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Vpliv toplotne prevodnosti različnih materialov orodij na strjevanje zlitine AlSi9Cu3

The Influence of Thermal Conductivity for Different Mould Materials on Solidification of AlSi9Cu3 Alloy

Izvleček

Življenjska doba orodij za tlačno litje je vse bolj pomembna. Orodna jekla za delo v vročem imajo najboljše razmerje med ceno in življenjsko dobo uporabe, zato jih uporabljamo za izdelavo orodij za tlačno litje. Vse večji pomen se daje toplotni prevodnosti in njenemu vplivu na strjevanje ulitkov. Povečana toplotna prevodnost skrajša cikel litja in hkrati podaljša življenjsko dobo orodij. Odločili smo se za simulacijo visoko tlačnega litja aluminijeve zlitine AlSi9Cu3. Simulacije smo izvajali s programskim orodjem ProCAST, geometrijo ulitkov in ulivni sistem pa smo oblikovali v programskem orodju SOLIDWORKS. Predvsem nas je zanimal vpliv različne toplotne prevodnosti trajnih form na strjevanje in ohlajanje ulitka. Namen raziskave je bil narediti izračune livarskih procesov enakih ulitkov, kjer smo spreminjali materiale, iz katerih so bile trajne forme izdelane, le-te so imele različne toplotne prevodnosti, gostote in ostale materialne lastnosti. Uporabili smo naslednje materiale za orodja: orodna jekla za delo v vročem – H-13, Dievar, HTCS-130, DAC-MAGIC in W350, maraging jeklo – MARVAL18 in pa zlitine s povečanimi toplotnimi prevodnostmi – CuAg12, Allper52 in Ni75Al. Slednje tri zlitine smo izbrali predvsem z namenom teoretičnega preučevanja vpliva povišane toplotne prevodnosti na strjevanje, cene takšnih orodij bi namreč najverjetneje bile previsoke v primerjavi z orodji, ki se največ uporabljajo v industriji. Rezultati so pokazali, da toplotna prevodnost vpliva na strjevanje, kar je razvidno tudi iz temperaturnih gradientov orodij in pa hitrosti ohlajevanja posameznega ulitka.

Ključne besede: Tlačno litje, orodna jekla za delo v vročem, toplotna prevodnost, aluminijeva livarska zlitina.

Abstract

The lifetime of pressure die casting moulds is progressively more important. Steels have the best price / lifetime ratio and are often used for production of die-casting moulds. Thermal conductivity and its effect on the solidification of castings are also increasingly important. Increased thermal conductivity shortens casting cycles and at the same time extends the lifespan of moulds. We decided to simulate high-pressure die casting of aluminium alloy 226 (AlSi9Cu3). The simulation was carried out in ProCAST software tool, the casting geometry and the casting system were created in the SOLIDWORKS software tool. In particular, we were interested in how different values of thermal conductivity of permanent moulds (dies) influence solidification and cooling of the cast. Therefore, the purpose was to make simulations of the same castings where we changed the permanent mould materials, which had different thermal conductivity, density and other material properties. We used the following materials for moulds: hot work tool steels – H-13, Dievar, HTCS-130, DAC-MAGIC and W350, maraging steel – MARVAL18 and alloys with increased thermal conductivity –

CuAg12, Allper52 and Ni75Al. The last three alloys were chosen primarily for theoretical study of the influence of increased thermal conductivity on the solidification, namely, the prices of such moulds would most likely be too high in comparison with the moulds that are most frequently used in the industry. The results showed that the thermal conductivity affects the solidification, which is also evident from the temperature gradients of the moulds and the cooling speed of the individual cast.

Key words: High-pressure die casting, hot work tool steels, thermal conductivity, Al-foundry alloy

1 Uvod

Ulitki so izdelki ene od ustanovnih industrij izdelovanja kovinskih izdelkov – livarstva. Izdelani so v enem koraku iz tekoče kovine oziroma taline brez vmesnih mehanskih operacij, kot sta na primer valjanje in kovanje. Oblikovani ulitki se torej razlikujejo od ingotov in drugih litih oblik, ki so samo vmesna faza svoje metalurške poti do končnega izdelka [1].

Zlitine Al–Si se lahko ulivajo z vsemi poznanimi tehnikami litja v enkratne in trajne forme. Aluminijevim zlitinam, ki se ulivajo tlačno, sta dodana še legirna elementa Fe in Mn, ker tvorita specifične faze, ki preprečujejo lepljenje ulitkov na stene orodja [5, 7, 8]. Poznano je, da aluminijeve zlitine topijo železo, to pa lahko pri strjevanju zlitine privede do nastanka faze železovega aluminida. Raztapljanja ni možno popolnoma preprečiti, zato je v zlitinah za tlačno litje dopustna višja vsebnost železa, kot v istih zlitinah za npr. gravitacijsko litje v enkratne peščene forme. Po drugi strani pa prevelika vsebnost železa v Al-zlitinah vodi do prevelikega izločanja železovega aluminida v obliki grobih igličastih vključkov, kar povzroča krhkost ulivane zlitine. Aluminijeva zlitina z vsebnostjo Si od 8 do 9 mas.% in Cu 3 mas.%, ter Al–Si zlitine s podevtektsko sestavo od 6 do 12 mas.% Si se najpogosteje uporabljajo v livarski industriji [1-5, 7, 8].

1 Introduction

Castings are the products of one of the founding industries for the production of metal products - foundry. They are made in one-step from a liquid metal, without intermediate mechanical operations, such as rolling and forging. Castings therefore differ from ingots and other cast shapes, which are only the intermediate phase of their metallurgical path to the finished product [1].

Al-Si alloys can be cast with all known casting techniques. The alloying elements such as Fe and Mn are added to the die cast aluminium alloys, because they form specific phases that prevent the casting to stick on the mould walls [5, 7, 8]. It is known that aluminium alloys dissolve iron, which can during the solidification of the alloy lead to the formation of the phase of iron aluminide. Dissolution cannot be completely prevented; therefore, in the alloys for high-pressure die casting, higher iron content is allowed than in the same alloys, for example for gravity casting in sand moulds. On the other hand, the excessive iron content in Al alloys leads to excessive precipitation of iron aluminides in the shape of coarse needle-like inclusions, which results in the brittleness of the cast alloy. Aluminium alloy with a Si content of 8 to 9 wt. % and Cu 3 wt. %, as well as Al-Si alloys with a subeutectic composition of 6 to 12 wt. % of Si are most

Zlitina z oznako AlSi9Cu3 je aluminijeva zlitina, s kemijsko sestavo podano v tabeli 1 (kemijsko sestavo smo dobili iz podatkovne baze programskega orodja ProCAST). Uporablja se predvsem za dele motorja v avtomobilski industriji (kolenasta gred, obročke ležajev, glava cilindra, itd.), elektroniko, rudarstvo, itd. Poznana je po zelo dobri livnosti in obdelovalnosti. Primarno strjevanje zlitine AlSi9Cu3 se začne pri temperaturi 562–564 °C (odvisno od kemijske sestave) s kristalizacijo primarnih zmesnih kristalov αAl, pri evtektski temperaturi 562 °C, se preostala talina prične strjevati po evtektski reakciji z izločanjem evtektika (αAl + βSi). Strjevanje se zaključi pri evtektski temperaturi 473 °C, ki je obenem tudi solidus temperatura (TS), katere produkt je heterogeni zlog (αAl +Al2Cu-Θ) [5, 6].

Običajno so trajne forme za litje zlitin izdelane iz kovinskih materialov. V kovinskih formah je namreč odvod toplote mnogo večji in tudi hitrejši, kot recimo pri enkratnih peščenih formah, zato imajo ulitki drobnozrnato mikrostrukturo, kar pa pomeni boljše mehanske lastnosti in večjo odpornost proti koroziji in eroziji. Hkrati pa je tudi površina ulitkov bolj kakovostna, merska odstopanja pa so manjša [5, 9]. Pri procesu tlačnega litja se sprosti toplota, ki vpliva tako na orodje, kot tudi na ulitek. Vpliv se najbolj odraža v obliki poškodb, le-te pa so posledica toplotnih sprememb med enim ciklom litja. Sam cikel litja poteka tako, da v zaprto orodje priteče talina, s temperaturo okrog 700° C, s tem pa temperatura orodja

commonly used in the foundry industry [1-5, 7, 8].

AlSi9Cu3 alloy is an aluminium alloy with the chemical composition given in Table 1 (the chemical composition was obtained from the ProCAST software database). It is mainly used for engine parts in the automotive industry (crankshaft, bearings, cylinder heads, etc.), electronics, mining, etc. It is well known for a very good casting properties and machinability. The primary solidification of the AlSi9Cu3 alloy begins at a temperature of 562-564 °C (depending on the chemical composition) by crystallization of the α_{Al} primary crystals at a 562 °C eutectic temperature, the residual melt begins to solidify by eutectic reaction by precipitation of the eutectic (α_{Al} + β_{Si}). The solidification is finished at an eutectic temperature of 473 °C, which is at the same time a solidus temperature (T_S) of which the product is a heterogeneous stacking (α_{Al} + Al_2Cu-Θ) [5, 6].

Typically, permanent moulds for casting alloys are made of metallic materials. Namely, in metallic moulds, the heat exchange is much greater and faster than, for example, in sand moulds; therefore, castings have a fine-grained microstructure, which means better mechanical properties and greater resistance to corrosion and erosion. At the same time, the surface of the castings has higher quality and the measurement deviations are smaller [5, 9]. In the process of high-pressure die casting, the heat is released which affects both, the mould and the cast. The impact is

Tabela 1. Kemijska sestava zlitine AlSi9Cu3

Table 1. Chemical composition of AlSi9Cu3 alloy

	Kemijski elementi so podani v mas.%. / Chemical elements are given in wt. %.										
	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Pb	Sn	Ti
Min	8,0		2,0	0,1	0,1						
Max	11,0	1,0	3,5	0,5	0,5	0,1	0,3	1,2	0,2	0,1	0,15

narase na maksimalno temperaturo. V nadaljevanju temperatura pade, zaradi delovanja hladilnega sistema orodja, nato se orodje odpre, kar pomeni, da okoliški zrak še dodatno ohladi orodje. Običajno se do tega koraka, orodje ohladi na 350 °C, nato orodje še premažejo s hladilno-ločilnim sredstvom, kar spet pomeni temperaturni šok za orodje in zaradi tega temperatura pade na okrog 220 °C. Nato se orodje spet zapre in cikel se ponovi, kar pomeni da je orodje pri tlačnem litju izpostavljeno cikličnim toplotnim nihanjem [5, 10].

K poškodbam orodja pa ciklično toplotno nihanje zelo pripomore, takšne poškodbe se kažejo predvsem kot razpoke v orodju. Le-te po navadi nastanejo na delih orodja, ki so toplotno najbolj obremenjeni. Zaradi cikličnega toplotnega nihanja takšne spremembe povzročijo izmenjavo temperature v tankih slojih na površini orodja, kar vodi do nastanka napetosti v orodju in posledično do nastanka razpok. Z zmanjšanjem temperaturnega oziroma toplotnega nihanja orodja lahko podaljšamo življenjsko dobo orodja. Hkrati pa lahko življenjsko dobo orodja podaljšamo tudi z zmanjšanjem napetosti med samim delovanje oziroma obratovanjem orodja, s pravilno toplotno obdelavo orodja ter hkrati tudi s pravilno izbiro jekla, s površinskimi prevlekami, pravilnim predgrevanjem orodja, optimizacijo parametrov litja, itn. [11].

Čas strjevanja ulitka in ohlajevalna hitrost sta dva zelo pomembna parametra, ki vplivata na kakovost ulitka. Končna mikrostruktura ulitka je namreč poleg kemijske sestave zlitine odvisna od teh dveh parametrov. Posledica tega, kakšno končno mikrostrukturo dobimo, pa so končne mehanske lastnosti ulitka. Daljši kot so časi strjevanja, večja kristalna zrna bomo dobili in mehanske lastnosti končnega ulitka bodo nižje [12, 13].

most reflected in damage on moulds, which are results of the thermal changes during one casting cycle. The casting cycle itself is carried out in such a way that a melt of approximately 700 °C flows into a closed mould, thereby increasing the temperature of the mould to a maximum temperature. In the following, the temperature decreases due to the operation of the cooling system of the mould, then it opens, which means that the ambient air further cools the mould. Usually until this step, the mould is cooled to 350 °C, then the mould is further coated with a refrigerant-separating agent, which again represents a temperature shock for the mould, and therefore the temperature drops to around 220 °C. Later on, the mould is closed again and the cycle repeats, which means that the mould is exposed to cyclic heat fluctuations at the high-pressure die casting [5, 10].

However, cyclical heat oscillation contributes to the formation of defects on the mould, and such defects are mainly shown as cracks in the mould. They are usually formed on parts of the mould that are the heat-stressed ones. Due to cyclic heat fluctuations, such changes cause temperature changes in thin layers on the surface of the mould, which leads to the formation of stresses in the mould and consequently to the formation of cracks. By reducing the temperature or heat fluctuations of the mould, it can extend the lifetime of the mould. At the same time, the life span of the mould can be extended by reducing the stresses during the operation itself by using the mould, with the proper heat treatment and at the same time using the correct selection of steel, surface coatings, proper preheating of the mould, optimization of casting parameters, etc. [11].

The solidification time and the cooling rate are two very important parameters that influence the quality of the cast. In

Zato smo se odločili, da bomo s pomočjo simulacij preučili vpliv toplotne prevodnosti različnih materialov orodij na strjevanje zlitine AlSi9Cu3. Večja toplotna prevodnost pomeni manjše temperaturne šoke za orodje, ker je odvod toplote večji.

2 Eksperimentalno delo

Za trajne forme, ki smo jih uporabljali v simulaciji, smo izbrali nekaj orodnih jekel za delo v vročem, ki se pogosto uporabljajo v industriji. Jeklo MARVAL18 pa je maraging (angl. martensite aging) jeklo. Kemijska

addition to the chemical composition of the alloy, the final microstructure of the casting depends on these two parameters. The consequence of final microstructure are the final mechanical properties of the cast. The longer the solidification times are the larger grains will be obtained, and the mechanical properties of the final casting will be lower [12, 13].

Therefore, we decided to use the simulations to study the influence of the thermal conductivity of various mould materials on the solidification of the alloy AlSi9Cu3. Namely, higher thermal conductivity means a reduced amount of

Tabela 2. Kemijska sestava preiskovanih jekel, podatki so podani mas.% [14-20].

Table 2. Chemical composition of investigated steels in wt. %. [14-20].

	H-13	Dievar	HTCS-130	DAC-MAGIC	W350	MARVAL18
C	0,39	0,35	0,31	0,36	0,38	0,03
Si	1,0	0,2	0,17	0,33	0,2	-
Mn	0,4	0,5	0,16	0,66	0,55	-
Cr	5,3	5,0	0,08	5,20	5,00	-
Mo	1,3	2,3	3,1	2,68	1,75	5,0
V	0,9	0,6	0,003	0,64	0,55	-
W	-	-	1,85	0,01	-	-
Ni	-	-	0,08	0,05	0,04	18,0
Cu	-	-	0,1	0,04	-	-
Co	-	-	-	-	-	8,0
Ti	-	-	-	-	-	0,5
Fe	Ostanek / Bal.	Ostanek / Bal.	Ostanek / Bal.	Ostanek / Bal.	Ostanek / Bal.	Ostanek / Bal.

Tabela 3. Toplotna prevodnost preiskovanih jekel [14-20]

Table 3. Thermal conductivity of investigated steels [14-20].

Toplotna prevodnost [W m^{-1} K^{-1}] / Thermal conductivity [W m^{-1} K^{-1}]						
Temperaturno območje / Temperature range	H-13	Dievar	HTCS-130	DAC-MAGIC	W350	MARVAL18
20 °C	25,0	37,0	60,4	25,7	28,9	27,0
200 °C	29,0	39,0	56,4	30,9	30,9	28,0
400 °C	30,0	32,0	48,5	34,8	30,7	27,4
600 °C	31,0	31,0	34,0	35,8	29,7	22,9

sestava jekel je podana v tabeli 2, vse vsebnosti legirnih elementov so podane v masnih odstotkih. Toplotna prevodnost vseh uporabljenih jekel pa je podana v tabeli 3. Podane so vse lastnosti, ki so jih podali proizvajalci. Uporabili smo šest jekel petih različnih proizvajalcev in sicer: Uddeholm (Böhler-Uddeholm H-13 in Dievar), Rovalma (HTCS-130), HITACHI (DAC-MAGIC), Böhler (W350) in Aubert&Duval (MARVAL18).

Za primerjavo rezultatov in sam vpliv toplotne prevodnosti na strjevanje ulitkov smo uporabili tudi materiale, ki imajo znatno večjo toplotno prevodnost od orodnih jekel za delo v vročem. Toplotne prevodnosti materialov, ki so bili uporabljeni v simulaciji, so predstavljene v tabeli 5. Uporabili pa smo naslednje materiale: bakrovi zlitini (CuAg12 in Allper52) in nikljevo zlitino Ni75Al. Kemijska sestava za posamezno preiskovano zlitino je podana v tabeli 4. Namen uporabe teh materialov je bil raziskati vpliv toplotne prevodnosti na temperaturne gradiente v samem orodju in ulitku. Namreč orodja iz takšnih materialov niso ekonomična, saj bi stala preveč v primerjavi s tistimi iz orodnih jekel za delo v vročem. Imajo pa povišano toplotno prevodnost v primerjavi z orodnim jeklom (tabela 5). Podatki v tabelah 4 in 5 so bili vzeti iz podatkovne baze programskega orodja ProCAST.

Geometrijo ulivnega sistema in samih ulitkov smo izrisali v programskem orodju SOLIDWORKS. Programsko okolje je zasnovano tako, da lahko izrišemo načrte tako v 2D, kot tudi v 3D tehniki in ima hkrati tudi veliko opcij, s pomočjo katerih lahko spreminjamo veliko parametrov. Uporabljamo ga lahko samo v operacijskem sistemu Microsoft Windows [21]. Geometrija, ki je bila izrisana, je predstavljena na spodnji sliki (Slika 1). V tabeli 6 imamo predstavljene dimenzije za vsak posamezen ulitek, oznake

temperature shocks for the mould, since the heat exchange is larger.

2 Experimental

For permanent moulds, which we used in the simulation, we selected some hot work hot steels, which are often used in industry. The MARVAL18 steel is maraging (martensite aging) steel. The chemical composition of the steels is given in Table 2; all the alloying elements are given in weight percent. The thermal conductivity of all used steels is given in Table 3. All the properties given by the manufacturers are presented. We used six steels of five different manufacturers: Uddeholm (Böhler-Uddeholm H-13 and Dievar), Rovalma (HTCS-130), HITACHI (DAC-MAGIC), Böhler (W350) and Aubert & Duval (MARVAL18).

To compare the results and influence of thermal conductivity on the solidification of castings, we also used materials that have significantly higher thermal conductivity than hot work tool steels. The thermal conductivity of the materials used in the simulation is presented in Table 5. The following materials were used: copper alloys (CuAg12 and Allper52) and nickel alloy Ni75Al. The chemical composition for each investigated alloy is given in Table 4. The purpose of the use of these materials was to investigate the influence of thermal conductivity on the temperature gradients in the mould itself and the casting. The moulds from such materials are not economical, since they would cost too much money in comparison to the moulds from hot work tool steels. However, they have higher thermal conductivity compared to tool steel (Table 5). The data in Tables 4 and 5 were taken from the ProCAST software database.

The geometry of the casting system and the castings itself was drawn in the

Tabela 4. Kemijska sestava preiskovanih bakrovih in nikljevih zlitin, podatki so podani v mas.%.

Table 4. Chemical composition for copper and nickel alloys in wt. %

	CuAg12	Allper52	Ni75Al
Cu	88	97.3	-
Ag	12	-	-
Ni	-	1.1	75
Al	-	-	25
Co	-	1.1	-
Be	-	0.5	-

Tabela 5. Toplotne prevodnosti uporabljenih materialov

Table 5. Thermal conductivity of copper and nickel alloys

Toplotna prevodnost [W m^{-1} K^{-1}] / Thermal conductivity [W m^{-1} K^{-1}]			
Temperaturno območje / Temperature range	CuAg12	Allper52	Ni75Al
20 °C	413	235	70
200 °C	391	233	71
400 °C	374	232	69
600 °C	361	231	65

posameznega ulitka so predstavljene na Sliki 3.

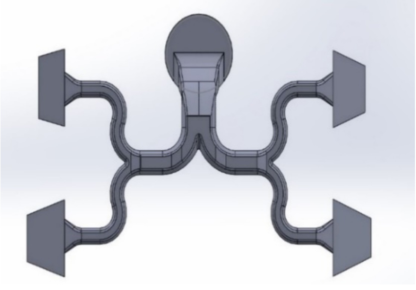
Tabela 6. Dimenzije in volumen za vsak posamezen ulitek

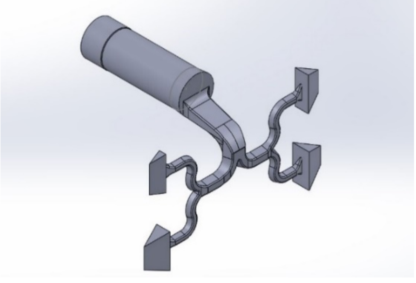
Table 6. Dimensions and volume for each casting

Oznaka ulitka / Casting number	a [mm]	b [mm]	V [mm^3]
1	100	50	102219
2	80	40	66002
3	80	40	66002
4	50	20	20387

SOLIDWORKS software. The software environment is designed to draw sketches both in 2D and 3D technology, and it also has many options that can help you to change a lot of parameters. It can be run only in Microsoft Windows [21]. The geometry that was drawn is presented in the figure below (Figure 1). Table 6 shows the dimensions for each individual cast, the marks of each cast are shown in Figure 3.

The calculation of foundry processes was carried out in the ProCAST software using the finite element method.

a) 

b) 

Slika 1. Prikazana je geometrija ulivnega sistema, ter ulitkov (a), kot tudi komora in bat (b)

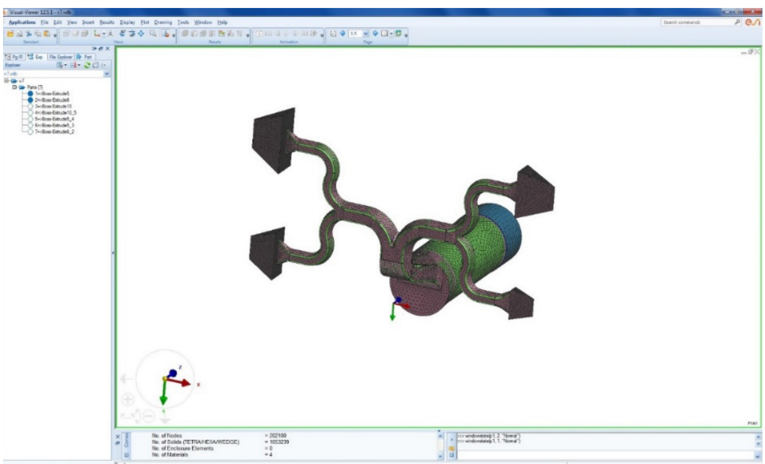
Figure 1. The geometry of the casting system and castings (a), as well as the chamber, and the piston (b) are shown

Sam izračun livarskih procesov je potekal v programskem orodju ProCAST po metodi končnih elementov. Najprej smo uvozili geometrijo iz SOLIDWORKS-a, nato pa smo zamrežili ulivni sistem, ulitke in orodje. V nadaljevanju smo nastavili livne parametre, in sicer je bila temperatura litja 720 °C, temperatura orodja in bata je bila 200 °C, lastnosti zlitine AlSi9Cu3 (solidus temperatura je bila 508 °C, likvidus temperatura je bila 588 °C, fizikalne, kemijske in mehanske lastnosti), lastnosti orodja (za vsak material posebej fizikalne, kemijske in mehanske lastnosti), pomike bata, itn. Po nastavitvi vseh parametrov smo pognali simulacijo. Med simulacijo so bili vsi parametri litja enaki za vse materiale, spreminjali smo le materialne lastnosti orodja. Na sliki 2 imamo predstavljen grafični vmesnik programskega orodja ProCAST, z geometrijo ulitkov in ulivnega sistema.

V nadaljevanju bodo predstavljeni rezultati simulacij litja in strjevanja zlitine AlSi9Cu3. Za lažje razumevanje ohlajevalnih krivulj za posamezen ulitek je na sliki 3 predstavljen sistem označevanja

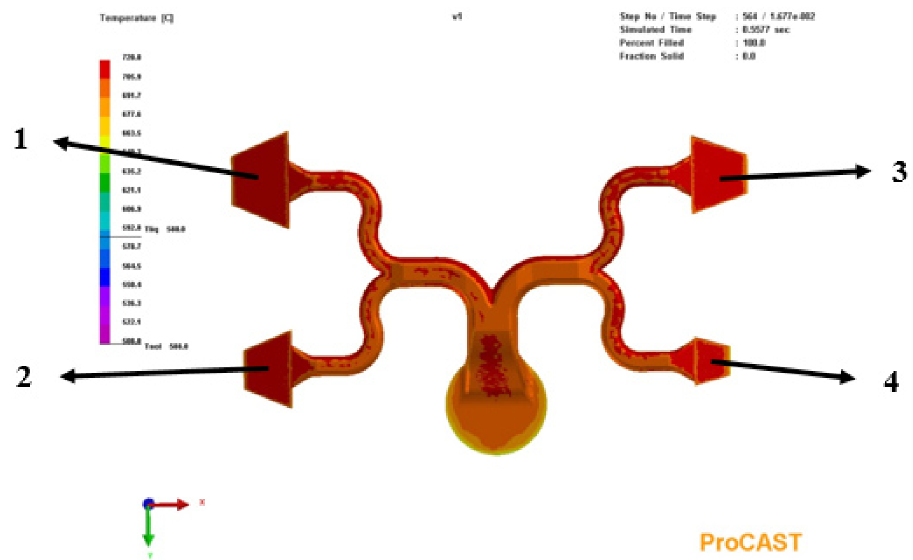
First, we imported the geometry from SOLIDWORKS, and then we mesh the casting system, castings and mould. In the next step we set casting parameters such as: the temperature of the casting being 720 °C, the temperature of the mould and the piston was 200 °C, the properties of AlSi9Cu3 alloy (the solidus temperature was 508 °C, the liquid temperature was 588 °C, the physical, chemical and mechanical properties), properties of the mould (for each material, especially physical, chemical and mechanical properties), piston movements, etc. After setting all the parameters, we run the simulation. During the simulation, all casting parameters were the same for all materials, only the material properties of the mould were changed. Figure 2 shows the graphical interface of ProCAST software, with the geometry of castings and casting systems.

The results of the simulation of casting and solidification of the alloy AlSi9Cu3 will be presented below. In order to simplify the understanding of the cooling curves for a single casting, marking of the individual



Slika 2. Grafični vmesnik programskega orodja ProCAST, z geometrijo ulitkov in ulivnega sistema

Fig. 2. Graphical interface of ProCAST software, with casting and casting geometry



Slika 3. Prikaz označevanja posameznega ulitka

Fig. 3. Marking of the individual castings.

posameznih ulitkov, ki smo ga uporabili. Največje dimenzije in hkrati tudi volumen ima ulitek 1, sledita ulitka 2 in 3, ter na koncu ulitek 4. Ulitka 2 in 3 imata enake volumne, a različno pozicijo v orodju (slika 3). Rezultati so razdeljeni glede na posamezen material orodja, ki smo ga uporabili pri simulaciji. Materialne lastnosti orodja oziroma materiala, iz katerega je izdelano orodje, so namreč tiste, ki vplivajo na hitrost ohlajevanja, strjevanja in krajše čase ciklov pri samem tlačnem litju.

3 Rezultati in diskusija

Zaradi večjega števila rezultatov, smo na tem mestu naredili primerjavo rezultatov za posamezen material. V spodnji tabeli (Tabela 7) imamo prikazano toplotno prevodnost za posamezen material orodja pri 400 °C in pa tudi čase strjevanja za vse

castings is presented in Figure 3. The largest dimension and volume has the casting 1, followed by castings 2 and 3, and at the end cast 4. Castings 2 and 3 have the same volumes, but different position in the mould (Figure 3). The results are divided according to the individual mould material used in the simulation. The material properties of the mould respectively the material from which the mould is made are those that influence the cooling speed, solidification and shorter cycles during the high-pressure die casting.

3 Results and Discussion

Due to the higher number of results, we made a comparison of the results for each mould material. In the table below (Table 7), we have shown the thermal conductivity of used mould materials at 400 ° C, as well ulitke. Kot je razvidno iz rezultatov, nam povišana toplotna prevodnost skrajša čas strjevanja. Zvišanje toplotne prevodnosti za 18,52 W m^{-1} K^{-1} (H-13 in HTCS-130) nam skrajša čas strjevanja za 1 s. To se sicer ne sliši veliko, a pri 50.000 ali pa 100.000 kosih oziroma ciklih je to veliko. Če primerjamo še čase strjevanja, kjer je bilo orodje iz jekla HTCS-130 in zlitino Ni75Al, kjer je razlika v toplotni prevodnosti 20,5 W m^{-1} K^{-1}, se nam čas strjevanja skrajša za 2,2 s. Kar je v primerjavi z orodnimi jekli veliko. To pa že nakazuje na to, da nam povišana toplotna prevodnost skrajša cikle litja in pa tudi hkrati podaljša življenjsko dobo orodij, kot smo tudi predvideli. Če primerjamo rezultate časov strjevanja ulitkov za orodna jekla, recimo za jeklo HTCS-130 z zlitino CuAg12, ki ima največjo toplotno prevodnost od preiskovanih materialov, opazimo, da je razlika v času strjevanja 9 s. To pa je že ogromna razlika. Potrebno pa je upoštevati še dejstvo, da je toplotna prevodnost zlitine

as the solidification times for all castings. As shown in the results, increased thermal conductivity shortens the solidification time. Increasing the thermal conductivity for 18.52 W m^{-1} K^{-1} (H-13 and HTCS-130) reduces the solidification time by 1 s. This does not sound a lot, but at 50,000 or even 100,000 cycles, this is a lot. If we compare the solidification times where the mould material was HTCS-130 and Ni75Al, the difference in thermal conductivity is 20.5 W m^{-1} K^{-1}, the solidification time is reduced by 2.2 s. In comparison to the hot work tool steels, this is a big difference. This already indicates that increased thermal conductivity shortens casting cycles and at the same time extends the life span of moulds, as we anticipated. If, however, we compare the results of the casting solidification times for tool steels, for example HTCS-130 with CuSg12 alloy, which has the highest thermal conductivity from examined materials, we can notice that the difference in the solidification time

Tabela 7. Primerjava toplotnih prevodnosti in časov strjevanja ulitkov za posamezen material

Table 7. Comparison of thermal conductivity and solidification time for each mould material

Material orodja / Mould materials	Toplotna prevodnost materiala pri 400 °C [W m^{-1} K^{-1}] / Thermal conductivity of material at 400 °C [W m^{-1} K^{-1}]	Čas strjevanja ulitka 1 [s] / Solidification time of 1st casting [s]	Čas strjevanja ulitka 2 [s] / Solidification time of 2nd casting 2 [s]	Čas strjevanja ulitka 3 [s] / Solidification time of 3rd casting [s]	Čas strjevanja ulitka 4 [s] / Solidification time of 4th casting [s]
H-13	30.0	37.5	28.8	31.0	16.0
Dievar	32.0	37.4	28.5	30.7	15.3
HTCS-130	48.5	36.5	27.9	30.0	15.4
DAC-MAGIC	34.8	36.9	28.4	30.5	15.5
W350	30.7	44.0	33.1	35.8	17.7
Marval18	27.4	39.2	29.8	32.0	16.1
CuAg12	374.0	27.5	21.7	23.3	12.7
Allper52	232.0	29.7	23.0	24.7	13.1
Ni75Al	69.0	34.3	26.8	28.9	14.8

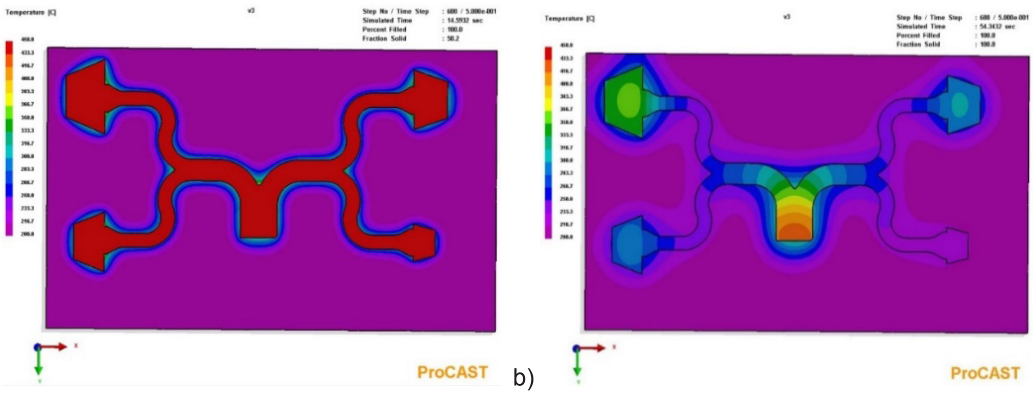
CuAg12 7,7 krat večja, kot jo ima orodno jeklo za delo v vročem HTCS-130.

Za primerjavo smo dodali še nekaj temperaturnih gradientov za posamezna orodja, kjer je tudi opazna razlika med različnimi orodji, ki imajo različne toplotne prevodnosti. Barvna temperaturna skala

is 9 s. This is already enormous difference, but it is necessary to take into account the fact that the thermal conductivity of CuAg12 is 7.7 times higher than in case of HTCS-130.

For comparison, we added some temperature gradients for individual

HTCS-130 – 48,52 W m^{-1} K^{-1}

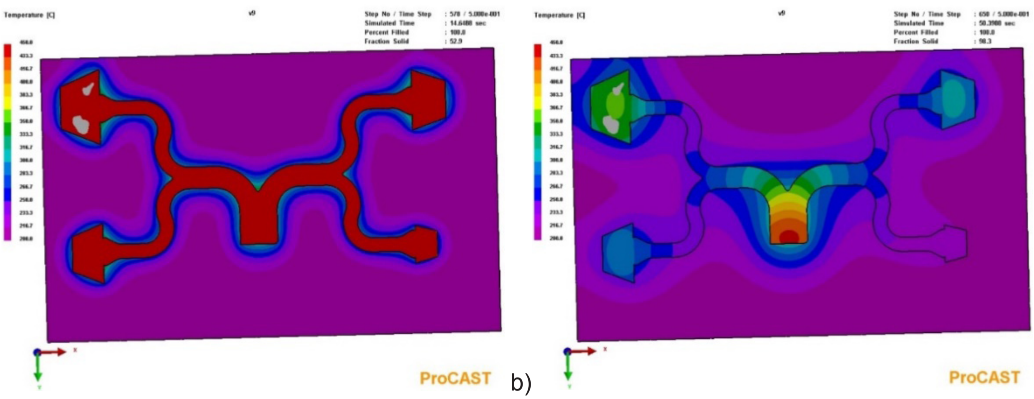


a) b)

Slika 4. Temperaturni gradient orodja iz jekla HTCS-130 (a) pri 50 % trdne faze in (b) pri 100 % trdne faze

Figure 4. The temperature gradient of the mould made of HTCS-130 steel (a) at 50 % of the solid phase and (b) at 1

Ni75Al – 69 W m^{-1} K^{-1}



a) b)

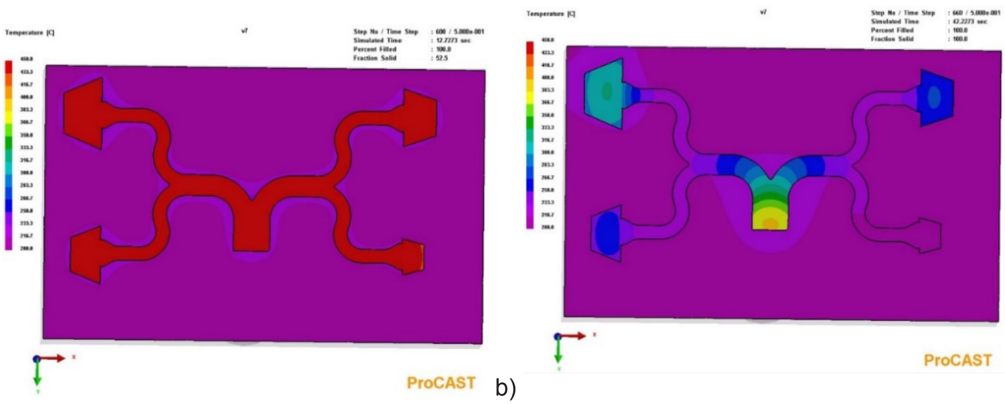
Slika 5. Temperaturni gradient orodja iz zlitine Ni75Al (a) pri 50 % trdne faze in (b) pri 100 % trdne faze

Figure 5. The temperature gradient of the mould made of Ni75Al alloy (a) at 50 % of the solid phase and (b) at 100 % of the solid phase

na levi strani rezultatov temperaturnih gradientov orodij (slike 4-6) je od 400 °C do 200 °C, medtem ko je na sliki 7 temperaturna skala orodja od 250 °C do 100 °C. Na sliki 8 imamo primerjavo hitrosti ohlajevanja za

moulds, where there is also a noticeable difference between different moulds with different thermal conductivity. The colour temperature scale on the left side of the temperature gradients of the moulds

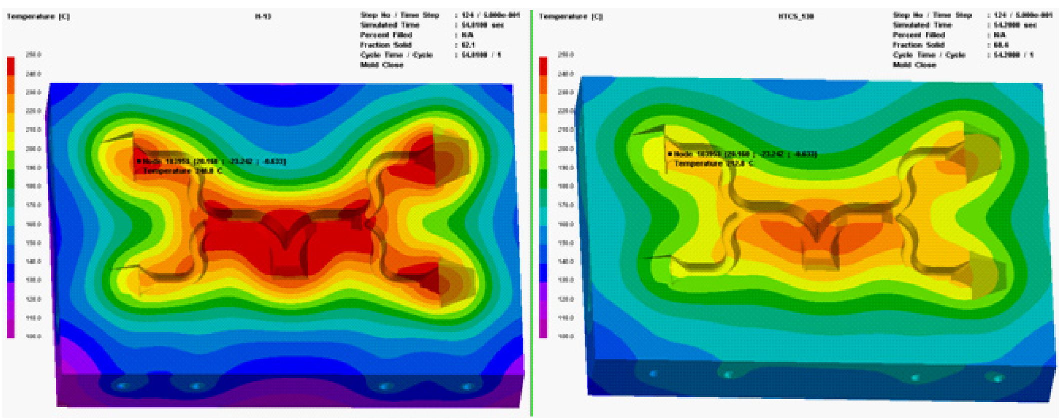
CuAg12 – 374 W m^{-1} K^{-1}



a) b)

Slika 6. Temperaturni gradient orodja iz zlitine CuAg12 (a) pri 50 % trdne faze in (b) pri 100 % trdne faze

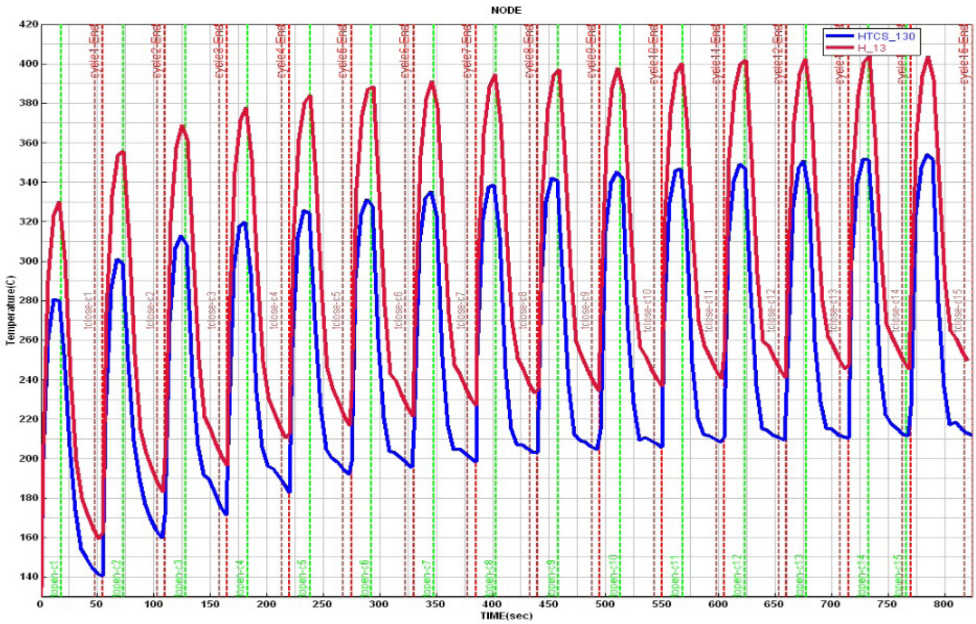
Figure 6. The temperature gradient of the mould made of CuAg12 alloy (a) at 50 % of the solid phase and (b) at 100 % of the solid phase.



a) b)

Slika 7: Primerjava temperaturnega gradienta po 15 ciklih (a) orodje iz jekla H-13 in (b) orodje iz jekla HTCS-130

Figure 7. Comparison of the temperature gradient after 15 cycles for the moulds made of hot work tool steels (a) H-13 and (b) HTCS-130



Slika 8. Primerjava hitrosti ohlajevanja za 15 ciklov litja, rdeča krivulja predstavlja hitrost ohlajevanja orodja iz jekla H-13 in modra orodje iz jekla HTCS-130

Figure 8. Comparison of the cooling rate of mould for 15 casting cycles, the red curve represents the mould made of H-13 steel and the blue curve mould made of HTCS-130 steel.

15 ciklov litja med orodnima jekloma H-13 in HTCS-130.

4 Sklepi

Rezultati izračunov livarskih procesov so pokazali, da je izmed preiskovanih orodnih jekel za delo v vročem najboljše jeklo HTCS-130. To je bilo pričakovano, saj ima jeklo HTCS-130 največjo toplotno prevodnost izmed vseh preiskovanih orodnih jekel za delo v vročem. Ostala orodna jekla imajo podobne toplotne prevodnosti, to se kaže tudi v rezultatih simulacij (čas strjevanja, temperaturni gradient, itn.), razen jekla W350, ki je imelo najdaljše čase strjevanja posameznih ulitkov, čeprav je toplotna prevodnost podobna toplotni prevodnosti

(Figures 4-6) ranges from 400 °C to 200 °C. Whereas, in Figure 7, the temperature scale is between 250 °C and 100 °C. In Figure 8, we have a comparison of the cooling rate for 15 casting cycles between the H-13 and HTCS-130 hot work tool steels.

4 Conclusions

The results of casting processes calculations have shown that among investigated hot work tool steels HTCS-130 is the best. This was expected because the HTCS-130 steel has the highest thermal conductivity of all analysed hot work tool steels. Other tool steels have similar thermal conductivity, this is also reflected in the results of the simulations (solidification time, temperature ostalih preiskovanih orodnih jekel za delo v vročem.

Če primerjamo rezultate orodnih jekel z rezultati preiskovanih zlitin, ki so imele nekajkrat večjo toplotno prevodnost, opazimo, da so časi strjevanja pri uporabi orodnih jekel daljši. Zlitina Ni75Al, ki ima toplotno prevodnost 69 W m-1 K-1 (pri 400 °C), ima čas strjevanja za ulitek 1 za 7 s krajši, kot je to pri ulitku, kjer je orodje iz orodnega jekla HTCS-130, ki ima toplotno prevodnost 48,52 W m-1 K-1 (pri 400 °C). Razlike so še večje, če primerjamo orodna jekla z zlitinama Allper52 in CuAg12, kot je razvidno tudi iz rezultatov (tabela 7).

S pomočjo simulacij smo potrdili, da toplotna prevodnost vpliva na čas strjevanja. Pri orodnih jeklih za delo v vročem ni bilo opaziti bistvenih razlik, odstopalo je le jeklo W350, kjer so ulitki imeli najdaljše čase strjevanja. Najboljše pa je bilo jeklo HTCS-130, kjer so ulitki imeli najkrajše čase strjevanja. Ugotovili smo tudi, da bi bil pri povečanju toplotne prevodnosti za 20 W m-1 K-1 cikel ulivanja 7 s krajši. To pa je ugodno s stališča povečanja produktivnosti proizvodnje, hkrati bi s tem podaljšali tudi življenjsko dobo orodja in povečali mehanske lastnosti ulitkov.

5 Zahvala

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gradient, etc.). Except for the W350 steel, which had the longest solidification times of all individual castings, although the thermal conductivity is similar to the thermal conductivity of other hot work tool steels.

If we compare the results of the tool steels with the results of the investigated alloys, which had several times higher thermal conductivity, we observed that the solidification times in the usage of tool steels are longer. A Ni75Al alloy having a thermal conductivity of 69 W m^{-1} K^{-1} (at 400 °C) has a solidification time of the cast 1 for 7 s shorter than in example, where the mould is made of HTCS-130 steel which has a thermal conductivity of 48.52 W m^{-1} K^{-1} (at 400 °C). The differences are even greater when comparing hot work tool steels with alloys Allper52 and CuAg12, as can be seen from the results (Table 7).

Using the simulations, we confirmed that the thermal conductivity affects the solidification time. There was no significant difference in case of hot work tool steels, only the W350 differed, with the longest solidification times. The best results were achieved in case of HTCS-130 steel, where castings had the shortest solidification times. We also found that if the thermal conductivity were increased by 20 W m^{-1} K^{-1}, the casting cycle would be 7 s shorter. This is favourable since thus the productivity of the production increases, while at the same time it would prolong the life span of the mould and increase the mechanical properties of the castings.

5 Acknowledgement

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AKTUALNO / CURRENT

Koledar livarskih prireditev 2019

Datum dogodka	Ime dogodka	Lokacija
29.-30.01. 2019	10. VDI-Fachtagung »Gießereitechnik« im Motorenbau 2019	Magdeburg, Nemčija
26.02. 2019	19. Druckgusstag	Schorndorf, Nemčija
14.-15.03. 2019	45. Aachener Gießerei-Kolloquium	Aachen, Nemčija
11.-12.04. 2019	63. Österreichische Gießerei Tagung	Schladming, Avstrija
27.-30.04. 2019	CastExpo	Atlanta, USA
21.-24.05. 2019	Moulding Expo	Stuttgart, Nemčija
25.-29.06. 2019	GIFA, NEWCAST, METEC, THERMPROCESS	Düsseldorf, Nemčija
18.-20.09. 2019	WFO-Technical Forum in 59. IFC Portorož 2019	Portorož, Slovenija

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