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INVESTIGATION OF THE INFLUENCE OF COOLING RATE ON SHRINKAGE CAVITY AND POROSITY FORMATION IN AL-SI ALLOY

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Abstract: *The report presents the results of a study the shrinkage porosity in Al-Si alloy with sub eutectic composition. The influence of the cooling rate (using metal and sand moulds) on the shrinkage cavity volume and porosity was studied. The results illustrate the effect of liquid and solid state shrinkage of the metal on this phenomenon. Simulation experiments were also carried out and analysed.*

Keywords: Manufacturing tevhnologies, Foundry technologies, *Casting of metals, Porosity*

1. Introduction.

One of the foundry technology fetures is the shrinkage of the metal - as the temperature of a metal decreases so does its volume and the linear dimensions of the casting. After solidification the volume of the metal sharply decreases by up to 10% causing some specific defects in castings. Hence the shrinkage is one of the most important characteristics of the alloy, determining the size of the casting, its density, porosity, stresses, cracks, deformations, etc. [1-3].

As a result of the volume and phase transformation shrinkage (depending on the type of alloy, the shape of casting and the way of pouring the metal in the mould) some empty cavities filled with gases from the metal are formed in the castings. Their surface is rough, dark, irregularly shaped unlike gas pores whose surface is smooth and shiny. Some large dendrites could also be observed on the internal surfaces of the cavities [4].

Depending on the location of these defects in the casting and the nature of the crystallization the shrinkage porosity could be concentrated (external or internal suctions) or scattered. The pores are usually not visible but when the porosity is formed in a thick sections of castings a large number of pores are grouped together and become visible.

The porosity is a side effect in the production of castings and must be avoided. Different methods and recommendations to remove or minimize them during the process are used:

- Simultaneous solidification method (for metals with narrow crystallization temperature interval and higher tendency to suction and cavity formation, thin-walled castings). Rapid cooling and solidification of the whole casting to form dispersed pores instead of concentrated suctions;
- Directed solidification - in this method crystallization proceeds gradually from one end of the casting to the other end which cools last or to a specifically designed rizer or the feeding system;
- Simultaneously feeding the mould with liquid metal through several feeders for simultaneous solidification;
- If there are thin and thick parts, feed through the thin ones to ensure simultaneous solidification and avoid concentrated porrosity.

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The cooling rate is one of the parameters influencing the shrinkage, respectively the formation of cavities (suctions) and porosity. When casting in sand molds, the cooling rate depends on the water content of the molding mixture. Similarly the heat transfer trough the metal mould depends on its temperature. In the present experiments the influence of the temperature of the metal mould and the water content in the sand on the suction and porosity formation in aluminum alloy (Al – 10%Si with near eutectic composition) to form porosity and suctions is investigated.

2. Test methodology

To determine the influence of the mold temperature and water content on the porosity and suction six test specimens of the same shape consisting of a conical and a cylindrical part were used for the present experiments. The molten metal is poured into three preheated metal molds each to a different temperature and into three sand molds each mold having a different moisture content of the moulding mixture.

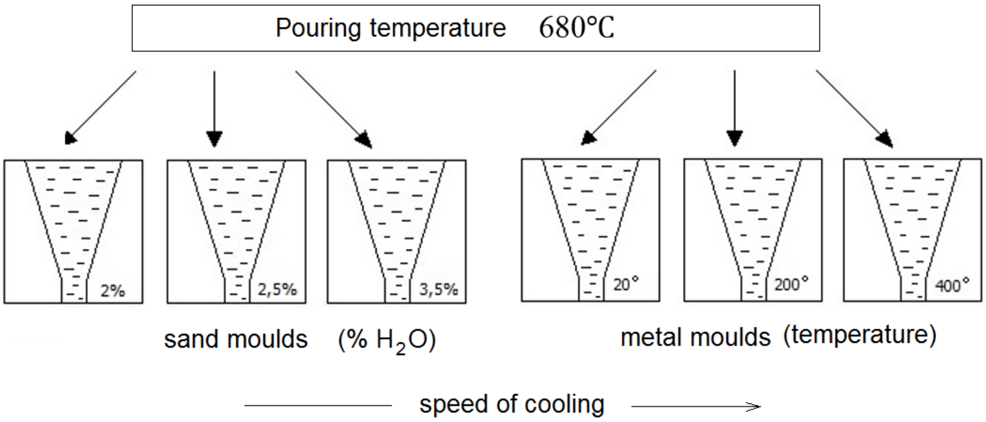


Fig. 1 Experiments setup

The volume of the concentrated porosity (suction) is determined by filling its volume with a low surface energy and good wetabilyty liquid (propanol). The volume of the liquid is measured with a graduated cylinder. The density of the casting and the respective porosity is measured from the cylindrical part at the bottom of the test pece and is calculated using three measurments picnometric method and electronic scale with 0.01g accuracy.

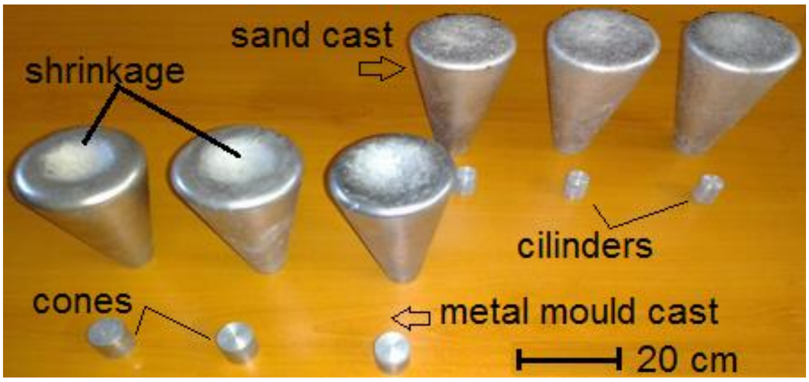


Fig. 2 Cast samples

The simulation of the experiments for the process of casting in metal molds is performed using special software - FLOW-3D CAST v5.1 and DS SOLIDWORKS for generating the 3D model and meshing. The stages and parameters of the simulation with FLOW-3D CAST v5.1 are: (i) creating a network of finite elements; (ii) setting the main parameters: pouring time, pressure, liquid metal temperature, chemical composition, mold temperature, pouring diameter, etc.

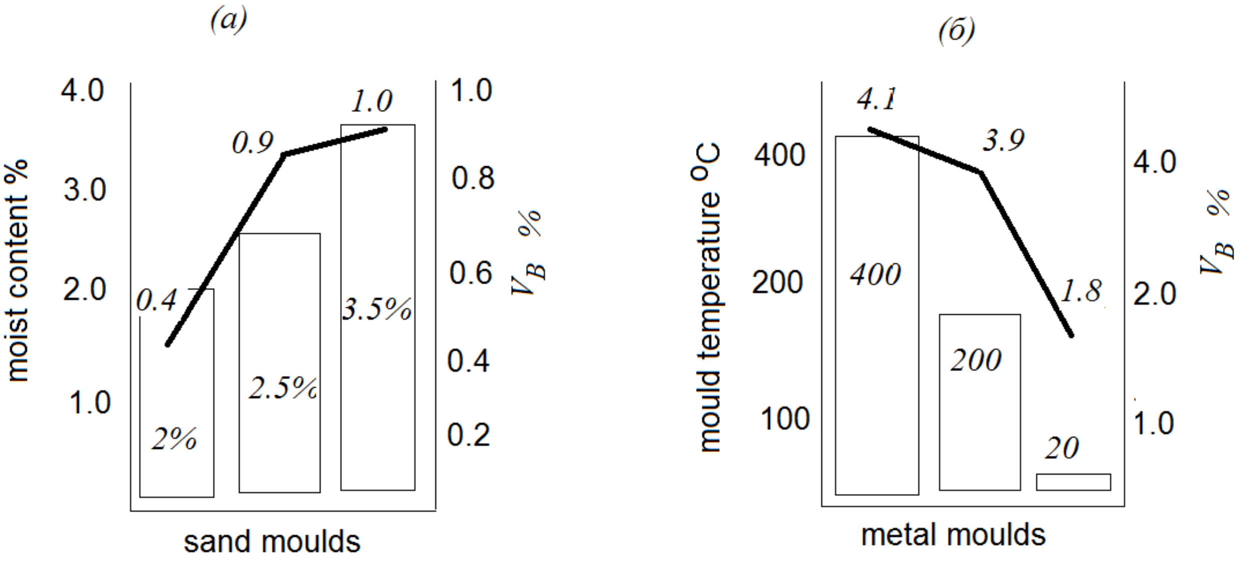
3. Analises of the results

The obtained results show that increasing cooling rate (increase of the moisture content in the sand) lead to increase of the shrinkage cavity volume. On the other hand further increase in the cooling rate by using the metal molds with much higher thermal conductivity (this is achieved by decrease in the metal mold temperature) has an opposite effect: namely decrease in the shrinkage cavity volume V_B (Table 1 and Table 2, Fig.3).

The data for measuring the porosity (indicated by the density of the casted alloy measured from the cilindrical samples - ρ, g/cm^3) shows no statisticaly significant change. The relative error estimated with three samples per measured factor was ε% ~ 10% which indicates that the detected responsible variety (ρ) change of 0,3% is unsignificant.

Table 1 Test data from the experiments

sample	V_B, cm^3	V_B %	ρ, g/cm^3	V_B, cm^3	V_B %	ρ, g/cm^3
	sand casted samples			metal mould casted samples		
Cone, 2% H_2O	0,7	0,4		2,6	1,8	
Cone, 2,5% H_2O	1,8	0,9		7,3	3,9	
Cone, 3,5% H_2O	2,0	1,0		7,6	4,1	
Cilinder, 2% H_2O			2,75			2,82
Cilinder, 2,5% H_2O			2,73			2,82
Cilinder, 3,5% H_2O			2,70			2,81



Фиг. 3 Shrinkage cavity volume in samples cast in sand (a) and metal moulds (b).

To explain the observed fenomenon of oposite response of V_B to the speed of cooling achived in sand (Fig 3, a) and metal (Fig. 3, b) mould castings we have to consider the established model for estimating the shrinkage cavity volume [4-6]. According to this model the shrinkage in the metal (and the corresponding shrinkage cavity volume (V_B) could be devided in three portions: (i) shrinkage during the cooling of the liquid; (ii) shrinkage due the "liquid-solid" pfase transformation (ΔV_{phs}); (iii) shrinkage of the solid state (it is multyplyed by a factor of 0.5 because we can consider that only half of the casting metal shrinks in complete solid state and the other half shrinks in mixture of solid and liquid phase). The equation corresponding to this model is as foloows:

$$V_B = \alpha_{liq}(T_{liq} - T_{sol}) + \Delta V_{phs} - 0{,}5\alpha_{sol}(T_{sol} - T_o),$$

where: α_{liq} - the shrinkage coefficient of the liquid metal; T_{liq} - the temperature of the liquid when pured in the mold; T_{sol} - the temperatute of the solidufication; α_{sol} - the shrinkage coefficient of the solid metal; T_o - the ambient temperature.

At lower cooling rates ($v_{cool} < v_{critical}$) the increase of the heat transfer (higher water content in the sand) lead to an increase in the shrinkage in both liquid and solid state (Fig. 4) due to the increased temperature intervals of shrinkage (T_{liq} - T_{sol}) and (T_{sol} - T_o). But the contraction in solid state grows more slowly. This leads to an increase in shrinkage cavity - according to the formula.

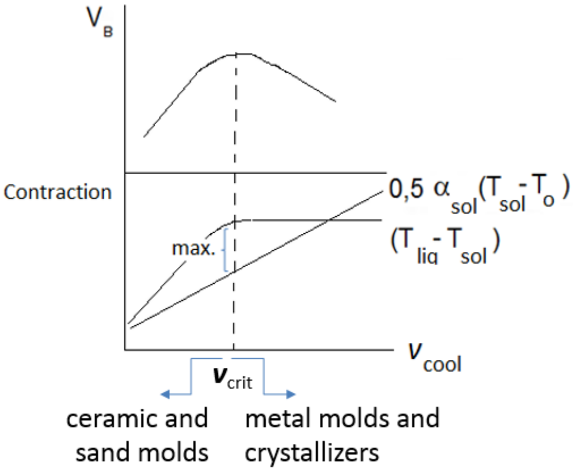


Fig. 4 A model describing the formation of shrinkage cavity volume in castings

When we have a higher cooling rate $v_{cool} > v_{critical}$ (e.g. casting in metal molds and crystallizers) the temperature of the cast metal surface decreases rapidly (i.e. we still have an increase in $T_{sol} – T_o$ and an increase in the contraction in the solid state) while the gradient in the liquid phase shrinkage stabilizes at certain level (i.e. greater increase in shrinkage due to T_{liq} - T_{sol} increase is not observed). This leads to a decrease in the V_B after reaching a certain cooling rate $v_{critical}$. Thus a curve is obtained with a maximum corresponding to the largest difference between shrinkage in liquid and solid state (according to the formula for V_B and graphs in Fig. 4) and the data obtained in this experiments fall on both sides of this "maximum" where low thermal conductivity ceramic materials and high thermal conductivity metallic materials have been used for the mould.

In general the simulation experiments give results relevant to the real experiments. They were conducted only with the metal mould option since no reliable imput data for the sand moulds with different moisture content were available in the software.

The simulation shows that due to the cross-flow during flooding and rapid cooling, a gas bubble forms in the lower cylindrical part. This was experimentaly approved (Fig. 5).

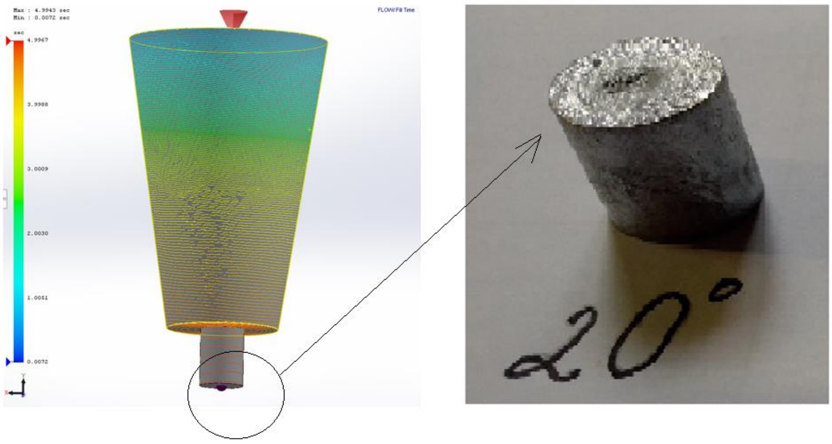


Fig. 5 Gas buble in the cylinder section

The results from the simulation of the solidification time closely correlate with the experiments. At 20 °C on the mold the time is the shortest and at 400 °C it is the longest (Fig. 6).

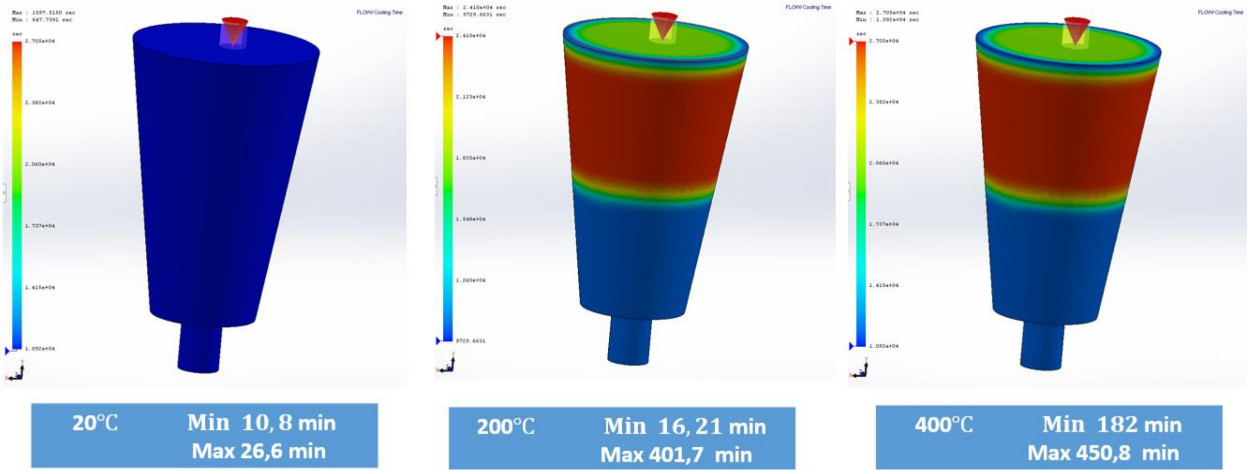


Fig. 6 Solidification time for experiments with different metal mould temperature.

It was found that in the coldest mould (20ºC) the porosity in the casting was distributed over the entire area evenly due to the high cooling rate (Fig. 7) only at the outer periphery the crystallization is with a higher speed wich will ensure porosity free surface of the casting. At mould temperature of 200 °C the cooling of the mould and liquid metal occurs simultaneously and the temperature and porosity are homogeneously distributed. At mould temperature of 400 °C, due to the high temperature and slow cooling a dendritic zones of solidification were observed with larger pores formation (red spots). This indicates conditions for formation of some concentrated shrinkage suction. The experiment shows maximum V_B on this sample.

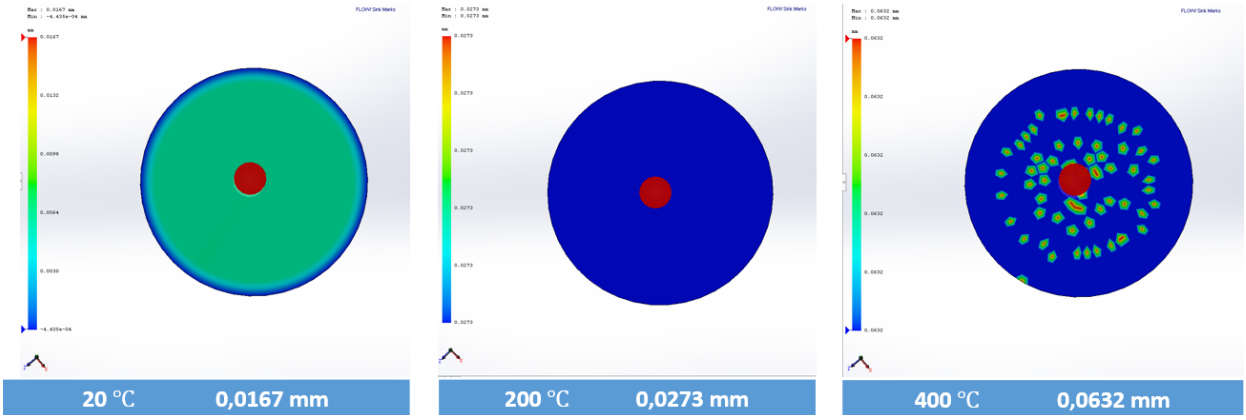


Fig. 7 Shrincage porosity (mm) - experiments with different metal mould temperature.

4. Conclusions

The volume of the suction (shrinkage cavity volume) formed at different cooling rates does not exceed 1% for casting in sand moulds and 4.1% for casting in metal moulds. The recommendations could be made that if metal moulds are to be used for Al-Si near eutectic alloys the mould preheat temperature must be kept below 200ºC in order to avoid porosity in the tick sections of castings.

The different influence of the mold temperature and the casting sand moisture on the heat dissipation rate and the suction behavior of the metal alloy has been confirmed:

- at lower cooling rates higher water content in the sand lead to an increase in the shrinkage in both liquid and solid state and the volume of the suction increases;

- when we have a higher cooling rate (e.g. casting in metal molds) the temperature of the cast metal surface decreases rapidly (solid state contraction increses but liquid phase shrinkage stabilizes at certain level) which leads to a decrease in the V_B.

The simulations of the experiments show relevant results. The cooling speed is significantly different when mould temperature is changed. The conditions for higher V_B predicted by the simulation are confirmed by the real experiments. These simulation experiments can be successfully used in the future to quantify the cooling rate of the metal in the casting process.

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