Published paper
Cardoso Legoretta, E., Atkinson, H.V. and Jones, H. (2007) *Cooling slope casting to obtain thixotropic feedstock.* In: Solidification Processing 07 Proceedings of the 5th Decennial International Conference on Solidification Processing, 23-25 July, Sheffield, UK.

Cooling slope casting to obtain thixotropic feedstock

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Abstract
Thixoforming, and related semi-solid processing routes for metallic alloys, require feedstock with a non-dendritic microstructure in the semi-solid state. The material then behaves in a thixotropic way in that, when it is sheared it flows and can be forced to fill a die and, when it is allowed to stand it thickens again. The New Rheocasting (the NRC process) is a recently developed semi-solid processing route. There are two versions of this route. In one, molten alloy is poured directly into a tilted mould and, through careful temperature control during cooling, a spheroidal semi-solid microstructure is achieved. The material in the mould is then upended into a shot sleeve and hence forced into a die. Alternatively, the molten alloy is poured onto a *cooling slope* and thence into a mould before processing. The aim of the work described in this paper was to develop understanding of the microstructural development during the initial stages of this process. The results for pouring A356 aluminium alloy via a cooling slope into a mould are presented.

Keywords: Cooling slope casting, thixotropic feedstock material, A356 Al alloy.

1. Introduction
Thixoforming and related semi-solid processing routes are based on the *thixotropic* behaviour of semi-solid alloy occurring when the microstructure in the semi-solid state consists of spheroidal solid particles in a liquid matrix. The spheroids tend to agglomerate when at rest or moving at low shear rates but disagglomerate at high shear rates. This means that the material will flow when it is sheared (with the consistency of heavy machine oil) but thicken if it is allowed to stand. The behaviour was first discovered for semi-solid metallic materials in the early 1970s [1] and is now exploited in a variety of commercial routes, particularly for aluminium alloys. There are advantages in relation to competing routes, such as high pressure die casting, because flow into the die is smooth and laminar, producing components with less porosity [2].

There are two major branches of semi-solid processing. In the 'thixo' routes, the material is pretreated to obtain the spheroidal microstructure, for example by magneto hydrodynamic stirring in the liquid state followed by solidification. The feedstock is then supplied to the semi-solid processing plant as a solid. The disadvantages of this type of approach are the cost of the intermediate step (solidification followed by reheating) and the fact that scrap produced during manufacture has to be returned to the feedstock producer for recycling [3]. The alternative branch of semi-solid processing is 'rheo' processing. Here liquid is cooled into the semi-solid state and treated during that cooling in such a way as to obtain the spheroidal microstructure rather than dendrites. The material is then processed directly from the semi-solid state rather than solidifying and then reheating. The 'rheo' routes are inherently more cost effective than the 'thixo' routes.

In 1990s, UBE industries patented a 'rheo' route which they termed the New Rheocasting (NRC) process [4]. The comparison with thixoforming is given in Figure 1 and the steps in the process are illustrated in Figure 2. Nucleation occurs on the cooling slope (1(a) in Figure 2) or on the wall of the cup (1(b) in Figure 2) and then the equilibration process in the semi-solid state leads to a relatively uniform spheroidal structure. The process is used industrially. The aim of the work described in this paper was to develop understanding of the microstructural development during the initial stages of this process i.e. in the mould before processing and with the cooling slope/mould combination. Fuller details are given in [5]. Other workers are also investigating this process [e.g. 6].

2. Experimental method
The alloy studied was hypoeutectic A356 aluminium alloy (6.82Si, 0.32Mg, 0.022Cu, 0.005Zn, 0.112 Fe, <0.005Mn, 0.10Ti, 0.013Pb, 0.042Sn, 0.006Ni, 0.005Cr – all figures are in wt%). This is one of the most common alloys used in semi-solid processing. 500 g of alloy was induction melted

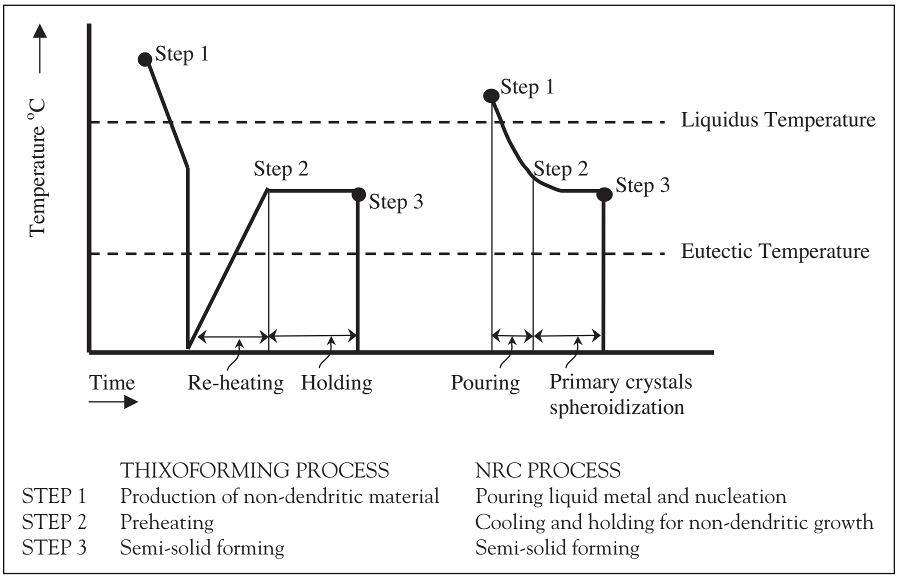

Figure 1: Temperature vs. time for thixoforming and NRC processes.

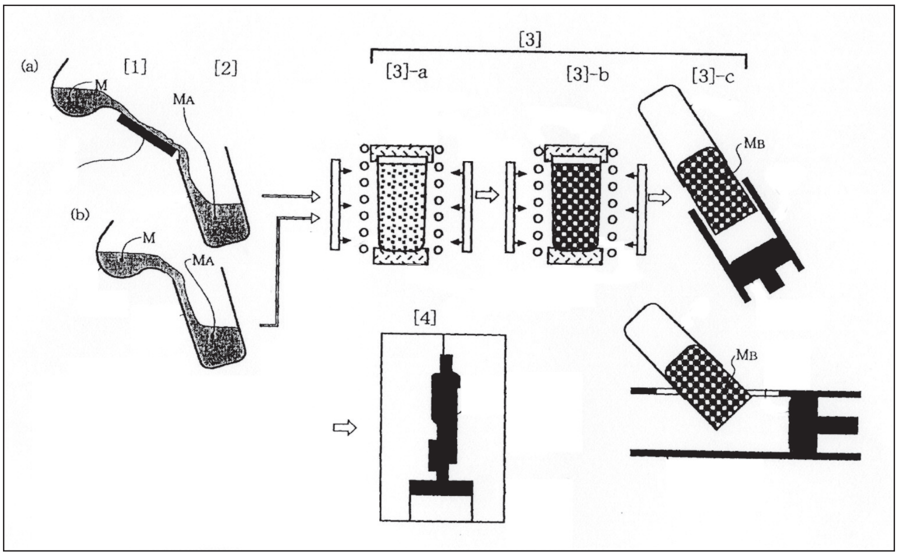

Figure 2: Schematic illustration of the development of thixotropic semi-solid structure in the NRC-process [4]. 1(a) is pouring down cooling slope with 1(b) pouring directly into the cup; 2 is the cup; 3-a is nucleation; 3-b is equilibration in the semi-solid state and holding with some heat input but still below the liquidus; 3-c is upending the semi-solid material into the shot sleeve (so the dross is left in the biscuit) and 4 is injection of the material into the die.

in an alumina crucible. To control the flow and temperature during the casting process, a bottom stoppered crucible with a graphite nozzle was used (Figure 3). During melting, the crucible was stoppered with a mullite rod, within which a K type thermocouple was located to monitor the temperature through melting and teeming. The alloy was melted at 700°C, held for 5 minutes and hydrogen degassed with a hexachloroethane tablet before pouring. Pouring was carried out at a range of temperatures between 620 and 680°C to assess the effect of superheat. The cooling slope was made of mild steel coated with boron nitride. It was cooled with circulating cold water. The mould material was stainless steel with 40 mm internal diameter and height 70 mm. Top, middle and end-of-slope microstructures were obtained from the remnant metal solidified on the cooling slope at the end of the casting process.

It should be noted that the aluminium alloy does not wet the mild steel slope and therefore runs as a narrow 'snake' down the slope, after an initial impact zone (Figure 4). Video sequences were obtained under a variety of conditions so that this could be explored further. The tilt angle between the cooling slope and the horizontal could be varied. The 'cooling length' is the length on the cooling slope with which the melt was in contact.

3. Results and Discussion

Figure 5 shows the effect of superheat. 'Wall', 'mid-radial' and 'centre' refer to the position in the solidified ingot (mid-height). The length on the cooling slope was 200 mm and the tilt angle 60°. Pouring with a low superheat (620 and 630°C) gave relatively globular structures, whereas for the medium superheat (650°C) the particle morphology was rosette-like, and at high superheat (680°C) a coarse dendritic structure formed. Figure 6 shows the remnant material microstructure for two different cooling lengths. At the bottom of the slope for the shorter length, (a), there is still some rosette-like structure visible. For the longer length, (b), the microstructure is essentially spheroidal but somewhat coarser. This is evidence that some spheroidisation is essentially achieved on the slope rather than through mechanisms occurring in the mould after travel down the slope. In addition, the microstructure in

Figure 6 (a) at the bottom of the cooling slope is essentially a 'photographic enlargement' of that at the top of the slope, suggesting that the majority of the nucleation has occurred in the upper part of the slope. It is thought that the initial area of the impact zone on the slope (see Figure 4) may play an important role. The impact area was largest in the first second of teeming at 25 cm^2, decreasing rapidly after the first second to an average of 12 cm^2. The influence of impact zone is under further investigation.

With the cooling slope, the key points are: copious nucleation; nuclei survival and suppression of dendritic growth. Nucleation is occurring through chilling on the slope, particularly in the impact zone. Crystal multiplication then occurs by, for example, the melting of dendrite arms and the deformation of dendrites caused by fluid flow [7,8]. The fluid flow down the slope provides shear to the initial dendrites to aid the dendrite breakup, transfer the newly formed grains throughout the melt and homogenize the temperature of the melt. Homogenization of the concentration gradients will tend to lead to suppression of dendrite formation and hence spheroid formation.

4. Concluding remarks

A decrease in pouring superheat leads to an increase in spheroidicity when A356 is subjected to cooling slope treatment. The microstructure of the remnant material from the slope indicates that some spheroidisation can be achieved on

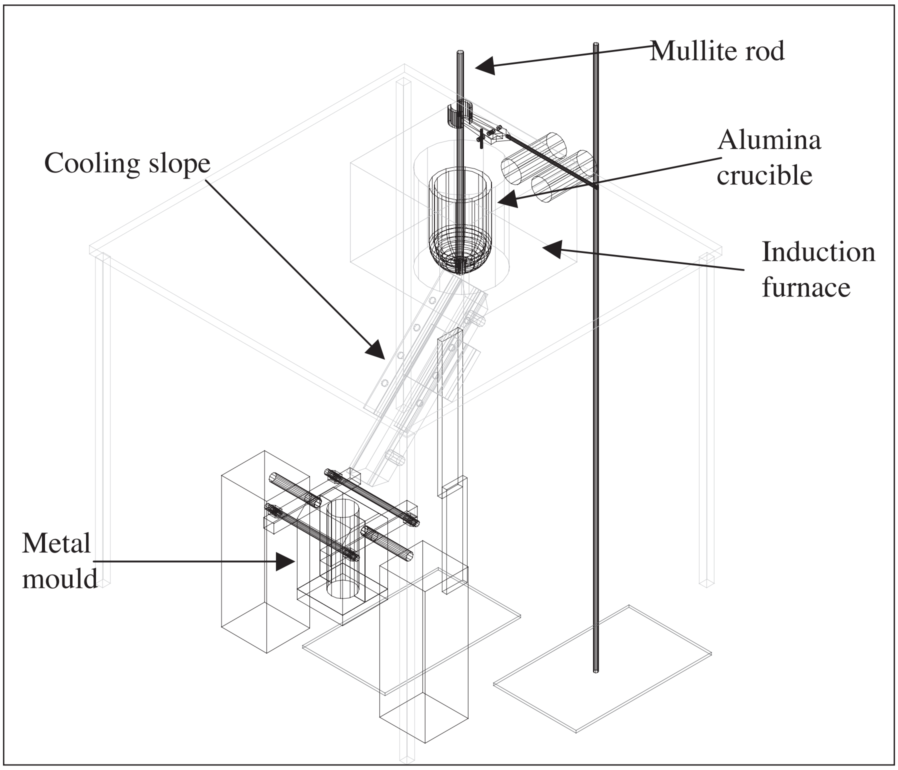

Figure 3: Cooling slope with bottom pouring from the crucible.

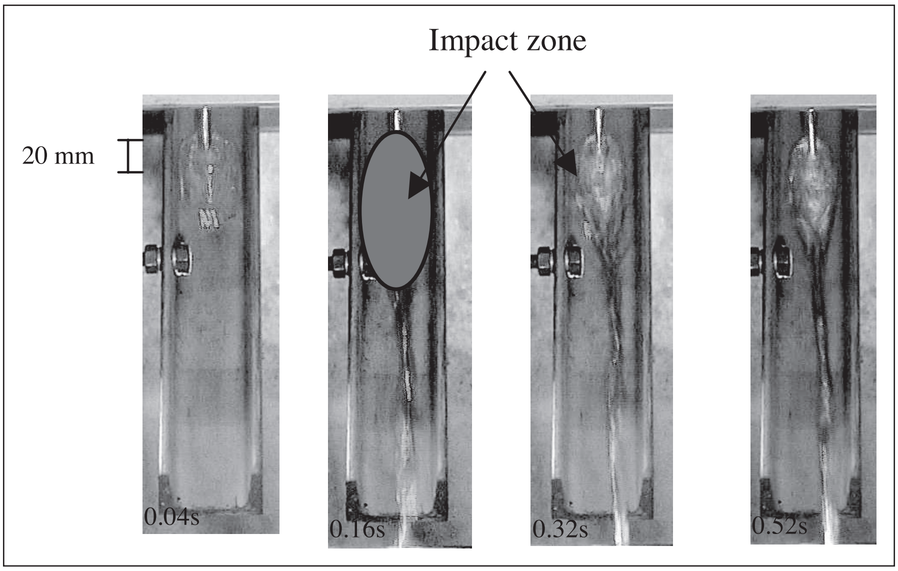

Figure 4: Sequential video images showing the molten A356 impacting on the cooling slope and then running as a narrow 'snake' down the cooling slope. Length of the cooling slope was 250 mm.

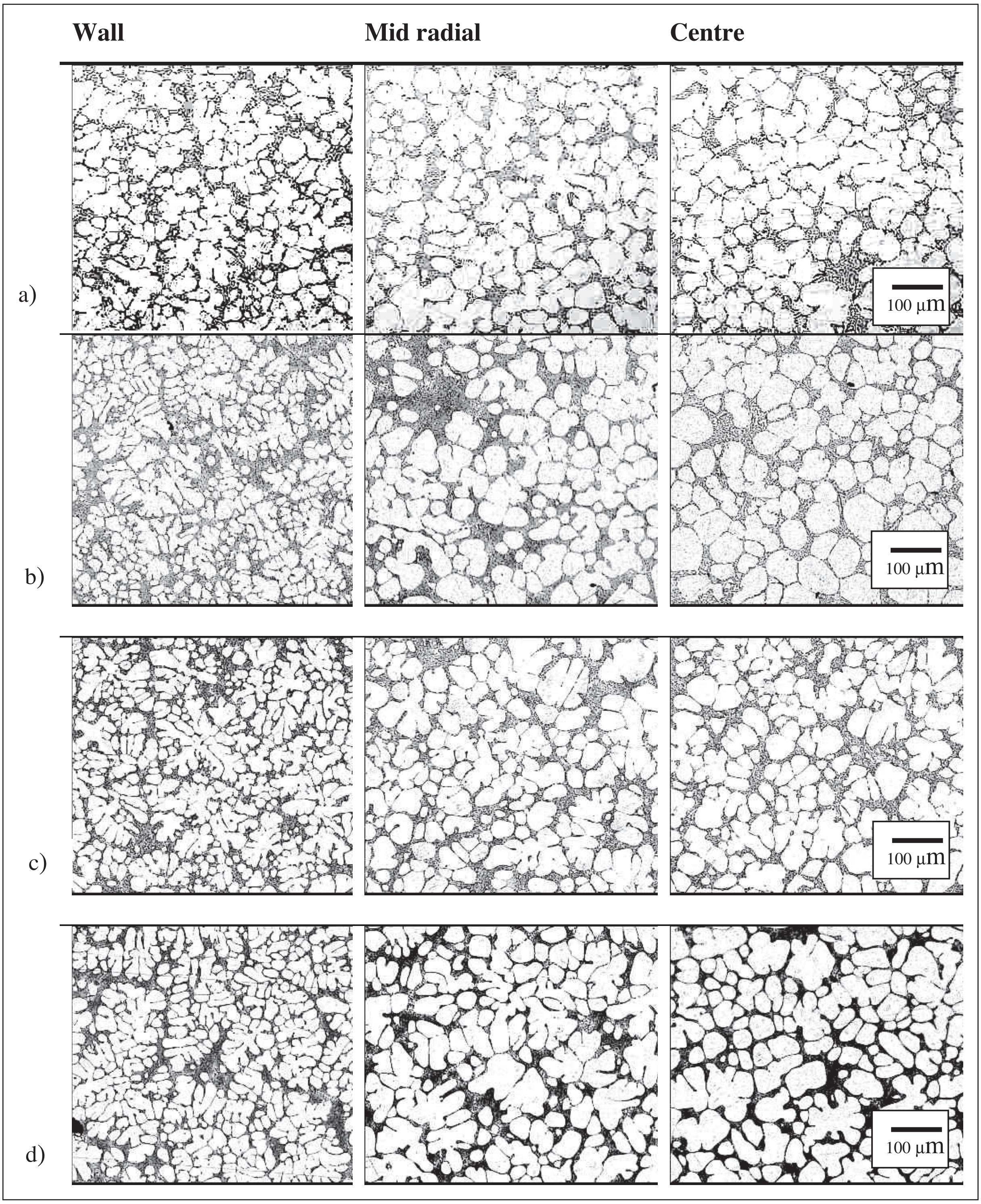

Figure 5: Effect of pouring temperature on samples poured into a cold stainless steel mould and then quenched. a) 620°C, b) 630°C, c) 650°C, d) 680°C.

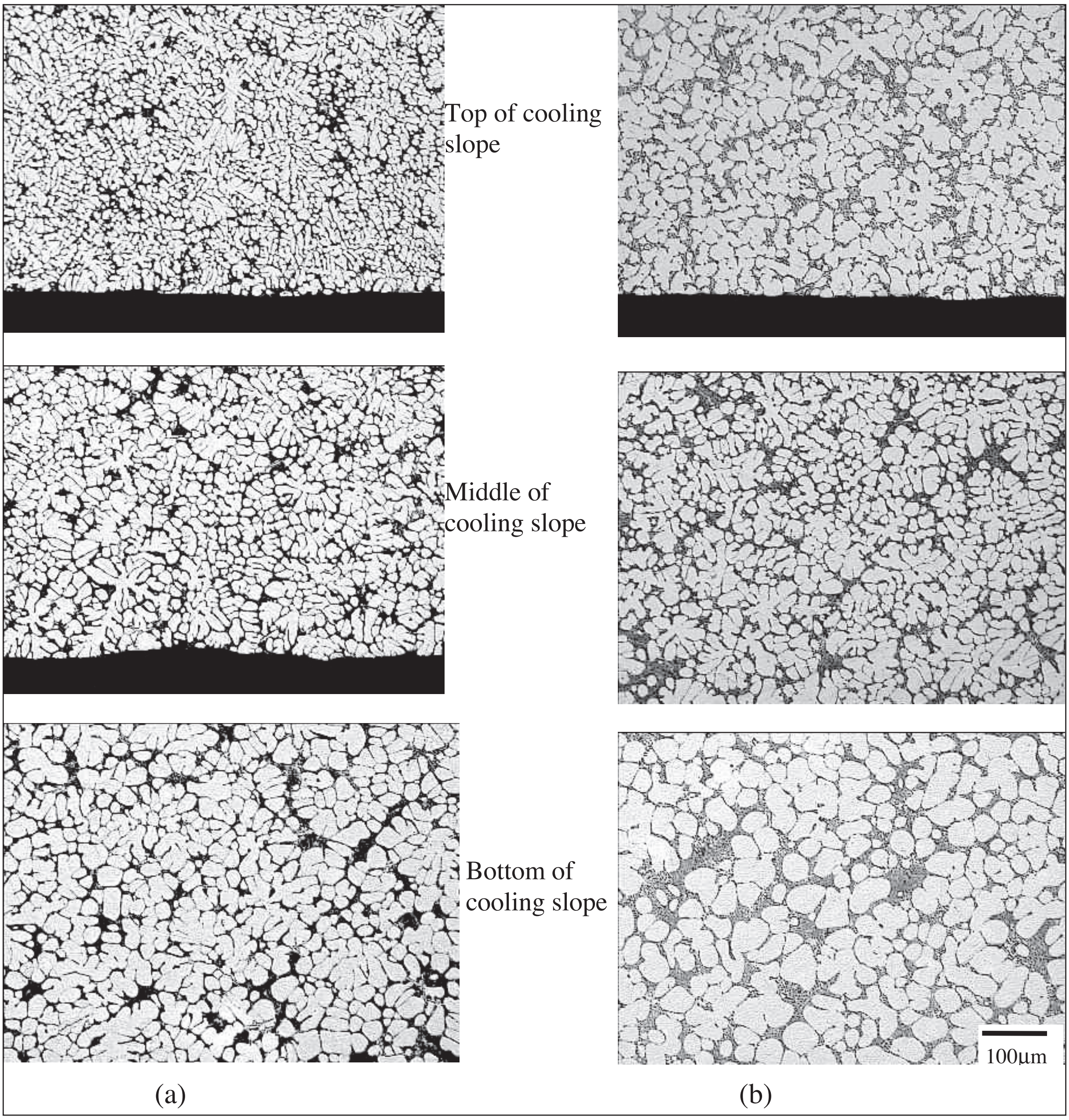

Figure 6: Microstructure of the remnant A356 on the cooling slope tilted at 45° and poured at: a) 630°C, 150 mm, b) 630°C, 250 mm.

the slope rather than in the ingot mould (although spheroidisation may continue there). It is thought that the area of the 'impact zone' (i.e. the area where the molten metal first contacts the slope) plays an important role in determining the resulting microstructure and that this dominates over the cooling length (the length of the slope where the metal is in contact overall).

Acknowledgements

ECL would like to thank the National Council of Science and Technology of Mexico (CONACyt) and SEP for financial support along with the Universidad Autónoma del Estado de Hidalgo. The authors are grateful to the Department of Engineering Materials at the University of Sheffield for the provision of laboratory facilities and to Dr Plato Kapranos for assistance with experiments.

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