Molnar, D.[1], Sandor, B.[2], Dul, J.[3]
Univerza Miskolc, Inštitut za metalurgijo in livarstvo, Madžarska /
Institute of Foundry Engineering, University of Miskolc, Hungary

Simulacija livnosti tekočih kovin z različnim reološkim obnašanjem

Flowability Simulation of Liquid Metals with Different Rheological Behaviour

Povzetek

Tlačno litje je proces, s katerim se dobi skoraj končna oblika izdelka in pri katerem talina pod tlakom turbulentno zapolnjuje livno votlino pred začetkom strjevanja. Obstajajo še druge tehnologije tlačnega litja kot ulivanje v testastem stanju, ki je bilo razvito, da se poveča kakovost ulitkov. Na simulacijo livnosti in sposobnosti zapolnjevanja forme vplivajo različni parametri kot temperatura taline in kokile, viskoznost v coni gobastega strjevanja, delež trdnih delcev in lastnosti toka. Razvili smo model krmilne prostornine za simulacijo litja v testastem stanju z uporabo trgovske računalniške opreme NovaFlow&Solid. Napravili smo več poskusnih simulacij, da bi preiskali livnost standardne zlitine AlSi7Mg in njeno testasto obliko.

Ključne besede: ulivanje v testastem stanju, obnašanje toka, tokovni preskus, računalniška simulacija

Abstract

High pressure die casting is a near net shape process where turbulent filling and rapid solidification occurs under high pressure conditions. Alternative die casting technologies such as rheocasting have been developed in order to increase the quality of castings. The simulation of flowability and fillability is influenced by several factors such as temperature of the melt and the die, viscosity behaviour in the mushy zone, solid particle ratio and flow properties. Here a control volume model is developed to simulate the rheocasting process based on the commercial software NovaFlow&Solid. Several simulation trials were carried out to examine the flowability of normal AlSi7Mg alloy and its semisolid version.

Key-words: semi-solid rheocasting, flow behaviour, flow-test, computer simulation

1 Ulivanje v testastem stanju

Lahke kovine se v velikem obsegu uporabljajo v avtomobilski industriji in industriji transportnih sredstev kot kovne ali livne zlitine. Pred kratkim je evropska aluminijska zveza (EEA) poročala, da se

1 Semi-solid metal processing

Lightweight metals are used extensively by the automotive and transport industries, both in wrought and cast forms. Recently the European Aluminium Association (EEA) reported that the amount of aluminium used je količina aluminija v novih evropskih avtomobilih povečala s 50 kg leta 1990 na 140 kg leta 2010 [1], zato ni presenetljivo, da še narašča trend uporabe aluminija in aluminijevih zlitin v avtomobilski industriji in industriji transportnih sredstev. Uliti aluminijski deli so predvsem kot deli šasij in deli obesnih mehanizmov, koles, krmilnih mehanizmov, glav valjev, zavornih bobnov, ojnic itn. Danes se po podatkih EEA uporablja okoli 73 % livnih zlitin v Evropi v sektorju transportnih sredstev [1]. Zaradi velike produktivnosti, dimenzijske stabilnosti in izvrstne površinske dodelave se velika količina teh delov izdeluje s tlačnim litjem.

Pri iskanju izboljšanih lastnosti zlitin so se v zadnjih štirih desetletjih razvile in vpeljale na tržišče številne tehnike litja kot oblikovanje v testastem stanju ali stiskalno litje. Stiskalno litje je način izdelave delov s skoraj končno obliko, pri katerem se tekoča kovina skuje v končno obliko znotraj zaprte kokile. Združuje trdnost in celovitost izkovka z ekonomičnostjo in prilagodljivostjo konstrukcije ulitka. Izvor procesa je Sovjetska zveza, potem se je sredi 1970tih let začel trgovsko uporabljati za izdelavo sestavnih delov iz neželeznih kovin. V primerjavi s klasičnimi tehnikami ulivanja imajo tako izdelani ulitki zelo dobro kombinacijo trdnosti in raztezka, ki izvira predvsem iz njihove velike gostote ter drobnejše in bolj homogene mikrostrukture [2].

1.1 Zahteve po podhladitvi

Gonilna sila vsake fazne transformacije vključno s strjevanjem je sprememba proste energije. Molsko ali prostorninsko prosto energijo lahko izrazimo kot

$$F = E + P \times v - T \times S, \qquad (1)$$

kjer je E notranja energija (tj. količina potrebnega dela za izločenje atomov iz

in new European cars had risen from 50 kg in 1990 to 140 kg in 2010 [1], so it is not surprising to see there is a growing tendency to employ aluminium and aluminium alloys in the automotive and transport industries. Cast aluminium components are mainly used in chassis and suspension applications, wheels, steering parts, cylinder heads, brake drums, connecting rods, etc. Today, based on data from the EEA, some 73 % of cast alloys go into the transport sector in Europe [1] and due to high production rate and dimensional stability as well as excellent surface finish and high volume production, a large number of these parts are produced by high pressure die casting method.

In the search for improved alloy properties, a number of casting techniques have been developed and introduced on the market in last four decades, such as semi-solid forming or squeeze casting. Squeeze casting is a casting method of producing near-net-shape parts in which the liquid metal charge is forged to shape inside closed dies. It combines the strength and integrity of forging with the economy and design of flexibility of casting. The process originated in the USSR, then in the mid-1970s became commercially available for custom manufacture of nonferrous components. Compared with conventional casting techniques, squeeze cast products have a very good combination of strength and elongation, which mainly comes from their high density and finer and more homogenous microstructures. [2]

1.1 The Undercooling Requirement

The driving force of any phase transformation, including solidification, is the change in free energy. The free energy per mole (molar free energy) or per unit volume faze v neskončnost), P tlak, v prostornina, T temperatura in S entropija. Termodinamika zagotavlja, da se lahko notranja energija v sistemu brez zunanjih vplivov le zmanjšuje. Spremembo proste energije lahko opišemo kot vsoto povečkov, ki so posledica sprostitev posameznih predpostavk:

$$\Delta F=-\Delta G_v+\Delta G_r+\Delta G_T+\Delta G_c+\Delta F_P \qquad (2)$$

Štirje pozitivni členi na desni strani enačbe so povečanje proste energije zaradi ukrivljenosti ploskve, temperature, sestave in spremembe tlaka. Sedaj pa ovrednotimo posamezne člene v tej enačbi.

Gonilna sila za ovrednotenje kroglastih kristalnih zrn je podhladitev ukrivljenosti. Ko se prostornina trdnega delca v tekočini zmanjšuje, se povečuje razmerje njegove površine in prostornine in prispevek medfazne energije k celotni entalpiji delca se povečuje. Tako se celotna entalpija trdne faze povečuje, če se velikost delcev v sistemu tekoče – trdno zmanjšuje.

Ko se velikost delca poveča za dr, kjer je r polmer delca, mora biti delo, potrebno za nastanek nove površine, d(4πr2γ)dr, enako delu, ki je posledica zmanjšanja proste prostorninske energije,

$$\frac{d}{dr}\left(4/3\ \pi r^3\ \Delta G_v\right) \qquad (3)$$

Če po diferenciranju oboje izenačimo, je povečanje proste energije:

$$\Delta G_v=2\gamma/r=\gamma K \qquad (4)$$

kjer je γ površinska energija med tekočino in trdnino in K je ukrivljenost. Potem se iz definicije za podhladitev:

$$\Delta T=\Delta G_v/\Delta S_f \qquad (5)$$

dobi,

$$\Delta S_f\ \ \Delta T_r=\gamma K \text{ or}$$

$$\Delta T_r=T_e-T_e^r=(\gamma/(\Delta S_f))K=\Gamma K \qquad (6)$$

kjer je ΔT_r podhladitev ukrivljenosti, Te ravnotežna temperatura (taljenja) krogle

(volumetric free energy) of a substance can be expressed as:

$$F = E + P \times v - T \times S, \qquad (1)$$

where E is internal energy (i.e. the amount of work required to separate the atoms of the phase to infinity), P is pressure, v is volume, T is temperature and S is entropy. Thermodynamics stipulate that in a system without outside intervention, the free energy can only decrease.

The change in free energy can be described by the sum of the increase resulting from the relaxation of each particular assumption:

$$\Delta F=-\Delta G_v+\Delta G_r+\Delta G_T+\Delta G_c+\Delta F_P \qquad (2)$$

The four positive right-hand terms are the increase in free energy because of curvature, temperature, composition, and pressure variation, respectively. Let us now evaluate the terms in this equation.

The driving force in the evaluation of spheroidal grains is the curvature undercooling. As the volume of a solid particle in a liquid decreases, its surface/ volume ratio increases and the contribution of the interface energy to the total free enthalpy of the particle increases. Thus, when the particle size decreases in a liquid-solid system, the total free enthalpy of the solid increases.

When the particle increases by dr, where r is the radius, the work resulting from the formation of a new surface, d(4πr2γ) dr, must be equal to that resulting from the decrease in the free volumetric energy,

$$\frac{d}{dr}\left(4/3\ \pi r^3\ \Delta G_v\right) \qquad (3)$$

Equating the two, after differentiation, the increase in free energy is:

$$\Delta G_v=2\gamma/r=\gamma K \qquad (4)$$

s premerom r in Γ Gibbs-Thomsonov koeficient.

1.2 Mehanizem nastanka kroglastega kristalnega zrna

Nastanek grobe mikrostrukture ali zorenje je pomemben vidik pri njenem nastajanju v testastem procesu. Predstavili smo odnose med velikostjo delcev, izotermnim strigov in časom trajanja striga, kar kaže, da se velikost delca pri tvorbi okroglega delca s časom veča, vendar se velikost delcev, če izhajamo iz dendritne rozetaste oblike, zmanjšuje. Med zorenjem delci postajajo manjši in povprečna velikost faze α-Al se veča, ker majhni delci izginjajo. Zmanjšanje medfazne energije celotnega območja je gonilna sila za Ostwaldovo zorenje, ki se lahko v primeru difuzijskega prenosa mase opiše s ti. enačbo za hitrost zlepljanja delcev med mešanjem (FSW – friction stir welding, op. prev.). Ta enačba prilagaja teorijo Ostwaldovega zorenja sistemom v testastem stanju:

$$D_m^3 – D_0^3 = F_{vf} \times K_{LSW} \times (t – t_0) \quad (7)$$

kjer je D_m povprečni premer delcev po času t, D_0 začetni povprečni premer, ko je t enak t_0, F_{vf} je funkcija prostorninskega deleža trdne faze in K_{LSW} je konstanta rasti.

V primeru konvektivnega nastajanja grobih delcev je bilo pokazano, da se s povečanim prenosom mase ne samo povečuje nastajanje grobih delcev, ampak se spremeni tudi kinetika nastajanja grobih delcev. Nova enačba za hitrost nastajanja delcev je bila izpeljana za delce, ki se gibljejo s Stokesovo hitrostjo. Potem se povprečna velikost delcev veča s časom kot

$$D^2 – D_0^2 = = A \times K_{LSW} \times ((1 – f_s)^{2/3}) / f_s \times \omega^{1/3} \times t \quad (8)$$

where γ is the liquid-solid surface energy, and K is the curvature. Then, from the definition of undercooling:

$$\Delta T=\Delta G_v/\Delta S_f \quad (5)$$

can be obtained,

$$\Delta S_f \ \Delta T_r=\gamma K \text{ or}$$

$$\Delta T_r=T_e-T_e^r=(\gamma/(\Delta S_f))K=\Gamma K \quad (6)$$

where ΔT_r is the curvature undercooling, Te is the equilibrium (melting) temperature for a sphere of radius r, and Γ is the Gibbs-Thomson coefficient.

1.2 Mechanism of Spheroidal Grain Evolution

Coarsening or ripening is an important aspect of the microstructure evolution in semi-solid processes. The relationship between particle size, isothermal shearing and shearing time has been presented which states that the particle size increases with time when spherodisation occurs, but particle size decreases when going from dendritic rosette-like shape. During ripening, the particles become smaller and the average size of α-Al phase increases, as small particles tend to disappear. The reduction in interfacial energy of particles total area is the driving force for the Ostwald ripening, which can be described by the so-called FSW rate equation in the case of diffusive mass transport. A rate equation adapts Ostwald's ripening theory modified to semi-solid systems:

$$D_m^3 – D_0^3 = F_{vf} \times K_{LSW} \times (t – t_0) \quad (7)$$

where Dm is the mean diameter of the particles after time t, D0 is the initial average diameter when t equals t0, Fvf is a function of solid volume fraction and KLSW is the growth constant.

In the case of convective coarsening it

kjer se parameter ω nanaša na frekvenco rotacije in A je konstanta, ki zajema difuzijski koeficient [3-5]

2 Simulacija procesa v testastem stanju

NovaFlow&Solid je paket programske opreme za simulacijo krmilne prostornine, ki ga je razvilo švedsko podjetje NovaCast Technologies AB in ga od leta 1993 stalno razvija. Zakoni o ohranitvi (mase, impulzov in energije) so fizikalno-matematična osnova programskih modelov. Ti zakoni o ohranitvi upoštevajo fazne prehode pri strjevanju ulitka, natančno geometrijo ulitka in kokile, izmenjavo toplote in mase z okolico.

Lastnosti fluidov imajo glavno vlogo pri razvijanju matematičnih modelov za simulacijo tokov tekočin. Treba je uporabiti jasne predpostavke, po katerih se predpostavi, da je lastnost tekočine konstantna in kako je odvisna od temperature, tlaka itn. Če so lastnosti odvisne od spreminjanja temperature, se pojavi nova povezava med različnimi enačbami o ohranitvi. Lastnosti vstopajo v enačbe o hranitvi kot koeficienti. Velikost teh koeficientov lahko spremeni celotno sliko toka.

Gostota tekočine je definirana kot količnik mase in prostornine tekočine. Če se vzame mejna vrednost količnika pri infinitezimalni prostornini, je s tem definirana enačba za gostoto ρ, [kg/m3]. V splošnem je gostota tekočine odvisna od temperature in tlaka. Pri tekočinah, pri katerih se lahko privzame, da so nestisljive, je njihova gostota odvisna le od temperature.

Specifična toplota je definirana kot količina toplote, ki je potrebna, da se segreje enota mase snovi za enoto temperature. Ta toplota se lahko meri v razmerah konstantne prostornine ali konstantnega tlaka. Pri

was shown that coarsening is not only enhanced, as fluid flow leads to a faster mass transport, but also the coarsening kinetics are changed. A new rate equation is derived for solid particles moving with Stokes speed. Then the average particle size increases with time as

$$D^2 - D_0^2 = A \times K_{LSW} \times ((1 - f_s)^{2/3}) / f_s \times \omega^{1/3} \times t \qquad (8)$$

where the parameter ω refers to the rotation frequency and A is the constant containing the diffusion coefficient. [3-5]

2 Simulation of Semi-Solid Process

NovaFlow&Solid is a Control Volume simulation software package which is developed by Swedish NovaCast Technologies AB under continual development since 1993. Conservation laws (of matter balance, pulse and energy) form the foundation of physical-mathematical models of the programme. These conservation laws take into account the phase transitions taking place in the solidifying casting, the exact geometry of the casting and mould, and heat mass exchange with environment.

Properties of fluids play a primary role for the development of mathematical models for fluid flow simulation. One should make clear assumptions about which property can be assumed to be constant and which depends on temperature, pressure, etc. Where properties depend on temperature variable, an additional coupling between various conservation equations arises. Properties enter as coefficients in the conversation equations. The magnitude of these coefficients can change the overall picture of the flow.

Mass density of the fluid is defined as the ratio of the mass of the fluid to the tekočinah sta toploti enaki. V sistemu SI je enota za specifično toploto J/(kg K).

Entalpija trdnin in tekočin se lahko definira kot

$$H = H_R + \int_{T_R}^{T} c_p \, dT \qquad (9)$$

kjer je T_R vzeta kot referenčna temperatura. Entalpija trdnin in tekočin je merilo vsebovane toplote v enoti mase. Zato se lahko za vsako temperaturo vzorca vsebovana toplota izračuna iz entalpije kot produkt entalpije in mase. Entalpija je po definiciji monotona krivulja, enota po SI je J/kg.

Toplota se lahko prenaša z difuzijo. Ta mehanizem prenosa toplote se imenuje prevajanje. Toplotni tok je definiran kot količina toplote, ki steče v enoti časa skozi enoto prereza. Toplotni tok pri prenosu toplote s prevajanjem opisuje Fourierjev zakon z enačbo:

$$q_i = -k \, \partial T/(\partial x_i) \qquad (10)$$

kjer q_i označuje toplotni tok, ki je vektor s tremi komponentami (v treh prostorskih smereh). Na desni strani enačbe sta temperaturni gradient in proporcionalnostna konstanta, ki predstavlja prevod toplote, katerega enota v SI je W/(mK).

Viskoznost opisuje zmožnost tekočin, da prenašajo gibalno količino z difuzijo. Po analogiji s Fourierjevim zakonom za prevajanje toplote je tok gibalne količine fluida:

$$\tau_{ij} = -\mu \, (\partial u_i)/(\partial x_j) \qquad (11)$$

kjer je proporcionalnostna konstanta μ dinamična viskoznost.

Zmnožek mase (m) in hitrosti (v) daje gibalno količino in njen tok se lahko dobi na naslednji način:

$$mv/tA = ma/A = F/A = \tau \, . \qquad (12)$$

Sila (F), deljena s ploskvijo (A), na kateri sila deluje, daje napetost (τ) na tej ploskvi.

volume occupied by this fluid. Taking the limiting value of this ratio for the infinitesimal volume, we obtain the defining equation of density ρ, [kg/m3]. In a general case, fluid density depends on temperature and pressure. For liquids, if the incompressibility assumption is adopted, density depends only on temperature.

Specific heat is defined as the amount of heat needed to heat up a unit mass of substance by one unit of temperature. This heat can be measured either under the condition of constant volume or constant pressure. For liquids they are identical, in SI the unit of the specific heat is [J/(kgK)].

Enthalpy for solids and liquids can be defined as

$$H = H_R + \int_{T_R}^{T} c_p \, dT \qquad (9)$$

where T_R has been chosen as a convenient reference temperature. The enthalpy of solids and liquids is a measure of the heat content per unit mass. Therefore, at any temperature, the heat content of the specimen can be calculated from the enthalpy by taking the product of the enthalpy times the mass of the specimen. Enthalpy, according to the definition, is always a monotonic curve. The SI unit of enthalpy is [J/kg].

Heat can be transmitted by means of diffusive exchange. This mechanism of heat transfer is conduction. Heat flux is defined as the amount of heat that flows per unit time through the unit of area. The flux of heat exchanged by conduction is described by the Fourier law, which is given by the equation

$$q_i = -k \, \partial T/(\partial x_i) \qquad (10)$$

where q_i denotes the heat flux, which is a vector with three components (in spatial directions). On the left side we have the temperature gradient and the proportionality constant k, which is the heat conductivity. The SI unit is [W/(K.m)].

Viskoznost taline kovinske zlitine je vedno odvisna od temperature. Za večino talin kovinskih zlitin se lahko viskoznost nad temperaturo likvidus privzame kot konstanta. Med temperaturo likvidus in temperaturo solidus se viskoznost testaste mešanice veča, kar upočasnjuje, včasih celo ustavi tok fluida. V SI je enota za viskoznost pascal (Pa). Poleg dinamične viskoznosti se pogosto uporablja tudi kinematična viskoznost (v). Kinematična in dinamična viskoznost sta med seboj povezani z enačbo

$$v = \mu/\rho \ [m^2/s]. \qquad (13)$$

Prag livnosti (CLFu) je delež tekoče faze, nad katerim se uporabljajo Navier-Stokesove enačbe. Kristali, ki nastajajo v

Viscosity describes the ability of fluids to transfer momentum by virtue of diffusion. By analogy to the Fourier law of heat conduction, the flux of momentum of the fluid is given by the equation

$$\tau_{ij} = -\mu \ (\partial u_i)/(\partial x_j) \qquad (11)$$

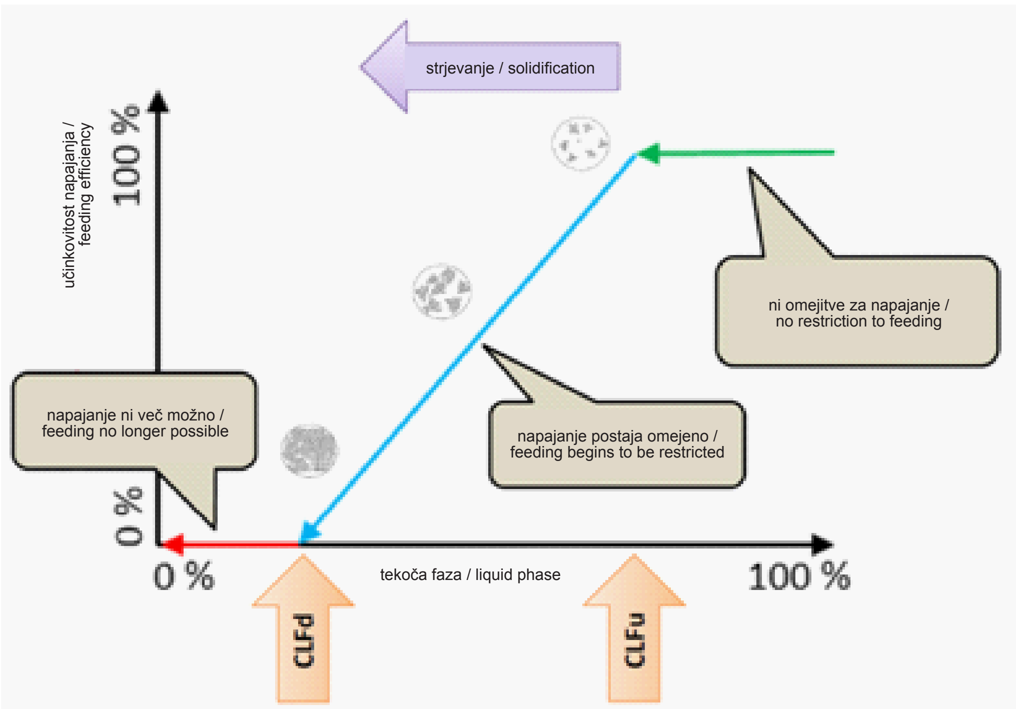
where the proportionality constant μ is the dynamic viscosity.

The product of mass (m) and velocity (v) gives momentum, and its flux can be obtained in the following way

$$mv/tA = ma/A = F/A = \tau \ . \qquad (12)$$

Force (F) divided by the surface (A) on which this force acts, gives the stress (τ) on this surface.

Viscosity of the metal-alloy melt is always temperature dependent. For most



Slika 1: Razlaga praga livnosti in praga pronicanja

Figure 1: Explanation of the fluidity and percolation thresholds

prostornini tekočine prosto tečejo skupaj s talino.

Prag pronicanja (CLFu) je vrednost deleža tekoče faze, pod katerim je tok taline brez plastične deformacije [6,7]. Prag livnosti in prag pronicanja pojasnjuje slika 1.

Tlačno litje je izdelovalni postopek, pri katerem se staljena kovina pod občutno povišanim tlakom vbrizga v jekleno kokilo livnega stroja, da se oblikuje ulitek. Proizvodni cikel tlačnega litja je sestavljen iz zajemanja taline, potiskanja bata in hitrega zapolnjevanja kokile. Jeklena kokila, navadno s temperaturo 200-300 °C, razprši latentno toploto in med strjevanjem bat deluje na ulitek s hidravličnim tlakom, da se kompenzira strjevalno krčenje. Zaporne sile do 4000 t so trgovsko izvedljive, da se vzdržijo veliki tlaki. Potem se kokila odpre in ulitek izvrže. Hidravlično energijo omogoča računalniški sistem, ki dovoljuje krmiljenje položaja kovine, hitrosti in pospeška bata, da se optimirata tok in tlak med zapolnjevanjem forme in med strjevanjem.

Med simulacijskimi poskusi smo preiskali učinke naslednjih tehnoloških parametrov:

- hitrost bata v prvi fazi (m/s),
- hitrost bata v drugi fazi (m/s),
- temperaturo kokile (°C),
- temperaturo taline (°C).

3 Preiskovana geometrija

Za analizo livnosti smo izdelali vzorec s posebno geometrijo, ki smo jo imenovali ‘meander’ in ki se lahko vidi na sliki 2. Celotna dolžina vzorca je bila 1874 mm in njegov prerez 50 mm^2. 3D geometrija je opisana kot mreža strukturiranega kubičnega elementa z dimenzijo 2 mm. Celotno število celic je bilo 949 050. Začetne in robne pogoje lahko vidimo na sliki 3.

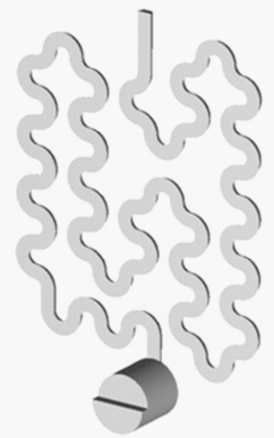
metal alloy melts, viscosity above the liquidus temperature can be assumed constant. Between the liquidus and the solidus temperature, viscosity of the semi-solid mixture grows, slowing down and eventually blocking the flow. In SI the unit of dynamic viscosity is the pascal (Pa). Besides the dynamic viscosity, the kinematic viscosity (v) is often used. Kinematic and dynamic viscosities are related to one other by the equation

$$v = \mu/\rho \ [m^2/s]. \qquad (13)$$

Fluidity threshold (CLFu) is the value of the liquid phase fraction above which the Navier-Stokes equations are applicable. The crystals nucleated in the liquid volume freely flow together with the melt.

Percolation threshold (CLFd) is the value of the liquid phase fraction below which the melt flow is absent without plastic deformation [6,7]. An explanation of the fluidity threshold and percolation threshold can be seen in Figure 1.

High pressure die casting (HPDC) is a manufacturing process in which molten metal injected with a die casting machine under force using considerable pressure into a steel mould or die to form products. A production cycle in HPDC consists of metal ladling, plunger movement and rapid die filling. The steel die, typically 200-300 °C, dissipates the latent heat, and during solidification the casting is pressurised hydraulically by the plunger to feed the solidification shrinkage. Locking forces up to 4,000 tons are commercially available to withstand the large pressures. Eventually, the die is opened and the casting is ejected. The hydraulic energy is provided by a computerised system that permits control of metal position, velocity and plunger acceleration to optimise the flow and the pressure during filling and solidification.



zlitina / alloy	EN AC - 42000
kokila / die	jeklo / steel 1.2343
kinematična viskoznost / kinematic viscosity	0.4 - 416 [×10e^{-5} m^2/s]
hitrost bata, 1. faza / piston velocity, 1st phase	0.1 - 1.8 [m/s]
hitrost bata, 2. faza / piston velocity, 2nd phase	1 - 3 [m/s]
temperature kokile / die temperature	180 - 240 [°C]
temperature litja / pouring temperature	586 - 650 [°C]

Slika 2: Ulitek 'meander' in začetni ter robni pogoji

Figure 2: Meander casting part and initial and boundary conditions

Podatki poskusov so v razpredelnici 1.

During simulation experiments the effect of the following technological parameters are examined:

- Piston velocity in the first phase (m/s);

Razpredelnica 1: Podatki poskusov

Table 1: Experimental matrix

poskus / experiment	zlitina / alloy	kinematična viskoznost / kinematic viscosity [10e^{-5} m^2/s]	hitrost bata, 1. faza / piston velocity 1st phase [m/s]	hitrost bata, 2. faza / piston velocity 2nd phase [m/s]	temperatura kokile / die temperature [°C]	temperatura taline / melt temperature [°C]	opombe / notes
A	Standard EN-AC 42000	0.4(1)	0.1	1	180	590	(2)
B	Standard EN-AC 42000	0.4(1)	0.1	(1→) 3	(180→) 240	(590→) 650	(3)
C	SB-1	(0.4→) 416	0.1	3	240	(650→) 590	
D	SB-2	(416→) 41.6	0.1	3	240	590	
E	SB-3	(41.6→) 4.16	0.1	3	240	590	
F	SB-3	4.16	(0.1→)0.5	(3→)2	(240→)200	590	
G	Standard EN-AC 42000	0.4(1)	(0.5→)0.1	(2→)3	(200→)150	(590→)650	
H	SB-4	8.3	0.2(4)	(15→)200	(650→)586		
I	SB-4	8.3	(0.2→)1.8	200	586		
J(5)	SB-4	8.3	1.8	200	586		
K(5)	EN-AC42100	8.3	1.8	200	586		

(1) iz podatkovne baze; (2) začetek 2. faze je premaknjen; (3) normalno pregreta zlitina;
(4) vsi postopki zapolnjevanja z dano hitrostjo bata; (5)spremenjena geometrija ulitka

(1) From software database; (2) Starting point of the 2nd phase is repositioned; (3) Normal overheated alloy;
(4) All filling process with a given piston velocity; (5) Modified casting geometry

4 Rezultati

Rezultati poskusov A in B so na sliki 3.

V poskusu A je bila obravnavana zlitina po standardu EN-AC 42000 pri temperaturi litja 590 °C (med $T_{liquidus}$ in $T_{solidus}$) pri hitrostih bata 0,1 in 1,0 m/s v kokili s temperature 180 °C. Izračunana dolžina toka je bila 270 mm, kar je 15 % celotne dolžine vzorca. Na rezultat je verjetno vplivala nepravilna nastavitev začetne točke 2. faze, ki je bila prestavljena. V poskusu B je bila ulita standardizirana pregreta zlitina EN-AC 42000 (temperatura litja 650 °C, temperatura kokile 240 °C, hitrost bata v 2. fazi 3 m/s). Dolžina toka je bila 920 mm, kar predstavlja 51 % celotne dolžine vzorca. Če je talina pregreta, se poviša temperatura kokile in doseže pravilen preklop, dolžina toka se poveča za 36 %.

V poskusih C, D in E smo preskušali zlitine v testastem stanju. Lastnosti testastega stanja so se dosegle s programsko datoteko: kinematična viskoznost se je prilagajala s temperaturo litja (416→41.6→4.16 $*10^{-5}$ m^2/s). Rezultate kaže slika 4.

Na osnovi poskusa E smo spremenili tehnologijo tako, da smo spremenili hitrosti bata in začetne temperature. Rezultate

- Piston velocity in the second phase (m/s);
- Temperature of the die (°C);
- Temperature of the melt (°C).

3 Examined geometry

For the analysis of flowability a special specimen geometry is developed which is called a “meander” and can be seen in Figure 2. Total length of the specimen is 1874 mm, and the cross section of it is 50 mm^2. The 3D geometry is described by a structured cubic element mesh with a dimension of 2 mm. The total number of cells is 949,050. Initial and boundary conditions can be seen in Figure 3.

The experimental matrix can be seen in Table 1.

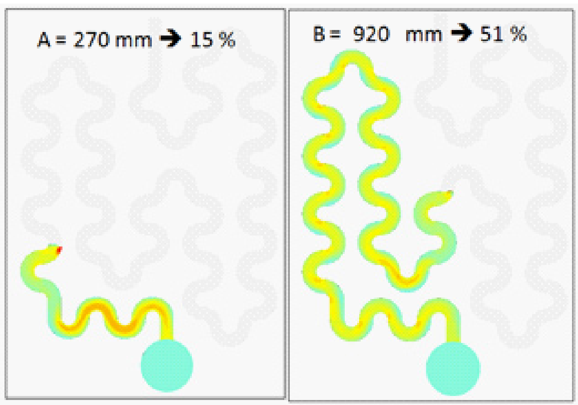
4 Results

The results of Experiment A and B can be seen in Figure 3.

In Experiment A a standard EN-AC 42000 alloy is calculated at 590 °C pouring temperature (between $T_{liquidus}$ and $T_{solidus}$), with 0.1 m/s and 1 m/s piston velocities for

	A	B
hitrost bata, 2. faza / piston velocity, 2nd phase [m/s]	1	3
temperature kokile / die temperature [°C]	180	240
temperature taline / melt temperature [°C]	590	650
preklop / switching point	prestavljeno / repositioned	
kinematična viskoznost / kinematic viscosity [×10e^{-5} m^2/s]	0.4	

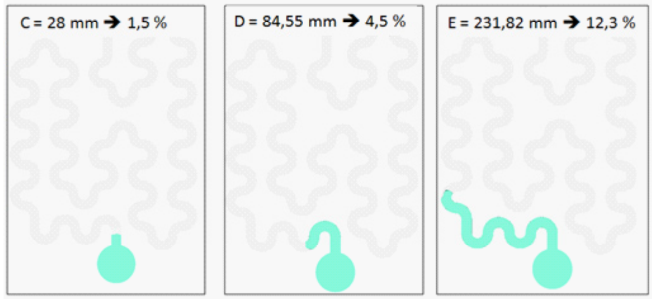
+ 36%



Slika 3: Rezultati poskusov A in B

Figure 3: Results of Experiments A and B

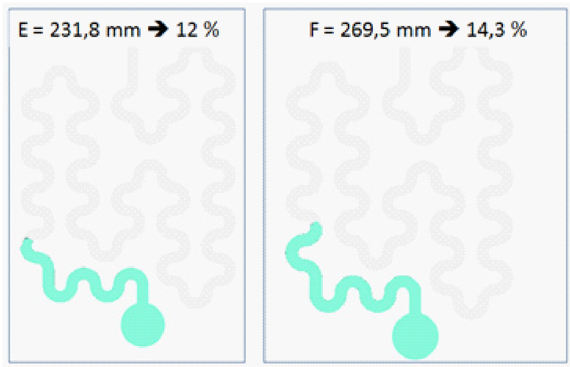
	C	D	E
hitrost bata, 2. faza / piston velocity, 2nd phase [m/s]	3		
temperature kokile / die temperature [°C]	240		
temperature taline / melt temperature [°C]	590		
kinematična viskoznost / kinematic viscosity [×10e-5 m²/s]	416	41,6	4,16



Slika 4: Primerjava rezultatov poskusov C, D in E

Figure 4: Comparison of the results of experiment C, D and E

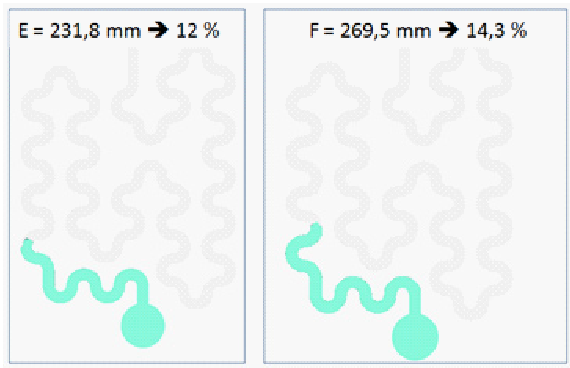
zlitina SB-3 / SB-3 alloy	E	F
kinematična viskoznost / kinematic viscosity [×10e-5 m²/s]	4,16	
hitrost bata, 1. faza / piston velocity, 1st phase [m/s]	0,1	0,5
hitrost bata, 2. faza / piston velocity, 2nd phase [m/s]	3	2
temperature kokile / die temperature [°C]	240	200
temperature taline / melt temperature [°C]	590	



Slika 5: Učinek tehnološke optimizacije

Figure 5: Effects of technological optimisation

EN AC-42000	G	B
kinematična viskoznost / kinematic viscosity [×10e-5 m²/s]	0,416	
hitrost bata, 1. faza / piston velocity, 1st phase [m/s]	0,1	
hitrost bata, 2. faza / piston velocity, 2nd phase [m/s]	3	
temperature kokile / die temperature [°C]	150	240
temperature taline / melt temperature [°C]	650	



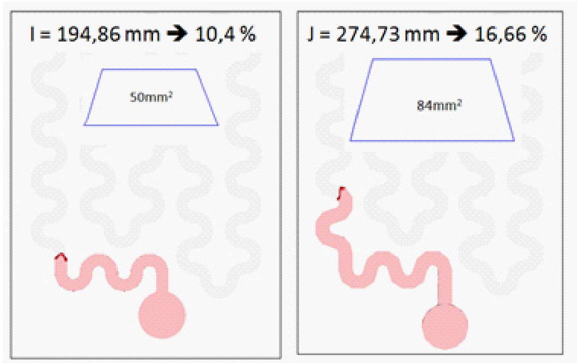
Slika 6: Vpliv temperature kokile na dolžino toka

Figure 6: Effects of die temperature on flow length

prikazuje slika 5. S to spremembo se je dolžina toka povečala za 2,3 %.

a die with the temperature of 180°C. The calculated flow length is 270 mm, which is

sprememba geometrije / geometry modification	I 50 mm²	J 84 mm²
kinematična viskoznost / kinematic viscosity [$\times 10e^{-5}$ m^2/s]	8,3	
hitrost bata, 1. faza / piston velocity, 1st phase [m/s]	1,8	
hitrost bata, 2. faza / piston velocity, 2nd phase [m/s]	1,8	
temperature kokile / die temperature [°C]	200	
temperature taline / melt temperature [°C]	568	



Slika 7: Učinki spremembe geometrije

Figure 7. Effects of geometry modification

Za standardizirano pregreto zlitino smo preiskali vpliv temperature kokile. S spreminjanjem vrednosti od 150 °C do 240 °C smo dosegli povečanje za 9,8 % (slika 6).

Na osnovi rezultatov, ki so jih dale spremembe, smo izboljšali geometrijo vzorca. Ohranili smo glavne mere, le prerez kanala smo povečali s 50 mm² na 84 mm². Učinek se vidi na sliki 7.

5 Sklepi

Povzeti rezultati so prikazani v razpredelnici 2.

Rezultati simulacije so pokazali, da tako material kot tehnološki parametri vplivajo na lastnosti in dolžino toka pri tlačnem litju v testastem stanju. Temperaturo gošče in pravilno temperaturo kokile se lahko določi s simulacijo, a natančna kinematična viskoznost ulivane zlitine se mora izmeriti med litjem. Sprememba geometrije vzorca je bila primerna za raziskovanje procesa, toda pri bodočih poskusih se bodo uporabljali prerezi 50 mm2, ker je debelina stene kanalov bližje dejanskim tlačno ulitim delom.

15% of the total length of the specimen. The result is probably also affected by the improper position of the starting point of the 2nd phase, which is repositioned. In Experiment B a standard overheated EN-AC 42000 alloy was cast (pouring temperature: 650 °C, die temperature: 240 °C, piston velocity in the 2nd phase: 3 m/s). The flow length is 920 mm, which is 51% of the total length of the specimen. If the melt is overheated, the die temperature is increased, and the correct switching point position is achieved, the flow length can be increased by 36%.

In Experiments C, D and E semi-solid alloys were examined. Semi-solid properties were developed based on the software database: the value of kinematic viscosity was modified by the pouring temperature (416→41.6→4.16 *10-5 m2/s). Results can be seen in Figure 4.

Based on the results of experiment E technological modifications were carried out by changing the piston velocities and the initial temperatures. Results can be seen in Figure 5. With the modification this flow length can be increased by 2.3%.

The effect of the die temperature on flow length was also examined for a standard

Razpredelnica 2: Povzetek rezultatov

Table 2: Summary of results

standardizirana zlitina proti standardizirani zlitini / standard alloy vs. standard alloy	prerez / cross section	kinematična viskoznost / kinematic viscosity	hitrost bata, 1. faza / piston velocity 1st phase	hitrost bata, 2. faza / piston velocity 2nd phase	temperatura kokile / die temperature	temperatura taline / melt temperature	sprememba dolžine toka / change of flow length
	mm²	m²/s	m/s	m/s	°C	°C	%
A→B	-	-	↑	↑	↑	↑	-36
G→B	-	-	-	-	↑	-	+9.8
standardizirana zlitina proti testasti zlitini / standard alloy vs. semi-solid alloy	**prerez / cross section**	**kinematična viskoznost / kinematic viscosity**	**hitrost bata, 1. faza / piston velocity 1st phase**	**hitrost bata, 2. faza / piston velocity 2nd phase**	**temperatura kokile / die temperature**	**temperatura taline / melt temperature**	**sprememba dolžine toka / change of flow length**
	mm²	m²/s	m/s	m/s	°C	°C	%
A→I	-	↑	↑	↑	↑	-	-5
testasta zlitina proti testasti zlitini / semi-solid alloy vs. semi-solid alloy	**prerez / cross section**	**kinematična viskoznost / kinematic viscosity**	**hitrost bata, 1. faza / piston velocity 1st phase**	**hitrost bata, 2. faza / piston velocity 2nd phase**	**temperatura kokile / die temperature**	**temperatura taline / melt temperature**	**sprememba dolžine toka / change of flow length**
	mm²	m²/s	m/s	m/s	°C	°C	%
C→E	-	↓	-	-	-	-	+10.8
I→J	↑	-	-	-	-	-	+6.2

overheated alloy. By changing the values from 150 °C to 240 °C, a 9.8% increment can be achieved (see Figure 6).

Based on the results modification of the specimen geometry was implemented. The overall dimensions were kept but the cross section of the channel flow was increased from 50 mm² to 84 mm². The effect of this can be seen in Figure 7.

5 Conclusions

A summary of results can be seen in Table 2.

Based on the simulation results it was found that both material and technological parameters affect the flow-length properties of semi-solid high pressure die castings. Pouring temperature of the slurry and the proper temperature of the die can be determined with the help of simulation, but the exact kinematic viscosity of the poured alloy must be measured during casting. Both geometry variations of the specimen are appropriate for the investigation of the process but in our future experiments the 50 mm2 cross-sectioned specimen will be used because the wall thickness of it is closer to real high pressure casting parts.

In future experiments casting samples will be poured and compared with the calculated results and the simulation model will be validated by the as-cast results.

V prihodnjih poskusih bomo ulite vzorce primerjali z rezultati računanja in simulacijski model bomo ovrednotili z dobljenimi rezultati v litem stanju.

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