

Grain Morphology of As-Cast Wrought Aluminium Alloys

Mark Easton^{1,2}, Cameron Davidson^{1,3}, David StJohn^{1,4}

¹CAST Co-operative Research Centre

²Department of Materials Engineering, Wellington Road, Monash University, Vic 3800 Australia

³CSIRO Process Science and Engineering, 1 Technology Court, Pullenvale, Qld 4069, Australia

⁴School of Mechanical and Mining Engineering, Staff House Road, The University of Queensland, Qld 4072, Australia

Keywords: Grain size, dendrite arm spacing, cooling rate, constitutional undercooling.

Abstract

Two of the most important microstructural features of alloys are the grain size and the dendrite arm spacing (DAS). Both grain refinement and the DAS depend upon alloy composition through constitutional undercooling, but in different ways. Grain size tends to be related to the initial rate of development of constitutional undercooling, whilst the DAS is more related to the amount of solute build-up towards the end of the solidification process. This means that element additions that have a large effect on the grain size, e.g. Ti, have much less effect on the DAS. With examples from a range of wrought Al alloys, this paper investigates how the interaction between alloy content, grain refiner additions and cooling rate affect the grain size, DAS and the grain morphology obtained in an alloy.

1. Introduction

Two of the key microstructural parameters in the as-cast microstructure of an alloy are the grain size and the dendrite arm spacing (DAS). Fundamentally, these parameters can be used to describe the morphology of a grain. Where the grain size is large and the dendrite arm spacing is small, the grains are dendritic; when the grain size is only a little greater than the dendrite arm spacing then a rosette or cellular grain morphology is observed, and if the grains are spherical or globular then no dendrites are observed. The grain size, DAS and grain morphology affect various properties of the alloy including their castability [1, 2], especially hot tearing resistance [3], and their mechanical properties [4].

There has been considerable work on determining the factors that affect grain size. These include the alloy composition [5-7], the number density and potency of nucleant particles [8] (which is influenced by particle size [9]), and the cooling conditions [10, 11]. Some of these factors also affect the DAS, especially the cooling rate and the alloy composition [12, 13], whilst others are less influential, i.e. nucleant particle number and potency.

The factor that is influenced by both alloy composition and cooling rate is constitutional undercooling (CU) and this influences both the grain size and the DAS. The parameter that is used to link both factors is the growth restriction factor,

$$Q = \sum_j m_j c_j (k_j - 1) \quad (1)$$

where m_l is the liquidus gradient, c_o is the alloy composition and k is the partition coefficient for each element j in the alloy. A simple equation has been found for linking the grain size and the alloy constitution through this parameter [8, 14], i.e.

$$d = \frac{1}{\sqrt[3]{fN_v}} + \frac{D \cdot \Delta T_n}{v \cdot Q} \quad (2)$$

where ΔT_n is the nucleation undercooling, N_v is the number of those particles, and f is the proportion that are active, D is the diffusion coefficient and v is the growth velocity. The cooling rate affects the growth velocity and a square root relationship has been found [6, 10].

The relationship between the DAS and Q is not quite as simple. Using a diffusion ripening model the DAS, can be related to the solidification time, t_f , through

$$\lambda_2 = 5.5(Mt_f)^{0.33} \quad (3)$$

$$M = \frac{-\Gamma}{\sum_{j=1}^n (Q_{0,j} - Q_{f,j})/D_j} \cdot \ln \left[\frac{\sum_{j=1}^n -Q_{f,j}/D_j}{\sum_{j=1}^n -Q_{0,j}/D_j} \right] \quad (3a)$$

for multi-component alloys [15, 16]. In this case there are two parameters related to Q : Q_0 at the beginning of solidification, which is the same as used in Equation 2 and Q_f at the end of solidification which is determined using the composition of the final segregated liquid. This formulation works reasonably well for the prediction of DAS in many alloys, but is limited by the assumptions in the model and factors other than diffusion controlled ripening influencing the DAS in commercial alloys [16].

2. Experimental

The details of the experimental procedure are described elsewhere [8, 10, 16]. In summary, four wrought alloys from the 1000 to 6000 series, which have a variety of alloying elements and Q values, were solidified at four cooling rates ranging from 0.3 to 15°C/s. A constant addition of 0.005wt% TiB₂ by an Al-3wt%Ti-1wt%B master alloy was made to each alloy so that the nucleant population was essentially equivalent for all of the alloys investigated. At the cooling rate of 1°C/s an additional three alloys were studied at two additional TiB₂ contents. Castings 40mm high and 30 mm in diameter were made in graphite moulds.

Metallographic samples were sectioned approximately 10mm from the base of the ingots. These were mechanically polished and anodised using a 0.5% HBF₄ solution for approximately 2 minutes at 20V. These samples were viewed optically with polarised light and the grain sizes were measured using a linear intercept technique (ASTM 112-96). At least two fields were calculated for each measurement with approximately 100 intercepts in each field depending on the grain size. The dendrite arm spacing was measured by finding a number of adjacent dendrite arms from one primary dendrite arm and measuring the distance between the dendrite centres. Wherever possible at least two fields were analysed for each measurement with approximately 50 secondary dendrite arms from multiple primary dendrite arms being counted in each field.

3. Results and Discussion

It is well known that the addition of Ti solute leads to a substantial decrease in the grain size for low solute alloys, such as alloy 1050 (Figure 1(a)), but has little effect on the grain size of alloys which have a much higher concentration of alloying elements (Figure 1(b)). However, the Ti content has little effect on the DAS in either case. This can also be seen pictorially in Figure 2.

Especially in alloy 1050 but also alloy 2014, the initial addition of grain refiner substantially decreases the grain size and the alloy is less dendritic. Since the addition of Ti further decreases the

grain size in alloy 1050, the grain morphology changes such that grains with a cellular or rosette morphology are observed. It is impossible to measure DAS on grains with such morphology, and consequently this point is missing from Figure 1(a). It appears that when the grain size to DAS ratio is below 3 and especially when it is close to 2, the measurement of DAS becomes impossible.

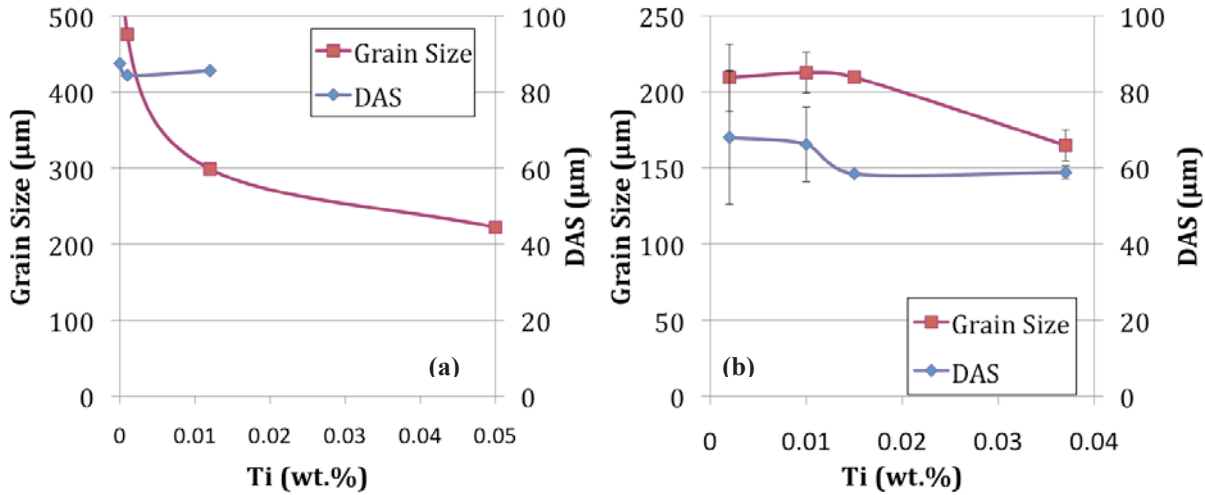


Fig. 1. Variation of grain size and DAS with the amount of Ti for (a) alloy 1050 and (b) 2014 at a cooling rate of 1°C/s and a TiB₂ addition of 0.005.wt.% as Al-3Ti-1B. There is no point for DAS at 0.05wt.% Ti as the grains were no longer dendritic.

Ti solute additions affect the grain size substantially in low solute alloys, as the effect of Ti on Q is almost two orders of magnitude greater than any other common element used for alloying with Al. However, Ti additions have very little effect on the DAS. This was found to be because Ti has little effect on the final value, Q_f , and this has a much greater influence over the DAS than the initial high value of Q_0 [16]. The reason for the large effect on Q_0 and the small effect on Q_f is because Ti is a peritectic element that segregates very strongly into the α -Al phase at the beginning of solidification and consequently has little effect on the CU at the end of solidification.

As noted earlier, the other important factor to consider is the cooling rate, as an increase in cooling rate is known to decrease both the grain size and the DAS. This is particularly observed in Figure 3, where it is apparent that when the cooling rate increases the grain size decreases, but there is also an obvious change in grain morphology from spherical to equiaxed dendritic. Figure 4(a) shows how the grain size and DAS are reduced by the cooling rate. The grain size reduces according to an equation of the form [10]

$$d = \frac{1}{\sqrt[3]{f(\dot{T})N_v}} + \frac{D \cdot \Delta T_n}{Q \cdot c \dot{T}^{1/2}} \quad (4)$$

where the cooling rate affects the number of active nucleants, and the growth velocity v is related to the square root of the cooling rate, in equation 2, via a fitting factor, c . This is because the thermal gradient and growth velocity are coupled in the solidification conditions used here.

Given that t_f is inversely proportional to the cooling rate, it would be expected that the cooling rate would reduce DAS according to the power-law relationship with the power of 0.33 (equation 3). The measured power exponent for these alloys ranged from 0.33-0.5 [16] which is a typical range of observed variation [17]. Even though the power index for cooling rate is similar for DAS and grain size, since increasing cooling rate tends towards a positive finite value rather than zero as it does for the DAS, the grains become more dendritic.

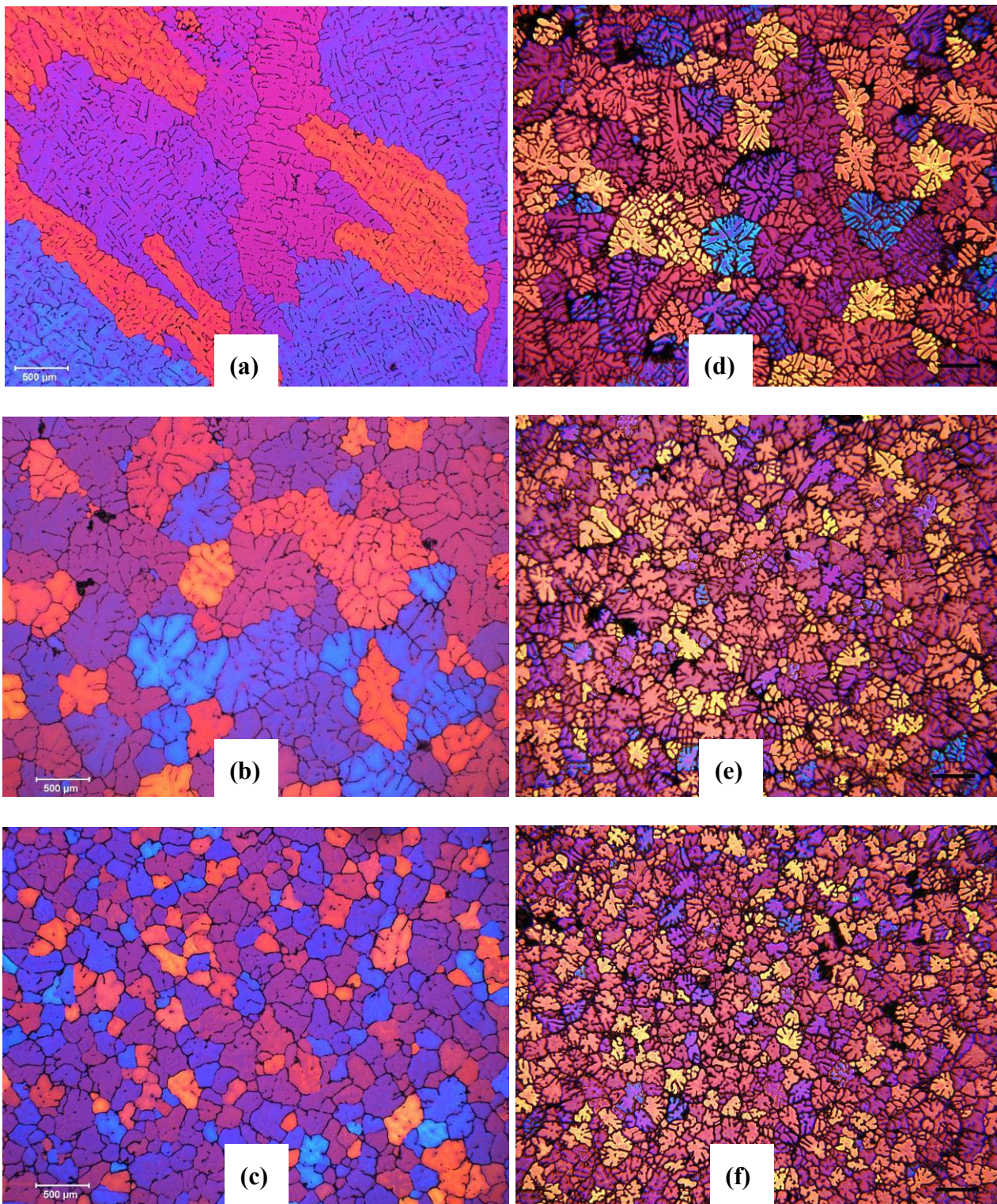


Fig. 2. Optical micrographs viewed under polarised light of alloy 1050 (a) without grain refiner addition (b) with 0.01%TiB₂ using a Al-3Ti-1B master alloy (c) with 0.02%TiB₂ and the addition of 0.05Ti solute and alloy 2014 (d) without grain refiner addition (e) with 0.01%TiB₂ using a Al-3Ti-1B master alloy (f) with the addition of 0.05Ti solute. The scale bar on all images is 500μm.

The grain size to DAS ratio increased with cooling rate for all alloys (Figure 4(b)). As was mentioned earlier, this ratio affects whether the DAS can be measured in a grain. For example, in Figure 3(a) a cellular morphology is observed and the d:DAS ratio is approximately 3.1, whilst in Figure 3(b), the ratio is only 1.5 assuming the same DAS as measured from Figure 3(a) and the grain morphology is definitely spherical. This suggests that a criterion can be used to define grain

morphology, i.e. if the d/DAS ratio is less than 2, the grain morphology is spherical or globular, when it is between 2 and 4 it is rosette-like or cellular and above 4 it is equiaxed dendritic.

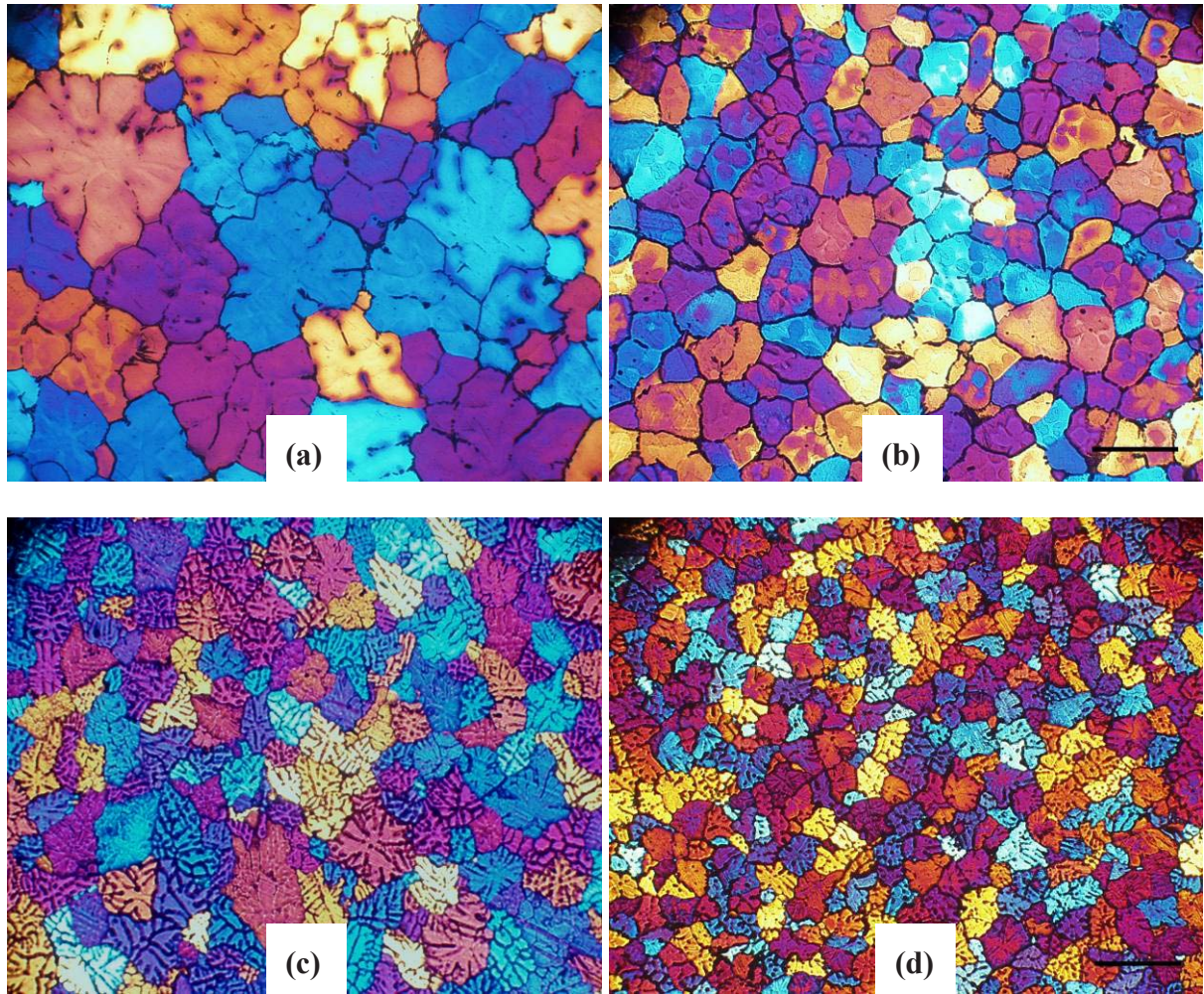


Fig. 3. Optical micrographs viewed under polarised light of Alloy 1050, grain refined with (a) 0.005wt.% TiB_2 at a cooling rate of $0.3^\circ C/s$, (b) with a further addition of 0.05wt.%Ti solute addition also at $0.3^\circ C/s$ and (c) 0.005wt.% TiB_2 at a cooling rate of $15^\circ C/s$ and (d) with a further addition of 0.05wt.%Ti solute addition also at $15^\circ C/s$. The scale bar on the images is $500\mu m$.

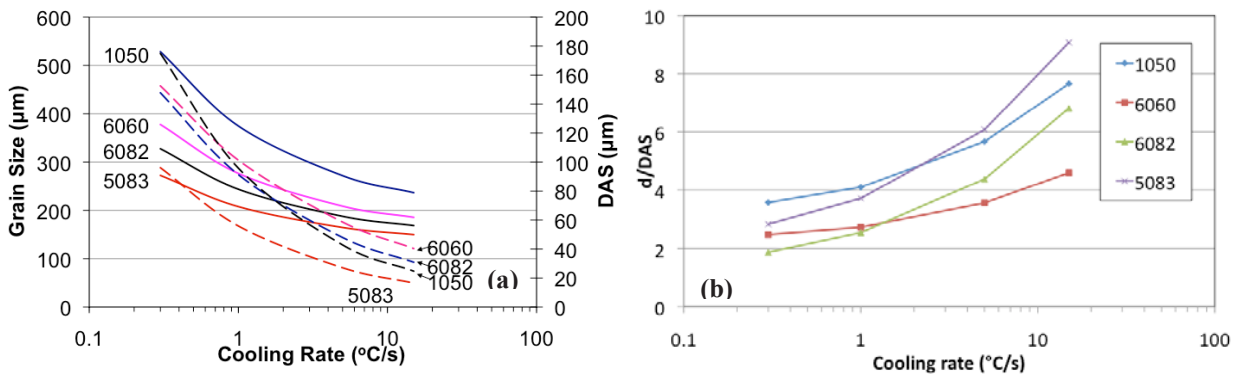


Fig. 4. (a) The effect of increased cooling rate on the grain size (full line) and DAS (dashed line) of the alloys which contain 0.005wt/% TiB_2 as Al-3Ti-1B [18]. (b) The ratio of grain size to DAS against cooling rate.

4. Summary and Conclusions

Both the grain size and the DAS are affected by alloy composition and cooling rate through CU parameters. The big difference is that the grain size is affected by the constitutional conditions as solidification begins, whilst the DAS is more affected by constitutional undercooling generated by the liquid remaining near the end of solidification. Hence solute additions that have a large effect on the grain size, such as Ti, do not have such a large effect on the DAS. Increasing cooling rate decreases both the DAS and the grain size, although it has a greater effect on the DAS despite having similar power-law relationships. This is because the grain size is also dependent upon the number of active nucleant particles in the melt, which provide a limit to the amount of refinement that can occur purely by increasing the cooling rate. The DAS, however, tends towards zero as the cooling rate increases. The different effects of solute addition and cooling rate on grain size and DAS means that a wide variety of grain morphologies can be generated. It is suggested that the ratio of grain size to DAS can be used to define the grain morphology. At ratios less than two the grain morphology is spherical, between 2 and 4 it is rosette-like or cellular and above 4 it is equiaxed dendritic. At ratios less than 3, the DAS can be difficult to measure directly, but can be calculated using equation 3, or indicative measurements can be obtained from less grain refined alloys of the same composition and at the same cooling rate.

Acknowledgements

The CAST Co-operative research centre was established under, and is supported in part by the Australian Government's Cooperative Research Centres scheme. Yeannette Lizama is thanked for her assistance with the metallography.

References

- [1] M.A. Easton and D.H. StJohn: *Inter. J. Cast Metals Res.*, Vol. 12, (2000), p. 393.
- [2] A. Dahle, S. Karlsen, and L. Arnberg: *International Journal of Cast Metals*, Vol. 9, (1996), p. 103.
- [3] S. Lin, C. Aliravci, and M.O. Pekguleryuz: *Metall. Mater. Trans. A*, Vol. 38A, (2007), p. 1056.
- [4] C. Càceres and Q. Wang: *Inter. J. Cast Metals Res.*, Vol. 9, (1996), p. 157.
- [5] I. Maxwell and A. Hellawell: *Acta Metall.*, Vol. 23, (1975), p. 229.
- [6] M. Johnsson: *Z. Metallkde.*, Vol. 85, (1994), p. 781.
- [7] M.A. Easton and D.H. StJohn: *Acta Mater.*, Vol. 49, (2001), p. 1867.
- [8] M.A. Easton and D.H. StJohn: *Metall. Mater. Trans. A*, Vol. 36A, (2005), p. 1911.
- [9] T.E. Quested and A.L. Greer: *Acta Mater.*, Vol. 52, (2004), p. 3859.
- [10] M.A. Easton and D.H. StJohn: *Mater. Sci. Engng. A*, Vol. 486, (2008), p. 8.
- [11] D.H. StJohn, M.A. Easton, and M. Qian: *Solid State Phenomena*, Vol. 141-143, (2008), p. 355.
- [12] K.P. Young and D.H. Kirkwood: *Metall. Trans. A*, Vol. 6A, (1975), p. 197.
- [13] M. Bamberger, B.Z. Weiss, and M.M. Stupel: *Mater. Sci. Technol.*, Vol. 3, (1987), p. 49.
- [14] M. Qian, *et al.*: *Acta Mater.*, Vol. 58, (2010), p. 3262.
- [15] M. Rappaz and W.J. Boettinger: *Acta Mater.*, Vol. 47, (1999), p. 3205.
- [16] M.A. Easton, C.J. Davidson, and D.H. StJohn: *Metall. Mater. Trans. A*, Vol. 41A, (2010), p. 1528.
- [17] L. Bäckerud, E. Król, and J. Tamminen, *Solidification characteristics of aluminium alloys vol. 1*, ed. L. Bäckerud. (Skandaluminium, Universitetsforlaget AS, Oslo, Norway, 1986).
- [18] M.A. Easton, J.F. Grandfield, D.H. StJohn, and B. Rinderer: *Mater. Sci. Forum*, Vol. 519-521, (2006), p. 1675.