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INVESTIGATION OF THE DENDRITE COHERENCY POINT IN SOLIDIFYING Al-Si FOUNDRY ALLOYS.

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Abstract

The dendrite coherency point, the fraction solid (f_s) at which the growing equiaxed dendrites begin to interact mechanically, has been determined in two commercial Al-Si-Mg alloys and a model alloy by rheological measurements and thermal analysis. At this point the semi-solid mixture starts behaving mechanically more like a solid, and defect generation, such as hot tearing, macrosegregation and porosity, is often assumed to commence after this point. The effects of adding grain refiner, of modifying the eutectic by addition of strontium to the melt, and of increasing the cooling rate have been investigated. It was found that a decrease in the cooling rate and the addition of grain refiner significantly increased the coherency point of the alloys tested. Addition of strontium appeared to reduce the grain size slightly, which led to a slightly higher f_s at the coherency point. Addition of Fe to the model alloys does not change the coherency point appreciably, but addition of Mg appears to increase the f_s associated with dendritic coherency. The addition of grain refiner increases the coherency point for both the Al-7% Si and Al-11% Si alloys, but appears to be more effective at increasing the coherency point of the 7% Si alloy than the 11% Si alloy. The results indicate that grain size, dendritic growth rate and constitutional supercooling correlates with the measurements of dendrite coherency.

Introduction

Foundrymen desire light metal alloys that produce consistently sound castings. However, determining the castability of an alloy remains part art and part science. There are potentially many factors besides the alloying elements that influence the soundness of a commercial casting, including melt superheat, cooling rate, gas content, condition and design of the mould, and temperature of the mould. The current research is an effort to investigate and characterize the castability of an alloy based on measurements that can be easily performed in the laboratory. The coherency is defined as the fraction of the melt solidified (f_s) when the tips of the dendritic crystals in the melt begin to impinge upon each other. At this point the dendrites interact both mechanically and thermally by forming an increasingly interconnected dendritic network. Depending on the shear strength of this network, the solid will become stationary, forcing the liquid melt to flow through the porous structure in order to feed the solidification shrinkage expected during solidification of most commercial aluminium alloys. It is not difficult to understand the significance of a low f_s at coherency. The feeding of certain regions of the casting may become problematic, leading to porosity problems, if the applied pressure or hydrostatic head is insufficient to force the melt through the interdendritic network[1]. Changes in the heat and mass transfer may also lead to hot tearing with a decreasing coherency point[2]. Therefore, the

coherency point may be an important indicator of alloy castability. Finally, the dendrite coherency point can be determined accurately by simple laboratory experiments[3-6]. The technique has been applied here to deteremine the effect of cooling rate, grain refinement, modification by Sr and alloying of two important Al-Si foundry alloys.

Experimental procedures

The commercial alloys were provided by Fundo a.s. An Al-10% Sr master alloy was added to the commercial alloys to modify the eutectic microstructure. A commercial 5:1 Al-Ti-B master alloy was used to promote grain refinement. The contact time was 30 minutes and the melt was stirred for 10-15 seconds two minutes prior to pouring the test samples.

The model alloys started with pure (99.995%) aluminium. Commercially pure silicon and magnesium and an Al-7.5% Fe master alloy were added as alloying additions. Two base model alloys were created by adding silicon to pure aluminium. The Al-7% Si and Al-11% Si model alloys were further alloyed by successively adding 0.14% Fe, 0.20% Mg, 0.05% Ti and 0.12% Ti to the Al-7% Si model alloy and 0.14% Fe, 0.16% Mg, 0.06% Ti and 0.15% Ti to the Al-11% Si model alloy. The amount of the alloying additions were chosen to reproduce the compositions of the commercial alloys.

Coherency Measurements

The coherency point for each of the test samples was determined using both rheological measurements and thermal analysis. Figure 1 shows the configuration used to measure the coherency point rheologically. A preheated graphite crucible is filled with the melt sample and fixed on a test stand within a resistance furnace. A calibrated type K thermocouple and a preheated steel stirring paddle were both immersed 1 cm into the melt. The stirring paddle is attached to a rheometer that rotates at 0.05 rpm. Both the rheological and temperature data were collected by a computer for later analysis. Three different cooling rates were obtained by cooling the sample within the furnace (0.3 K/s), by removing the furnace from around the sample and cooling in air (0.7 K/s) and by blowing pressurized air onto the crucible (3.0 K/s). The rheological coherency point was determined graphically by examining a graph of the change in the torque measurement with fraction solid (dTq/df_s, where Tq is the measured torque) vs. f_s. The f_s was calculated by analyzing the temperature data using a computer program developed by Tamminen[5].

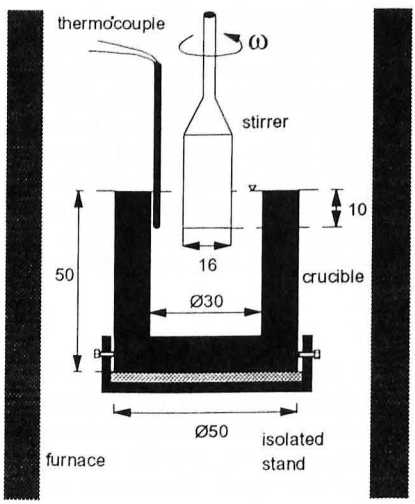

Figure 1. Schematic illustration of the rheological setup.

The thermal analysis used two thermocouples, one in the center (T_c) and one adjacent to the wall of the crucible (T_w). The procedure is exactly identical to the method developed by Bäckerud

et.al.[7]. The minimum of T_w-T_c vs. f_s is identified as the coherency point, as described by Tamminen[5]. Both thermal analysis and rheological measurements was repeated three times each with a new melt sample. The final rheological and thermal coherency points are an average of the coherency points obtained for each of the three tests.

Metallography

The grain size for each of the alloys studied were obtained by casting samples under identical experimental conditions as were used during the thermal analysis. The samples were sectioned at the same depth as the thermocouples were immersed, anodized in an electrolyte [7] and viewed under an optical microscope. The linear intercept method was used to measure the grain size.

Results and discussion

Two commercial foundry alloys, with 7 and 11 % Si, were the basis of this investigation, which was further extended to include model alloys with lower levels of impurities. The effect of grain refinement, cooling rate, trace elements and eutectic modification have been explored.

Table I shows the main constituents from the chemical analysis of the two commercial alloys. The commercial 7% Si-alloy is similiar to a 356-type alloy. As shown in the table, both alloys initially contained some titanium (~0.12%). This must be taken into consideration when experimental results are evaluated.

Table I. Main constituents of the commercial alloys [wt%]

Sample	Si	Fe	Mg	Ti
Al-7%Si	6.80	0.15	0.174	0.129
Al-11%Si	11.20	0.13	0.172	0.117

Figure 2 shows a comparison of the coherency results from rheological measurements and thermal analysis, in addition to measured grain size, as a function of the content of grain refiner in the two commercial alloys. The grain size shows the expected decrease when the content of grain refiner increases, with a corresponding general trend that fraction solid at the coherency point increases. The curve from rheological measurements of the Al-7%Si alloy has a maximum at 0.05% Ti, which is difficult to interprete. Increasing grain refining implies that a larger number of grains are nucleated and grow at a lower rate. This occurs when the partitioned elements cause a reduced growth rate, because the impurities pile-up in the diffusion layers ahead of the growing dendrite tips. More segregation is also the explanation to the earlier coherency in Al-11%Si than in Al-7%Si [8]. The equiaxed dendrites in a grain refined alloy nucleates and grow at a lower undercooling with a corresponding lower growth rate and larger tip radius than in the unrefined alloy, with the surroundings more saturated in most alloy elements. The tips will hereby impinge at a later stage of growth, which corresponds to a postponed coherency point. More abrupt increase in fraction solid at coherency are observed for the first titanium additions than for the next. As is noticed in figure 2, rheological measurements and thermal analysis experiments do not give the same fraction solid at the coherency point, although they are close and show similiar trends. Difference in measuring technique and critical conditions might provide an explanation. In rheological measurements mechanical strength, through friction between the grains, is the physical critical condition, whereas in thermal analysis increased heat flow, conduction vs. convection, is the main issue. Figure 3 shows the structural differences between not-grain refined

and grain refined (with 0.20% Ti) Al-7% Si.

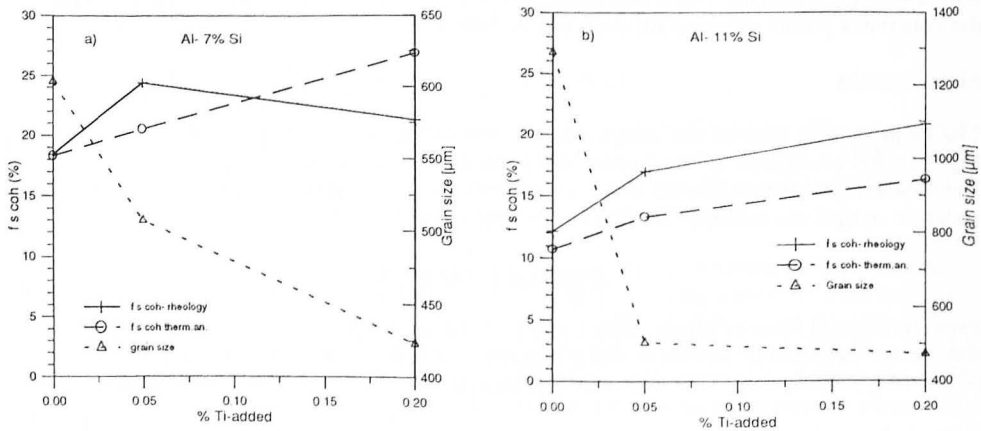

Figure 2. Effect of grain refinement on the coherency point, measured by thermal analysis and rheology, and grain size in a) Commercial Al-7%Si and b) Commercial Al-11%Si. [0.7 K/s]

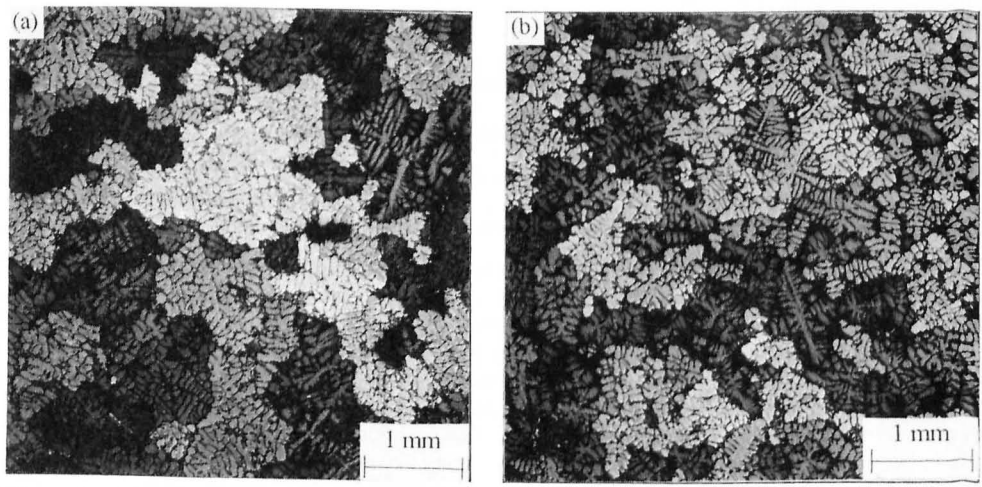

Figure 3. Micrographs showing the effect of grain refinement in commercial Al- 7% Si. a) not grain refined and b) grain refined with 0.20% Ti.

Figure 4 shows the effect of cooling rate on dendritic coherency in the commercial alloys. In both alloys an increase in cooling rate gives a decrease in the grain size and an earlier coherency point. Increasing the cooling rate increases both the grain density and the dendritic growth rate. This effect is explained by an increase in melt undercooling resulting in activation of more numerous nuclei, and that the growth rate of the primary equiaxed dendrites essentially is controlled by the imposed undercooling and heat flow. The increase in the dendritic growth rate appears to dominate over the reduction in grain size, which explains the decrease in fraction solid at coherency with increasing cooling rate. Differences between the 7% Si and 11% Si alloys are

largely due to the difference in constitutional conditions arising from the growth restriction from Si and a smaller freezing range, which reduces the effect of the cooling rate and the power of the grain refiner in Al- 11% Si. Figure 5 shows examples of the structural changes experienced when cooling rate is increased.

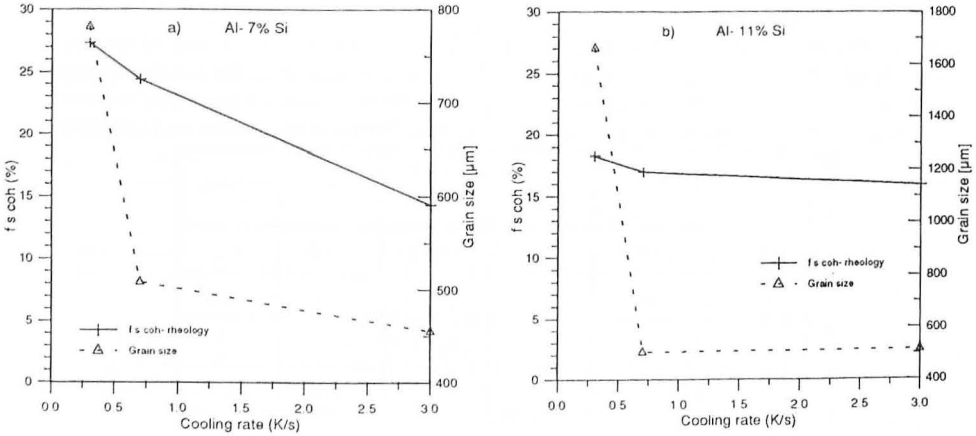

Figure 4. Effect of cooling rate on dendrite coherency, determined rheologically, and grain size in a) Commercial Al-7%Si-0.05%Ti and b) Commercial Al-11%Si-0.05%Ti.

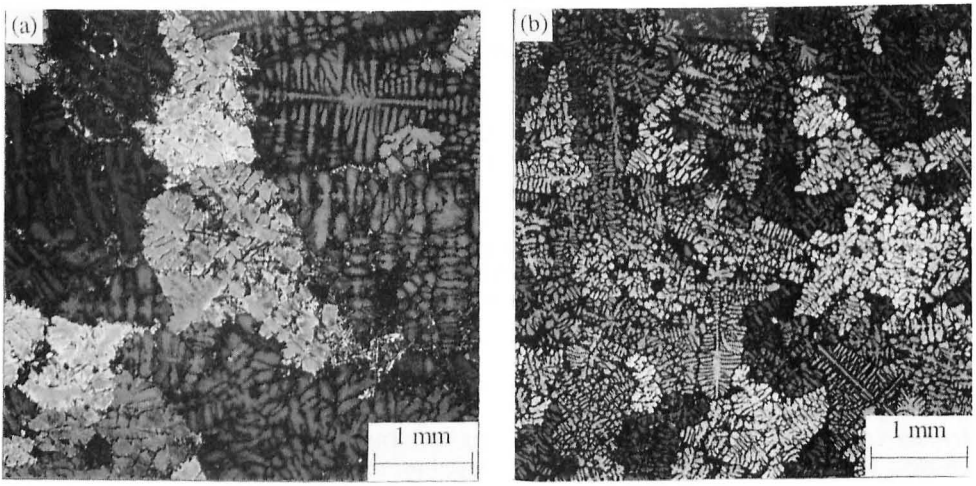

Figure 5. Micrographs showing the effect of cooling rate in commercial Al- 7% Si. a) 0.3 K/s and b) 3 K/s.

The effect of a eutectic modifying addition of 200ppm Sr to the commercial alloys, grain refined with 0.05% Ti, are shown in Table II. Eutectic modifiers are added to commercial alloys to improve the mechanical properties by changing the Si-phase from a platelike to a fibrous morphology. Modification also decreases the grain size in Al-Si alloys by increasing the

nucleation temperature and gives a lower eutectic temperature and a higher eutectic composition, leading to a longer freezing range[8]. As is observed from Table II, coherency is delayed in both alloys when they are modified. This might be explained by the increased effectiveness of the grain refiner. Therefore, the coherency point might be increased by the reduced grain size. This explains why the effect of the modifier on the coherency point is small, because the grain size does not change very much with its addition.

Table II. Effect of a 200ppm Sr addition on coherency parameters in the two commercial alloys, grain refined with 0.05% Ti. [0.7K/s]. f_s^{coh} is fraction solid at the coherency point, T^{coh} is the temperature at the coherency point, t_{coh} is the time elapsed from nucleation to coherency and ΔT_{coh} denotes the temperature difference between nucleation and coherency.

Alloy and additions	f_s^{coh} (%)	T^{coh} (°C)	t_{coh} (s)	ΔT_{coh}
Al- 7% Si- 0.05%Ti	20.5	609.5	35.9	8.7
+ 200ppm Sr	22.9	606.0	35.0	13.0
Al-11%Si-0.05%Ti	13.3	581.5	23.1	5.7
+ 200ppm Sr	16.4	575.1	30.4	12.4

Figure 6 shows the coherency points for the model alloys with successive additions of iron, magnesium, 0.05% titanium, and ~0.14% Ti to the same melt. The starting points are pure binary Al-Si alloys and the composition of the last model alloys is identical with respect to the main alloying elements to the commercial alloys, but with lesser amounts of impurities and trace elements. The general effects and differences observed in Figure 6 can be interpreted by considering how the additions influence the governing solidification pattern. Small additions of iron seems to have little effect on coherency, while the magnesium addition delays the coherency point somewhat, indicating either a change in grain density or dendrite growth rate. For small levels of addition, below the solid solubility limit, the growth rate of equiaxed dendrites has been shown to be inversely proportional to $mC_0(k-1)$ [9]. Iron has a product m(k-1) of 2.9, magnesium 4 and silicon 5.5. A relatively unaffected coherency point with an addition of 0.14% iron and a delayed coherency point for ~0.20% Mg is in accordance with Mg being more effective in suppressing the dendrite growth rate. Grain refinement has the same effect as in the commercial alloys, and the same discussion apply. In the 11%Si-alloy with additions of iron and 0.06% Ti some irregular deviations are observed between the coherency points determined by rheology and thermal analysis.

Tables III and IV present a summary of the experimental results presented in this article, in addition to other related coherency parameters. As shown in the tables the rheologically determined coherency fraction solid is quite reproducible. The tables also shows that with grain refinement a postponed coherency point is accompanied by a lower coherency temperature(T^{coh}) and increases in temperature difference(ΔT_{coh}) and elapsed time(t_{coh}) between nucleation and coherency. Increased cooling rate gives lower coherency temperature and increased ΔT_{coh} and t_{coh} accompanying earlier coherency.

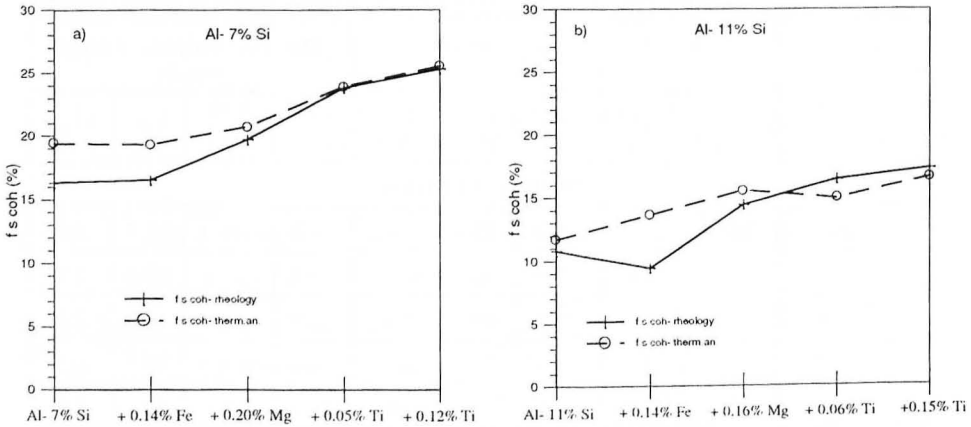

Figure 6. Effect of successive additions of iron, magnesium, ~0.05% Ti as Al-5Ti-1B and ~0.15% Ti in a) pure Al- 7% Si and b) pure Al- 11% Si. The level of additions is chosen to reproduce the composition of the commercial alloys.[0.7 K/s].

Table III. Results from rheological measurements and thermal analysis, commercial alloys.

Alloy	Rheological measurements					Thermal analysis, average results			
	Exp.1 (%)	Exp.2 (%)	Exp.3 (%)	f_s^{coh} (%)	T^{coh} (°C)	f_s^{coh} (%)	T^{coh} (°C)	t_{coh} (s)	ΔT_{coh}
COMMERCIAL ALLOYS									
Al-7%Si	19.8	18.3	17.2	18.4	607.6	18.3	610.3	29.1	6.8
+0.05%Ti	23.8	24.7	24.7	24.4	603.5	20.5	609.5	35.9	8.7
+0.20%Ti	20.5	20.5	22.5	21.2	605.2	26.2	608.0	41.4	12.6
Al-11%Si	14.1	11.8	10.3	12.1	578.0	10.7	580.7	21.0	1.5
+0.05%Ti	17.6	16.5	16.8	17.0	573.9	13.3	581.5	23.1	5.7
+0.20%Ti	21.4	22.1	19.0	20.8	574.1	16.0	582.3	26.8	7.7
7Si-0.05Ti 0.3K/s	24.4	27.2	27.5	27.3	611.7				
3K/s	14.0	14.5	14.5	14.3	604.3				
11Si-0.05Ti 0.3K/s	19.2	19.0	16.7	18.3	579.9				
3K/s	16.8	16.7	18.0	15.9	570.3				

Table IV. Results from rheological measurements and thermal analysis, model alloys.

Alloy	Rheological measurements					Thermal analysis, average results			
	Exp.1 (%)	Exp.2 (%)	Exp.3 (%)	f_s^{coh} (%)	T^{coh} (°C)	f_s^{coh} (%)	T^{coh} (°C)	t_{coh} (s)	ΔT_{coh}
MODEL ALLOYS									
Al-7Si	16.5	16.4	16.0	16.3	609.6	19.4	608.4	33.7	4.4
+0.14% Fe	13.5	18.0	17.9	16.5	610.3	19.3	610.6	29.4	2.5
+0.20% Mg	19.2	19.5	20.3	19.7	609.2	20.7	610.4	31.4	2.7
+0.05% Ti	23.8	23.2	24.5	23.8	607.8	23.9	609.2	37.5	6.2
+0.12% Ti	24.0	25.5	26.5	25.3	606.8	25.5	608.3	40.1	8.7
Al-11Si	9.6	10.1	12.6	10.8	579.4	11.7	581.1	20.2	-0.1
+0.14% Fe	10.2	7.8	10.3	9.4	580.2	13.6	581.5	21.1	-0.7
+0.16% Mg	14.4	13.8	14.9	14.4	578.6	15.5	581.2	23.6	-0.3
+0.06% Ti	15.9	17.1	16.2	16.4	579.0	14.9	581.4	24.3	1.7
+0.15% Ti	17.8	16.3	17.5	17.2	579.7	16.5	581:8	27.7	2.2

Conclusions

Measurements of dendrite coherency can be related to the governing constitutional and growth conditions, basically as a compromise between density of grains and dendrite growth rate. The results show that increasing grain refinement postpones coherency, increased cooling rate gives earlier coherency, modification a slightly postponed coherency and minor alloying additions seems to have an effect corresponding to their growth restricting effects.

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