Shape rheocasting of high purity aluminium

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ABSTRACT

It is demonstrated experimentally that 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 high purity aluminium without a solidification temperature range. Nucleated embryos grow coupled with convection by induction during thermal arrest. The semi-solid structure during thermal arrest is captured after rheo-processing and casting. Fundamental solidification principles are used to describe observations of the solid to liquid ratio in the time range during thermal arrest.

Keywords: CSIR-RCS, solidification, nucleation of phase transformation, convection, crystal structure

It was stated before that semi-solid casting can not be implemented for near eutectic alloys and almost pure metals because it is practically impossible to obtain a uniform temperature profile in the reheated slug [1]. More recently, it was claimed that pure metals and eutectic alloys are not suitable for semi-solid metal (SSM) processing because of the lack of a solidification temperature range [2,3].

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 [4]. 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 [5] called the CSIR Rheo Casting System (CSIR–RCS). Previously processed alloys include, Al-7Si-Mg [6] and Al-Cu-Mg-(Ag) [7] casting alloys, Al-Cu-Mg, Al-Mg-Si and Al-Zn-Mg-Cu wrought alloys [8] as well as Si_p/Al metal matrix composites [9].

The aim here is to demonstrate, in an initial trial, that it is possible to rheocast high purity aluminium using the CSIR-RCS in combination with high pressure die casting (HPDC).

A 10 kg batch of high purity aluminium nuggets was melted in a 20 kg resistance heated tilting furnace and degassed with argon. A sample was poured from the melt, cooled and sectioned to analyse the chemical composition using a Thermo Quantris optical emission spectroscope. The measured 99.86% Al composition can be defined as high purity aluminium [10].

The sequence for casting follows: about 400 g of liquid metal was manually poured (metal temperature in the furnace was measured during casting) from the tilting furnace into the stainless steel processing cup and manually transferred 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 (1.7 kW power and manual set forced air cooling) stopped after some time (in seconds) elapsed from the start of processing (determined by trial-and-error) 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.

Figure 1 shows the thermocouple measurement curve for the metal in the processing cup. Temperature logging starts when the rheo-processing is manually initialised. The temperature curve starts off at about 275 °C because of the temperature of the thermocouple after cooling off from the previous processing cycle. The temperature starts to rise when the thermocouple is inserted into the metal, up to 660 °C equalling the melting point of aluminium where the thermal arrest plateau occurs [11,12]. Processing stopped after an elapsed time of 39 seconds, from the start of processing, which was determined by trial-and-error during previous casts in the trial.

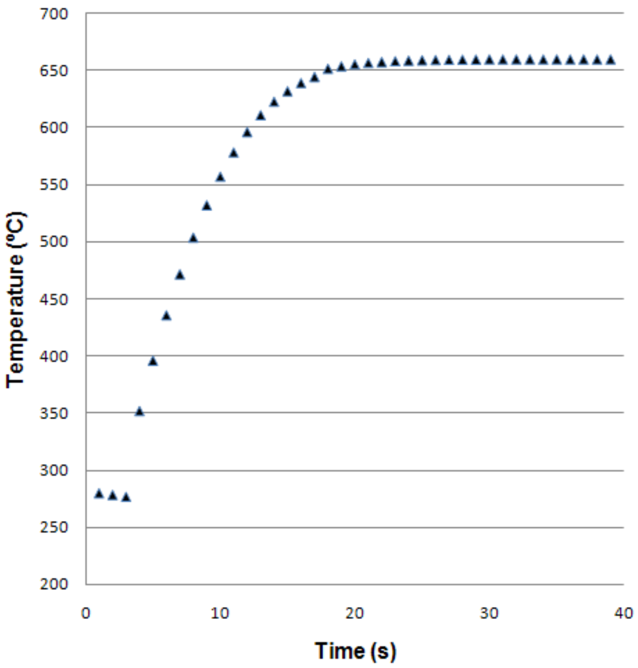

Figure 1. Plot of temperature vs. time measurements for processing time of the aluminium in the cup. (actual rheocast plate)

The HPDC component was a plate of dimensions 100 x 55 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. The electro-polishing step with 5ml perchloric acid in 95 ml acetic acid at 30 V DC potential and room temperature [13] already revealed the microstructure. 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 microstructure.

The whole HPDC casting (including the plate, runner and biscuit) that was produced for this temperature curve is shown in Figure 2. The surface of the plate is somewhat rough indicating the rheo-processed metal had a relatively high solid fraction at the time die filling took place. Fold-over of protrusions on the biscuit, during handling, is clearly visible giving an indication of the malleability of the metal. A bulk hardness of 19.5 Vickers (5 kg load) was measured on the cross section of the plate.

Figure 2. The actual semi-solid rheocast high purity aluminium plate (including the runner and biscuit)

Figure 3 shows the internal microstructure of the aluminium metal in a cross section view of the plate. A globular or spherical microstructure is characteristic of semi-solid microstructures in aluminium alloys and magnesium alloys [4]. Two structural features can be properly distinguished, one is the light gray structural feature of spherical shapes and the other is the darker gray structural feature of the inter-spherical regions. The spheres can be found over a long range distance in the cross section at this low magnification.

The physical mechanism by which this microstructure is produced can be explained by starting with a thought experiment along the following lines [14]. The liquid aluminium temperature drops as heat is extracted after pouring superheated metal into the cup. Thermal arrest sets in after the metal temperature reaches the fusion temperature of aluminium. Thermal arrest, in Figure 1, occurs because the latent heat of fusion is released during the solidification process and the time necessary for fusion 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.

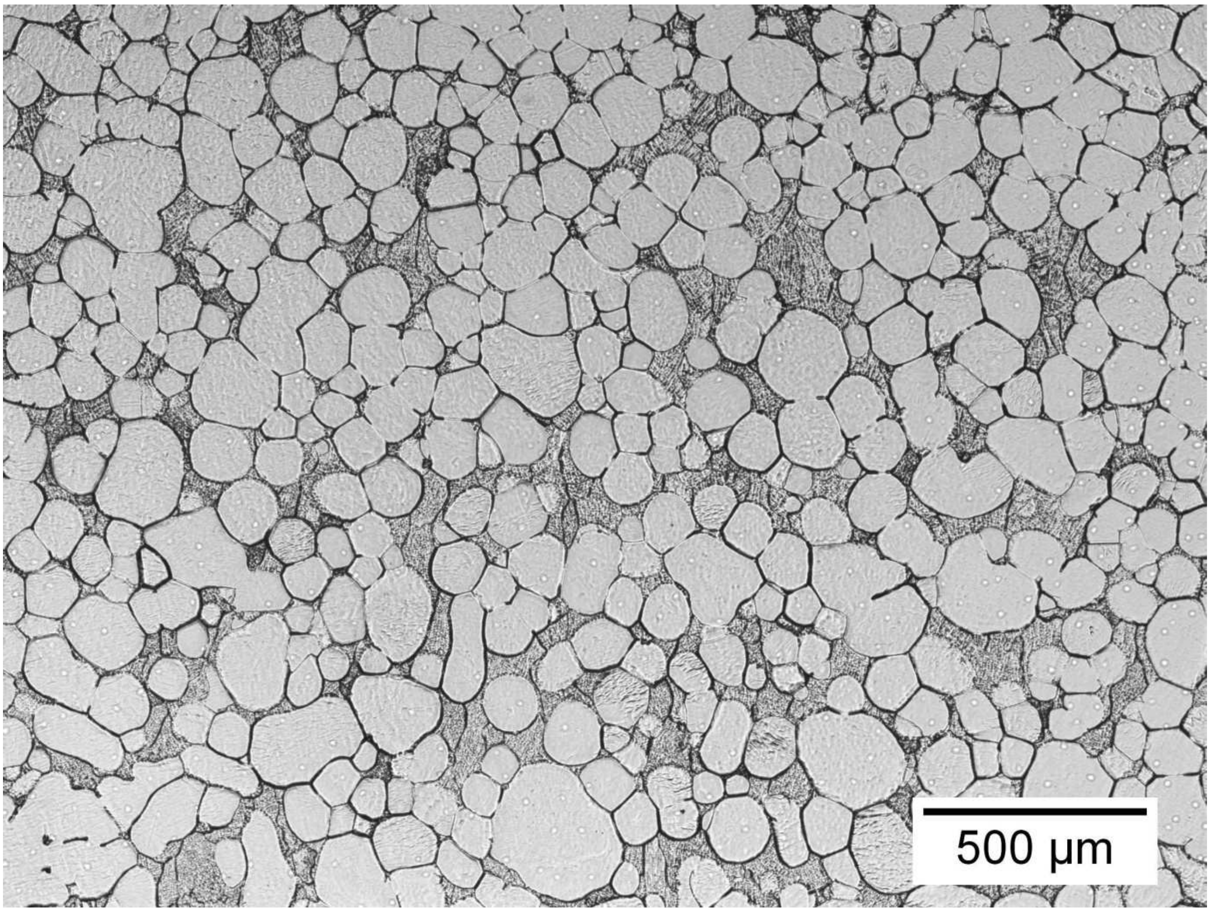

Figure 3. Internal microstructure of the metal in the plate viewed in cross section. Light gray spherical shapes were the solid phase aluminium (σ-Al) and dark gray inter-spherical areas were the liquid phase aluminium (λ-Al) before final solidification in the die.

Fundamental solidification theory [14] is applied here to describe these experimental observations. Figure 4(a) shows the microstructure of the same starting metal as the plate. In this case it was rheo-processed and solidified only in the cup (no HPDC). In standard solidification terms the liquid has transformed after losing the latent heat of fusion to a single phase solid (α-Al). The grains are equi-axed because the induction field induced convection on the grains of which the effect is well recognised [15].

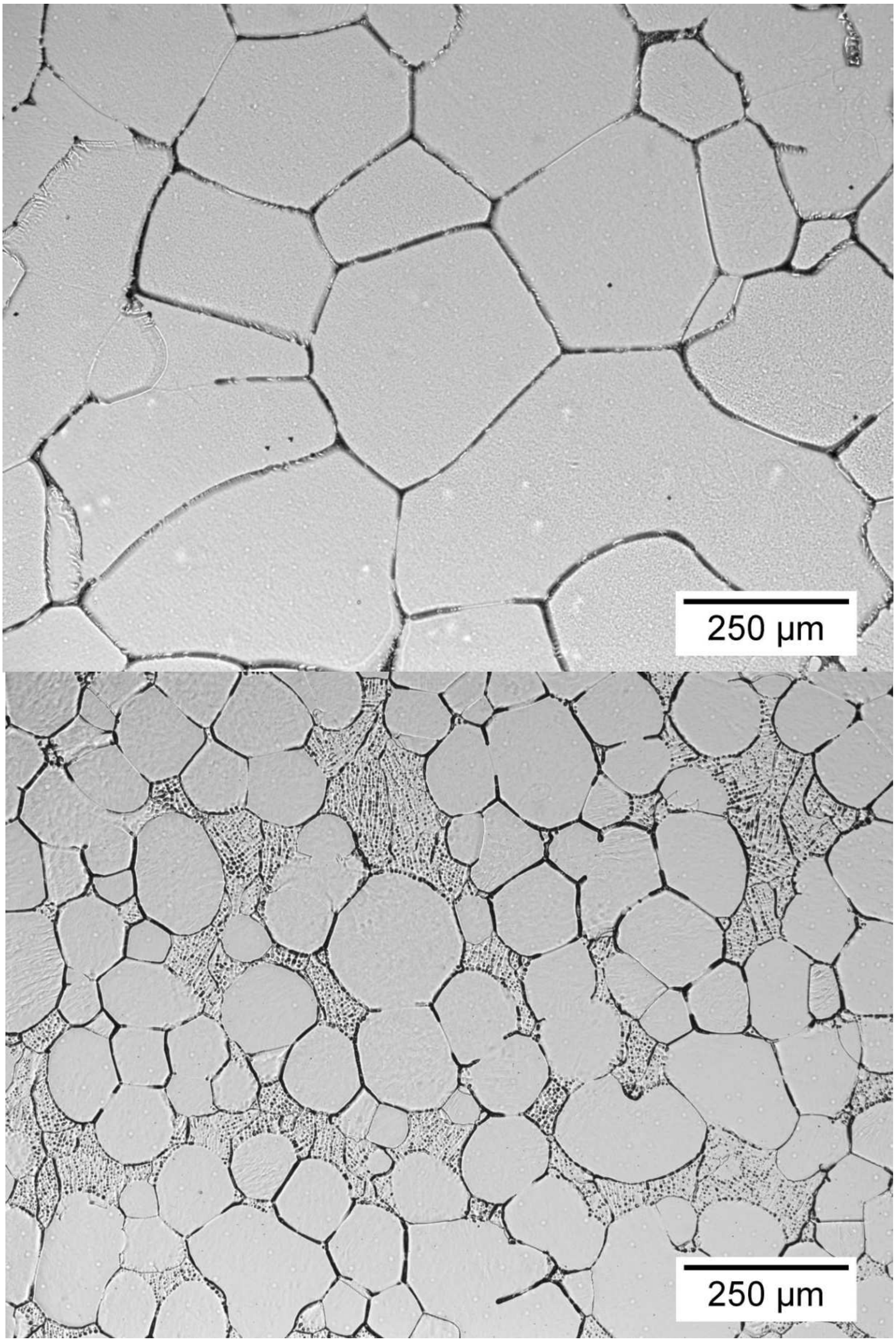

Figure 4. Microstructures of solidified high purity aluminium that was (a) rheo-processed and solidified in the cup (not HPDC) and (b) rheo-processed and HPDC (plate)

Figure 4(b) shows again, at higher magnification than Figure 3, the rheo-processed and HPDC plate's microstructure in cross section. In this instance it appears that there are two distinct phases and we refer to the light gray spherical structure as σ-Al and the dark gray structure as λ-Al. Referring back to the thermal arrest period, this observation can be explained where the solid and liquid phases coexisted and it can be understood that upon the fast heat extraction rate or quenching when die filling occurred that the coexisting phases were captured in time. High pressure die casting is known to achieve very high cooling rates [16].

The phases of pure aluminium are normally described as a function of the temperature range i.e. liquid or solid (α-Al). Because in the case of Figure 4(b) there are two distinct solid structures in the quenched state which is a function of thermal arrest time, references to σ-Al (signifying the fraction of aluminium that was solid during thermal arrest period before casting) and λ-Al (signifying the fraction of aluminium that was liquid during the thermal arrest period before casting) become necessary. Therefore, liquid (λ-Al) and solid (σ-Al) is a distinction in the quenched microstructure captured in time during thermal arrest. In reality σ-Al is the precursor embryos of α-Al.

This last statement brings about the question of nucleation of the solid phase from the liquid at the start of thermal arrest for this rheocasting system. It is well known that nucleation in pure aluminium can be effected by inoculation with Ti and B [17]. Applying electric current pulse (ECP) on pure aluminium is also known to cause grain refinement but it was shown that nucleation occurs on the mould wall and that ECP disturbs crystal embryos which drift into the liquid phase [12]. Nucleation can occur, with this system, in a similar manner on the inside wall of the processing cup while heat is removed by the forced air cooling. At a metal pouring temperature of 700 °C nucleation occurred on the cup wall, but formed a solid layer growing radially inwards resulting in separation of liquid and solid when transferred into the shot sleeve of the HPDC machine. A relatively low induction power contributed little to dislodging probable embryos from the cup wall.

Metal pouring temperature was found, here, to have a more significant effect on nucleation. The metal pouring temperature was reduced to 670 °C (10 °C above the melting point) for the casting made in question. The lower metal pouring temperature and the pouring turbulence effected nucleation on the pouring spout of the furnace which was made for practical pouring reasons. In the semi-solid processing knowledge domain the cooling slope combined with low superheat is a very well recognised and simple technique to produce globules of a small size [18,19].

Considering Figure 4, the question of recalescence [14] is addressed lastly. In effect, embryos (σ-Al) are established by heterogeneous nucleation on the surface of the pouring spout and are swept into the liquid phase. The σ-Al crystals now behave as homogenous embryos which will grow larger or disappear depending on their size. Heat is continuously extracted at a given rate by the CSIR-RCS coil during processing. The forced air cooling heat extraction rate balances more in favour of crystal growth and therefore counters recalescence during processing. If processing stops, at some ratio of σ-Al to λ-Al during the thermal arrest period and left to solidify where the heat extraction rate does not keep the balance, larger σ-Al crystals will grow at the expense of smaller σ-Al which is consumed by recalescence. The resulting microstructure looks like Figure 4(a). On the other hand, if processing stops at the same ratio of σ-Al to λ-Al during the thermal arrest period (semi-solid metal state) and is quenched in the HPDC machine, recalescence will not have time to consume smaller σ-Al, resulting in a microstructure such as Figure 4(b) with a larger size distribution of σ-Al quenched in during the thermal arrest period.

In conclusion, it is shown here experimentally that pure aluminium can be rheo- or semi-solid processed using the CSIR–RCS combined with HPDC. It is possible, not because of a solid to liquid ratio solidification temperature range, but because of a solid to liquid ratio during the thermal arrest time range. The high heat extraction rate during HPDC and the kinetics of solidification during thermal arrest make it possible to capture the semi-solid structure in time. All experimental observations made in this letter can be explained and described by existing fundamental solidification principles. Casting of pure aluminium with convection coupled growth, as in this case, could possibly make an experimental contribution to fundamental questions about the subject [15], although there could also be possible heat transfer or electrical conductivity applications. Experiments with near eutectic or eutectic aluminium alloys and maybe even peritectic alloys are planned.

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