Quantitative Analysis of Grain Refinement via Residual Stress Measurements in Cast Aluminum Alloys by Neutron Diffraction

F. D'Elia¹, C. Ravindran¹, and D.G. Sediako²

- ¹ Department of Mechanical and Industrial Engineering, Ryerson University, Toronto, ON, Canada M5B2K3
- ² National Research Council, Canadian Neutron Beam Centre, Chalk River, ON, Canada

Introduction

There is an enhanced interest in aluminum casting alloys for automotive and aerospace applications. The interest in these alloys is spurred by the need to produce lighter and more fuel efficient vehicles. The aluminum-copper (Al-Cu) casting alloys are among the most common aluminum casting alloys. B206 is a relatively new Al-Cu alloy with excellent mechanical properties, high temperature strength and good low-cycle fatigue properties. However, despite the advantages, this alloy is very difficult to cast. Its long freezing range makes interdendritic feeding during solidification difficult, thereby resulting in numerous casting defects, including porosity and hot tears [1].

Hot tears are cracks forming during casting solidification as a result of insufficient feeding in areas of elevated stress [2]. The stresses responsible for these tears are thermal stresses generated during solidification and mechanical stresses resulting from restrained casting contraction. A better understanding of the methods to improve hot tearing resistance of B206 would enable wider use of this alloy in industrial applications.

Extensive research has been carried out on the effect of grain refinement on hot tearing [3, 4, 5, 6]. Past studies determined that grain refinement has a beneficial effect on reducing hot tearing and that two mechanisms are responsible. The first mechanism is related to the grain structure. Specifically, a fine globular grain structure allows grain sliding during high temperature deformation, thereby alleviating evolving strains [3, 4]. The second mechanism is related to the permeability of liquid through interdendritic regions. In an alloy with heavily branched dendrites, liquid metal flow must be accommodated via narrow interdendritic regions, while in an alloy with equiaxed grains, liquid metal easily flows via larger intergranular regions [5, 6]. Despite the commonly known beneficial effect of grain refinement on reduction of hot tears, no literature is available with quantitative data relating grain refinement to hot tearing.

In this research, neutron diffraction (ND) was used to measure elastic residual strain (ex-situ) in castings with distinct levels of hot tearing. The research quantified the impact of grain refinement on hot tearing of B206 Al alloy. For B206 aluminum alloy experiments, hot tears were observed in the midsection of the horizontal bar, as shown in Figure 1. The severity of hot tearing in B206 was manipulated by adding selected amounts (0.02 and 0.05 wt%) of titanium using an Al-5Ti-1B master alloy in cut-rod form (Figure 1). The alloys were poured at 710 °C with a constant mold temperature of 380 °C.

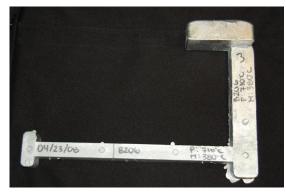


Fig. 1(a) Unrefined

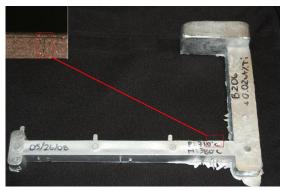


Fig. 1(b) 0.02 wt% Ti

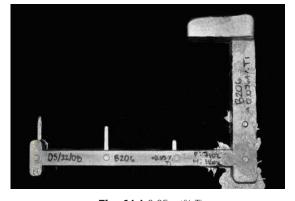


Fig. 1 (c) 0.05 wt% Ti

Fig. 1 Effect of grain refiner on hot tearing in B206 alloy.

Strain measurements for B206 were performed on three castings: one casting made with an unrefined alloy, one casting made with 0.02 wt% Ti addition and one casting made with 0.05 wt% Ti addition. The location of the linescan where lattice strain measurements were obtained is indicated in Figure 2. The linescan was 4 mm below the top edge of the horizontal bar (indicated by red line in Figure 2). The (hkl) planes of interest were the close-packed (111) and the (200) plane.

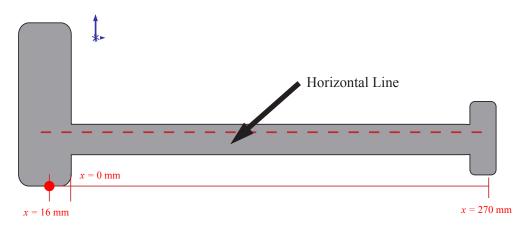


Fig. 2 Linescan location (drawing not to scale).

Results

Figure 3 presents the residual strain in the x-direction (ϵx) for the B206 unrefined alloy and 0.02 and 0.05 wt% Ti-containing B206 alloys. For the unrefined alloy, compressive strain was observed. This suggested that the horizontal bar was free to shrink once a hot tear formed near the solidus temperature. The free (unrestrained) contraction of the bar enabled development of compressive strains.

In the case of the refined alloys, a mix of tensile and compressive strains was observed. A significant relaxation of strain to a compressive state was visible for both refined alloys. The location of this relaxation was equivalent to the location of the 90° junction between the downsprue and horizontal bar in the permanent mold (i.e. sharp corner). Further, analysis of the strain profiles illustrates that the discontinuity in strain magnitude was greater for the 0.02 wt% Ti condition. This was likely due to the small hot tear that was present on the 0.02 wt% Ti alloy's surface. In the case of the 0.05 wt% Ti condition, the relaxation in strain magnitude was not significant enough to form a hot tear.

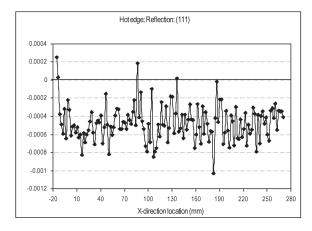


Fig. 3 (a) Unrefined

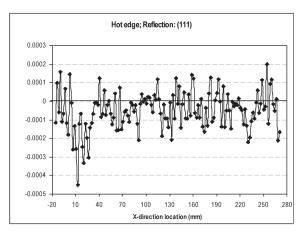


Fig. 3 (b) 0.02 wt% Ti

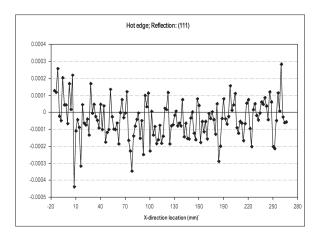


Fig. 3 (c) 0.05 wt% Ti

Fig. 3 Strain profiles for B206 castings [(111) reflection].

The average strain and strain variance are presented in Figure 4 for the (111) and (200) reflections. The average strain was significantly reduced with grain refiner additions for the (111) reflection. This was expected, as the grain refined microstructure likely enabled uniform feeding of liquid metal during casting solidification, which compensated the axial contraction of the horizontal bar, and therefore, alleviated developing strains.

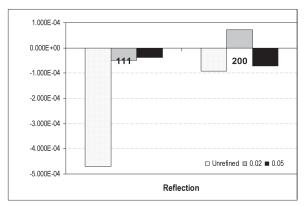


Fig. 4 (a) Average strain.

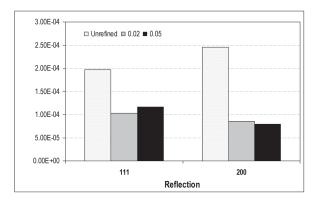


Fig. 4 (b) Average strain variance.

Fig. 4 Average strain and strain variance for B206 alloy castings.

In the case of the (200) reflection, mixed strain values were observed for the casting conditions. The strain for the (200) reflection was less sensitive to the effect of grain refinement, as observed in Figure 4a (only a small change in strain magnitude was observed). The average strain variance shown in Figure 4b suggests that grain refiner enhanced strain homogeneity, for both (111) and (200) reflections.

Conclusions

This study suggests that grain refinement is a practical method to reduce hot tearing severity. The fundamental mechanisms of Ti-B grain refiner's influence on hot tearing in B206 were as follows.

- Hot tears were virtually eliminated in B206 with addition of Ti-B grain refiner.
- Neutron diffraction revealed that the total residual strain measurements were in agreement with the hot tearing severity of B206. It was observed that, average residual strain was significantly less for the grain refined castings. Further, the strain homogeneity was improved with grain refiner additions. As a result, the grain refined castings were less prone to hot tear formation.

References

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