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The effect of major alloying elements on the size of the secondary dendrite arm spacing in the as-cast Al-Si-Cu alloys

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Abstract

A comprehensive understanding of melt quality is of paramount importance for the control and prediction of actual casting characteristics. Among many phenomenons that occur during the solidification of castings, there are four that control structure and consequently mechanical properties: chemical composition, liquid metal treatment, cooling rate and temperature gradient. The cooling rate and alloy composition are among them most important. This paper investigates the effect of some major alloying elements (silicon and copper) of Al-Si-Cu alloys on the size of the secondary dendrite arm spacing. It has been shown that both alloying elements have reasonable influence on the refinement of this solidification parameter.

Keywords: Secondary dendrite arm spacing; AlSiCu alloy; Aluminium casting; Solidification

1. Introduction

Casting is a process of melting metals and pouring them into the mold in order to produce the required solid shape. It is the simplest and most economic process sometimes the only technically feasible method of obtaining a required solid shape. The process is applicable to different materials such as metals, ceramics, plastics and glass. Among metals aluminium alloys have been in widespread use in the automotive industry due to its good casting characteristics and mechanical properties. This is mainly due to the outstanding effect of silicon and copper in the improvement of casting characteristics, combined with other physical properties, such as mechanical properties and corrosion resistance. Silicon is one of the most significant alloying elements incorporated in aluminium alloys. Its addition is to improve castability, fluidity, reduce shrinkage and to render superior mechanical properties. Copper presence improves tensile strength at the expense of a reduction in ductility and corrosion resistance.

In designing cast automotive parts it is important, beside chemical composition, to have an intimate knowledge of how the alloy solidifies at different cross sections of the cast part and how this influences mechanical properties. This knowledge enables the designer to ensure that the casting will achieve the desired properties for its intended application. Of the many phenomenons that occur during the solidification of castings, there are four that control structure and consequently mechanical properties: chemical composition, liquid metal treatment, cooling rate and temperature gradient. Among them cooling rate play most significant role. The effect of cooling rate on the structural features of aluminium alloys such as grain size, secondary dendrite arm spacing (SDAS), eutectic silicon structure and the morphology of iron and manganese phases has been investigated by many authors [1-10]. The general consensus from the previous work is that increasing the cooling rate refines the grain size, modifies silicon particles, and decreases SDAS.

The Figure 1 shows that the solidification of cast Al-Si-Cu alloys starts at liquidus temperature with precipitation of primary alpha phase from the liquid. Microstructure of a sample from AlSiCu alloy shows bulky area of α-Al matrix, large needles form of Al-Si eutectic (dark) and AlCu2 eutectic precipitated particles (pink). The lines with arrows indicate the approximated temperatures at which theses phases start to precipitate. Total solidification time of generic AlSiCu alloy is also depicted.

A primary α-aluminium dendrite network forms between 580 - 610°C. The exact temperature depends mainly on the amount of silicon and copper in the alloy. The primary phase grows as solid crystals having dendrite shape. This leads to an increase in the concentration of silicon and copper in the remaining liquid. Between 570-555°C the first temperature plateau on the cooling curve (aluminium – silicon eutectic temperature) can be recognized. Reaching the aluminium-silicon eutectic temperature, the solidification proceeds at constant temperature with the formation of the eutectic solid phase in the space left between dendrite arms. The copper enriched phase, represented by the second plateau start to precipitate (between 525 – 507°C) from the last portion of the melt close by solidus temperature.

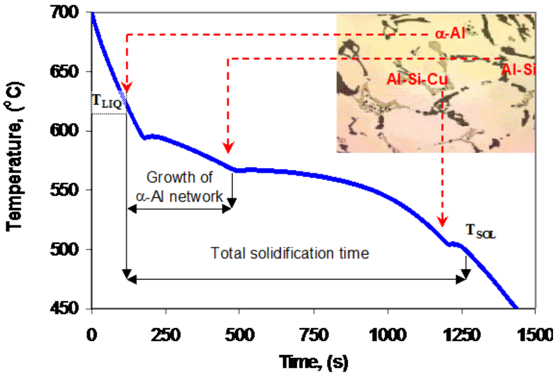


Fig. 1. The cooling curve of AlSiCu alloy with schematically designated areas of typically precipitated phases

As can be seen from Figure 1 solidification of any alloy start at liquidus temperature with undercooling related to the formation of many small crystals-nucleus in the melt. Further cooling of the melt is follows with the precipitation of the primary dendrite network of α-Al crystal. A dendrite is a characteristic three like structure of crystal growing as molten metal freeze. Dendrites normally grow from a single nucleus both forwards (primary) and sideways (secondary) which may be only a few microns in diameter. At the beginning the primary dendrite arm growth until at the given temperature (dendrite coherency temperature) and fraction solid (dendrite coherency fraction) they reach each other. The further development of the α-aluminium dendrite structure is characterized by growth of secondary or even tertiary branches, which grow along preferred crystallographic direction.

Most important practical aspect of the dendrite structure is the SDAS that represents the distance between secondary dendrites in the solidifying structure of cast metals and alloys. This quantity is significant because it has been shown that many mechanical properties can be related to it [1-4, 8, 11, 14, 15], with the best properties always associated with the smallest SDAS. In many ways, SDAS is just a measure of the overall fineness of the cast microstructure. A small value of SDAS implies that the structure is fine, with all of the associated benefits including smaller grains, finer intermetallics, better microhomogeneity and less as well as better distributed porosity. All of these desirable features of the cast structure are responsible for the good mechanical properties associated with small SDAS. As can be seen in Figure 2, there is an inverse relationship between the cooling rate and SDAS (e.g. the higher the cooling rate, the lower the SDAS) [1]. The choose of six alloys give a good indication how various content of alloying elements (especially silicon and copper) effect the size of DAS.

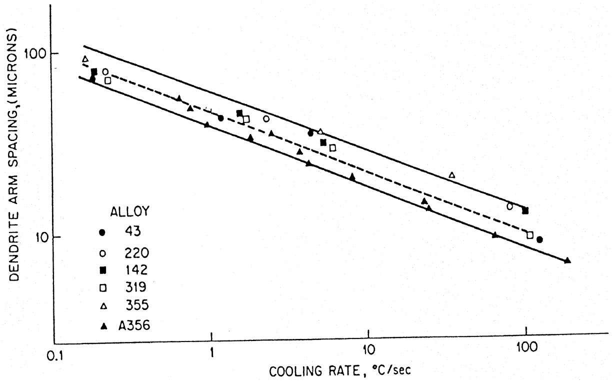


Fig. 2. The effect of average cooling rate on the size of dendrite arm spacing for six aluminium alloys [1]. The data cover a range of cooling rates of three order of magnitude

Spear et.al. [1] in their paper discussed the methods of measuring dendrite microstructure and the effect of solidification rate and alloy composition on the cell size. According to them there is at least three different measurements which may be used to describe dendrite refinement. These measurements are: dendrite arm spacing, dendrite cell size and dendrite cell interval. Dendrite arm spacing is the distance between developed secondary arms, dendrite cell interval is the distance between centre lines of adjacent dendrite cells and dendrite cell size is the width of individual cells. An excellent discussion about the best method of measuring dendrite size is containing in reference 1. The relation between the cooling rate and dendrite size was investigated for six aluminium alloys at various rates. The Figure 2 shows the results of their investigation. As can be seen, the size of the dendrites is strongly affected by the cooling rate. However, the chemical composition of the alloys has also some effect on this structural characteristic. This effect is not easy recognized due to the leading effect of the cooling rate. Unfortunately, the effect of the chemistry on the SDAS has not been extensively investigated in the literature. Recently, Zhang et.al. [4] studied the influence of process parameters such as: chemical composition, cooling rate, mold temperature and pouring temperature on the size of SDAS of cast aluminium cylinder heads. The influence of chemical composition has been analysed using three aluminium alloys AlSi7Mg0.3, AlSi9Cu1Mg0.3 and AlSi7Cu3Mg0.3. They found that various content of silicon and copper have significant effect on the size of SDAS even by high cooling rate. However, both papers did not cover the full range of silicon and copper contents that could be interesting for producers of as cast automotive parts. Therefore, in the present work, the aimed has been made to assess the effect of major alloying elements such as silicon and copper on the size of the SDAS of the Al-Si-Cu series of alloys produced under similar conditions and studied by identical techniques. In order to achieve this the content of the silicon was varied from 1 to 10 wt.% while the content of copper was in the range from 0 to 5 wt,%.

2. Experimental Procedure

2.1. Materials

Eleven synthetic Al-Si compositions were produced at the Nemak casting research and development department. The experiments were performed using Al-Si11 alloy with the trace of Cu, Mg and other elements (for details see alloy 1 in Table 1), that has been diluted by adding certain amount of pure aluminium in order to reach designed content of silicon. The chemical compositions of the resulting alloys with different content of silicon (only major alloying elements are presented, all content in wt.%), as determined using (OES) are presented in Table 1.

Table 1.

Alloy	**Si**	Fe	Cu	Mn	Mg	Zn
1	**10.99**	0.09	0.002	0.04	0.32	0.007
2	**9.71**	0.08	0.001	0.03	0.24	0.006
3	**8.59**	0.10	0.001	0.03	0.24	0.006
4	**7.57**	0.10	0.002	0.03	0.22	0.006
5	**6.97**	0.10	0.002	0.03	0.22	0.007
6	**6.05**	0.11	0.002	0.02	0.21	0.007
7	**4.70**	0.11	0.002	0.02	0.21	0.007
8	**3.72**	0.12	0.002	0.02	0.19	0.009
9	**2.75**	0.12	0.002	0.02	0.18	0.009
10	**2.06**	0.13	0.002	0.02	0.17	0.008
11	**1.30**	0.13	0.002	0.02	0.17	0.009

In order to analyse the effect of various content of copper on the size of the SDAS nein synthetic Al-Si-Cu compositions were produced by melting a charge of Al-6 wt.%Si-0.002 wt.% Cu base alloy (alloy 6 from Table 1 has been used as started alloy). To reach targeted content of copper various amounts of pure copper and Al-Si master alloy are added to the melt. Table 2 shows the chemical composition of the resulting alloys.

Table 2.

Alloy	Si	Fe	**Cu**	Mn	Mg	Zn
1	6.02	0.08	**0.37**	0.002	0.21	0.005
2	6.09	0.08	**0.76**	0.002	0.30	0.005
3	6.19	0.07	**1.42**	0.002	0.27	0.005
4	6.25	0.08	**1.76**	0.002	0.28	0.004
5	6.15	0.07	**2.13**	0.002	0.25	0.005
6	6.07	0.07	**2.23**	0.002	0.26	0.005
7	6.10	0.07	**2.60**	0.002	0.26	0.005
8	6.21	0.07	**3.20**	0.002	0.27	0.005
9	6.17	0.08	**4.71**	0.002	0.25	0.004

2.2. Melting Procedure

Previously prepared samples for each targeted alloys are firstly charged in the ceramic cups, loaded in an electric resistance furnace and melted. During all experiments the melt temperature was kept constant at the 700°C ± 5°C. After melting down, all samples with masses of approximately 80g ± 2g where left to solidified under the same conditions. The thermoelement has been inserted into test sample (alloy 1 from Table 1) in order to determine the cooling rate. The temperature range between liquidus and solidus temperature divided with total solidification time (see Figure 1) has been used to calculate the rate of solidification. The cooling rate for all samples was 0.15°C/sec.

2.3. Metallography

Solidified cylindrical samples are sectioned vertically. One half of the sample has been used for chemical analysis while other half has been used for quantitative measurements of the SDAS. Metallographic samples were prepared by standard grinding and polishing procedures. Zeiss Axiotech light optical microscope has been used in this work for the SDAS measurement. Figure 3 depicted a difference between DAS and SDAS.

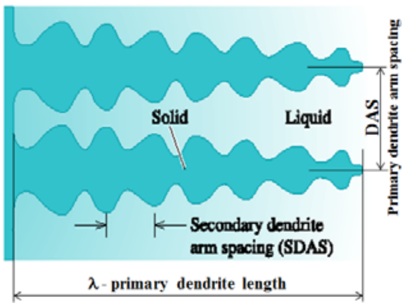


Fig. 3. Schematic representation of dendrites showing the difference between primary and secondary dendrite arm spacing

The SDAS is a measure of the length scale between two adjacent SDAS and it is usually an order of magnitude smaller than the primary arm spacing. In this work the line intercept method was utilized to measure the SDAS. The applied magnification was 25 times. The size of the SDAS has been obtained as a average value of at least 10 measurements.

3. Results and Discussions

AlSiCu alloys constitute one of the commercially important classes of Al alloys. These alloys are extensively used in production of very intricate automotive parts such as engine block and cylinder heads. This usage often requires excellent mechanical properties of those alloys. In order to achieve it the structure of the cast part with very diverse cross sections has to be closely controlled. It is well known that various cooling rates during solidification can lead to variation in the amount and shape of various morphological characteristics of as cast structures, which in turn can lead to different mechanical properties. A well-known effect of varying cooling rates on the size of the SDAS is effusively exploited in the literature [1- 4, 11-14, 17-19]. In addition the effect of alloying elements on the size of the SDAS by aluminium-silicon alloys was not so extensively investigated. Only few researchers [1, 4] have examined the effect of variation in the alloy composition on the size of the SDAS. Generally it has been found that various content of silicon and copper have some effect on the size of the SDAS, although the effect is usually small comparing with that obtained by varying different cooling rate. The present work study the effect of major alloying elements, silicon and copper on the size of the SDAS in the Al-Si-Cu alloys.

3.1. The influence of silicon and copper on the size of the SDAS

The dendrite structure of aluminium alloys is a key microstructural feature, characterized mostly by the primary and secondary arm spacing as it was schematically shown in Figure 3. For the as cast or the heat treated conditions, the fineness of these individual properties is recognized to yield superior mechanical properties to coarser ones [1 - 4, 8, 15, 16]. The influence of various contents of the silicon and copper on the size of the SDAS is presented in Figures 4 and 5. The each point on Figures 4 and 5 correspond to the average value of the SDAS based on the ten measurements. Vertical bars represent the standard deviations for each series of measurements. The higher silicon and copper contents reduced the size of the SDAS. When the content of silicon increase above 8 wt.%, this effect is insignificant; any increase above 3 wt.% of copper refine the dendrite but at a much lower rate. Dependence between the SDAS and silicon or copper content could be expressed by second order polynomial equations with high correlation coefficient.

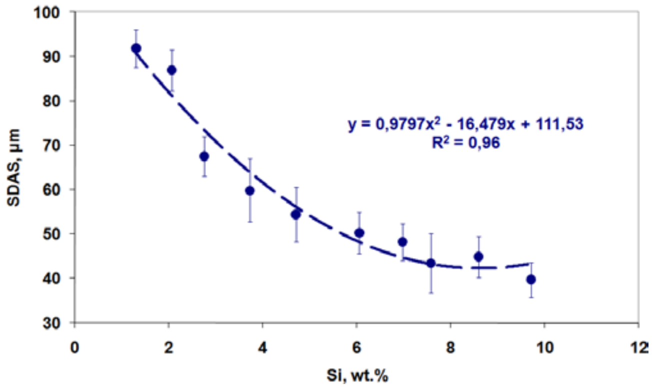


Fig. 4. The effect of the various silicon contents on the size of the SDAS. There is appreciable refining effect as the content of silicon varied between 1 and 8 weight percent

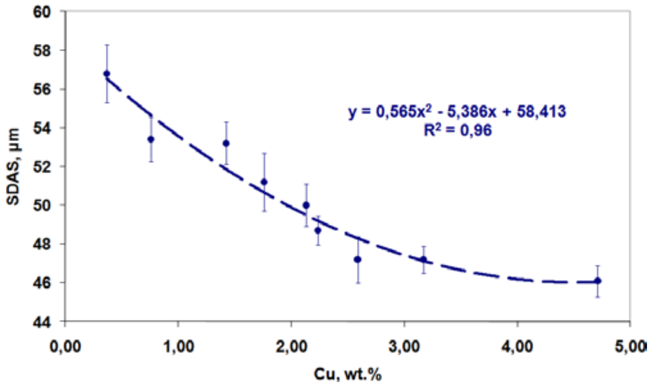


Fig. 5. The effect of the various copper contents on the size of the SDAS. The increases in the copper content from 0 to 3 weight percent refine considerably the size of the SDAS

Microstructural changes that occur with increasing silicon content are shown in Figures 6 (a to e). These micrographs depict the development of a smaller SDAS as silicon content increases. Structure analysis presented in Figures 6 and 7 show that addition of silicon and/or copper decrease the size of the SDAS. Measurement done by image analysis were confirmed that the average size of the SDAS decrease from 91.8 µm to 39.7 µm according to addition of silicon from 1 to 10 wt. % respectively. The effect is more significant until silicon reach the content of 8 wt.%. Further increase in the content of silicon has almost no effect on the size of this microconstituent.

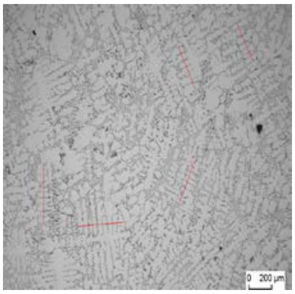
Similar, but considerably smaller effect can be recognized by addition of copper in the AlSiCu melt. The data presented in Figure 5 shows that the size of the SDAS slightly decrease from 56.8 µm to 46.1µm when the content of copper in the AlSiCu melt increase to approximately 4.7 wt.%.

These results are not unexpected. It is well known from the literature [1, 19], that the size of the dendrites is, beside the cooling rate of solidification, dependent on the level of alloying elements present in the melt. During the primary solidification of the aluminium alloys the alloying elements are not evenly distributed between solid and liquid phases. Excess amount of solute displace away from the solidification interface into the melt resulting in the increase in the volume of solute placed between already formed dendrite arms. This supersaturation (or related constitutional undercooling) represent the driving force for the grow of dendrites. The space between α-aluminium dendrite arms must increase to accommodate increasing amount of solute elements. Then higher concentration of alloying element will cause precipitation of finer dendrite and vice versa, dendrite at low concentrations are more spherical in appearance as it was illustrated in Figures 6a, 6e, 7a and 7e.

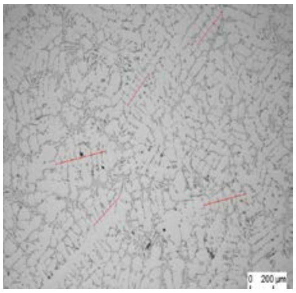
It is also expected that the elements with higher solubility in aluminium melt are less effective in reducing the size of the SDAS. Therefore, the effect of the same content of copper is slightly smaller that of the same content of silicon.

Comparing results from figure 2 with the results presented in Figures 4 and 5, it is evident that the cooling rate has more significant effect on the size of the SDAS compare to the chemical composition of the alloy.

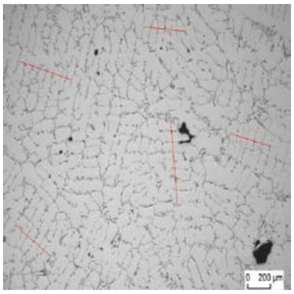
So, by designing some cast product, the effect of the cooling rate on the SDAS has to be firstly considered. At the same time the effect of chemical composition can not be neglect. Especially in the case when the chemical composition of elements defined by customer are given in the broad range. Picking up either the lower (6.0 wt.%) or upper (8.0 wt.%) content of silicon from the AlSi7Mg (356 alloy according to American nomenclature) alloy specification, distinctly change the size of the SDAS in solidified as cast structure for approximately 7 µm. Therefore, the effect of chemistry on the size of the SDAS has to be understood and properly used in order to obtain requested quality of cast products. This effect is getting more important as we are closer to the riser side of our cast product. Consequently, the effect of the chemical composition should be used for fine tuning in order to reach desired size of the SDAS.



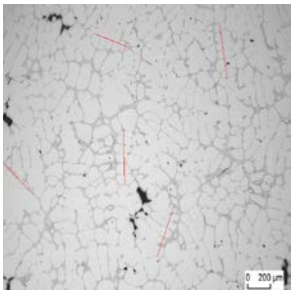
a) Al -10 wt.% Si alloy



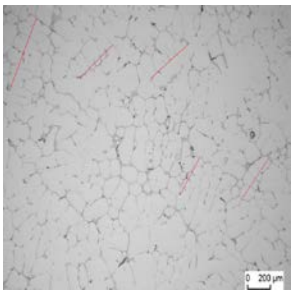
b) Al - 8 wt.% Si alloy



c) Al - 6 wt.% Si alloy

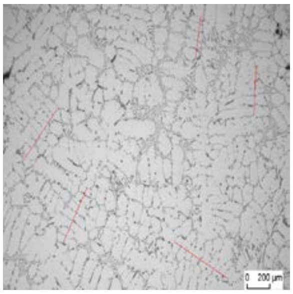


d) Al - 4 wt.% Si alloy

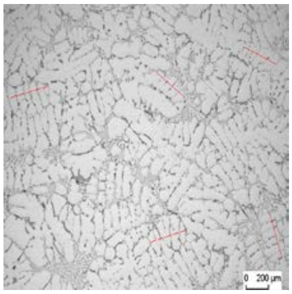


e) Al - 2 wt.% Si alloy

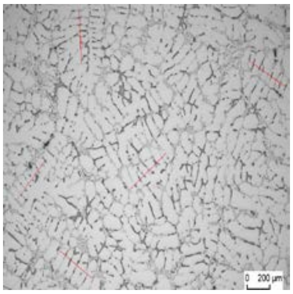
Fig. 6. Light optical micrographs of aluminum-silicon alloys as a function of various content of silicon



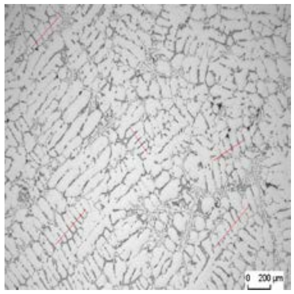
a) Al – Si 6 – Cu 0.76 alloy



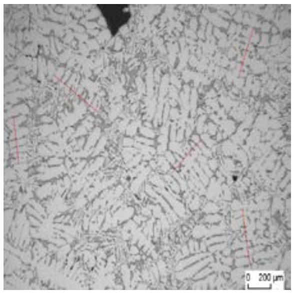
b) Al – Si 6 – Cu 1.76 alloy



c) Al – Si 6 – Cu 2.23 alloy



d) Al – Si 6 – Cu 3.20 alloy



e) Al – Si 6 – Cu 4.71 alloy

Fig. 7. Optical micrographs showing the effect of various content of copper (wt.%) in Al-Si-Cu alloys on the size of the SDAS

4. Conclusions

Experiments have been carried out to observe the effect of silicon additions between 1.3 and 9.7 wt.% and copper additions between 0.37 and 4.7 wt.% on the size of the secondary dendrite arm spacing (SDAS) in Al-Si-Cu alloys. It was found that addition of silicon and copper reduce slightly the size of SDAS comparing to the effect of the cooling rate but still not so insignificant that they influence can be ignore. This decrease in the size of the SDAS seems to correlate well with a formation of a large volume of solute during solidification of the aluminium alloys with high content of silicon and copper. The obtained results are in agreement with the available literature data.

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