Effect of Grain Refinement on the Fluidity of Two Commercial Al-Si Foundry Alloys

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The effect of grain refinement on the fluidity of AlSi7Mg and AlSi11Mg has been investigated by spiral tests. Two different types of grain refiners have been evaluated. An A1Ti5B1 master alloy was added to different Ti contents. Since the commercial alloys had a high initial content of titanium, model alloys were made to investigate the fluidity at low grain refiner additions. Commercial alloys grain refined only by boron additions have also been investigated. The results from the fluidity measurements have been verified by measuring the dendrite coherency point of the different cast alloys. Although different, the two methods show similar trends. The spirals from each fraction grain refiner cast were subsequently investigated metallographically at the tip of the spirals and at a reference point a distance behind, but no obvious difference in structure was observed. For both alloys, an increase in fluidity is observed as the content of grain refiner increases above 0.12 pct Ti, while the fluidity is impaired with increased grain refinement below 0.12 pct Ti. The alloys grain refined with ~0.015 pct B show the highest fraction solid at dendrite coherency, the smallest grain size, and the best fluidity.

1. INTRODUCTION

During solidification of a solute-rich aluminum foundry alloy, equiaxed dendrites start to grow into the undercooled liquid. In the first stages, these dendrites can grow relatively independently of each other, but after a certain range of growth, depending on dendrite growth rate and grain density, the primary dendrite tips impinge onto the neighboring dendrites. This is identified as the dendrite coherency point, the point at which a more or less continuous three-dimensional dendrite network is formed in the semi-solid material. Previous work [7-15] has shown that several parameters affect the point where the dendrite network is formed, and dendrite coherency is expected to have significant influence on the castability of these alloys.

The castability is an important feature of all aluminum foundry alloys, restricting the applicability of the alloys for casting purposes. Castability is a wide concept including characteristics such as form-filling ability, fluidity, hot-tearing susceptibility, and feeding behavior. One of the important factors that may limit the quality of a casting is the ability of the liquid alloy to flow and fill the mold pattern as cooling and solidification progress. Fluidity is empirically defined as the length the metal flows in a channel with a small cross-sectional area, while solidifying. Fluid flow is also important with respect to feeding, i.e., material transport to compensate for shrinkage. Therefore, some relationship between fluidity and feeding is expected since both depend on the ability of the melt to flow during solidification. The solidification mode, morphology, and rate and the grain density are important, determining the size and irregularity of the developing solid, which, combined with the strength and physical properties of the material, define the point of flow inhibition in these channels. Two well-known test methods to investigate the fluidity are the spiral test, often in sand molds, and the vacuum-fluidity test, in glass tubes.

Many other parameters have been identified to affect the fluidity and feeding capability of aluminum alloys. Among these are melt superheat, temperature gradients, latent heat, alloy composition, eutectic modification, and grain refinement. The formal definition of fluidity is the inverse of viscosity, but it has come to reach another meaning in casting terminology. In fact, casting fluidity is independent of the viscosity of the liquid, according to the work by Bastien et al. This indicates that interdendritic fluid flow is of low significance in the fluidity test and that the length of flow is determined by the earlier stages of solidification. However, a mixture viscosity characterizing the suspension of crystals and melt may be more significant with respect to fluidity.

Fluidity is a complex parameter that is affected by the properties of the metal and the mold and the pouring conditions, the solidification condition being the underlying controlling factor. Flemings predicted that the mechanism by which the flow is stopped changes as the solidification mode is altered. Pure metals and dilute alloys solidify with a smooth, compact growth front, continuously tapering the central flow channel. The flow is stopped somewhere behind the flow tip, where the growth fronts meet and obstruct the flow path, closing the channel entrance.

Solute-rich alloys, on the other hand, solidify in a mushy manner. Here, equiaxed dendrites are expected to be nucleated at and transported by the flow tip. These dendrites finally stop the flow when they reach a critical fraction solid. Fluidity is expected to level off, or even increase slightly, with increasing alloy content. Pai and Jones showed that solidification in the flow tips stops the flow in mushy freezing alloys and confirmed that extensive inter-
locking and bridging between the dendrites near the tip takes place. The mold acts as a perfect heat sink during flow, since the flow tip is continuously exposed to a cold mold channel during its advancement. Campbell[15] also noted that the semisolid mixture at the tip stops flowing at the fraction solid where the dendrites impinge, giving a significant increase of viscosity of the slurry. Flemings et al.[1] calculated the critical fraction solid for a fluidity test vs pressure head and found that it increases with increasing pressure head, converging toward about 35 pct solid.

The relationship between this mechanism of flow stoppage and dendritic coherency is obvious; in fact, it is dendrite coherency–network establishment. This suggests that alloys solidifying with an equiaxed structure should be expected to exhibit a firm relationship between dendrite coherency and fluidity.

Lang[9] has measured the effect of increasing the silicon content in binary Al-Si alloys with a bar casting. Figure 1 illustrates the results. From the figure, it is observed that fluidity decreases in the range of solid solubility and increases slowly as fraction eutectic increases. This can also be interpreted as a confirmation of the contribution from interdendritic flow to the fluidity being relatively small. A curious feature is that maximum fluidity lies in the hyper-eutectic region, around 18 to 19 pct Si and not at the eutectic composition as for other systems, e.g., Al-Mg.[9] This effect is partly described by an enthalpy consideration, i.e., $H_{Si} > H_{Al}$.[7]
Grain refinement of aluminum alloys, usually achieved by additions of master alloys based on Al-Ti or Al-Ti-B, often improves the mechanical properties and porosity distribution of the final product. A new method to effectively grain refine Al-Si foundry alloys has recently been introduced, showing important and commercially attractive characteristics, such as no fading (reduced grain refining efficiency with time). The essence of this method is that boron is added as a silicon-based master alloy containing about 1 to 2 wt pct boron. Since the solid solubility of boron in silicon is about 1 wt pct, dissolving the addition is expected to give a uniform dispersion of boron in the liquid. Only a small amount of boron is necessary to give a small grain size. The method is being introduced commercially under the brand name SiBloy, trademark of Elkem Aluminum ANS, Oslo, Norway.

Although the method of grain refinement has been known for decades, its influence on the castability has still not been established, possibly because test methods affect experimental results. Loper and Loper and Prucha state that adding grain refiners containing Ti reduces the fluidity of Al-Si casting alloys, although experimental confirmation of this statement is missing. Mollard et al. reports a reduction in fluidity of an Al-4.5 pct Cu alloy when adding 0.15 pct Ti using a vacuum fluidity test apparatus. Lang, on the other hand, expected an increase in fluidity when grain refining agents were present because of the reduced possibility of growing large dendrites. Lang also measured a significant increase in fluidity with boron additions in the range of 0.04 to 0.07 pct to Al-Si alloys, tested with a bar casting. Alsem et al. took a different approach to measuring fluidity, using a mold shaped like a tuning fork. An addition of 0.04 pct Ti as AlTiSB1 to an AlSi7 alloy gave a considerable increase in the shortest running lengths, as compared to the alloy without additions. The other lengths were reported to be unchanged.

This article presents an experimental investigation of the effects of grain refining additions on dendrite coherency and fluidity and is a first step in investigating the correlation between dendrite coherency and castability of aluminum alloys. Although the solidification conditions during spiral testing are quite different from those of dendrite coherency measurements, especially with respect to fluid flow and cooling conditions, the underlying solidification mechanisms are expected to be crucial.

The objective of this experimental work consist of two
II. EXPERIMENTAL

A. The Experimental Alloys

Two hypoeutectic Al-Si alloys, AlSi7Mg and AlSi11Mg, have been investigated in this study. The AlSi7Mg alloy is very similar in composition to a 357-type alloy in the alloy designation system of the Aluminum Association.[21] Table I gives the content of the major alloy elements in all base alloys investigated.

The basis of this investigation was two commercial alloys (C), supplied by Fundo a.s., Hoyanger, Norway. Three grain refiner additions (AlTi5B1) were investigated: 0, 0.05, and 0.12 pct Ti, giving total titanium contents of 0.12, 0.17, and 0.32 wt pct. Due to the relatively high initial content of titanium in the commercial alloys, Ti-free model alloys (M) with similar nominal compositions were made. In these alloys, three grain refiner additions were investigated: 0, 0.05, and 0.12 pct Ti, the final composition of the model alloy being similar to that of the initial commercial alloy.

In addition to investigating the effect of grain refining by the AlTi5B1 master alloy, alloys grain refined with boron (B) were studied. These alloys were supplied by Elkem Aluminum ANS, and no extra additions were necessary since boron was added during the industrial production.

B. Test Apparatus and Procedure for Fluidity Measurements

The spirals were molded in quartz sand, with a gating system developed to minimize problems with entrapped gas in composite materials.[19] Figure 2 shows the mold design. The gating system consists of a pouring cup, a rectangular tapered sprue, a runner, an open riser, and a choke. The riser is intended to trap bubbles formed by turbulence during filling of the mold, before they enter the spirals. The two archimedian spirals, each with a cross section of $4 \times 10$ (mm), consisted of 3.5 turns, giving a maximum running length of 120 cm each. Both of the spiral ends were vented. The running length was defined as the length of the spiral from the tip to the riser.

The alloys were melted in an induction furnace. Alloy additions were made directly to the melt, and the contact time for the AlTi5B1 grain refiner was 30 minutes. The melt was poured when the contact time was reached and the temperature was correct. Three double spirals were cast for each alloy, i.e., a total of six spirals for each heat. The maximum temperature was measured with a digital thermometer located in the pouring cups of the first and last molds during pouring. The experiments were performed at a superheat of about 75 °C, relative to the equilibrium liquidus, giving pouring temperatures of 700 °C and 670 °C for AlSi7Mg and AlSi11Mg, respectively.

C. Determination of the Dendrite Coherency Point

Small pieces (1 to 2 kg) of the alloy ingots were separately melted and stabilized at 750 °C to 800 °C in a resistance furnace. Except for the alloys grain refined with boron only, grain refinement was achieved by adding an AlTi5B1 master alloy followed by vigorous stirring using a graphite rod. The contact time for the first sample was 30 minutes. Two minutes before sampling, the melt was stirred for approximately 30 seconds.

Two experimental techniques have been used to determine the dendrite coherency point: rheological measurements and thermal analysis.

For the rheological measurements, a sample of the melt was transferred from the holding furnace to the preheated graphite crucible in the rheological setup. The experimental setup is shown in Figure 3. The thermocouple adjacent to the wall and the boron-nitride covered paddle-type steel stirrer in the center were immersed 1 cm into the melt, as shown in the figure. When the temperature had stabilized, the furnace was removed, and the crucible was cooled naturally in air. At a temperature of about 700 °C, the rheometer and paddle were started, with a rotation speed of 0.05 rpm. The temperature and torque values were collected simultaneously by a computer. The dendrite coherency point was identified as the fraction solid where the torque increased sharply.[13,14]

For thermal analysis, a preheated graphite crucible was filled by immersing it into the melt. The crucible with specimen was placed on an 8-mm-thick FIBERFRAX® felt, and two thermocouples were placed in the melt, 1 cm above the bottom, one close to the wall and the other at the center.

![FIBERFRAX](https://example.com/fiberfrax.png) is a trademark of Standard Oil Engineered Materials Co., Niagara Falls, NY.
of the crucible. The thermocouples of type K (alumel-chromel), covered with a thin layer of boron-nitride to prevent reactions with the melt, were calibrated against high-purity aluminum (99.998 pct) with a melting temperature defined to 660 °C. The temperatures were monitored with a computer via amplifiers and an A/D converter. This arrangement gave a precision of ±0.7 K in the temperature measurements. The dendrite coherency point was identified by the first minimum in the difference between the temperatures at the wall and in the center after nucleation.[320]

In both experiments, a FIBERFRAX lid was placed on top of the crucibles to reduce heat loss from the melt surface. This setup gave a cooling rate of about 1 K/s just before the start of solidification. All experiments were reproduced at least three times with a new melt sample. The fraction solid was calculated from the temperature measurements using a procedure developed by Tamminen.[290]

D. Metallographical Investigation

Metallographic samples were made at similar experimental conditions as in the coherency measurements. All sam-
pies were anodized, and grain sizes were measured with the linear intercept method in an optical microscope. Samples from the cast spirals were cut for metallographic investigation, as shown in Figure 4.

### III. EXPERIMENTAL RESULTS

#### A. The AlSi7Mg Alloys

Figure 5 shows the coherency parameters for the AlSi7Mg alloys as a function of the content of titanium, with an extra point for the boron-refined alloy. As may be observed in the figure, increasing the grain refinement, i.e., increasing the grain density, gives a decrease in grain size and an increase in fraction solid at dendrite coherency ($f_{coh}$) determined by rheology and thermal analysis. The alloy grain refined with boron only has the smallest grain size and the highest fraction solid at dendrite coherency.

Figure 6 shows the change in running length with increasing grain refinement in the AlSi7Mg alloys. The temperature indicated for each fraction of grain refiner is the average of the temperatures recorded in the first and the last pouring cups. Table II summarizes the fluidity results for the AlSi7Mg alloys. The results indicate that the running length is reduced with increasing Ti content below 0.12 pct Ti, whereas an improvement in fluidity is observed with grain refinement above this limit. The alloy grain refined with boron has a significantly larger running length than all other alloys.

Figures 7(a) through (f) show the micrographs from the center of the spiral tips and at a position 20 cm from the riser for the commercial AlSi7Mg alloys, with 0, 0.05, and 0.20 pct Ti added, respectively. There are no significant differences between the samples with increased grain refinement; i.e., the grain size is relatively constant. A somewhat finer structure can be observed at the spiral tip, probably because the tip has a higher cooling rate.

#### B. The AlSi11Mg Alloys

Figure 8 shows the effect of grain refinement on the coherency parameters of the AlSi11Mg alloys. The same trends as observed in Figure 5 are evident, but the reduction of grain size is much larger and the fraction solid at dendrite coherency less for AlSi11Mg than for AlSi7Mg.

Figure 9 shows the effect of grain refinement on the running length of the AlSi11Mg alloys. The temperature is again the average of the pouring temperatures. As may be observed in the figure, increasing the content of titanium by adding grain refiner clearly increases the running length of the material. The alloy grain refined with boron has the best fluidity of all alloys. Table III summarizes these results and the length of each spiral.

In both the AlSi7Mg and the AlSi11Mg alloy, the individual difference between the two spiral lengths in the double-spiral mold was calculated to be 1 to 1.5 cm on average.

When comparing the results in Figures 6 and 9, it is observed that the running length of AlSi11Mg is larger than for AlSi7Mg, confirming the observations by Lang[9] in Figure 1.

In both Figures 6 and 9, a difference in behavior is observed at 0.12 pct titanium. The initial Ti content of the commercial alloy was at this level, and the last grain refinement addition brought the model alloy to 0.12 pct titanium. The observed difference may be explained by the fact that commercial AlTi5B1 grain refiners lose some of their performance upon remelting, due to settling and agglomeration of TiB₂ nucleants. At 0.12 pct Ti, the largest running length and the highest fraction solid at dendrite coherency belong to the model alloy. This can also be interpreted as an indication of the effect of grain refinement on fluidity, i.e., effective grain refinement increasing the running length. These considerations are confirmed by Tables II and III. Figure 8 shows that the alloy grain refined with boron reaches dendrite coherency significantly later and has a smaller grain size than all the other alloys. The
fluidity of this alloy is considerably better, as shown in Figure 9.

**IV. DISCUSSION**

Addition of grain refiners decreases the grain size. The cooling rate also has a strong effect upon the final grain size. When the cooling rate is increased, larger undercooling may be achieved, which can accelerate the nucleation rate, resulting in a reduced grain size. These considerations apply when the coherency experiments and the spiral tests are compared. In the spiral test, the spiral tip is continuously exposed to the cold mold channel at room temperature as it flows, producing a high cooling rate and melt undercooling, due to the small cross-sectional area. In the coherency experiments, on the other hand, the cooling rate is about 1 K/s, which is probably much lower than that experienced by the tips of the spirals. This implies that the differences in grain size effected by grain refinement are less profound at the higher undercoolings in the spirals. The cooling rate also influences the dendrite coherency point, since the large dendrite growth rate obtained at a high cooling rate makes the dendrites impinge earlier, decreasing the fraction solid at dendrite coherency.1,4

The effect of material flow and deformation is also very important to the development of microstructure in the spirals. The solid microstructure starts to develop as soon as the liquidus temperature is reached and continues as the material flows along the spiral channel. This must ultimately lead to significant stresses being imposed upon the growing dendrites as they move and interact with each other. Fragmentation and deformation of the dendrites result from mutual mechanical contacts and by remelting because of the turbulent flow. As the dendrites become coherent, two things can be pictured. The dendrite network which forms may be strong and stiff enough to resist the imposed stresses, thereby stopping further macroscopic flow. Alternatively, the dendrite network may be deformed by the flow pressure.

As has been shown here and in the literature,1-4 the dendrite coherency point is affected by several parameters. As an example, the development of a coherent dendrite network by grain impingement is postponed if the alloy is well grain refined and/or is slowly cooled. Of course, the structure and morphology at the dendrite coherency point are also very different, depending on when the network was established. An early coherency point can usually be related to a highly branched structure, suggesting very weak and thin dendrite interconnections, while a late coherency point is related to a more globular structure with broader contact areas between the dendrites and only small interdendritic areas.

The micrographs in Figure 7 show that there are no characteristic, observable structural differences in the spirals with increasing grain refinement. The results clearly show that the running length is increased with increasing grain refinement without giving any obvious change in structure after the end of solidification. A very likely explanation of this tendency is the effect of fragmentation and network breakage. Breaking the dendrite network requires some stress, which ultimately leads to energy dissipation, reducing the driving force for material transport. This mechanism for material transport is termed "burst feeding."15

Since the structure becomes more globular with increased grain refinement, the likelihood of fragmentation decreases. In the non-grain-refined alloy, the structure is highly branched, especially at high growth rates and when fluid flow alters the diffusion fields ahead of the growing dendrite tips.

Another factor which is also important is how the strength develops when the dendrite network is established, i.e., if it increases slowly or rapidly. A slower increase in strength in AlSi11Mg compared to AlSi7Mg provides an explanation of the slightly higher fluidity reported for AlSi11Mg. This effect can be explained by the higher heat of crystallization liberated during solidification of the AlSi11Mg alloy, due to the higher silicon content, which can lead to softening and partial remelting of the dendrite network, as has been observed by Chai.3 The difference in latent heat between AlSi7Mg and AlSi11Mg is in the range of about 50 J/g (13 pct). In addition, the dendrites are longer, thinner, and more branched in the case of AlSi11Mg. Therefore, the coherent network of the AlSi11Mg alloy is susceptible to shearing, which helps to explain the longer spiral length.

The effect of pouring temperature also has to be considered when evaluating fluidity. In Figure 6, for AlSi7Mg, and in Figure 9, for AlSi11Mg, the average pouring temperature for each grain refiner content has been plotted. Kolsgaard19 has reported that a 10 °C increase in pouring temperature increases the running length of AlSi7Mg by 7 cm, for the identical spiral mold. This is a very important factor, being about 15 pct of the experimental running lengths and even larger than most of the measured changes with grain refining additions. In Figures 10(a) and (b), the temperature-adjusted running lengths are shown for the AlSi7Mg and AlSi11Mg alloys, respectively, where the identical temperature correction was assumed for the AlSi11Mg alloy. Although this correction is only an approximation, it gives an idea of the influence of the pouring
temperature. From both Figures 10(a) and (b), it can be observed that the fluidity is somewhat reduced up to a titanium content of 0.12 pct, but an increase of the titanium content above this limit, or grain refinement with ~0.015 pct B, increases the fluidity. There seems to be a transition at around 0.12 pct Ti. If the results in Figure 10 are compared to the coherency results for the alloys, in Figures 5 and 8, a relationship between dendrite coherency and fluidity is observed above 0.12 pct Ti for both alloys. An increased fraction solid at dendrite coherency corresponds directly to increased fluidity. Below 0.12 pct Ti, the tendencies are opposite, i.e., postponed coherency and reduced running length. No satisfactory explanation of this relationship is known, but it might be structurally and morphologically related, changing the shear strength of the developing solid network.

The liquidus temperature of the alloys might also have an influence on the fluidity. Grain refinement is related to an increase in nucleation (or liquidus) temperature, which means that the material starts to solidify at a higher temperature. This temperature increase is in the range of about 3 °C to 5 °C, depending on the amount and type of grain refiner, and corresponds to an increase in running length of about 2 to 3 cm. It may be concluded that the pouring temperature has a much stronger effect on fluidity than grain refinement in the spiral test. However, casting of thin-walled sections may be expected to be improved by efficient grain refinement.

As mentioned in Section I, Mollard et al. reported a decrease in fluidity with an addition of 0.17 pct Ti to an AlCu4.5 alloy. As shown by Hoefs et al., grain refinement of AlCu4 by addition of AlTi5B1 only produces a small reduction in grain size, and the initial grain size is comparatively much smaller than in AlSi7Mg (about half) and AlSi11 (about one-third) alloys. The small change in grain size and the very globular structure in AlCu4.5 compared to the AlSiMg alloys provide an explanation of this disagreement, because the coherency and strength of the network do not change significantly for the AlCu alloys.

The effects of the oxide skin and dissolved hydrogen on the fluidity are uncertain. The strength of the oxide skin enclosing the leading tip of the flowing stream is a factor that may restrict the movement of the material, since the energy barrier to break this skin has to be exceeded for flow to continue. In the spiral test, the driving pressure for flow is high, giving a relatively high flow rate of the metal. This pressure could also influence the liberation of dissolved gas from the liquid during solidification. During pouring and filling of the molds, oxidation of the metal will take place and the oxides will be mixed with the flowing stream. In this way, nuclei for gas bubbles are present and become active as soon as the pressure barrier for nucleation is exceeded. As soon as gas bubbles are formed in the material, the driving pressure for flow may be reduced by an amount corresponding to the back pressure from the bubbles. This is an effect which is difficult to evaluate, since the gas contents of the materials were not measured. No systematic investigations of the effect of dissolved gas on fluidity have been reported in the literature, but a reduction would be expected.

V. CONCLUSIONS

Increasing the grain refinement postpones dendrite coherency and reduces grain size. The dendrites impinge at a higher fraction solid. However, the fluidity does not show a unique relationship to grain refinement in the alloys investigated, AlSi7Mg and AlSi11Mg. Grain refinement additions with an AlTi5B1 master alloy indicate a transition point at 0.12 wt pct Ti. Above this level, fluidity is im-
proved with grain refinement, whereas it is impaired with titanium additions below 0.12 pct Ti.

A1Si7Mg and A1Si11Mg alloys grain refined with boron show superior properties compared with those grain refined with AlTi5B1, since they have a significantly higher fraction solid at dendrite coherency, a smaller grain size, and a better fluidity. Some of the changes in fluidity observed with grain refinement can be related to the developing rheological properties of the material, such as coherency and strength, and to the increase in liquidus temperature with grain refinement, reducing the melt superheat.

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