Shape rheocasting of unmodified Al-Si binary eutectic

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ABSTRACT

It is demonstrated experimentally that by using the Council for Scientific and Industrial Research Rheo Casting System and high pressure die casting it is possible to semi-solid process and cast into a shape unmodified Al-Si binary eutectic without a solidification temperature range. Silicon leads the aluminium coupled crystal growth subjected to convection by induction during thermal arrest. The semi-solid structure during thermal arrest is captured after rheo-processing and casting.

Keywords: CSIR-RCS; solidification; phase nucleation; convection; microstructure, casting

Introduction

It is generally stated that eutectic alloys and pure metals are not suitable for semi-solid metal (SSM) processing because of the lack of a solidification temperature range [1-4] although rheo-processing of eutectic Al-Si was attempted before [5].

Semi-solid refers to the metal in a state consisting of liquid and solid while processing refers to any subsequent forming step. Rheocasting is a branch of semi-solid processing where the liquid metal is cooled, with some form of agitation, to some temperature between the liquidus and solidus of the particular alloy and is then subsequently cast; resulting in a globular or spherical primary solid microstructure [6]. The Council for Scientific and Industrial Research (CSIR) developed and patented a rheo-processing system which uses combined coils for induction stirring and simultaneous forced air cooling [7] called the CSIR Rheo Casting System (CSIR–RCS). Previously processed alloys include, Al-7Si-Mg [8] and Al-Cu-Mg-(Ag) [9] casting alloys, Al-Cu-Mg, Al-Mg-Si and Al-Zn-Mg-Cu wrought alloys [10], Si_p/Al metal matrix composites [11] and more recently high purity aluminium [12].

The aim here is to demonstrate that it is possible to rheocast the unmodified Al-Si binary eutectic alloy using the CSIR-RCS in combination with high pressure die casting (HPDC), following on the previous high purity aluminium rheocasting work [12].

Materials and methods

A 10 kg batch of Al-Si binary eutectic was produced by melting 7.5 kg high purity aluminium nuggets in a 20 kg resistance heated tilting furnace and adding 2.5 kg Al-50% Si to the melt; the total melt was degassed with argon afterwards. A sample was poured from the melt, cooled and sectioned to analyse the chemical composition using a Thermo Quantris optical emission spectroscope. The composition measured was 12.2 wt% Si, 0.1 wt% Fe, 1 ppm Sr, 152 ppm P and Na not detected. We term this alloy Al-Si binary eutectic and not near-eutectic because Al-Si near-eutectic alloys referred to in literature almost without exception contain relatively large amounts of other elements together with close to 12.6 wt% Si [13-16].

The sequence for casting follows: The alloy temperature in the furnace was set at 587°C, 10ºC above the binary melting point. About 400 g of liquid metal was manually poured from the tilting furnace into the stainless steel processing cup. Transfer of the cup was manually performed to a single coil version of the CSIR–RCS where processing started when the cup entered the coil. A thermocouple measured the temperature of the metal in the cup. Processing (1.5 kW power and manual set forced air cooling) stopped after 125 seconds elapsed from the start of processing at which point the cup was ejected from the coil and manually transferred to the LK DCC130 HPDC machine for die filling (die temperature set to 240 °C, cartridge heated). The injection shot was manually triggered when the billet was in the shot sleeve and the piston followed the set computer controlled injection velocity profile.

Another sample was poured from the furnace into the processing cup and left to cool in air i.e. not rheo-processed and not HPDC.

Results and discussion

Figure 1 shows the thermocouple measurement curve for the alloy in the processing cup. The temperature rises, when the thermocouple is inserted into the metal, up to 578 °C equalling the melting point of Al-Si binary eutectic where the thermal arrest plateau occurs [17].

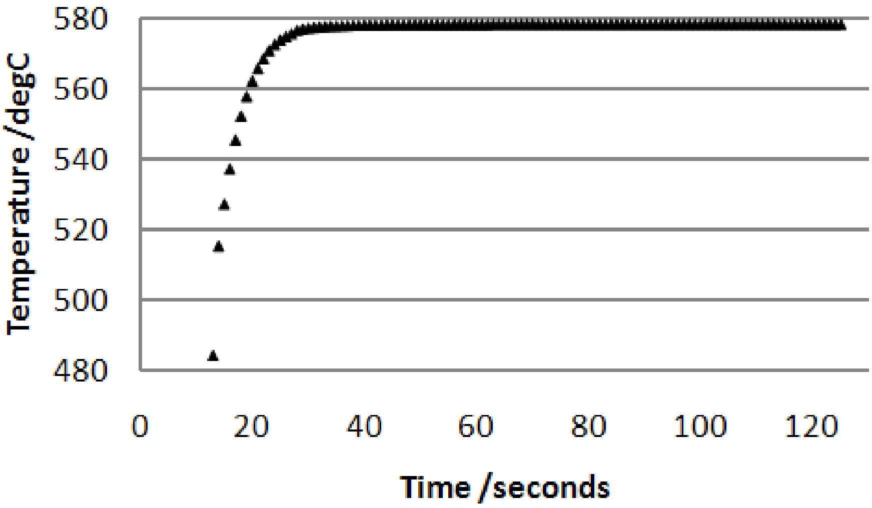


Figure 1. Plot of the temperature measurements for the actual processing time of the Al-Si binary eutectic in the cup

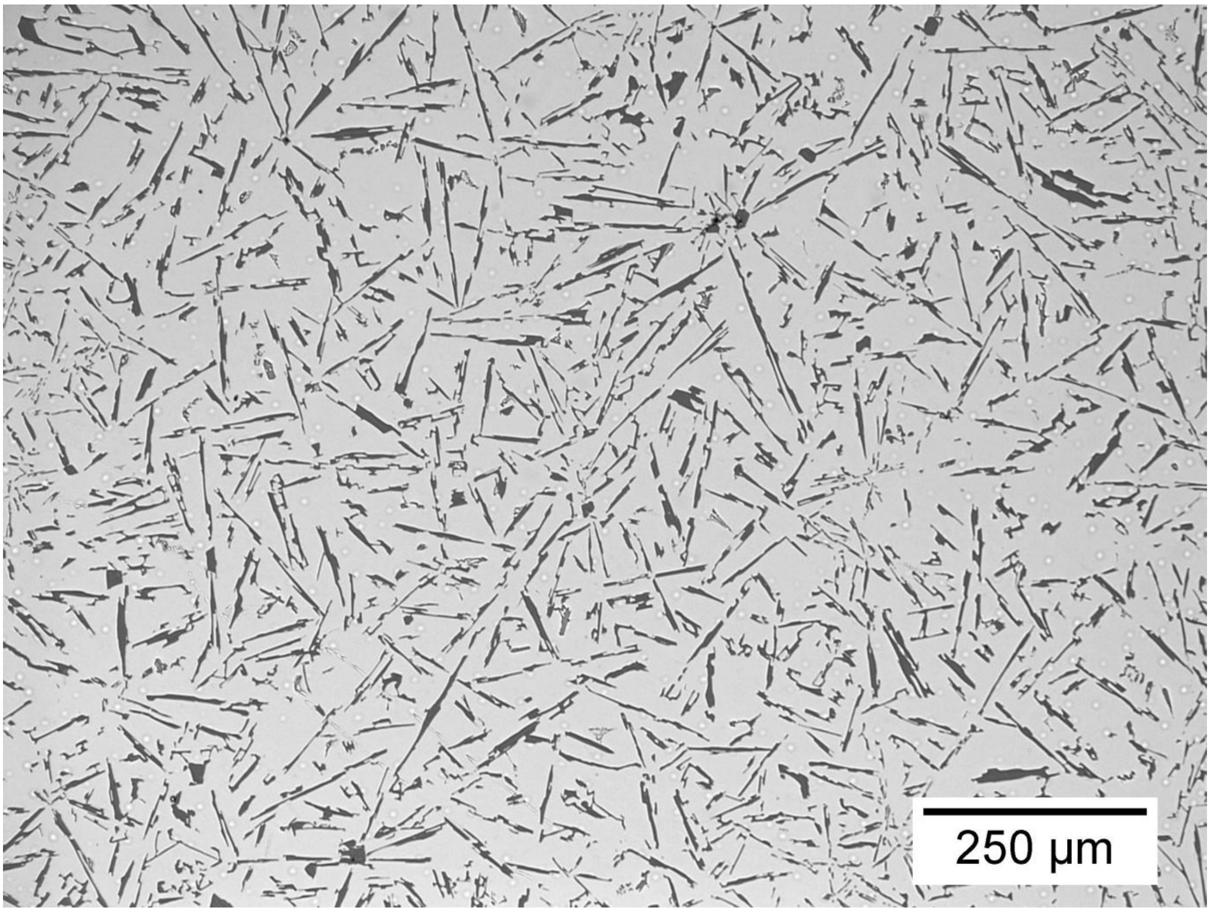
The HPDC component was a plate of dimensions 100 mm x 55 mm x 6 mm excluding the biscuit and the runner. The top-end of the plate was sectioned in the transverse orientation, mounted in bakelite hot mounting resin and finally mechanical polished with colloidal silica. It was not necessary to etch the samples after final polishing because the contrast between aluminium and silicon is adequate. A Leica DMI5000 M optical microscope equipped with a Leica DFC480 camera and Image–Pro MC v6.0 imaging software was used to record the microstructures.

The whole HPDC casting (including the plate, runner and biscuit) that was produced for the temperature curve in Figure 1 is shown in Figure 2.

Figure 2. The actual semi-solid rheocast Al-Si binary eutectic plate, including the runner and biscuit

Figure 3a shows the conventional irregular structure of this unmodified Al-Si binary eutectic solidified with only pouring and a slow heat extraction rate in air. Figure 3b shows a radically and uniquely different microstructure after rheo-processing during thermal arrest and completed solidification at a high heat extraction rate with HPDC.

Figure 3b also shows the characteristic globular or spherical SSM microstructure. In this case, three structural features can be properly distinguished, two of them are the dark structural features of angular shapes, on the one hand, included by the light structural feature of spherical shapes, on the other hand, and the third is a gray structural feature of the inter-spherical regions. Notice that the dark angular shapes are associated and included within the light spherical shapes.



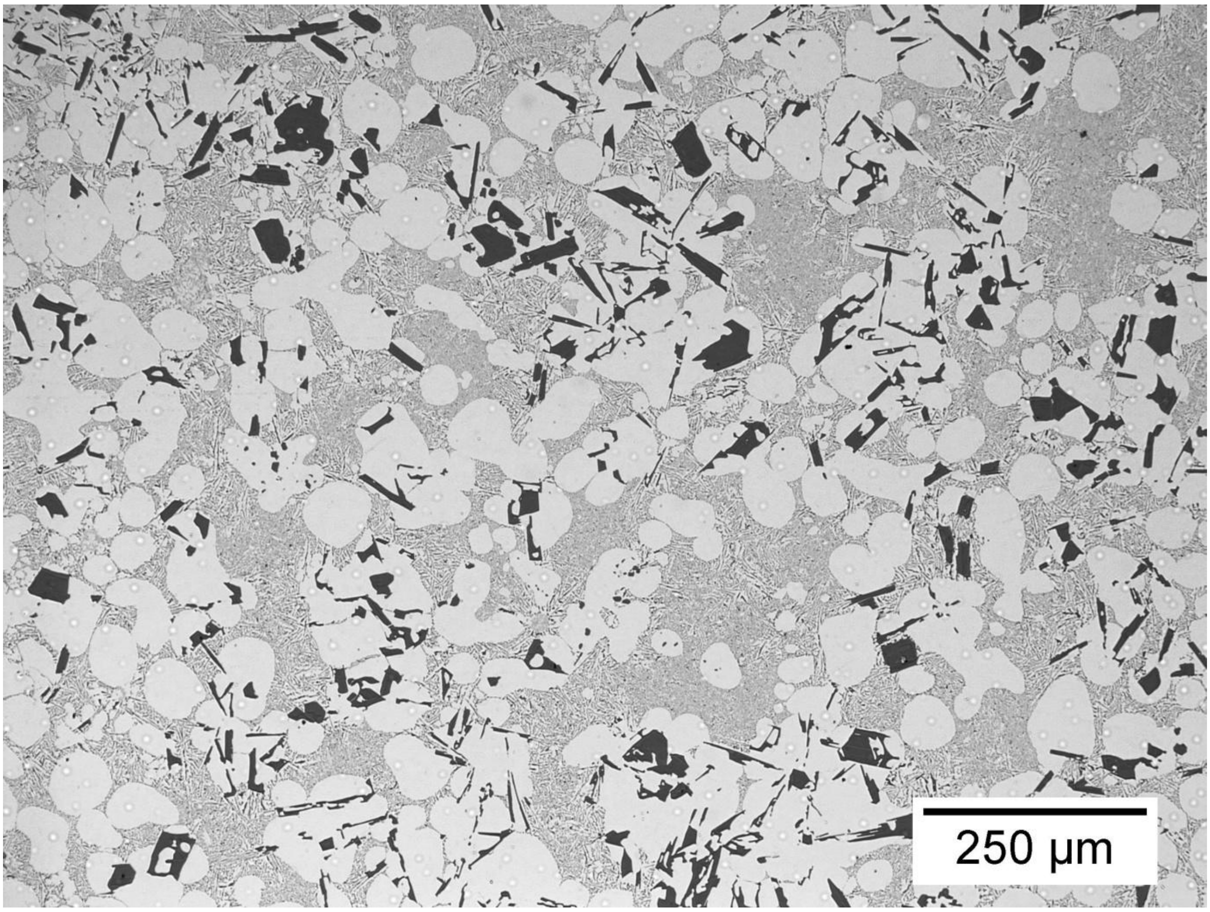


Figure 3. Microstructures of unmodified Al-Si binary eutectic processed differently. (a) Solidification by air cooling after pouring alloy from the furnace into the processing cup and (b) rheo-processed for 125 seconds and HPDC. (Unetched).

Normally, the phases of Al-Si binary eutectic composition are described as a function of the temperature range i.e. either liquid or solid above or below the melting point of the eutectic composition. In the solid state there are also two solid phases i.e. Al-rich phase (α-Al) and Si (β-Si). Also, the phases in solidified hypo- and hypereutectic Al-Si compositions respectively consist of proeutectic α-Al and β-Si to distinguish them from the same phases in the eutectic. Figure 3b seems to show proeutectic α-Al, β-Si and eutectic liquid but it can not be since the alloy here has the eutectic composition. To make the distinction of phases during thermal arrest we therefore refer to: σ-Al as the solidified aluminium and ψ-Si as the solidified silicon phases which were present at the time of casting while λ-liquid as the liquid fraction that was present during thermal arrest at the time of casting.

These distinctions are necessary as one can not interpret the microstructure of Figure 3b in the normal way because there is no alloy solidification temperature interval; keeping with the convention for high purity Al [12].

In essence, σ-Al, ψ-Si and λ-liquid are a function of rheo-processing time during thermal arrest and HPDC while α-Al, β-Si and eutectic liquid are a function of temperature and composition; all three phases are respectively equivalent.

Microstructures were also chemically characterised with energy dispersive x-ray spectroscopy (EDS) (JEOL JSM-6510 scanning electron microscope; ThermoScientific UltraDry detector; ThermoScientific NSS 2.3 X-ray MicroAnalysis software). Figure 4a shows an area consisting of λ-liquid and ψ-Si included in σ-Al; note that it is not easy to distinguish between Al and Si because of their small atomic mass difference. The EDS composition maps (Fig. 4c and 4e) and accompanying spectra clearly show that λ-liquid consists of both Al and Si (Fig.4b) while σ-Al is virtually pure Al with some Si in solid solution (Fig.4d) and ψ-Si is virtually pure Si with Al picked up from the matrix (Fig.4f).

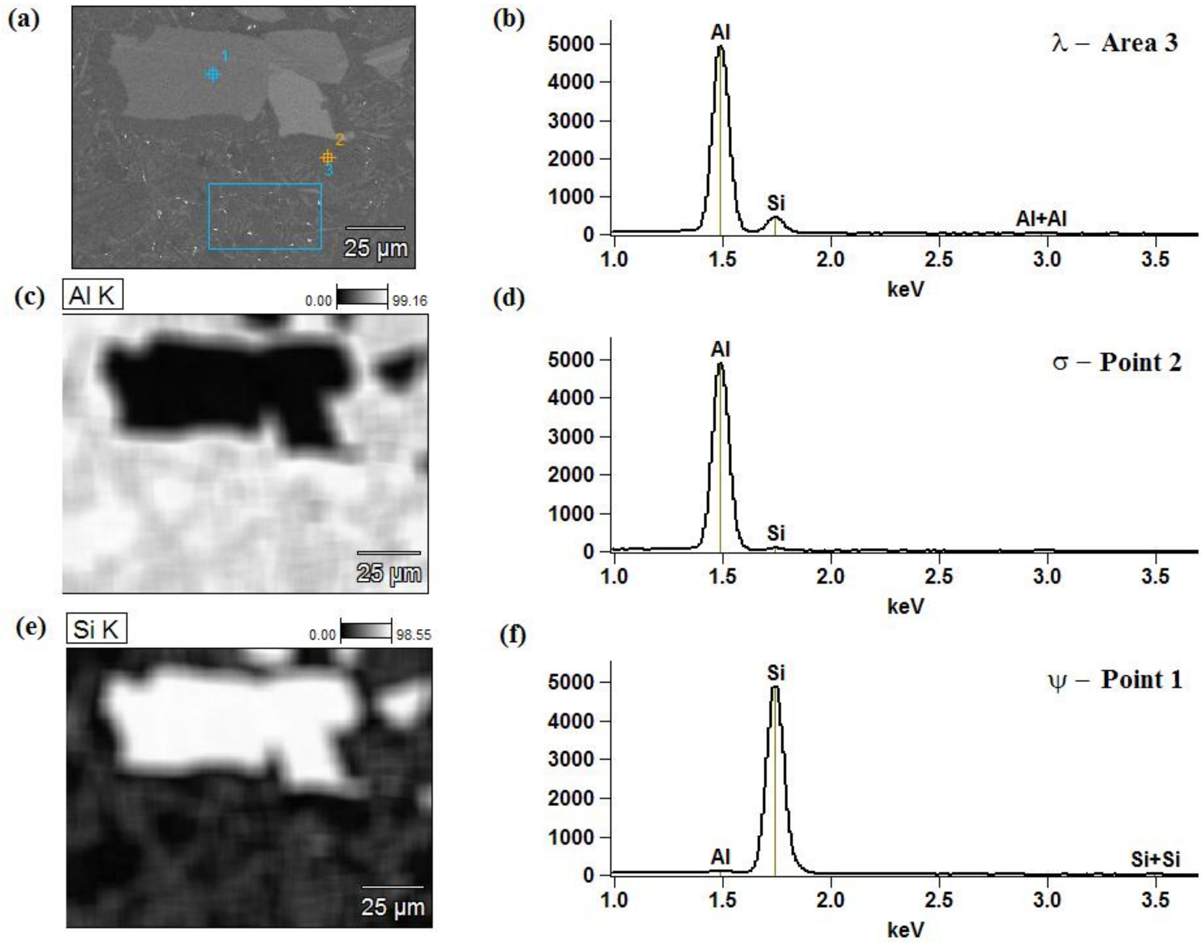


Figure 4. EDS characterisation of the rheocast microstructure. (a) Backscattered electron image of the polymorphic area which include σ-Al, ψ-Si and λ-liquid. EDS spectra for (b) λ-liquid – Area 3 in image 4a, (d) σ-Al – Point 2 in image 4a, and (f) ψ-Si – Point 1 in image 4a. EDS composition maps of (c) Al in image 4a, and (e) Si in image 4a.

The physical mechanism by which this microstructure is produced can be explained by starting with a thought experiment along the following lines [18]. The eutectic composition liquid temperature drops as heat is extracted after pouring superheated metal into the cup. Thermal arrest sets in after the metal temperature reaches the melting temperature of the eutectic composition. Thermal arrest, in Figure 1, occurs because the latent heat of fusion is released during the solidification process and the time necessary for solidification is determined by the heat extraction rate. Solidification or phase transformation does not happen instantaneously but the liquid and solid phases coexist. Only once solidification is complete does the temperature drop again with further heat extraction.

Standard solidification theory [18] can be used to describe the experimental observations in Figure 3b. It is accepted that irregular eutectics form in cases where one of the two phases is faceted while the other is non-faceted characteristic of metal-non metal systems like Al-Si. It is also accepted that the faceted phase “leads” the eutectic morphology growth. Therefore the faceted phase must nucleate first and the non-faceted phase will follow in growth. It seems to be the case for the ψ-Si included in σ-Al globular grains of Figure 3b.

The low metal pouring temperature and the pouring turbulence effected nucleation of ψ-Si on the pouring spout of the furnace which was manufactured for practical pouring reasons. In the field of semi-solid processing the cooling slope combined with low superheat is a very well recognised and simple technique to increase nucleation which produces globules of a small size [19,20]. On the other hand, phosphorus in minor quantities, forming AlP, is known to nucleate primary Si in hypereutectic Al-Si alloys [21] and is known to modify the Al-Si eutectic morphology with segregated primary Si crystals [22]. Figure 3a indicates that the 152 ppm P in our alloy did not nucleate any block-like primary Si crystals; therefore phosphorus induced nucleation seems to be unlikely. The impression of Si-cuboids in Figure 3b results for the sample preparation sectioning through the faceted Si flake orientations.

In turn, the non-faceted σ-Al can athermaly nucleate heterogeneously on facets in the ψ-Si faceted morphology [18]. Subsequent growth of σ-Al and ψ-Si proceeds in a coupled manner during the thermal arrest period; unlike the Zn-Al regular binary eutectic of which the phases separate during rheo-processing [23]. There will be Si protrusions into the liquid ahead of the Al growth front because Si leads the growth. The result is a microstructure containing globules of ψ-Si included in σ-Al and modified λ-liquid after quenching in the high pressure die casting machine known to achieve high cooling rates [24]. The grains are equi-axed because of the induction field induced convection on the grains which the effect of is well recognised [25].

The cooling rate effect on solidification of unmodified Al-Si eutectics is already commonly recognised. Slow cooling rates result in coarse flake-like microstructures while fast cooling rates result in modified fibrous microstructures and there is an intermediate cooling rate where the transition occurs depending on the thermal gradient and the growth velocity [26]. With this in mind, Figure 3b is therefore not intuitive from normal processing of the eutectic Al-Si alloy in that it contains both the excessively coarse flake and the modified fine fibrous Si morphologies, side by side, in the same casting. Rheo-processing during thermal arrest equates to very slow cooling with the characteristic coarse flakes while the fine fibrous structure results from HPDC.

Conclusions

It is shown here experimentally that unmodified Al-Si binary eutectic can be rheo-processed using the CSIR–RCS combined with HPDC. Processing and casting is possible, not because of a solidification temperature range, but because of a time range during the thermal arrest. All experimental observations made in this letter can be explained and described by existing solidification principles. Casting of unmodified Al-Si binary eutectic with convection coupled growth could possibly make an experimental contribution to fundamental questions about the subject [25]. Experiments with Sr-modified Al-Si binary eutectic are planned.

Acknowledgements

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