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An Analysis of the Effect of Grain Refinement on the Hot Tearing of Aluminium Alloys

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Abstract

Using the CAST hot tearing rig, grain refinement was found to delay the onset of strength development and load transfer in the mushy zone and reduce the severity of hot tearing. A modified RDG model for dendritic equiaxed grains predicted that grain refinement reduces the hot tearing susceptibility by delaying strength development and interdendritic feeding. However, a modified RDG model for cellular equiaxed grains suggested that reducing the grain size should also decrease the permeability of the mush consequently increasing the hot tearing susceptibility. Over grain refinement leading to hot tearing has been observed elsewhere. It was concluded that a fine equiaxed, dendritic grain morphology was optimum to reduce hot tearing.

1. Introduction

An important reason for the addition of grain refining master alloys in direct chill casting is to reduce the rate of hot tearing/cracking. However, the mechanism by which grain refiners reduce the rate of hot tearing is not obvious. It is commonly known that columnar and twinned columnar crystals are detrimental to hot tearing [1], due to the load concentrations at grain boundaries and the easy crack path through the microstructure. Hence a columnar to equiaxed transition facilitated by grain refiners is important to achieve an equiaxed microstructure. However, it is not clear whether it is only important to obtain an equiaxed grain structure or whether it is important to refine the grain structure as much as possible to reduce the hot tearing susceptibility.

One of the most advanced hot tearing prediction models is that of Rappaz, Drezet and Gremaud (RDG) [2]. This model calculates the pressure drop in the interdendritic liquid due to the feeding of shrinkage and imposed displacement between grains caused by thermal stresses. If the pressure is sufficient a hot tear is assumed to form in the region of the mush where solid bonding has not yet occurred, i.e. at fraction solid less than the solid bonding coherency point. Thus, the incidence of hot tearing is a function of the rate of strain imposed on the mush, the length and permeability of the mush, the fraction solid versus temperature curve and the coherency fraction solid. The correlation between hot tearing and strain rate has been recently confirmed experimentally in direct chill casting by M'Handi et al [3]. A modification of this model assumes that hot tear propagation is a function of the capillary pressure and thus intergranular liquid film thickness [4]. Grain size does not appear as a parameter in the RDG model as it was developed for columnar grain morphologies and does not explain the effect of grain refinement on hot tearing.

The RDG model can be modified to incorporate grain refinement effects in three ways:
1. Changing the permeability length scale from the secondary dendrite arm spacing (DAS) in the case of columnar grains to the grain size in the case of equiaxed grains because these grains have more globular than dendritic grain morphologies,
2. Changing the upper and lower limits of the integral/region over which feeding occurs, i.e. the solid bonding coherency point and the fraction solid at which it stops behaving like a liquid, and
3. Changing the capillary pressures by changing the liquid film thickness between grains. Smaller grain size implies thinner liquid films between grains at a given fraction solid and therefore greater capillary pressures to be overcome before a tear propagates.

If factor 1 is predominant then the purpose of grain refinement is solely to obtain an equiaxed grain structure and further grain refinement is unnecessary or even slightly detrimental, as further reductions in grain size will decrease the permeability [5], thus grain refiner additions can be minimised. If producing a fine equiaxed grain structure is important, i.e. factor 3, then addition levels above the minimum grain refinement addition required for the achievement of the columnar to equiaxed transition will be beneficial in reducing hot tearing susceptibility. How grain refinement affects factor 2 has yet to be determined but it is known that it delays the onset of initial strength development during solidification [6]. This means that the mushy zone is pliable, i.e. acts more like a liquid than a solid, reducing the build up of shrinkage stresses for longer, as thermal strains cannot be transmitted when the mush has no strength, and possibly reducing the susceptibility to hot tearing. However, there are reports of ‘over grain refinement’ leading to increase in hot tearing rates at grain sizes of less than 100μm [7].

A modification of the RDG model incorporating these three factors has been developed by Grandfield et al [4]. The calculated hot tearing susceptibility for equiaxed grain structure (HCC_e) is the inverse of the critical strain rate for hot tearing csr_e,

$$csr_e = \frac{d^2}{180(1+\beta)B\mu L^2}\left[P_m + \frac{4\gamma}{d\left(1-\sqrt[3]{f_{scoh}}\right)}\right] - \frac{V\beta A}{(1+\beta)BL} \tag{1}$$

where

$$A = \frac{1}{T_l - T_{coh}}\int_{T_{coh}}^{T_{mpk}} \frac{f_s(x)^2}{\left(1-f_s(x)\right)^2}.dx\,,\quad B = \frac{1}{T_l - T_{coh}}\int_{T_{coh}}^{T_{mpk}} \frac{f_s(x)^2 F(x)}{\left(1-f_s(x)\right)^3}.dx\,,\quad F(x) = \frac{1}{T_l - T_{coh}}\int_{T_{coh}}^{T_{mpk}} f_s(x).dx\,,$$

d is the equiaxed grain size, μ viscosity, γ surface tension, P_m metal head pressure, β bulk shrinkage, V growth rate, L length of the mushy zone, f_s fraction solid, T_{mpk} the temperature at which strain is transferred through the mushy zone and T_{coh} is the solid coherency temperature. This equation indicates that there is a substantial reduction in hot tearing susceptibility on the columnar to equiaxed transition when compared with the original RDG model. Equation 1 suggests that factor 1 will be predominant over factor 3.

Another modification, proposed by the current authors, which is useful for dendritic equiaxed grains as distinct from cellular equiaxed grains, assumes that the grain size affects factors 2 and 3 but not 1,

$$csr_e = \frac{\lambda^2}{180(1+\beta)B\mu L^2}\left[P_m + \frac{4\gamma}{d\left(1-\sqrt[3]{f_{scoh}}\right)}\right] - \frac{V\beta A}{(1+\beta)BL} \tag{2}$$

where λ is the secondary DAS.

The purpose of this paper is to investigate how grain refinement affects hot tearing and to subsequently suggest the optimum grain morphology required to minimise hot tearing from an experimental basis (hot tearing rig) and theoretical basis (modified RDG model).

2. Experimental Methods

Alloy 6061, containing 0.8%Si, 0.7%Mg, 0.2%Fe, 0.1%Cu, 0.05%Mn and 0.2%Cr, was cast in the hot tearing rig with no grain refiner addition (0.001% Ti) and for Al5Ti1B grain refiner additions at 0.005, 0.01 and 0.05% Ti. All compositions in this paper are given in weight percent.

The hot tearing rig has been described extensively elsewhere [8]. The rig consists of two bars with constrained ends, fed from the same riser. One cast bar is connected to a tensile machine that measures the load developed during solidification. The load measured is an indication of the balance of the stress developed in the solid skeleton due to the strain applied due to solidification shrinkage and the ability of the mush to relax that stress. The other bar is fixed at both ends to act as an I-beam for hot tearing observation. The measured load development on cooling has been previously related to the hot tearing susceptibility of the alloy [8].

The grain size and DAS of the alloys were measured by the linear intercept technique described in ASTM standard E112-96 on anodised samples viewed under polarised light.

As a comparison to the experimental work, the modified RDG models were used for theoretical analysis of the same alloy system (both equations 1 and 2). For the RDG modelling, the fraction solid was determined by ThermoCalc®, T_{coh} is taken to be 536.7°C for alloy 6061, which is the final eutectic and a fraction solid of 0.99. The physical properties of the alloy used were from Rappaz et al [2]. Casting parameters that approximate VDC casting were used in this analysis.

3. Experimental Results

At the beginning of solidification, there is no strength in the material (Figure 1). As solidification continues a load begins to develop which indicates that the material is starting to resist deformation, suggesting that a solid network is forming. Non-grain-refined alloy (0.001%) and the alloy with the lowest grain refiner addition (0.005% Ti) start to develop strength at about 620-625°C, while the well grain-refined alloys (0.01% and 0.05%Ti) develop strength at about 600-610°C. As temperature decreases further, the measured load increases, initially at a very low rate and then increasing more rapidly, which appears to correspond with the formation of the eutectic structures.

The alloy without grain refiner addition has a columnar grain structure with a very large grain size (Figure 2). By adding grain refiner to a level of 0.005%Ti, the material still has a columnar structure but also has some equiaxed features, with a grain size of approximately 450 μm. Further increases in grain refinement leads to a finer equiaxed microstructure, with grain sizes of approximately 290 and 200 μm for the 0.01 and 0.05% Ti respectively. In all cases, the DAS was approximately 60 μm.

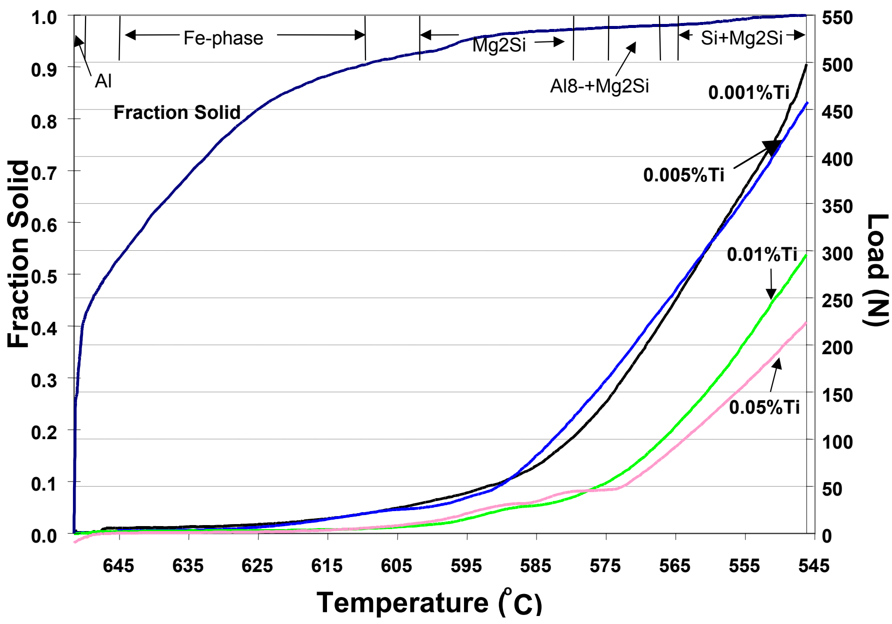

Figure 1: Load development of alloy 6061 during solidification with different grain refiner levels as indicated. Fraction solid value and phase formation as temperature decreases are also indicated.

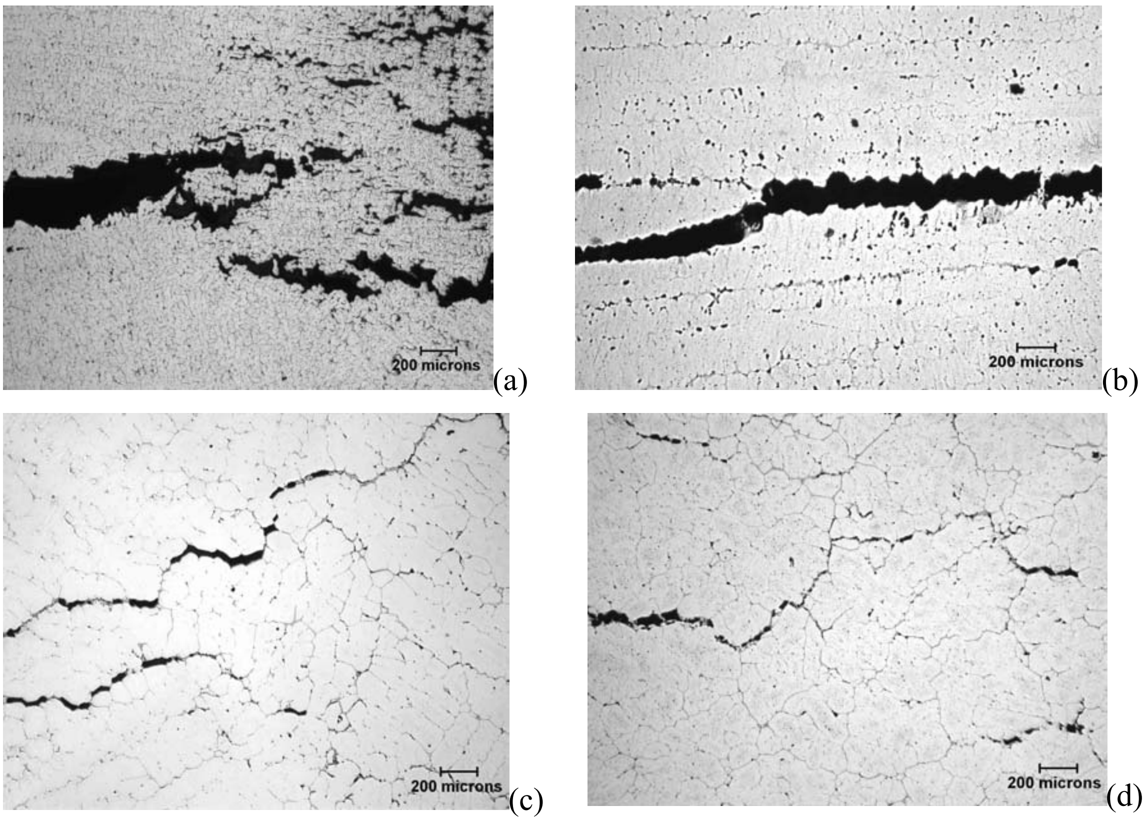

Figure 2: Optical micrographs showing microstructural features in the hot spot area of cast bars for alloy 6061. (a) 0.001%Ti, (b) 0.005%Ti, (c) 0.001%Ti and (d) 0.05%Ti. The tensile stress is applied in the vertical direction relative to the micrographs.

It is observed that the load developed decreases with increased addition of grain refiner (Figure 1). Figure 2 shows that the severity of the cracking observed also decreases as the grain refiner additions are increased, even for decreasing equiaxed grain size. Therefore it appears that in the range of grain sizes observed here, the hot tearing decreases with grain size and the load response of the alloy as measured in the rig gives a good indication of the hot tearing susceptibility of the alloys.

4. Discussion

Figure 1 shows that load development begins later in the grain refined samples. This indicates that grain refinement delays the strength development and that the mush is more pliable, i.e. more liquid-like, until later in the solidification sequence. If it is assumed that the onset of load development is equivalent to T_{mpk} in equation 1, then the effect of this can be analysed using the modified RDG model.

In Figure 3, the effect of both the grain size and the temperature at which strength develops and interdendritic feeding begins, i.e. T_{mpk}, on the hot tearing susceptibility according to equation 1 is shown. As the grain size decreases, the hot tearing susceptibility increases, particularly at grain sizes of 200-400 μm, due to the decrease in permeability. Countering this is the effect of delayed onset of interdendritic feeding caused by grain refinement, which decreases the hot tearing susceptibility. The model calculations for the alloy discussed in this work, indicates that the magnitude of these two effects are similar in opposite directions (Table 1), with the permeability effect being slightly stronger. Therefore equation 1 cannot explain the reduction in hot tearing caused by grain refinement observed in the experimental results (Figure 2).

However, if equation 2 is used instead, a decrease in the hot tearing susceptibility is observed with increased grain refinement (Table 1), which more closely matches the experimental results (Figure 2). Therefore, it appears that reducing the grain size reduces the hot tearing susceptibility by delaying the fraction solid (or temperature) at which strength develops, i.e. when strain can be transferred, and by reducing the liquid film thickness reducing the propagation of hot tears. In other words, factors 2 and 3 identified in the introduction are operating but factor 1 is not.

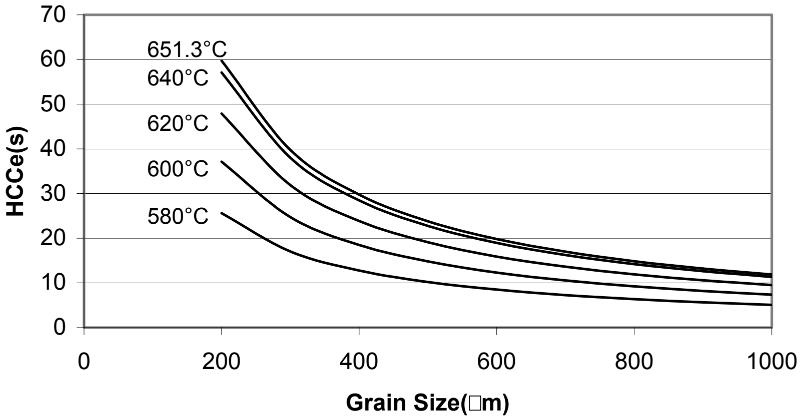

Figure 3: The effect of changing the temperature at which strain can be transferred through the mushy zone, T_{pmk}, and grain size on the hot tearing susceptibility (HCC_e) for equiaxed grains for alloy 6061, according to equation (1).

Table 1. Table showing the hot crack susceptibility (HCC_e) calculated for the RDG model for each of the grain refiner levels in the experimental work. The grain size was adjusted from the measured lineal intercept value to a grain size according to [9].

Ti content	Grain size (μm)	Adjusted grain size (μm)	Load onset (°C)	HCC_e (s) Equation 1	HCC_e (s) Equation 2
0.005	450	758.7	620	12.5	20.1
0.01	290	488.7	605	17.7	10.8
0.05	220	370.9	595	18.5	7.0

Factor 1 is probably not important in the experimental results, because the equiaxed grains have a dendritic morphology and hence the DAS is probably the length scale affecting the permeability. However, if the grain size is refined further, with the DAS remaining constant, the grain morphology would become more cellular and hence equation 1 may be a better description of the hot tearing behaviour than equation 2. This means that the hot tearing susceptibility will increase again for cellular equiaxed grain morphologies. This observation is supported by the work of Warrington and McCartney [7] on 7000 series alloys. They found that dendritic equiaxed grain morphologies had lower hot tearing susceptibilities than finer grain sizes with a more cellular grain structure.

Therefore the results presented appear to agree with the conclusions of Warrington and McCartney [7], in that the grain morphology, as well as the grain size is important in hot tearing. Using the two different modifications to the RDG model (equations 1 and 2) to incorporate different equiaxed grain morphologies rather than just the grain size provides the basis for explanation of the experimental data. Thus, it can be hypothesized that the grain morphology to reduce hot tearing is equiaxed and small, but with a dendritic morphology.

Since the grain size and morphology depends upon the solidification conditions and the alloy constitution, the optimum grain size will depend on these factors, which should be the focus of future work.

5. Conclusions

From experimental results and model predictions, it was found that grain refinement decreased the hot tearing susceptibility by causing a columnar to equiaxed transition and by reducing the equiaxed grain size. An important factor, confirmed by both experimental results and the model predictions is that the point at which the mush began to behave more like a solid than a liquid is delayed. However, it was also predicted that if the grain size were reduced, the permeability of the mush would decrease causing the hot tearing susceptibility to increase. Evidence of this was not observed experimentally, probably because the grains were found to have a dendritic equiaxed morphology. However refinement of a cellular equiaxed grain morphology may increase the hot tearing susceptibility for the stated reason. Thus, it is proposed that a fine dendritic equiaxed grain morphology has the greatest resistance to hot tearing.

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