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# THE EFFECT OF MOULD TEMPERATURE AND COOLING CONDITIONS ON THE SIZE OF SECONDARY DENDRITE ARM SPACING IN Al-7Si-3Cu ALLOY

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## Abstract

The secondary dendrite arm spacing (SDAS) is one of the most important microstructure features of as-cast structure in hypoeutectic aluminum alloys. The size of SDAS depends on many factors such as liquid metal treatment, temperature gradient, cooling rate/solidification time and chemical composition of melt. Among them the cooling rate/solidification time have dominant impacts. In industrial production of castings, when the chemical composition of melt has been chosen, the cooling conditions will control the solidification process.

In this paper the effect of various pre-heating mould temperatures and cooling conditions (with and without water cooling) on the SDAS in AlSi7Cu3 were studied. For that purpose the permanent metal mould with the cooling system incorporated in one die was designed. The solidification time was affected by the mould temperature. It was found that the influence of mould temperature on SDAS was less pronounced in the presence of water cooling. The experimental results concerning the value of SDAS were compared with calculated value of SDAS obtained as a result of solidification process simulated by WinCast FEM Software.
*Key words: The secondary dendrite arm spacing (SDAS), Al-Si-Cu alloy, the mould temperature, cooling conditions*

## Introduction

Application of Al–Si cast alloys in car engine parts such as engine block and cylinder heads is expected to be a growth area in many countries in which they are manufactured in the recent years. In designing cast automotive parts, it is important to possess knowledge on the solidification phenomena and their effect on mechanical properties of different cross sections of casting. This knowledge enables the designer to ensure that the casting will achieve the desired properties for its intended application [1-4].

The solidification of cast aluminum alloys starts with separation of a primary α-phase from the liquid. After nucleation, when the temperature lowers, the primary phase grows as solid crystals having dendritic shape. When the eutectic temperature has been reached, the solidification proceeds at constant temperature with the formation of the eutectic solid phase in the space left between dendritic arms.

The secondary dendrite arm spacing (SDAS), which is defined as the distance between the protruding adjacent secondary arms of a dendrite, has been used in recent years to describe the metallurgical structure of cast materials. It is well known that various cooling rates during solidification can lead to variation in the amount and various morphological characteristics of as-cast structures, which in turn can lead to different mechanical properties [1, 5-7]. Castings having a finer microstructure show better tensile and fatigue properties, particularly for cast aluminum alloys, this improvement is related to a lower SDAS value. Studies on the effect of SDAS on tensile properties report that the tensile strength and ductility are found to decrease with increasing value of SDAS [10]. The SDAS influences the size of eutectic Si and porosity and also affects the Ultimate Tensile Strength (UTS), Yield Strength (YS) and elongation. Finer SDAS leads to sound casting by reducing the porosity and the size of eutectic Si, which solidifies in between dendrite arms [8 - 12].

Parameters that control the solidification of castings, and consequently, microstructure and mechanical properties, are as follows: chemical composition, liquid metal treatment, cooling rate and temperature gradient. Among these parameters the cooling rate is most important.

In a literature survey, a number of different theoretical and experimental models to treat dendritic growth can be found. These models permit the correlation of microstructural features with solidification process parameters. According to Grugel [13], although the primary dendrite spacing is constant during a steady-state solidification process, SDAS is notably modified along the primary arms. Such a behavior can be explained on the basis of a coarsening process of the dendrite arms during the solidification. Several researchers, including Whisler and Kattamis [14] and Feurer [15] have analyzed the coarsening phenomenon in dendritic growth. One of the most effective models to deal with a correlation between SDAS and solidification parameters was proposed by Feurer [15]. For secondary arm spacing, Feurer developed a theoretical model that relates secondary dendrite arm spacing, $\lambda_2$, to the local solidification time, $t_f$. The Feurer model was based on the work of Kattamis et al. [16]. According to Feurer [15, 16], the secondary spacing, $\lambda_2$ is a function of $t_f$, and is given by the equation:

$$\lambda_f = 4.36(Mt_f)^{1/3} \quad (1)$$

where: M is defined as coarsening parameter with the value for aluminum alloys usually in the range of 1-10.

SDAS is determined by soldification time through the mushy zone, with longer solidification time resulting in larger values of SDAS. The equitation (1) is often used as a mathematical model to simulate solidification process of aluminum castings.

The size of the dendrites is affected not only by heat transfer rate during solidification of the casting into mould but also by the chemical composition of the alloy.

In casting production, such as production of cylinder heads, the factors that can affect the solidification rate can be summarised as:

local temperature of the mould, especially in the area of combustion chambers of the cylinder head, which can be controlled by the cooling system in the mould;

pouring temperature;

geometric configuration of the cylinder head in the combustion chamber area, and of the risers [11].

Because of the evident importance of SDAS, many automotive companies have specified SDAS values in engineering data for aluminum castings. Increasing the strict control of SDAS enables the production of castings with improved properties. This, however, requires development of new processing technologies.

The aim of the present paper was investigation of the effect of the casting parameters, such as the mould temperature and cooling conditions on the size of SDAS in AlSi7Cu3 alloy. For that purpose the permanent metal mould made of hot work tool steel 4Cr5MoSiV1 was used. During the casting experiments the pouring temperature, chemical composition of the alloy and casting time were kept constant. The mould temperature was varied in the range of 250-350 °C, whereas for each examined temperature two different cooling conditions (with and without water cooling) were applied. According to the experimental conditions and permanent mould geometry, the solidification process was simulated using the WinCast Finite Element Software. The experimental values of SDAS were compared with the results of simulation and the relative deviation was calculated.

## Experimental

### *Material and experimental procedure*

The AlSi7Cu3 alloy supplied by NEMAK, Wernigerode was used for experimental studies. The alloy was supplied in the unmodified form. The chemical composition of the alloy was determined using the Optical Emission Spectroscopy (OES) showing the following composition (in wt.%): 8.74 Si, 0.25 Fe, 3.493 Cu, 0.176 Mn, 0.175 Mg, 0.0104 Cr, 0.0288 Ni, 0.130 Zn, 0.020 Pb, 0.003 Sn, 0.115 Ti, 0.0012 Sr and 87.77 Al.

The alloy was remelted in the laboratory furnace (the maximum capacity of 10 kg) and hold at 750ºC. Before pouring the melt was degassed for 15 min by passing dry argon. Refiner and modifier were not used for the melt treatment. The casting temperature was kept constant at 720 °C.

In order to estimate the effect of mould temperature and cooling conditions on the SDAS one set of experiments was performed using the permanent mould shown in Fig 1.

*Fig. 1 Design of permanent metal mould*

The mould was pre-heated up to three different temperatures, i.e.: 350, 300 and 250 °C using the laboratory burner. In order to ensure the proper cooling conditions for each mould temperature "internal" cooling technique using water as a cooling medium was used.

For this purpose a metal mould made of hot work tool steel 4Cr5MoSiV1 was used. Before pouring of molten metal, cavity surfaces were coated with a thin layer of heat resistant material such as sodium-silicate. A ceramic filter was placed in slag trap of mould before the casting. The molten metal was fed directly into the mould under gravity.

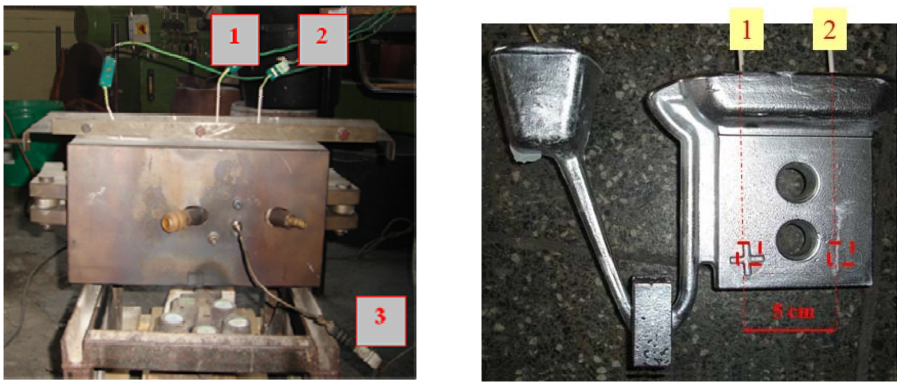



*Fig. 2 Position of thermocouples in metal mould and casting (tip of thermocouples at 2 cm from the bottom of the casting)*

The temperature variations during the solidification process of the melt were controlled by placing two thermocouples in mould cavity (nr. 1 and 2 in Fig 2.). Due to the control of pre-heating mould temperature (in the following text denoted only as mould temperature) one thermocouple (3) was inserted in the outer wall of the left mould die. The distance between the thermocouples positioned in the mould cavity was 5 cm and the tips of both thermocouples were at 2 cm from the bottom of casting (see Fig. 2). The temperature of water used as cooling medium was constant, i.e. 12 °C.

The analysis of the cooling curves was supplemented by metallographic analysis. Samples for metallographic examination were sectioned from the obtained castings (corresponding to each experimental condition) and taken from the positions where the tip of thermocouple 1 and 2 were positioned. In this paper the results of metallographic analysis were presented only for the sample corresponding to the tip of thermocouple 1. Samples were prepared by standard grinding and polishing procedures. NIKON Epiphot 200 light optical microscope has been used for microstructure observation.

The line intercept method was utilized to measure the SDAS which was determined as a ratio of length segment to the number of arms. The image analyzer software, NIS Elements 2.10 was utilized to estimate the size of SDAS. The final size of the SDAS has been obtained as an average value of at least 10 measurements.

Experiments of solidification process of AlSi7Cu3 alloys in the permanent metal mould shown above were also simulated by WinCast Finite Element Software taking into account all experimental parameters (pouring time, pouring temperature as well as physical properties of alloy and mould geometry). Mathematical model used for the calculation of SDAS was based on the equitation (1). By substituting an alloy-specific value of M (in this work the value of M was 1.4) into the above equation, the magnitude of SDAS can be easily calculated for each volume that comprises the casting model.

In order to estimate the sensitivity of mathematical model on chages in mould temperatures, the experimental values of SDAS corresponding to the position of the tip of thermocouple 1 were compared with the calculated values of SDAS resulting from the simulation process which corresponds to the same position as in the real casting.

## Results and discussion

The cooling curves recorded for AlSi7Cu3 alloy at various mould temperatures and cooling conditions (with and without water cooling) were used to determine the solidification time. The solidification time was defined as time interval between liquidus and solidus temperature. These temperatures were obtained from the first derivatives of the cooling curves. The metallographic samples were taken from the position close to the tip of the first thermocouple where the SDAS was measured. Solidification time and the corresponding values of SDAS for all experimental conditions are presented in Table 1.

*Table 1. Variation of solidification time and SDAS with respect to mould temperature and cooling conditions*

| Sample | $t_f$, s | SDAS(exp), μm | SDAS(calc), μm | ΔSDAS, μm |
|---|---|---|---|---|
| 350NW_1 | 51.7 | 25.2 | 29.0 | 3.8 |
| 350WW_1 | 43.2 | 22.2 | 27.3 | 5.1 |
| 300NW_1 | 36.8 | 21.2 | 25.9 | 4.7 |
| 300WW_1 | 28 | 21.4 | 23.7 | 2.3 |
| 250NW_1 | 9.8 | 19.9 | 16.7 | -3.2 |
| 250WW_1 | 8.3 | 19.4 | 15.8 | -3.6 |

**NW = without water cooling, WW = water cooling*

It was found that the reduction of mould temperature leads to the decrease of the SDAS. However, it can be noticed that lower value of SDAS were achieved in the presence of water cooling. Comparing the SDAS for all used mould temperatures with and without water cooling it can be seen that the effect of the mould temperature on SDAS is less pronounced in the presence of water cooling. The effect of mould temperature with and without water cooling on SDAS of AlSi7Cu3 alloy was illustrated in the Fig. 3.

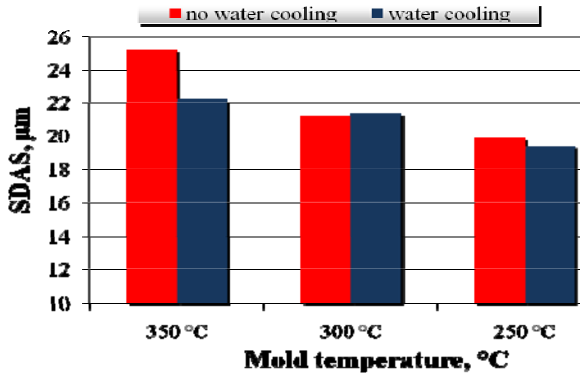



*Fig. 3 The effect of mould temperature and cooling conditions on SDAS*

The maximum value of SDAS (25.2 µm) was achieved in the case of mould temperature 350 °C without water cooling where solidification time was 51,7 s. The minimal value of SDAS (19.4 µm) was related to the mould temperature of 250 °C with water cooling and solidification time of 8.3 s. In addition, it can be noticed that without water cooling the change of the mould temperature from 350 to 250 °C leads to reduction of SDAS of 5.3 µm. In the presence of water cooling the same decrease of mould temperature provides the reduction of SDAS of 2.8 µm, which indicates that water cooling lowers the effect of mould temperature on the SDAS. Fig. 4 shows the microstructure of Al-Si7-Cu3 alloy corresponding to the samples 350 NW_1 (left) i 350 WW_1 (right in Fig. 4.)

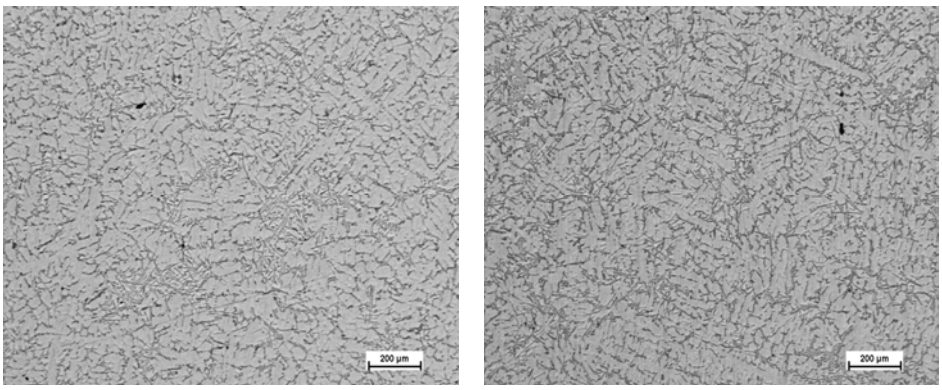
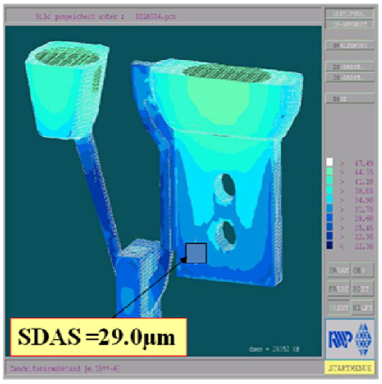
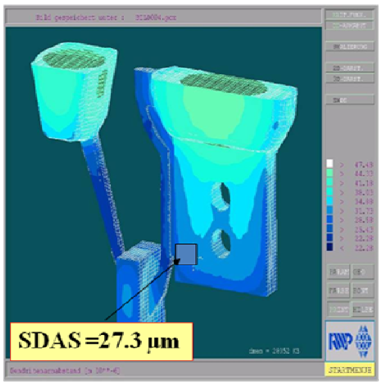


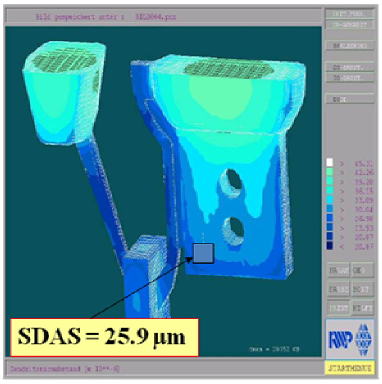

*Fig. 4 Microstructure of Al-Si7-Cu3 alloys corresponding to the sample 350 NW_1 (left) microstructure of the sample 350 WW_1 (right)*



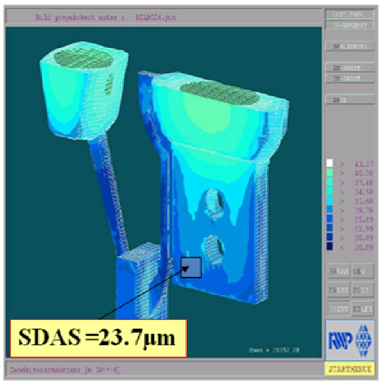
*a) Tmould=350 °C without water cooling*



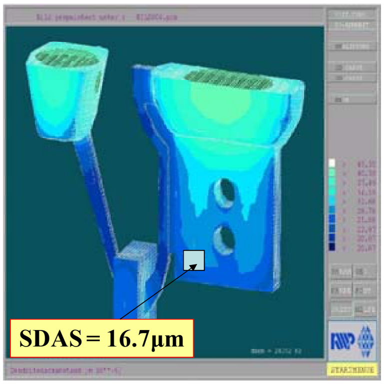
*b) Tmould = 350 °C with water cooling*



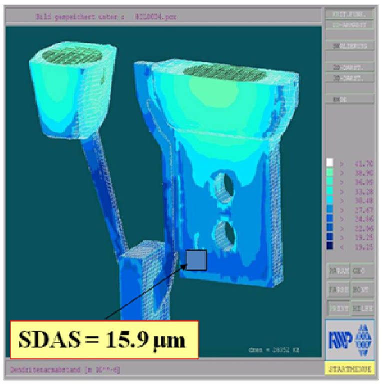
*c) Tmould=300 °C without water cooling*



*d) Tmould = 300 °C with water cooling*



*e) Tmould=250 °C without water cooling*



*f) Tmould = 250 °C with water cooling*

*Fig. 5 Simulation of solidification process of AlSi7Cu3 alloy in permanent mould following the different experimental conditions*

Comparing the experimental and simulation results of SDAS it can be noticed the same trend of SDAS depending on the mould temperature and solidification time. Fig 5 illustrates the results of simulation process carried out by WinCast software following the experimental conditions. It was found that there is a strong temperature gradient from the bottom to the top of the casting. Higher temperature of the metal at the top gradient causes a large variation in SDAS to develop across the casting from the bottom to the top, and to a lesser degree, from the center to the exterior of the casting.

The measured values of SDAS were compared to the calculated values of SDAS in the metallographic samples which corresponding positions in the casting are marked out with one square in Fig. 5.

The measured SDAS versus calculated SDAS is shown in Fig. 6. The relative deviation of experimental and simulated values of SDAS, ΔSDAS are also presented in Table 1. These results indicate that the calculated values of SDAS are higher than experimental values particularly for higher mould temperature (300 and 350 °C). For the lower mould temperature the calculated values of SDAS are lower than experimental showing the negative value of relative deviation.

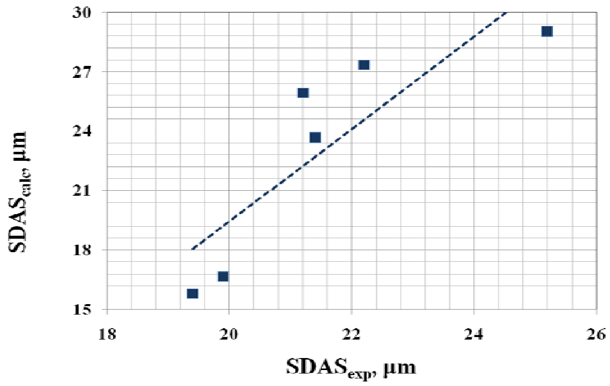



*Fig. 6 Measured SDAS versus calculated SDAS*

This could be interpreted in terms of sensitivity of the mathematical model to the mould temperature and cooling conditions variation. In addition, the heat transfer coefficient should be also included in the validation of simulation process because as a variable it depends on the mould temperature. As a second option for that problem could be the local mesh quality that could be ascribed as another variable. As the solidification models could adequately predict SDAS, choices made in setting boundary conditions might affect the quality of the results. The importance of these results is the attempt to extend solidification modeling beyond the usual foundry practice.

## Conclusion

Based on the present work the following conclusion could be drawn:

(1) Variation of the experimental conditions, including decrease of mould temperature from 350 to 250 °C and using for each mould temperature two different cooling conditions (with and without water cooling) has led to the

change of solidification time. With shorter solidification time SDAS decreases. The reduction of SDAS values in AlSi7Cu3 alloy is caused by the decrease of the mould temperature. However, the effect of the mould temperature on the value of SDAS was lowered in the presence of water cooling where cooling media plays the main role.

(2) It is assumed that higher agreement between the experimental and simulation results could be achieved by changing the boundary conditions and/or testing the other mathematical models available in the literature.

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