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EFFECT OF GRAIN REFINEMENT AND MODIFICATION OF EUTECTIC PHASE ON SHRINKAGE OF AlSi9Cu3 ALLOY

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Paper describes influence of grain refining and of modification on feeding behavior of Al – alloys. Research was made with the AlSi9Cu3 alloy. Three samples of basic, grain refined, and modified alloy were cast by the newly developed method for determining susceptibility to shrinkage and into the Quick cup measuring cells for simple thermal analyses which were simultaneously done with all these samples. Castings were then analyzed with X-raying, density measurements, visually observed and metallographically examined. Also grain size was determined with light microscopy and polarized light.

Key words: AlSi9Cu3 alloy, shrinkage, solidification morphology, sink

Utjecaj usitnjavanja zrna i modifikacije eutektičke faze na stezanje pri skrućivanju AlSi9Cu3 legure. Ovaj rad opisuje utjecaj dodatka cjepiva i modifikatora na ponašanje napajanja Al-legura. Istraživanja su provedena na AlSi9Cu3 leguri. Tri su uzorka, iz osnovne legure, cijepljene i modificirane, lijevana u „Quick Cup" mjerne ćelije primjenom novo razvijene metode za određivanje osjetljivosti na stezanje pri skrućivanju. Jednostavna toplinska analiza provedena je simultano u sva tri uzorka. Odljevci su potom ispitani određivanjem gustoće, vizualnom kontrolom i metalografskom analizom. Također, veličina zrna je određena optičkom mikroskopijom u polariziranom svjetlu.

Ključne riječi: AlSi9Cu3 legura, stezanje pri skrućivanju, morfologija skrućivanja, uvlaka

INTRODUCTION

All metals and alloys with exception of Bi are shrinking during cooling, mostly during the solidification process. In order to avoid shrinking porosity, casting process, and gating and feeding system must be properly designed. Solidification front must move towards the feeding system where solidification is then completed. No separate liquid pockets where solidification ended without feeding should exist. In order to meet these demands the feeders and feeder necks must have suitable modules to keep metal liquid during transport to the solidification front [1].

There exist two types of solidification, exogenous and endogenous.

Exogenous solidification is typical for pure and eutectic alloys that solidify at constant temperatures. Solidification starts there on interface with the mould where solid layer of metal is formed, and solidification front is then moving towards the center of casting or towards the area of the highest temperature. Exogenous solidification type is further divided into three subgroups, i.e. solidification with smooth shell, dendritic solidification, and spongy-layer solidification.

Endogenous solidification is typical for alloys with hypo and hypereutectic compositions that are solidifying in a temperature range. Solidification starts throughout the whole volume of the casting, and solid shell on interface with the mould is formed more slowly. There are two subtypes of endogenous solidification. One is mushy, and the other one is shell-forming type [2]. Solidification types are mixed in all the real cases. Solidification starts with one prevailing type which is changed into another one after some time. This mechanism depends on cooling rate since this is changed during the solidification process [2, 3].

Type of solidification has also influence on feeding ability of alloy. Alloys with smooth-wall type of solidification have the best feeding abilities which result that feeder neck remains liquid during the whole solidification process and thus transport of liquid metal to the solidification front is enabled. Feeding ability of alloys is lower with the endogenous dendritic type and it becomes even worse with the mushy-type solidification where flow of liquid metal is disturbed by floating crystals that are already present in liquid metal. Feeding abilities of alloys dependent on solidification type are presented in Figure 1.

Nucleation potential has big influence on shrinkage porosity, as well. When alloy is properly grain-refined it has higher nucleation potential than the basic alloy and

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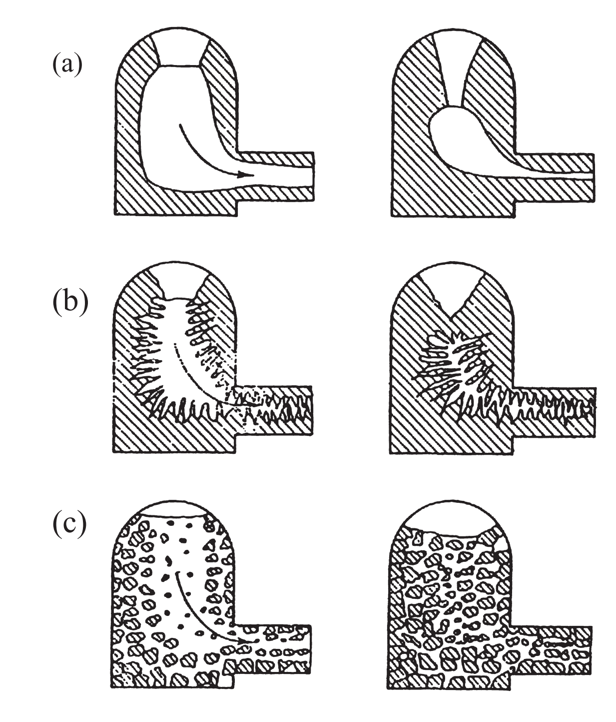

Figure 1 Metal flow from feeder to casting, depending on type of solidification: smooth shell (a), dendritic (b) and mushy (c) [2]

the course of crystallization is taking place with higher number of nuclei. This results in number of primary crystals and better distribution of shrinking porosity [2]. Grain refining has beneficial effect on feeding ability of an alloy since smaller crystals in melt are more movable and can more easily reach the solidification front [4]. Interdendritic feeding is more problematic in later sequences of solidification process due to smaller formed dendrites but it has advantage due to finer shrinkage porosity distribution and lower porosity fraction [5]. On the other hand, grain refining can worsen feeding ability, causing endogenous type of solidification [2]. Consequence of endogenous type is also sink of casting walls as solid casting shell is not firm enough to stay the pressure, resulting from shrinking during the solidification process.

Feeding ability and porosity are influenced by modification, as well. Gas porosity is usually consequence of dissolved hydrogen in the melt that increases with additions of modifying agents [5, 6]. In some cases, this is even advantageous since gas porosity can compensate shrinkage during the solidification. Modification can also lead to higher amount of shrinking porosity as Sr additions cause irregular solidification front resulting in entrapped liquid areas that are not fed and what is causing micro shrinkage porosity. Such defects do not appear if sodium is used as modifying agent [5].

EXPERIMENTAL

Test casting for determining the feeding ability was developed on basis of castings that R. Hummer [7] used

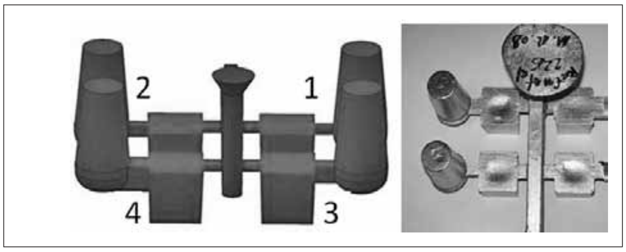

Figure 2 CAD geometry of test casting with various feeder necks (a) and test casting of basic alloy with sink on cubes and feeders (b)

Table 1 **Sizes and modules of feeder necks**

No. of cube	Module of feeder neck / cm	Dimensions of feeder neck / mm
1	1,25	5 × 5 × 10
2	1,88	7.5 × 7.5 × 10
3	2,5	10 × 10 × 10
4	3,75	15 × 15 × 10

for studying feeding ability of cast iron. Test casting was composed of four cubes with dimensions 30×30×30 mm. Each cube was connected to feeder by feeder neck. Feeder necks had different dimensions that resulted in different modules. Module of cubes was 5 cm, and modules of feeder necks are presented in Table 1. 3D CAD model is presented in Figure 2a.

Analyses of feeding ability as functions of grain refinement and modification have been performed with the AlSi9Cu3 alloy. Grain refining agent was the AlTi5B1 master alloy with additions of 0,05 wt. % of Ti. AlSr10 master alloy with addition of 0,01 wt. % Sr was used as modifying agent. The first sample represented basic alloy, the second one was grain-refined alloy, and the last one was made of modified alloy. Samples of 1000 g melt were prepared and cast into mould for test casting and into the Quick Cup measuring cell for simple thermal analysis.

Test castings were then analyzed with light microscope, X-rayed with YXLON MU 2000 X-ray device, while density measurements were made with the Mohr scales. Amount of shrinking porosity together with the fraction of sink as due to shrinkage during the solidification process were measured. Castings from the Quick Cup measuring cell were analyzed with Olympus BX 61 light microscope and grain sizes of α_{Al} grains and sizes of β_{Si} eutectic phase were determined using the program analysis 5,0.

RESULTS AND DISCUSSION

Macro analysis of test castings made of the basic and the grain-refined alloy showed that there was great sink on upper sides of cubes and lateral sides of feeders. Sink in the castings made of the modified alloy occurred in smaller degree only on cubes. Figure 2b is presenting

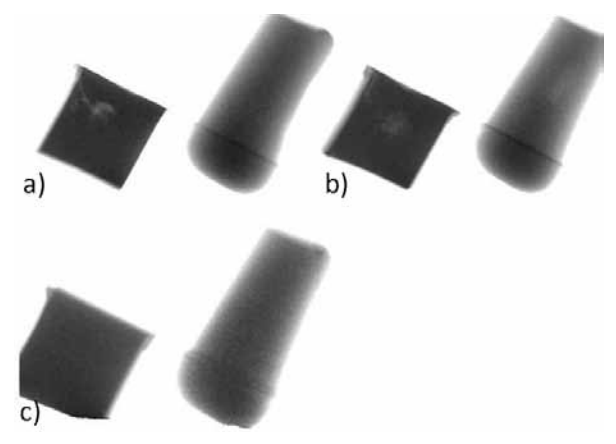

Figure 3 X-ray photos of No. 1 cubes: basic alloy (a), grain-refined alloy (b), and modified alloy (c)

test casting of the basic alloy where sink can be seen. Sink was the lowest on the No. 4 cube that had the highest module of feeder neck and metal could flow from feeder to cube for longer time. Reason for sink is usually endogenous mushy solidification where solid shell at wall of the casting is not firm enough to stay pressure of melt in the casting.

Size, shape, and position of shrinkage porosity were determined by X-ray analysis. Sink was found too. Shrinkage porosity had form of larger holes in the sample of basic alloy, while in the grain-refined alloy it was finely dispersed in the area of final solidification – center of cubes. Lower amount of shrinkage porosity was observed in the casting of modified alloy, and there was also smaller sink of cube walls. Figure 3 is showing X-ray images of No. 1 cubes of all the three samples.

Density measurement showed similar results as X-ray analyses. Table 2 presents results of density measurements for cubes and feeders with corresponding shrinkage porosity and also sink as result of alloy shrinkage. Basic alloy sample showed the lowest density in the No. 3 cube and the highest one in the No. 2 cube. Same results were obtained with light-microscope analysis of cross sectioned cubes and feeders, shown in Figure 4. Similar results were obtained with the grain-refined sample where the lowest density had the No. 3 cube and the highest one the No. 1 cube. It was seen in Figure 4 that the No. 3 cube had the highest fraction of shrinkage porosity which corresponded with the density measurements, while the lowest fraction of shrinkage porosity had the No. 4 cube but there appeared huge sink that represented loss of density, thus the highest density had the No.1 cube. The highest density in the sample of modified alloy had the No. 1 cube, and it could be seen that there was no sink. The lowest density had the No. 4 cube. It could be seen that there was sink only on the Nos. 2, 3 and 4 cubes. Densities in the modified sample were in average for 0,02 kg/dm^3 lower than in the other two samples, and reason for this is higher gassing of the alloy that caused gas porosity which compensated shrinkage porosity.

Table 2 **Densities of cubes and feeders for all the samples / kg/dm^3**

No. of cube	1	2	3	4
Basic alloy				
Cube density	2,646	2,655	2,622	2,650
Feeder density	2,656	2,653	2,670	2,655
Grain refined alloy				
Cube density	2,646	2,633	2,618	2,641
Feeder density	2,649	2,644	2,661	2,638
Modified alloy				
Cube density	2,652	2,609	2,579	2,556
Feeder density	2,629	2,644	2,661	2,652

Results obtained with the cross-sectioned castings are comparable with the results obtained with the density measurements and X-ray analyses. It can be seen that in cubes made of the basic alloy, the shrinkage porosity was the highest in the No. 3 cube and the lowest in the Nos. 1 and 2 cubes. It was also found that there was almost no shrinkage porosity in feeders in all the cases but sink was observed with the basic alloy and the grain-refined alloy. This suggested that feeding system for test casting was not correctly designed. Shrinkage porosity was better distributed and was finer due to grain refinement of the grain refined alloy. Amount of porosity was the highest in the No. 3 cube and the lowest in the No. 4 cube. Also sink was observed there. Densities were slightly higher in the basic alloy, followed by the grain-refined alloy. Reason for this was sink as density loss in density measurements. If sink would not be taken in account in density measurements, density would be the same and this confirmed that there was greater sink in the grain-refined alloy as result of changed solidification type to the mushy one. Amount of shrinkage porosity in the modified alloy was lower than in the other two alloys but it was found that there was present gas porosity throughout the whole volume of cubes and feeders. This was consequence of Sr addition that caused higher gassing of Al melt [8]. Additional gassing was caused due to 10 minutes delayed pouring. Formed gas porosity has compensated shrinkage porosity during the solidification so there was no sink on feeders and on the No. 1 cube and fraction of shrinkage porosity was lower, as well. This result corresponded to references [5] and [6] too.

Cooling curve with characteristic temperatures and corresponding reactions of the basic alloy that was poured into the Quick Cup measuring cell is presented in Figure 5 while all the cooling curves are presented in Figure 6. Table 3 presents characteristic temperatures, where T_P (°C) is the pouring temperature. It can be seen that minimum liquidus temperatures $T_{L\ min}$ (°C) of the basic and of the modified alloy are approximately the same, they are 562,3 °C for the basic alloy and 565,0 °C for the modified one. Liquidus temperature is about 10 °C higher with the grain-refined alloy, which is result

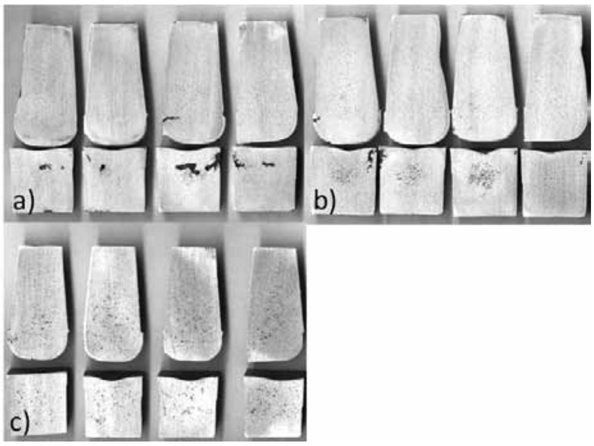

Figure 4 Cross sections of cubes and feeders: basic alloy (a), grain-refined alloy (b), and modified alloy (c)

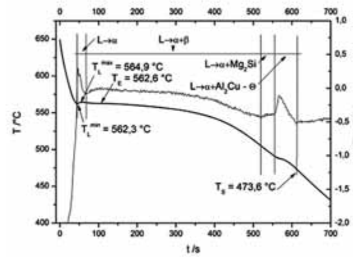

Figure 5 Cooling curve of basic alloy from Quick Cup measuring cell with characteristic temperatures and reactions during solidification

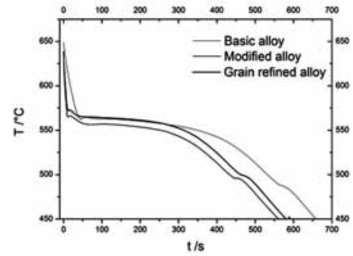

Figure 6 Cooling curves of all the three samples from Quick Cup measuring cell

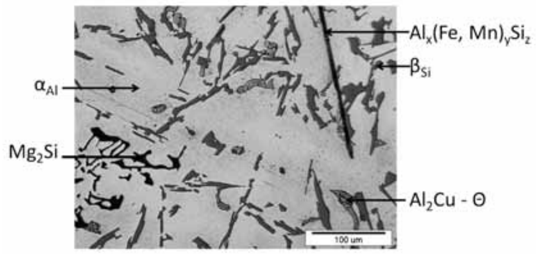

Figure 7 Bright-field micrograph of the basic alloy, cast into the Quick Cup measuring cell, with defined microstructural constituents

of grain refinement where under-cooling is not needed for formation of nuclei [3]. Also recalescence in primary crystallization, ΔT_L (°C), was lower with the grain-refined alloy (0,8 °C), followed by the basic and the modified alloy. It was 2,6 and 1,2 °C, respectively. $T_{L\,max}$ (°C) is the maximal liquidus temperature. Eutectic reaction is taking place at the minimum eutectic temperature, $T_{E\,min}$, being 562,6 °C only with the modified alloy since it is for 6 °C lower due to Sr modification [5] that is causing temperature drop. There was found also recalescence with the eutectic reaction, being ΔT_E = 0,5 °C. Solidification is completed with reactions representing solidification of remnant liquid into (α + Mg_2Si) eutectic at temperature T_{E2} (°C) and (α + Al_2Cu – Θ) eutectic at temperature T_{E3} (°C). Solidus temperature T_S (°C) is thus between 488,9 and 473,6 °C.

Microstructural constituents in the basic alloy were determined with metallographic analyses and taken from references [8] and [9]. Figure 7 is presenting micrograph of the basic alloy, cast into the Quick Cup measuring cell, with microstructural constituents. Next to phases α_{Al} and β_{Si} also ($Al_x(Fe,Mn)_ySi_z$) iron containing phase was found. It precipitated at the beginning of solidification. During cooling process, the stoichiometry of this phase changed [9]. There were observed also Mg_2Si and Al_2Cu-Θ eutectic phases in the microstructure.

Grain sizes and sizes of eutectic β_{Si} phase were measured metallographically in polarized light and in bright field. Effects of grain refinement and modification were determined. Grain sizes were determined according to the ASTM E 112-96 standard. Grain size in the basic alloy from the Quick Cup measuring cell was 841 μm, in the grain-refined alloy only 469 μm, and in the modified one 1000 μm. Sizes of eutectic β_{Si} phase were measured microscopically in bright field. The average particle size in the basic alloy was 44,41 μm, in the grain-refined one 56,16 μm, and in the modified one only 11,63 μm. These results show that grain refining with Ti and modification with Sr were successful. Figure 9 is presenting bright-field micrographs of the basic and the modified alloy from the Quick Cup cell.

CONCLUSIONS

It was found that grain refining and modification of the AlSi9Cu3 alloy affect the solidification morphology

Table 3 **Characteristic temperatures from cooling curves for each alloy**

Temperatures / °C	T_p	$T_{L\,min}$	$T_{L\,max}$	ΔT_L	$T_{E\,min}$	$T_{E\,max}$	ΔT_E	$T_{E\,2}$	$T_{E\,3}$	T_S
Basic alloy	678,4	562,3	564,9	2,6	562,6	562,6	0	505,1	490,9	473,6
Grain-refined alloy	638,7	572,1	572,9	0,8	565,1	565,1	0	510,7	502,5	488,3
Modified alloy	635,8	565,0	566,2	1,2	556,5	557,0	0,5	505,6	497,3	488,9

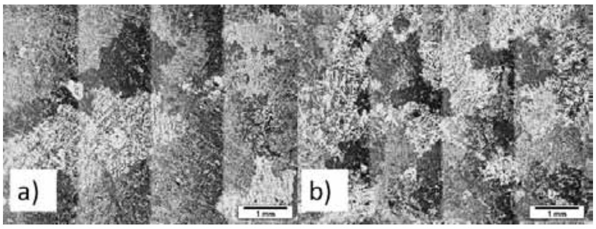

Figure 8 Micrographs in polarized light: basic alloy (a), grain refined alloy (b)

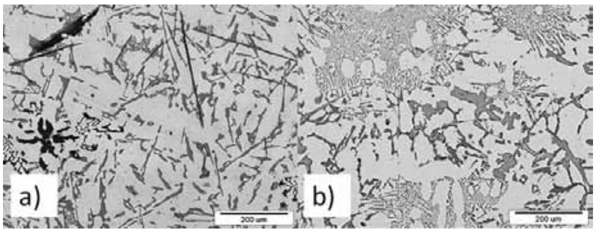

Figure 9 Bright-field micrographs: basic alloy (a), modified alloy (b)

and feeding ability too. Shrinkage porosity in the test casting made of the basic alloy was coarse in the center of cubes where melt solidified the last. Shrinkage porosity was much finer and better dispersed in the grain-refined alloy thus having favorable influence on mechanical properties. Sink appeared on top walls of cubes and side walls of feeders of these two alloys. Reason for this was endogenous mushy-type of solidification while under-pressure in the casting and feeder during the solidification process represented additional unfavorable influence. Density of the basic alloy was slightly higher than that of the grain-refined one, and reason for this was that sink that was taken as density loss in the density measurements, otherwise densities would be the same. Further, it was also found that sink was greater in the grain-refined alloy than in the basic one as consequence that type of solidification changed into mushy one. Sink in the modified alloy was present only on the Nos. 2, 3 and 4 cubes but none was observed on the No. 1 cube and on feeders. There was also lower shrinkage porosity but higher fraction of gas porosity that was consequence of the Sr modification. Gas porosity has compensated shrinking and sinks during the solidification, so there was lower shrinkage porosity but densities were also lower than in the other two alloys because of high gas porosity. Since shrinkage porosity occurred mainly in cubes and not in feeders, it proved that solidification started in feeders and was completed in cubes, and that was wrong. It was obvious that the feeding system of test castings was incorrectly designed. In further analyses of feeding ability, the feeding system for test castings should be changed.

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Note: The responsible translator for English language is prof. dr. A. Paulin, Slovenia.