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PROGRESSIVE METHOD OF POROSITY PREDICTION FOR ALUMINIUM CASTINGS

NAPREDNA METODA NAPOVEDOVANJA POROZNOSTI V ULITKIH IZ ALUMINIJA

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The final integrity of a casting is greatly influenced by the presence of porosity. A progressive way to predict the presence of porosity is the use of modern computer simulation programs. The main aim of the performed experiments was to verify the potentials of this promising method of porosity prediction. A calculation of advanced porosity prediction was performed for an aluminium alloy using an advanced porosity module included in the ProCAST software. This calculation takes into account all the basic phenomena, causing the micro- and macroporosity. For the experimental purposes, we used a mold with a specific shape – Sanduhrprobe. The materials used in the experiments were not loaded from the software database, because the results could have been distorted by the deviations from the particular material we used. To achieve precise results, we used a thermal analysis to get accurate data about the used alloys. Important solidification events affecting the porosity formation such as recalescence, nucleation undercooling temperature, coherence point and rigidity point were determined from the cooling curve and its first derivate. These data were then included to the database of the simulation software and used in the simulation process.

Keywords: simulation, thermal analysis, porosity, aluminum alloys

Končna kvaliteta ulitka je precej odvisna od poroznosti. Napredna metoda za napovedovanje poroznosti je uporaba moderne računalniške simulacije. Glavni namen preizkusov je bilo preverjanje obetajoče metode za napovedovanje poroznosti. Izračun napovedovanja poroznosti je bil izvršen za aluminijevo zlitino z naprednim modulom za poroznost, vključenim v programsko opremo ProCAST. Izračun upošteva vse osnovne pojave, ki povzročajo mikro- in makroporoznost. Za eksperimente je bila izbrana forma s specifično obliko – peščene ure. Materiali, uporabljeni za eksperimente, niso bili naloženi iz datoteke programske opreme, ker bi bili lahko rezultati drugačni od materiala, ki smo ga uporabili. Da bi dobili natančne podatke, je bila uporabljena termična analiza uporabljene zlitine. Pomembni pojavi pri strjevanju, ki vplivajo na poroznost, kot so rekalescenca, temperatura podhladitve pri nukleaciji, točka skladnosti in točka togosti so bile določene iz ohlajevalne krivulje in njenega prvega odvoda. Ti podatki so bili vključeni v datoteko simulacijskega programa in uporabljeni pri simulaciji.

Ključne besede: simulacija, termična analiza, poroznost, aluminijeve zlitine

1 INTRODUCTION

Many defects can occur during the fabrication of aluminum casting alloys. The most frequent are those associated with porosity. In this type of alloys, porosity forms during solidification, in the mushy zone, where two mechanisms take place: hydrogen segregation and precipitation (hydrogen porosity), and insufficient interdendritic feeding (micro-shrinkage). This resistance causes a local pressure drop in the liquid due to Darcy's law[1]. During the recent years, simulation software has allowed us to predict and prevent porosity defects in castings. Thanks to the development of high-capacity computational equipment, high-quality simulation software is now accessible to the foundries around the world[2]. The submitted work presents a case study, where the data utilized in the simulation programs is optimized to make it representative for a resin-based-mold gravity-casting process in order to predict the amount and the character of porosity. The simulation of the mold temperature distribution and metal cooling curves is analyzed and compared with the experimental values as well as with the porosity in real castings. The experimental data are utilized to improve the accuracy of the solidification simulation and porosity prediction in our department.

2 EXPERIMENTAL WORK

2.1 Used alloy and its properties

The AlSi7Cu0.5Mg alloy was used in the presented studies. Its chemical composition is listed in **Table 1**. Company NEMAK that helped us with the experiments uses the mentioned alloy in its production knowing the exact composition of every batch, so it was possible for us to make an identical alloy for the simulation purposes.

Table 1: Chemical composition of AlSi7Cu0.5Mg alloy in mass fractions, *w*/%

Tabela 1: Kemijska sestava zlitine AlSi7Cu0,5Mg v masnih deležih, *w*/%

Element	Si	Fe	Cu	Mn	Mg	Al
w/%	7.18	0.15	0.49	0.061	0.375	91.54
Element	Zn	Ca	Ti	Sr		
w/%	0.01	0.0006	0.17	0.0106		

2.2 Mold material, design and properties

Resin-based sand was selected as the mold material. It was a compound of silica sand SH 32 ($D50$ = 0.38 mm; w = 1.5 % of silica sand), resin Avenol NB 700 (w = 25 % of resin) and hardener Katalysator 4040. The design of the mold and the casting is based on a German porosity test called sanduhrprobe. The shape of the casting was chosen with respect to the porosity formation. The main aim was to find the right shape for the mold cavity, so that various types of porosity could occur during solidification.

2.3 Thermal analysis

In the experimental work, a thermal analysis was executed mainly to obtain useful data for the simulation software. One of the main advantages of the used software is the possibility to consider the presence of a mushy zone in association with the porosity formation. Several metallurgical parameters are required in order to properly characterize a mushy zone. The permeability, which depends on the number and tortuosity of flow channels, as well as precise information on the interdendritic liquid such as its composition, viscosity, density, etc., are necessary. The dendrite coherency and dendrite rigidity also affect the characteristics of a mushy zone. These parameters vary with the temperature, time and location[3].

Figure 1 shows the placement of five thermocouples for the thermal analysis: two thermocouples were placed into the mold cavity, the rest of them were placed in the mold. To record the thermal-analysis data during the experiments a compact portable data logger, Omega RDXL 121-D, was used. The temperature-versus-time cooling curves for the samples poured were recorded. The cooling curves were used for calibrating the material created in ProCAST.

The influence of the cooling rate on the solidification and porosity formation can be explained by considering the point, at which free dendrites come into contact with each other – the dendrite coherency point (DCP) and also the rigidity point (RP)[4]. The DCP and RP are suggested to be related with the formation of porosity defects during the solidification process. **Figure 2** shows a comparison between the cooling curves recorded with the two thermocouples located in the centre and the wall of the mould. The first maximum difference between the wall and the centre thermocouple ($\Delta T = T_W - T_C$) during the evolution of Al dendrite networks was used to determine the DCP as plotted in **Figure 2**. This difference occurs because the thermal conductivity of solid Al (the dendrite network) is twice as large as that of the surrounding liquid Al. The RP was identified in a similar way[5].

2.4 Rigidity point

The rigidity point is the solid fraction at which the dendrite structure of a solidifying alloy becomes mechanically rigid. Beyond the dendrite rigidity point, the feeding becomes difficult and it is only possible with the aid of a positive external pressure (risers or applied mechanical pressure) or a strong negative internal pressure (solidification contraction and capillary forces). In the AlSi7Cu0.5Mg alloy this occurred at approximately 89 % solidification – at a temperature of 561 °C.

2.5 Coherency point

In the case of a low solid fraction (0–20 %) there is usually no difficulty feeding the solidification shrinkage as the dendritic network is not yet coherent and the liquid feeding of a molten metal, or the mass feeding of dendritic grains, is easily accomplished. In the case of a higher solid fraction, the dendrites join to form a continuous dendritic network. The solid fraction at which this occurs is called the dendrite coherency point. In the used alloy the dendrite coherency point occurs at 17 % solidification – at a temperature of 607 °C.

In order to make an effective and accurate simulation model, another piece of information needs to be entered into the ProCAST database: the solid-fraction curve. The solid fraction is defined as the percentage of the solid phases formed at any point during solidification. The ProCAST simulation model uses the solid-fraction curve to predict the micropore formation in the examined aluminium-alloy system. The corresponding numerical

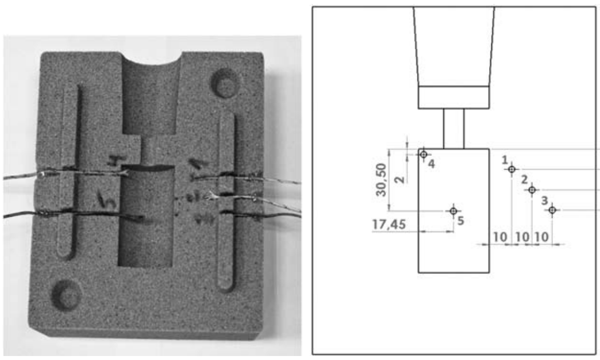

Figure 1: Placement of the thermocouples
Slika 1: Namestitev termoelementov

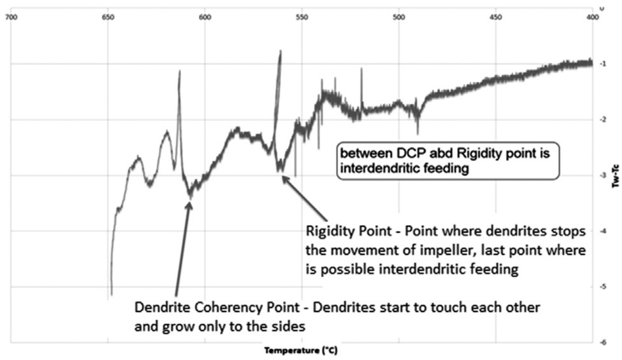

Figure 2: Temperature versus $T_w - T_c$ curve
Slika 2: Krivulja odvisnosti temperature in $T_w - T_c$

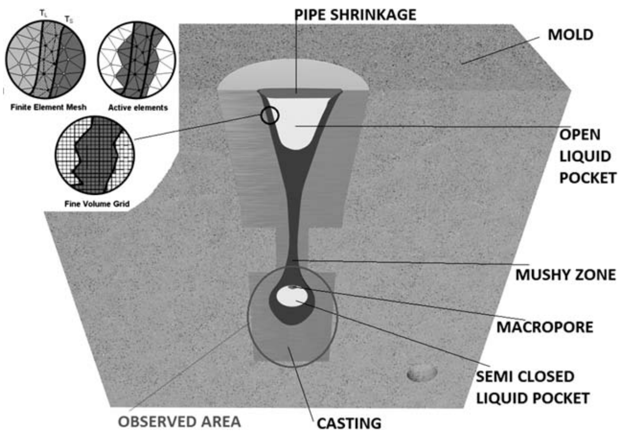

Figure 3: Fine volume grid and liquid regions during solidification
Slika 3: Drobna prostorninska mreža in področja taline med strjevanjem

values for the liquidus and solidus temperatures are T_{liq} = 617 °C and T_{sol} = 489 °C. The solid-fraction curve was entered into the ProCAST database. All the obtained alloy data were entered into ProCAST, allowing us to make a relatively precise simulation model; in addition, the data from the thermocouples placed in mold were also included into the database (providing the information about the real heat-interference coefficient for the used alloy and the mold).

3 SIMULATION

The method for porosity prediction presented in this study allows a numerical simulation of the hydrogen and shrinkage porosity by considering the following factors that contribute to the porosity formation: heat transfer, temperature of the melt and the mold, cooling rate, hydrogen redistribution during solidification, fluid flow that feeds the solidification shrinkage and pressure-drop index based on Darcy's law within the interdendritic liquid. The simulations were made using software ProCAST. This software solves the conservation equations using the finite-element method. The mesh employed in the solution of the system is made of fine tetrahedral volume elements. A mesh of 487,364 nodes and 1,451,840 elements was involved to define the mold and casting.

The porosity predictions were made in the advanced-porosity module (APM). In the APM, the microporosity model, based on the solution of Darcy's equation and microsegregation of gas, was coupled with macroporosity and pipe-shrinkage predictions. In order to accurately calculate the pressure drop within the mushy zone, a dynamic refinement technique was implemented: a fine and regular finite-volume (FV) grid was superimposed onto the finite-element (FE) mesh used for the heat-flow computations (**Figure 3**).

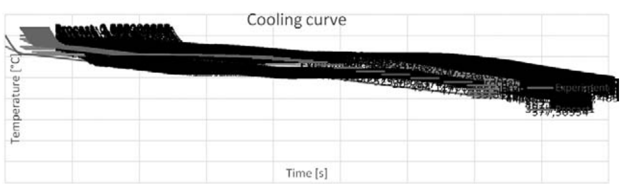

Figure 4: Cooling-curve comparison
Slika 4: Primerjava krivulj ohlajanja

The casting material was the AlSi7Cu0.5Mg alloy and resin sand was used as the material of the mold. The primary parameters used in the simulation included specific heat, thermal conductivity, density, latent heat, solidus and liquidus temperatures. Most of these data was obtained with a thermal analysis of the real alloy. The aim was to obtain most of the data from the real conditions and use a minimum amount of the data from the preset ProCAST databases, so that the simulation results would correspond with reality. Regarding the process conditions, the initial temperature of the resin-sand mold was set at 20 °C and the pouring temperature was varying from (730, 710, 680 to 650) °C. The heat taken from the mold was set to the air-cooling boundary condition. The velocity for gravity filling (based on experiences) was set to 0.56 m/s. The interface conditions between the melt and the mold were set with respect to the type of the mold material and the metal cooling curve. **Figure 4** compares the cooling curve monitored with the thermocouple with the ProCAST simulation. The calculated profile is in very good agreement with the experimental result, which we achieved by gradually modifying the heat-transfer conditions and also the mold properties. From the graph it can also be seen that the initial temperature set in ProCAST was slightly higher than the temperature from the real thermocouple. The reason for this increase was the fact that the thermocouple was not preheated and during the measurements it took a particular amount of heat from the melt, so it was necessary to consider this deviation.

When all the thermophysical data, boundary conditions, simulation parameters and heat-transfer coefficients are determined, the simulation calculations can proceed.

4 RESULTS

For a metallographic examination, all the castings were sectioned vertically along the centerline to observe the internal porosity; these surfaces were grinded by using 250 and 500 SiC emery papers. The percentage of microporosity was determined for the area of the whole sample and compared with the simulation results.

4.1 Macrostructure analysis

Figure 5 represents the cast samples – sample 1 (a), sample 2 (b), sample 3 (c), sample 4 (d). As can be seen, dark clusters, assumed to indicate gas-porosity defects, are found in the middle of the sample casts poured at 680 °C and 650 °C (samples 3, 4). Fewer porosity defects in the center area are observed at a higher pouring temperature (samples 1, 2).

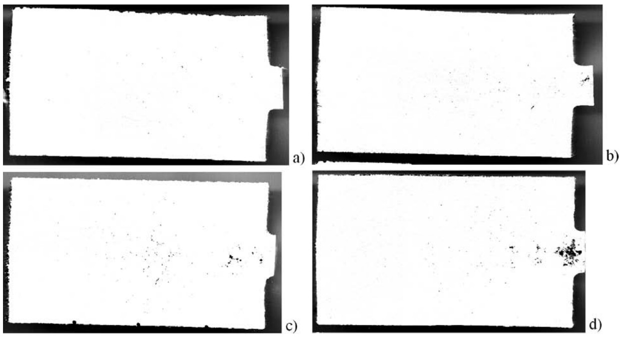

Figure 5: Porosity
Slika 5: Poroznost

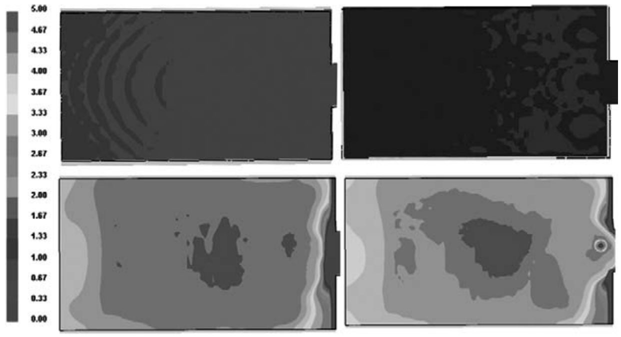

Figure 6: Porosity – ProCAST
Slika 6: Poroznost – ProCAST

Solidification shrinkage is one of the casting defects that can also be identified in **Figure 5** (samples 2, 3, 4). It represents a dimensional reduction of the metal changing from the molten to the solid state due to insufficient feeding. The color of the sample shown on **Figure 5d** is fairly dark when compared with the others. This indicates that here the porosity defect is bigger and deeper. At the pouring temperature of 730 °C the internal solidification shrinkage is almost unnoticeable thanks to good feeding conditions.

Figure 6 shows the results of a total-porosity analysis made after the solidification. The images show the cross-sections of the casting, as in the real experiments. The color spectrum represents the percentage amounts of the total-porosity prediction in the analyzed areas. For all the simulations, the spectrum was set to the same value (specifically, 5 % of porosity), so the results can be compared and the evaluation is meaningful. Samples 1 and 2 show lower amounts of the total porosity in the center areas, but sample 2 shows an increased probability of the porosity presence in the upper area, as can also be confirmed with the real sample (**Figure 5**). When comparing simulated sample 3 with the real sample, we can find common features: the gas porosity is concentrated in the middle, while the cluster of the internal shrinkage porosity is closer to the top. Sample 4 is different: one big cluster of the internal shrinkage porosity due to insufficient feeding is near the narrowed part and the porosity below is concentrated above the center. The above-mentioned results represent just the first steps of an extensive work being underway, but these experiments already show a promising method for porosity prediction.

5 CONCLUSIONS

A method was tested to increase the accuracy of simulating the macroporosity of aluminum-silicon-alloy castings produced by gravity casting into a resin-based sand mold.

The used thermal analysis proved to be a useful method to determine a wide range of solidification features vital for precise simulations. This approach can provide the fundamental data and relationships for the simulation software like various characteristics of the temperature and time, alloy composition, addition elements, cooling conditions, etc., which ultimately affect the porosity formation.

The percentage of the formed porosity increases with the decreasing cooling rate. When the cooling rate is low, there is an evolution of hydrogen gas bubbles due to a sudden decrease in the hydrogen solubility during solidification (gas pores). There is also combined gas-shrinkage porosity.

Future work will focus on fully identifying the types of porosity on the analyzed area (with electron scanning microscopy) so that we can, with certainty, recognize gas porosity, shrinkage porosity and blow-hole defects. In addition to the material presented in this article, further on, we will use various materials with different solidification intervals to be able to obtain proper boundary conditions. The temperature of the mold will vary as well.

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