Pyrolysis

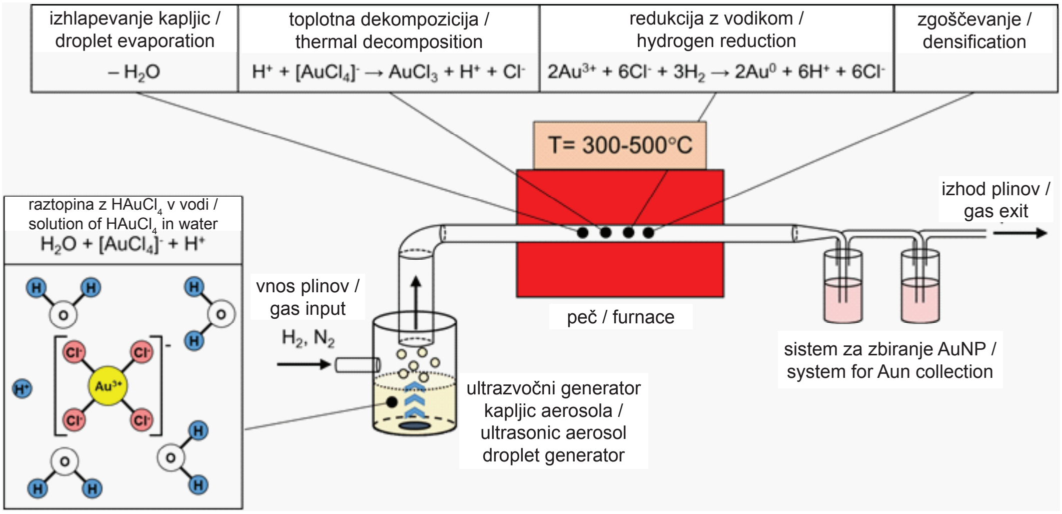
Nanomaterials (nanoparticles, nanotubes, nanopyramids, etc. with at least one dimension below 100 nm) have different properties compared to materials with ordinary dimensions. Their altered physical and chemical properties come from a large surface-to-volume ratio and a high surface activity. Because of this, they are useful in various fields (electronics, chemistry, biotechnology, medicine) [1]. Especially interesting are gold nanoparticles (AuNPs), as they have an additional property, called Surface Plasmon Resonance (SPR) [2]. This causes the oscillation of conduction electrons on the surface of the nanoparticles, stimulated by incident light. AuNPs have good physical, chemical and optical properties because of the Plasmon Resonance [3-5]. Usually, AuNPs are biologically unreactive and, as such, are suitable for biomedical imaging and therapy [6,7]. Such AuNPs can be conjugated and functionalized with peptides, medicine and can be used for diagnosis and cancer treatment [8-10]. From our research, it was shown that spherical AuNPs with sizes of 50 nm are the most optimal for biomedical applications [11]. As such, the aim of our research was the synthesis of spherical AuNPs with a narrow size distribution around 50 nm (70% of all AuNPs), with a high content of Au (at least 99.99 wt.% Au).

od spodaj navzgor (bottom-up) in od zgoraj navzdol (top-down). Primeri od spodaj navzgor so sol-gel, kemično naparjevanje, sinteza s plamenskim razprševanjem, različne pirolize in atomska ali molekularna kondenzacija [12-15]. Metode od zgoraj navzdol vključujejo lasersko ablacijo, nanolitografijo in visoko-energetsko mletje [16-17]. Te metode so trenutno primerne za proizvodnjo majhnih količin nanodelcev z večjimi odstopanji v oblikah in velikostih nanodelcev pri proizvodnji različnih serij. Metoda od spodaj navzgor, imenovana ultrazvočna razpršilna piroliza (Ultrasonic Spray Pyrolysis – USP), ima dober potencial za odpravo teh tehnoloških težav in za bolj nadzorovano sintezo nanodelcev [14,18]. Na splošno je piroliza proces kemične razgradnje različnih spojin pri povišanih temperaturah. Z metodo USP dodatno uvajamo ultrazvok za razprševanje začetne raztopine z želenim materialom v kapljice. Te kapljice so nato izpostavljene visoki temperaturi, tako da se material znotraj kapljic kemično razgradi s pirolizo in pridobijo nanodelci čistih elementov. Prednost metode USP je preprostost postavitve posameznih procesnih segmentov in spreminjanje njihove konfiguracije, neprekinjene sinteze nanodelcev in možnosti sinteze čistih nanodelcev iz različnih materialov. Pomanjkljivost je nizka učinkovitost metode pri uporabi neoptimizirane USP naprave, ki se uporablja za laboratorijske namene, zaradi izgub raztopljenega materiala na konstrukcijskih elementih naprave USP.

Glavni elementi standardne USP naprave so ultrazvočni generator, reaktorska peč in sistem za zbiranje nanodelcev (slika 1). Obstajajo različne surovine, ki jih je mogoče uporabiti za pripravo začetnih raztopin za sintezo AuNP (spojine, ki vsebujejo Au). V našem primeru je bila zaradi njene cene, razpoložljivosti in kemične stabilnosti izbrana tetrakloroavrična kislina $HAuCl_4$ (s),

Different production methods for nanoparticles are known; they are divided into bottom-up and top-down approaches. Bottom-up examples include sol-gel, chemical vapour deposition, flame spray synthesis, various pyrolysis and atomic or molecular condensation [12-15]. Top-down methods include laser ablation, nanolithography and high-energy milling [16-17]. Currently, these methods are suitable for production of small quantities of nanoparticles with major variations in shapes and sizes of the nanoparticles from the production of different batches. A bottom-up method, called Ultrasonic Spray Pyrolysis – USP, has good potential for removing these technological issues, for a more controlled nanoparticle synthesis [14,18]. Pyrolysis in general is a process of chemical decomposition of various compounds at elevated temperatures. With the USP method, we additionally introduce ultrasound for dispersing a precursor solution with our desired material into droplets. These droplets are then exposed to high temperature, such that the material inside the droplet is decomposed chemically via pyrolysis and nanoparticles of pure elements are obtained. The advantage of the USP method is the simplicity of setting up individual process segments and changing their configuration, continuous nanoparticle synthesis and the possibility of synthesizing pure nanoparticles from various materials. The disadvantage is the low efficiency of the method when using an un-optimized USP device used for laboratory purposes, due to losses of the dissolved material on the construction elements of the USP device.

The main elements of the standard USP device are the ultrasonic generator, the reactor furnace and a system for nanoparticle collection (Figure 1). There are various raw materials, which can be used for preparing precursor solutions for AuNP



Slika 1: Sinteza AuNP s konvencionalnim USP

Figure 1: AuNP synthesis with the conventional USP

ki smo jo uporabili tudi v prejšnjih raziskavah s sintezo USP. Začetno raztopino smo pripravili z raztapljanjem $HAuCl_4$ v vodi [19, 20].

Iz literature je znano, da so velikosti sintetiziranih AuNP odvisne od ultrazvočne frekvence [14,18,19,21], ki določa velikost kapljic aerosola in od koncentracije raztopljenega Au v kapljicah. Zaradi vibracij ultrazvoka pod površino raztopine, se kinetična energija molekul raztopine hitro poveča. To povzroči, da se majhne kapljice ločijo od površine raztopine s premagovanjem površinske napetosti. Z visokofrekvenčnim ultrazvokom (0,5-3 MHz) se kapljice ustvarjajo v velikostni porazdelitvi od 1 do 15 mikrometrov [22].

Z uporabo nizkih koncentracij raztopljenega zlata (0,5 g/l - 5,0 g/l Au) v začetni raztopini vsaka kapljica vsebuje tako količino materiala, da se po izhlapevanju in sušenju oblikujejo naslednje velikosti delcev: i) s premerom nekaj 10 nm pri 0,5 g/l Au in ii) s premerom več kot 100 nm pri 5,0 g/l Au v začetni raztopini.

synthesis (compounds containing Au), in our case, tetrachlororauric acid $HAuCl_4$(s) was selected, due to its price, availability and chemical stability, as shown in our previous research with USP synthesis. The precursor solution was prepared by dissolving $HAuCl_4$ in water [19,20].

From literature it is known that the sizes of the synthesized AuNPs depend on the ultrasound frequency [14,18,19,21], which determines the sizes of the aerosol droplets, and the concentration of the dissolved Au in the droplets. Due to vibrations of the ultrasound below the solution surface, the kinetic energy of the solution`s molecules is increased rapidly. This causes small droplets to overcome surface tension and break away from it. With a high-frequency ultrasound (0,5-3 MHz), droplets are created in a size distribution from 1 to 15 micrometers [22].

By using low concentrations of dissolved gold (0,5 g/l – 5.0 g/l Au) in the precursor solution, each droplet contains such an amount of material that, after evaporation

Kapljice začetne raztopine se prenesejo v peč z nosilnim plinom. V peči se AuNP oblikujejo v skladu s stopnjami sinteze:

1. izhlapevanje in krčenje kapljic ($HAuCl_4$ z vodo),
2. toplotna dekompozicija $HAuCl_4$ v $AuCl_3$,
3. redukcija $AuCl_3$ z vodikom in tvorba Au,
4. zgoščevanje delcev.

Naštete stopnje sinteze potekajo istočasno s konvencionalnim USP. Iz kapljic aerosola z manjšimi premeri (2r>1μm) nanodelci nastanejo veliko hitreje kot pri večjih kapljicah (2r<10μm). Tako imamo v USP hkrati majhne delce in kapljice, ter možnost nastanka nanodelcev različnih velikosti in oblik zaradi trčenja in združevanja kapljic z delci. To ni primerno za sintezo ciljnih AuNP.

Z običajnim USP smo sintetizirali AuNP z velikostmi od 10 do 300 nm, z različnimi oblikami, od sferičnih, nepravilnih, trikotnih in cilindričnih [19] (slika 2). Prisotno je bilo tudi veliko nečistoč. Takšni AuNP niso bili primerni.

Podrobnejše študije [14,18,21,23] so pokazale, da so oblike sintetiziranih AuNP odvisne od hitrosti izhlapevanja kapljic ter hitrosti difuzije ionov $[AuCl_4]^-$ in H^+ znotraj kapljice. Hitrosti teh mehanizmov so pri USP odvisne od več dejavnikov: koncentracija začetne raztopine, velikosti kapljic, število kapljic in relativne vlažnosti v sistemu, hitrost prenosa kapljic v peč z nosilnim plinom, tlak v sistemu, dimenzije transportnih cevi in temperaturo v peči. Za nastavitev primernih parametrov (koncentracija začetne raztopine, pretok plinov, temperatura peči) so potrebne informacije o lastnostih začetne raztopine, kot so gostota in površinska napetost, značilnosti raztopljene $[AuCl_4]^-$ ter difuzije ionov v raztopini in rast AuNP.

Na podlagi predstavljene študije je bil cilj našega raziskovalnega dela postavitev modificirane USP naprave za sintezo

and drying, the following particle sizes are formed: i) with diameters of a few 10 nm at 0,5 g/l Au and ii) with diameters of more than 100 nm at 5.0 g/l Au in the precursor solution.

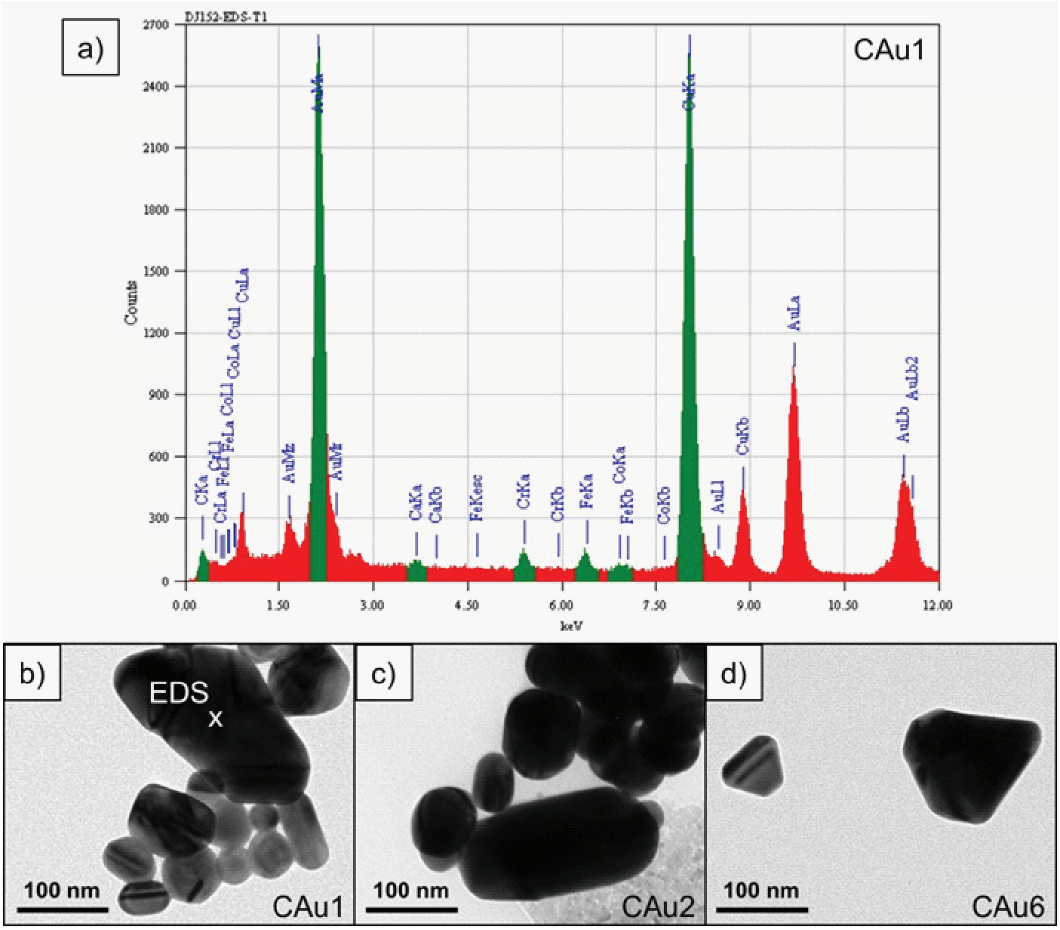
Droplets of the starting solution are transported into the furnace with a carrier gas. Inside the furnace, the AuNPs are formed according to the following synthesis stages:

1. Evaporation and droplet shrinkage ($HAuCl_4$ with water)
2. Thermal decomposition of $HAuCl_4$ into $AuCl_3$
3. Reduction of $AuCl_3$ with hydrogen and the formation of Au
4. Densification

The listed synthesis stages are taking place at the same time with the conventional USP. With smaller diameters of the aerosol droplets (2r>1μm), nanoparticles are formed much sooner than with larger droplets (2r<10μm). Therefore, nanoparticles of different sizes and shapes can be synthesized, due to droplet collisions and coagulation. This is not suitable for synthesizing the targeted AuNPs.

With the conventional USP, we have synthesized AuNPs with sizes from 10 to 300 nm, with different shapes, from spherical, irregular, triangular and cylindrical [19] (Figure 2). A lot of impurities were also present. Such AuNPs were not suitable.

More detailed studies [14,18,21,23] have shown, that the shapes of the synthesized AuNPs depend on the rate of droplet evaporation and the rate of ion diffusion $[AuCl_4]^-$ and H^+ inside the droplet. These rates with USP synthesis depend on several factors: Precursor solution concentration, droplet sizes, number of droplets and relative humidity in the system, velocity of droplet transportation into the furnace with the carrier gas, pressure in the system, dimensions of the transport pipes,



Slika 2: a) EDS analiza AuNP, izdelanih s konvencionalnim USP; b) TEM slika okroglih in nepravilnih AuNP s temperaturo sinteze 260°C-500°C; c) prisotnost cilindričnih AuNP pri sintezi s temperaturo 280°C-500°C; d) prisotnost trikotnih AuNP pri sintezi s temperaturo 260°C. Vsebnost C in Cu v EDS analizi izhaja iz mrežice za TEM, na katero so bili naneseni analizirani AuNP

Figure 2: a) EDS analysis of AuNPs obtained with conventional USP; b) TEM image of spherical and irregular AuNPs at synthesis temperatures from 260°C-500°C; c) Presence of cylindrical AuNPs at synthesis temperatures from 280°C-500°C; d) Presence of triangular AuNPs at synthesis temperatures of 260°C. The C and Cu content in the EDS analyses comes from the TEM formvar grid, on which the AuNPs were examined

AuNP (slika 3). S to spremembo smo ločili izhlapevanje kapljic od preostalih stopenj sinteze in vnesli redukcijski plin neposredno v reakcijsko peč. Na ta način smo lažje nadzorovali izhlapevanje kapljic in kemične

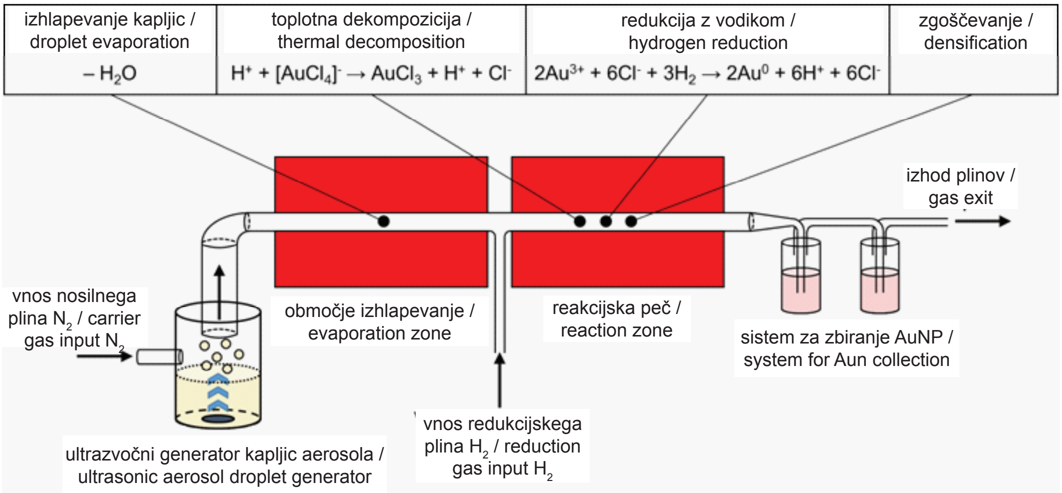
and temperature inside the furnace. For setting up suitable parameters (precursor solution concentration, gas flow, furnace temperature), information is needed for the starting solution properties, such as density reakcije, da bi dosegli želene velikosti sferičnih AuNP. Predpostavili smo, da bo ločena stopnja izhlapevanja omogočala bolj optimalno difuzijo materiala znotraj kapljice ($[AuCl_4]$- in H+) in nastanek sferičnih AuNP. Mehanizmi sinteze AuNP iz $HAuCl_4$ z USP s tako zasnovo še niso pojasnjeni v literaturi.

Izvedli smo več poskusov z modificiranim USP z različnimi izbranimi vplivnimi parametri (ultrazvočna frekvenca 2,5 MHz, koncentracije zlata v raztopini $HAuCl_4$ od 0,5 do 5 g/l Au, pretok nosilnega plina dušika od 1,5 do 4,5 l/min, pretok redukcijskega plina vodika od 1,0 do 2,0 l/min, temperatura peči 50-100°C za območje izhlapevanja in 300-400°C za reakcijsko peč). Sintetizirane AuNP smo analizirali z različnimi metodami karakterizacije za prepoznavanje njihovih velikosti, oblik, kemične sestave in stopnje aglomeracije. Na podlagi teh rezultatov smo nato presodili glede vpliva posameznih parametrov na mehanizme nastanka AuNP. Ugotovili smo, da AuNP nastanejo iz kapljic in iz plinske faze. To pomeni, da so tvorjeni

and surface tension, and characteristics of the dissolved $[AuCl_4]$-, ion diffusion inside the solution and AuNP growth.

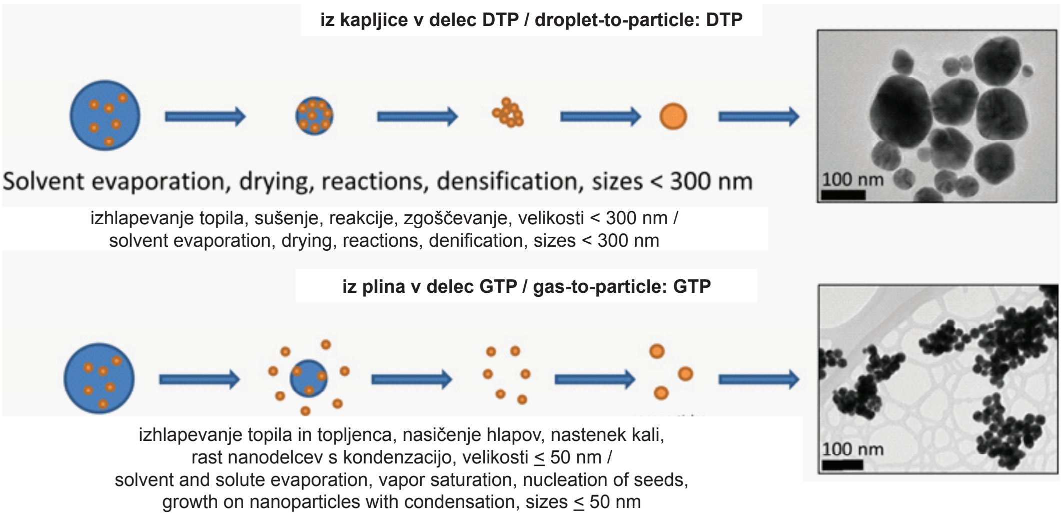
Based on the presented studies, the objective of our research work was setting up a modified USP device for the synthesis of AuNPs (Figure 3). With this modification, we have separated the droplet evaporation from the rest of the synthesis stages and introduced the reduction gas directly into the reaction furnace. In this way, we could control the evaporation and chemical reactions in order to achieve the desired sizes of spherical AuNPs. We presumed, that a separate evaporation stage would allow for a more optimal material diffusion inside the droplet ($[AuCl_4]$- and H+) and would result in the synthesis of spherical AuNPs. The mechanisms of AuNP synthesis from $HAuCl_4$ by USP with such a design are not yet clarified in the literature.

Several experiments were performed with the modified USP, with different selected influential parameters (2.5 MHz



Slika 3: Modifikacija konvencionalnega USP - postopka z ločenim območjem za izhlapevanje kapljic in z vnosom redukcijskega plina neposredno v reakcijsko peč

Figure 3: Modification of the conventional USP with a separate evaporation zone and reduction gas input directly into the reaction zone



Slika 4: DTP in GTP mehanizma pri USP, s pripadajočimi AuNP glede na mehanizem nastanka

Figure 4: DTP and GTP mechanisms in USP, with obtained AuNPs corresponding to the formation mechanisms

iz kombinacije mehanizmov nastanka DTP (Droplet-To-Particle, iz kapljice do delca) in GTP (Gas-To-Particle, iz plina v delce) [14] (slika 4). Naslednja ugotovitev je bila, da sta parametra z največjim vplivom na nastanek bila koncentracija Au v začetni raztopini in pretok plinov N_2 in H_2. Na podlagi teh ugotovitev smo postavili model nastanka, ki pojasnjuje, kako lahko spremenimo ta dva parametra in dosežemo prevlado GTP mehanizma v sistemu. Na ta način lahko dobimo želene AuNP. Model je bil potrjen s sintezo ciljnih, sferičnih AuNP z velikostno porazdelitvijo okoli 50 nm.

Za nadaljnje delo je potrebno oblikovati optimiziran sklop modificiranega USP z večjo učinkovitostjo, kjer bi preprečili nalaganje AuNP na stene transportnih cevi. To je možno z izgradnjo posameznih elementov USP s primernimi materiali za preprečevanje nalaganja. Za povečanje zmogljivosti izdelave večjih količin AuNP z USP sintezo in premik na industrijsko raven je potrebno preučiti in razviti nove

ultrasound frequency, gold concentrations in $HAuCl_4$ solution from 0.5 to 5 g/l, nitrogen carrier gas flow from 1.5 to 4.5 l/min, hydrogen reduction gas flow from 1.0 to 2.0 l/min, heating temperatures of 50-100°C for the evaporation zone and 300-400°C for the reaction furnace). The synthesized AuNPs were characterized with various characterization techniques for identification of their sizes, shapes, chemical composition and degree of agglomeration. Based on these results, we have surmised the influence of individual parameters on the AuNP formation mechanisms. We have found out, that the AuNPs are formed from droplets and from the gas phase. This means that they are formed from a combination of DTP (Droplet-To-Particle) and GTP (Gas-To-Particle) formation mechanisms [14] (Figure 4). The next finding was that the parameters with the most influence on formation were the Au concentration in the precursor solution and N_2 and H_2 gas flows. Based on these findings, we have set komponente ter sklope USP na podlagi ugotovitev v tem raziskovalnem delu: od proizvodnje aerosola in transport kapljic, dimenzij transportnih cevi ter pogoji pretoka plinov, izhlapevanje/sušenje kapljic in grelni elementi (difuzijski sušilniki, elektrouporovne ali indukcijske peči, gretje z mikrovalovi), do zbiralnega sistema (zbiranje v suspenzijah ali v elektrostatičnih precipitatorjih, glede na uporabo končnih nanodelcev).

Za nadaljnje študije o mehanizmih nastanka AuNP in aplikacijah AuNP je treba sintezo preučiti tudi s drugimi začetnimi sestavinami, namesto $HAuCl_4$. Za sintezo AuNP v razponu od 10 do 50 nm je treba uporabiti tudi dodatne stabilizacijske snovi, ki so primerne za testiranje biokompatibilnosti in potencialno uporabo v biomedicinskih aplikacijah, kar je trenutno primarna uporaba AuNP.

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up a formation model, which explains how we can change these two parameters and achieve dominance of the GTP mechanism in the system. In this way we can obtain the desired AuNPs. The model was confirmed with synthesis of the targeted, spherical AuNPs with a size distribution around 50 nm.

For further work, an optimized assembly with increased efficiency of the modified USP should be designed, where the AuNP deposition would be prevented. This should be done by constructing the individual USP elements with suitable materials for deposition prevention. In order to upscale the USP synthesis of AuNPs to an industrial level, the following components of the USP should be revised and developed a new, based on the findings in this research work: Aerosol generation and droplet transport, transport tube dimensions and gas flow conditions, evaporation/drying and heating elements (diffusion driers, electroresistance or induction furnaces, microwaves), collection system (collection in suspensions or electrostatic precipitators, based on final application).

For further studies regarding AuNP formation mechanisms and applications of AuNPs, the synthesis should also be examined using precursors other than $HAuCl_4$. Additional stabilization agents should also be used for synthesis of AuNPs in the range of 10 – 50 nm, more suited for biocompatibility testing and potential use in biomedical applications, which is currently the primary application of AuNPs.

Acknowledgment

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AKTUALNO / CURRENT

Koledar livarskih prireditev 2018

Datum prireditve	Ime prireditve	Lokacija prireditve
16.-18. 01. 2018	EUROGUSS	Nuernberg, Nemčija
07.- 08.03. 2018	Aachener Giessereikolloquium	Aachen, Nemčija
26.- 27.04. 2018	Grosse Giessereitechnische Tagung (Osterreich, Schweiz, Deutschland)	Salzburg, Avstrija
23.- 25.05. 2018	17th International Foundrymen Conference	Opatija, Hrvaška
5. - 7. 06. 2018	Castforge	Stuttgart, Nemčija
12.- 14.09. 2018	58. mednarodno livarsko posvetovanje	Portorož, Slovenija
23.- 27.09. 2018	73rd World Foundry Congress »Creative Foundry«	Krakow, Poljska

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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 nervnotežnih 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 jo lahko mehansko (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.

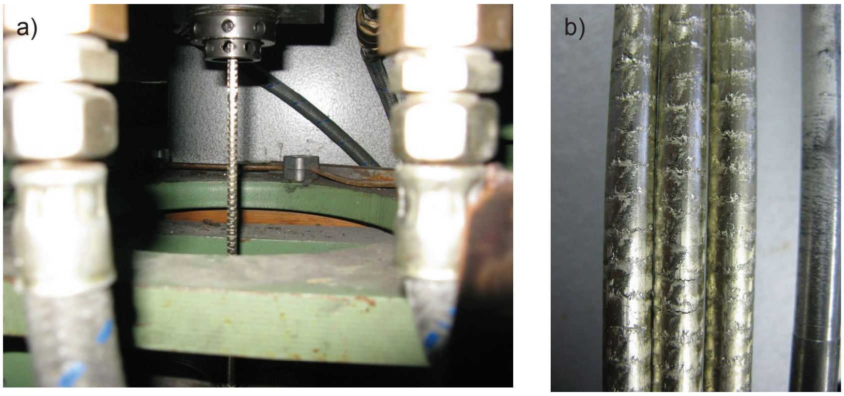
On the other hand Cu-based shape memory alloys were found to reveal the shape memory effect in 1964 [5]. The main advantages of Cu-based SMA are their low price compared to other SMAs. Many Cu-based SMAs have a better thermal and electrical stability and a higher operating temperature. Their very high 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 obločno 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 ternerne 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 (forgoing, 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 nadalnje 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 ProCAST[1], 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. uporabiljena je bila tudi zrcalna simetrija skozi ploskev XY, tako da je izračunan

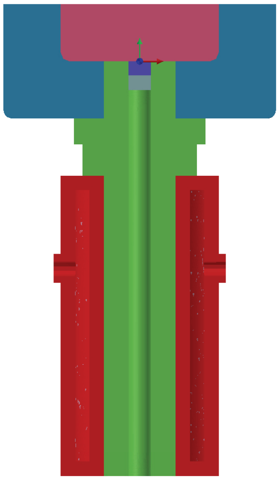
[1] ProCAST je blagovna znamka skupine ESI Group

the impact on continuous casting process. Here we use a commercial software package ProCAST[1] 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 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 systemmodel 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 odvisnot topotne upornosti od fazne 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 ºC, 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 Tl = 1058 ºC, solidus pri Ts = 1020 ºC, 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 strejavnja, 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.

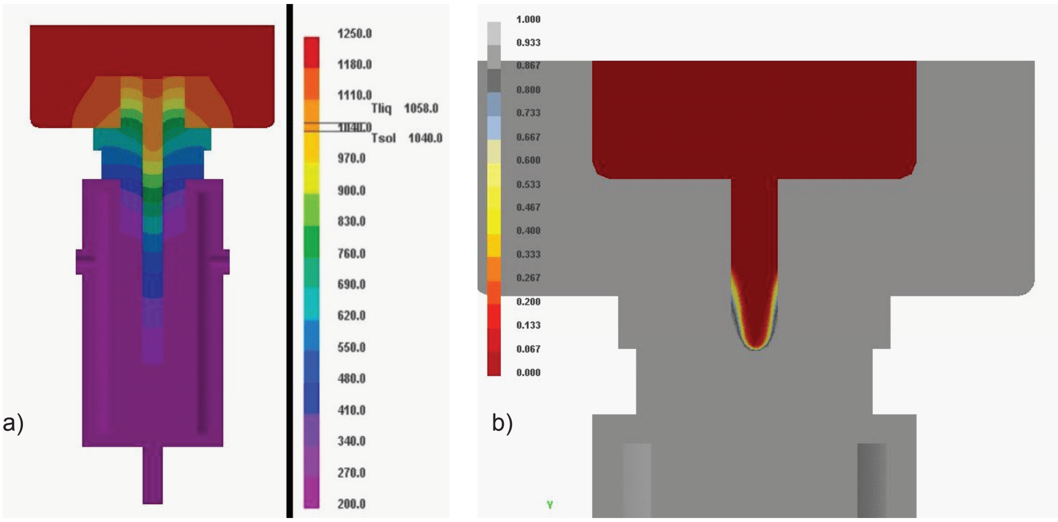
Prenos toplote na kristalizator je težko pravilno modelirati, saj na prenos toplote iz strjenega plašča zlitine na steno kristalizatorja močno vpliva krčenje zlitine pri strjevanju. Oblika meniskusa (na sliki 3b) je rezultat topologije prenosa toplote. Ta geometrija preprečuje večji vpliv zahtevnih

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 Tl = 1058 ºC and solidus Ts = 1020 ºC, 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 form 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 vrtinci ali turbulence. 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, temperaturno odvisne lastnosti materiala 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 okolij 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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Microstructure and Functional Properties of Cu-based Shape Memory Alloys (3405).

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AKTUALNO / CURRENT

Osrednje hrvaško livarsko posvetovanje

V Opatiji na Hrvaškem je v času od 15. do 17. maja letos potekal osrednji hrvaški livarki dogodek, 16. Mednarodno livarsko posvetovanje pod motom: GLOBALNA LIVARSKA INDUSTRIJA- Perspektive za bodočnost.

Posvetovanje je organizirala metalurška fakulteta Univerze v Zagrebu s sodelovanjem Naravoslovno tehniške fakultete Univerze v Ljubljani, Univerze Sever iz Koprivnice in predstavništva korporacije Elkem AS iz Norveške, Predstavništva v Sisku. Letošnje livarsko posvetovanje je je potekalo pod pokroviteljstvom predsednice Republike Hrvaške Kolinde Grabar- Kitarović, in ob podpori Ministrstva za znanost in izobraževanje Republike Hrvaške, Univerze v Zagrebu, Srednje evropske livarske iniciative(MEGI), Hrvaške gospodarske zbornice, Sisačko-moslavačke županije in mesta Sisak.

Na posvetovanju je predstavljeno 31 predavanj, od tega 11 v posterski sekciji. Izvlečki predavanja so objavljeni v Zborniku posvetovanja, v katerem je vstavljen tudi CD-ROM s kompletnimi predavanji. Na posvetovanju je sodelovalo tudi 8 študentov Metalurške

Pogled na dvorano posvetovanja

fakultete, ki so v okviru študentske sekcije predstavili 4 predavanja. Finančno podporo za sodelovanje študentov je zagotovil Študentski servis Sisak.

Posvetovanja se je udeležilo skupno okoli 140 udeležencev iz Hrvaške in 9 tujih držav (Avstrije, Bosne in Hercegovine, Češke, Nemčije, Makedonije, Romunije, Slovaške, Slovenije, Srbije in Velike Britanije).

Organizatorji so poudarili, da je glavna prioriteta posvetovanja v smeri zagotavljanja dviga konkurenčnosti livarn s racionalizacijami in optimizacijami proizvodnje odlitkov, na podlagi fokusiranih inovacij na področju sodobnih konceptov razvoja materialov in tehnologij.

Livarsko posvetovanje je spremljala tudi livarska razstava na kateri je sodelovalo 20 razstavljavcev. Razstave so se udeležili proizvajalci livarske opreme in materialov, programskih paketov za simulacijo strjevanja in ulivanja kovin v različne forme, predstavniki proizvajalcev merilne opreme in opreme za preizkušanje.

V sklopu posvetovanja je bila organizirana tudi okrogla miza na temo: Oživitev hrvaškega livarskega združenja. Okrogla miza na to temo je organizirana, ker je delovanje Hrvaškega livarskega združenja povsem ugasnilo v zadnjih letih. Prejeli smo posebno povabilo in prošnjo, da se te okrogle mize udeležimo predvsem s ciljem, da predstavimo pozitivne prakse in izkušnje iz delovanja Društva livarjev Slovenije.

Poročala: *mag. Mirjam Jan-Blažić*

AKTUALNO / CURRENT

Konferenca MME SEE 2017 v Beogradu

Pod naslovom 3. MME SEE 2017- Metallurgical and Materials Engineering Congress of South East Europe je med 1. in 3. junijem letos potekalo v Beogradu strokovno srečanje, ki ga je organiziralo Združenje metalurških inženirjev Srbije, Tehnološko-metalurška fakulteta, Univerza v Beogradu, Društvo livarjev Srbije, Metalurška akademska mreža držav jugovzhodne Evrope, Inštitut za tehnologijo jedrskih in drugih mineralnih surovin, Inštitut za kemijo, tehnologijo in metalurgijo ter Inštitut za jedrske vede Vinca. Gre za mlajšo prireditev sodeč po letih obstoja, ki pa se uspešno razvija in raste.

V dveh dneh se je izmenjalo veliko visoko kakovostnih informacij in rezultatov. Razpravljalo se je o različnih temah s metalurškega področja in inženirstva materialov. Na srečanju je bilo predstavljenih 65 prispevkov, od tega 3 plenarna predavanja, 4 vabljena in 14 ostalih predstavitev ter 44 plakatnih predstavitev. Vse predstavitve so zajele študijsko več različnih področji kot so: fizikalna metalurgija in struktura materialov; proizvodnja železovih in neželezovih kovinskih izdelkov; litje kovin; oblikovanje kovin; prašna metalurgija; novi

mag. M. Debelak,
prof. dr. K. Raić,
mag. M. Jan-Blažić,
prof. dr. Ž. Kamberović

in napredni materiali; nanotehnologija; recikliranje in zmanjševanje odpadkov; prevleke, cinkanje, korozija in zaščita materialov; novi industrijski dosežki; nadzor procesov in modeliranje; surovine; varjenje in preiskušanje materialov; okoljske tehnologije in čistejša proizvodnja.

Kongres je prinesel sveže ideje in ponudil svoja priporočila za boljše razumevanje znanstvene in inženirske strategije prihodnosti ter pričakovane smeri na področju metalurgije in inženiringa materialov. Predstavljena predavanja so pokazala, da obstajajo vizije razvoja na področju metalurgije in inženiringa materialov. Vidike, ki so bili izpostavljeni na tem strokovnem srečanju je mogoče povzeti v naslednjih točkah:

- Potrebno je povečati ozaveščenost vseh pomembnih sodelujočih v procesu strateškega zviševanja kakovosti proizvodnje (izobraževalni sistem, znanstvena in strokovna združenja, množični mediji itd.). Ni dvoma, da je vlaganje v strokovni razvoj ključno in koristno za prilagajanje in vključevanje v bolj razvite gospodarske kroge.
- Predelava in/ali preoblikovanje trajne industrijske infrastrukture predstavlja končno zahtevo v prihajajočem obdobju. Mlada, tehnološko izobražena, dobro plačana in moralna generacija intelektualcev bi morala začeti novo obdobje, obdobje obnovitve in trajnostnega razvoja..
- Tretja tema, ki je bila izpostavljena na kongresu je nova industrijska politika, porazdelitve sredstev v inovativna industrijska področja z uporabo novih/sodobnih/recikliranih materialov in sledenje načelom trajnostnega razvoja. Ta področja morajo biti ustrezno podprta z izobraževalnim razvojem, prilagajanjem zahtevam novega industrijskega okolja in popolno vgraditev v Evropske tehnološke in znanstvene ustanove v prihodnjih letih. Ta dejavnost mora vključevati zelo pomembna okoljska vprašanja.

Slišali smo tudi ugotovitev, da je Srbija v Evropi na samem vrhu po številu patentov in inovacij in ob tem so njihovi znanstveniki in raziskovalci, kar se tiče citatov njihovih del,visoko na lestvici. Dejstvo pa je žal tudi to, da srpski znanstveniki objavljajo izjemne dosežke, ki pa ostajajo neopaženi s strani vlagateljev in industrije.

Poročala: *mag. Mirjam Jan-Blažić*

AKTUALNO / CURRENT

Seminar za jeklo livarne in livarne temprane litine

dr. Konrad Weiss, RWP GmbH

Tik pred delovnim pričetkom letošnjega 57. mednarodnega livarskega posvetovanja Portorož 2017, t.j. 13.09.2017 je Društvo livarjev Slovenije organiziralo seminar za livarne jeklo in temprane litine pod naslovov: Zasnova ulivnega sistema in napajalnika za jeklo in temprano železo. Izvajalec seminarja je bil ugleden strokovnjak s področja livarstva, dr Konrad Weis iz firme RWP GmbH iz Nemčije. Seminarja se je udeležilo 14 slušateljev - predstavnikov livarn, ali poslovnih sitemov, ki so člani Društva livarjev Slovenije: CIMOS d.o.o., CRONING LIVARNA d.o.o., LITOSTROJ JEKLO d.o.o., LIVARNA TITAN d.o.o.. in OMCO FENIKS d.o.o. Slušatelji so uvodoma osvežili in na novo utrdili svoja znanja o jeklu in tempranem železu. V nadaljevanju so podrobno obdelane osnovne tehnike napajalnika oz. tematika strjevanja in napajanja, nasičenost in podlage za izračun ter zasnove ulivnega sistema in napajalnika za obe vrsti litine-pomeni za jeklo in temprano železo. Najbolj zanimiv del seminarja pa je bil v zaključku, ko je predavatelj predstavil udeležencem vrsto praktičnih izkušenj in primerov iz različnih livarn.

Vsi udeleženci seminarja so na začetku seminarja prejeli posebno brošuro v nemškem jeziku s slovenskim prevodom, sama predstavitev pa je s strani predavatelja potekala v angleškem jeziku.

Poročala. *mag. Mirjam Jan-Blažić*

AKTUALNO / CURRENT

Seminar za livarne sive in nodularne litine

Skladno s programom izobraževanja Društva livarjev Slovenije za leto 2017 je Društvo v času od 19.-20.10.2017 organiziralo z izvajalcem ÖGI – Avstrijskem livarskim inštitutom iz Leobna , seminar pod naslovom: Peščeni materiali za forme in jedra. Seminarja so se udeležili predstavniki naslednjih livarn-članic Društva livarjev Slovenije: CIMOS d.d., ETA d.o.o., KOVIS LIVARNA d.o.o., LIVAR d.d., LIVARNA GORICA d.o.o., OMCO FENIKS d.o.o. in VALJI d.o.o.

V tem primeru gre za praktično usmerjen seminar, ki je potekal v laboratoriju za peske v ÖGI-Avstrijskem livarskem inštitutu v Leobnu. Slušatelji so uvodoma osvežili in utrdili osnovna znanja o pesku za izdelavo form skozi postopke priprave, krožni proces formarskih materialov, materialov za izdelavo form in preizkušanje formarskih materialov. Poglobljeno so obravnavali zahteve , ki jih materiali za izdelavo form morajo izpolnjevati kot so: sposobnost trajnega oblikovanja, sposobnost pretoka, obstojnost forme oz. njena trdnostna stabilnost, propustnost za pline, obstojnost pri visoki temperaturi, sposobnost razpada in ponovna uporabnost. Preizkušanje materialov za izdelavo form je potekalo v laboratoriju

Udeleženci seminarja v ÖGI Leoben

OGI in sicer po konvencionalnih in novih metodah s sodobno opremo za preizkušanje, s katero razpolagajo v inštitutu. Slušatelji so bile seznanjeni tudi s vplivi metode preizkušanja in priprave vzorca na vrednosti preizkušanja svežih peskov, o natančnosti preizkušanja oz. vplivih izdelave in obdelave preizkušancev na le-to.

Glede na to, da so formarski materiali najobčutljivejši materiali v livarni, zahtevajo izobraženega preizkuševalca s izkušnjami, znanjem o materialu, poznavanjem toleranc in s sposobnostjo za ukrepanje pri odstopanjih. Slušatelji so bili podrobno seznanjeni o vplivih pri pripravi vzorcev in pri ravnanju z njimi ter o možnih vzrokih za napake.

Slušatelji so kot preizkuševalci v OGI- laboratoriju za peske lahko opravili tudi preizkuse peska, ki so ga prinesli iz svojih livarn. Pred preizkusi so vsi preizkuševalci dobili od osebja inštituta napotke za preizkušanje v obliki VDG-pisnih navodil. Vsak preizkuševalec je preizkušal peske naprej kot v lastnem laboratoriju, ob opazovanju vzajemnega načina dela in ugotavljanja kaj je potrebno spremeniti in izboljšati. Zaželeno je bilo, da se zastavlja sproti čim več vprašanj in da se nenehno vodi pogovor o razlikah in poteku preizkušanj ter o medsebojnih zapažanjih. Priporočeno je bilo, da se po možnosti izvrši čim več preizkusov. Vse preizkusne vrednosti so se sproti morale vnašati v tabele, katere so bile potem oddane v vrednotenje osebju inštituta, ob koncu prvega dne seminarja. Drugega dne seminarja se je nadaljevalo z delom v laboratoriju in z diskusijo o rezultatih preizkusov, katere je je vsak slušatelja na konca seminarja prejel z napotki.

Vsi udeleženci seminarja so na začetku seminarja prejeli posebno brošuro v nemškem jeziku s slovenskim prevodom, sama predstavitev pa je s strani predavatelja potekala v angleškem jeziku.

Poročala: *mag. Mirjam Jan-Blažić*

AKTUALNO / CURRENT

Osnovni seminar za neželezne livarne

V programu dela Društva livarjev Slovenije za leto 2017 smo načrtovali izvedbo dveh seminarjev za neželezove livarne. Glede na prevladujoči interes in največjo zastopanost livarn visoko tlačnega litja v Društvu, sta oba seminarja bila pripravljena za tlačne livarne in v obeh primerih je izvajalec seminarja bil ÖGI- Avstrijski livarski inštitut iz Leobna, s katerim Društvo na področju izobraževanja sodeluje bolj intenzivno od leta 2015 dalje. Prvi seminar dopolnilnega izobraževanja za tlačne livarne pod naslovom: Osnove tehnologije tlačnega litja - od osnov do optimiranja procesa je potekal letos, dne 28.11.2017 na Gospodarski zbornici Slovenije v Ljubljani. Seminarja so se udeležili predstavniki naslednjih livarn ali poslovnih sistemov: CIMOS d.d., DIFA d.o.o., HIDRIA ROTOMATIKA d.o.o.,ISKRA ISD d.o.o., MAHLE LETRIKA KOMEN d.o.o., MARIBORSKA LIVARNA MARIBOR d.d., TALUM d.d. in TELKOM d.o.o. Slušatelji seminarja so se uvodoma seznanili s pregledom vseh livarskih postopkov s poudarkom na mestu, ki ga v tem seznamu zavzema postopek tlačnega litja s svojimi prednostmi in slabostmi Nadaljevalo se je s predstavitvijo vrst tlačnih strojev, zgradbo in postavitvijo celice za tlačno litje in predstavitvijo zaporedja procesa. In potem še poglobljeno o litju prilagojeni konstrukciji, s katero se zagotavlja optimiranje ulitka in topologije ter kvalitetno orodje ali forma za tlačno litje. V zaključnih poglavjih seminarja so bile predstavljene in podrobneje obravnavane vse tri faze postopka tlačnega litja, optimiranje procesa tlačnega litja in zlitin za tlačno litje.

Udeleženci seminarja na GZS

Vsi udeleženci seminarja so na začetku seminarja prejeli posebno brošuro v nemškem jeziku s slovenskim prevodom, sama predstavitev pa je s strani predavatelja potekala v angleškem jeziku.

Večina udeležencev tega seminarja o tlačnem litju se bo vključila že v decembru letos v nadaljevalni seminar za tlačno litje s praktičnim delom, ki bo potekal v ÖGI- Avstrijskem livarskem inštitutu v Leobna, o katerem bomo poročali v prvi številki Livarskega vestnika naslednje leto.

Poročala: *mag. Mirjam Jan-Blažić*