Interplay among solidification, microstructure, residual strain and hot tearing in B206 aluminum alloy

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ABSTRACT

Hot tearing is a complex phenomenon attributed to alloy solidification, microstructure and stress/strain development within a casting. In this research, the conditions associated with the formation of hot tears in B206 aluminum alloy were investigated. Neutron diffraction strain mapping was carried out on three B206 castings with varying levels of titanium (i.e. unrefined, 0.02 and 0.05 wt%). Titanium additions effectively reduced grain size and transformed grain morphology from coarse dendrites to fine globular grains. Further, thermal analysis suggested that grain refinement delayed the onset of dendrite coherency in B206 and therefore enhanced the duration of bulk liquid metal feeding for the refined casting conditions. As a result, the interactive effects of such factors resulted in a more uniform distribution of strain, and subsequent higher resistance to hot tearing for the grain refined castings.

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1. Introduction

Hot tearing is a common and serious defect occurring during solidification of alloys. The subject of hot tearing has been extensively studied and numerous theories have been proposed [1–9]. Recent reviews by Sigworth [10] and Eskin [11] summarize many of these theories, which suggest that hot tearing is a complex phenomenon with various factors influencing their formation. Perhaps the most significant and accepted theory related to hot tearing is that proposed by Pellini [4]. He claimed that hot tearing is a strain-controlled phenomenon that occurs if the accumulated strain in a hot spot reaches a critical value. Pellini suggested that the magnitude of strain (and subsequent hot tear severity) was dependent on many interacting variables of which he classified as either "mechanical factors" (e.g. casting and mold design) or "metal factors" (e.g. microstructure, grain size). The current study demonstrates the direct correlation between these factors and the hot tearing behavior of B206 aluminum alloy.

Aluminum–copper (Al–Cu) alloy B206 is a high strength and ductile alloy showing promise for use in automotive suspension components [12]. In fact, in the heat-treated state, this alloy has mechanical properties approaching those of ductile iron, but its high susceptibility to hot tearing continues to limit its industrial use [13]. Past research suggests that grain refinement can significantly improve the B206 alloy's resistance to hot tearing

[14–16]. Specifically, grain refinement was found to enhance liquid permeability and transform grain morphology from coarse dendrites to finer globular grains. In turn, the alloy's ability to accommodate strain due to solidification shrinkage was improved. However, a struggle remains in developing a viable technique to quantify the strain responsible for hot tearing.

Neutron diffraction provides a feasible technique for non-destructive measurement of residual strain at the depth of the sample material. Residual strain can arise in castings from thermal gradients causing inhomogeneous casting contraction and mechanical factors (e.g. sharp corners) opposing casting contraction within a rigid mold. The advantage of neutron diffraction lies in the ability of neutrons to penetrate deeply into the bulk of sample material, thereby enabling residual strain analysis for a larger volume of the sample. Past research [17–22] typically relied on the use of measurement probes such as load cells and LVDTs to monitor contraction stresses and strain during casting. However, despite the useful data obtained from these instruments, certain limitations remain. For instance, the load cell effectively identifies the onset temperature of hot tearing by determining the instant a relief in contraction stress occurs. However, unlike neutron diffraction, such a technique cannot be applied to actually quantify the magnitude of stress. In the case of strain, the LVDT provides an accurate measure of total casting contraction during solidification, but is unable to measure strain in localized regions along a casting. Neutron diffraction, on the other hand, can be effectively used to generate profiles of residual strain (and stress) along a casting, thereby enabling a direct correlation between casting solidification, microstructure and strain at critical regions. Such a capability

is advantageous in the study of hot tearing, since these defects form at localized regions (i.e. hot spots) along castings.

The goal of this research was to characterize the interactive effects of solidification, microstructure and residual strain on hot tearing in B206. The hot tearing severity of B206 was systematically manipulated through additions of Ti-based grain refiner. Thermal analysis was carried out to examine the solidification characteristics of the unrefined and refined B206 casting conditions. Further, the microstructure of each condition was characterized using optical and scanning electron microscopy. Finally, neutron diffraction was effectively used to map residual strain along critical regions of the castings. In turn, these results enabled an improved understanding of the hot tearing characteristics of B206.

2. Experimental procedure

2.1. Melting and casting

Casting experiments were carried out at the Centre for Near-net-shape Processing at Ryerson University in Toronto, Canada. The B206 alloy was cast using permanent mold casting. The permanent mold consisted of a downsprue with a 260 mm long horizontal bar with an end restraint, as shown in Fig. 1. The horizontal bar's cross-section was 20×20 mm^2. The mold was specifically designed to induce hot tears. The $90°$ junction between the downsprue and horizontal bar (denoted sprue–bar junction from hereon), in conjunction with the end restraint, restricted the horizontal bar from contracting freely during solidification. As a result, hot tears formed along the horizontal bar. The severity of hot tearing was manipulated by varying the amount of Ti through controlled Al–5Ti–1B master alloy additions. Three addition levels were investigated, namely: unrefined, 0.02 wt% Ti and 0.05 wt% Ti.

The B206 alloy was obtained in ingot form from Alcan Inc. The alloy composition was determined using an optical emission spectrometer and is given in Table 1. All castings were made with virgin ingot material (i.e. no recycled alloy was used). The alloy was degassed using 0.25 wt% sodium fluorosilicate prior to being poured at a temperature of 720 °C (i.e. 70 °C superheat) in a mold preheated to 380 °C. Casting parameters were limited to one superheat and one mold temperature to prevent the influence of cooling rate on grain size. The cooling rate was ~23 °C/s for all casting conditions.

Three K-type thermocouples connected to a data acquisition unit were used to monitor the casting temperature. The sampling rate of the thermocouples was seven readings per second. The thermocouples were placed in the horizontal bar, at 25.4 mm, 127.6 mm and 229.8 mm from the downsprue. Approximate locations of these thermocouples are indicated with circles in Fig. 1. The thermal data collected was used to characterize the solidification characteristics of the B206 castings.
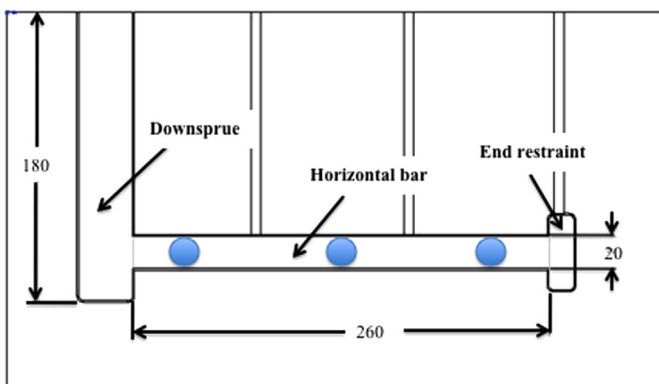

Fig. 1. Permanent mold (dimensions in mm).

Table 1
Composition of B206 alloy (wt%).

Cu	Mn	Mg	Fe	Si	Ni	Zn	Sn	Ti	Al
4.9	0.38	0.24	0.05	0.04	< 0.01	< 0.01	< 0.01	< 0.01	Bal.

2.2. Neutron diffraction strain mapping

Neutron diffraction strain mapping was performed at the Canadian Neutron Beam Centre in Chalk River, Ontario, Canada. The experiments were carried out with a monochromatic beam of neutrons ($\lambda = 2.371$ Å) and a first-order diffraction ($n = 1$). Bragg's Law was used to determine the lattice spacing, d_{hkl}, of crystallographic reflections of interest at a given location along the castings. The (hkl) reflections of interest were the (111) and (311) reflections. These reflections were selected because of their ability to both produce high intensity diffraction peaks and maintain a rectangular neutron beam sampling volume. Both factors ensured that good statistical data was generated. A reference stress-free sample was sectioned from the downsprue of each casting and subsequently machined to $3 \times 3 \times 20$ mm^3 size, thereby ensuring that remaining residual strains were relieved. These samples were then used to determine the stress-free lattice spacing, d_{0-hkl} for each casting condition. Finally, the elastic lattice strain, ε_{hkl}, was calculated using the peak shift method given in Eq. (1).

$$\varepsilon_{hkl} = \frac{d_{hkl} - d_{0-hkl}}{d_{0-hkl}} \qquad (1)$$

Using the measured strain along the x (ε_x), y (ε_y) and z (ε_z) directions, the residual stress along these orientations (i.e. σ_x, σ_y and σ_z) was then determined from generalized Hooke's law (Eq. (2)).

$$\sigma_{x,y,z} = \frac{E}{(1+\upsilon)} \left\{ \varepsilon_{x,y,z} + \left[\frac{\upsilon}{(1-2\upsilon)} \right] (\varepsilon_x + \varepsilon_y + \varepsilon_z) \right\} \qquad (2)$$

where:

$\upsilon =$ Poisson's ratio
$E =$ Young's modulus of elasticity

Strain (and stress) measurements were performed on three castings of the B206 alloy: one casting with an unrefined alloy, one casting containing 0.02 wt% Ti and one casting containing 0.05 wt% Ti. The measurements were carried out on the castings once solidification was complete and the samples were removed from the mold. As a result, the residual strain measurements were *ex situ*. The resulting B206 castings are illustrated in Fig. 2. In the case of the unrefined casting, a large hot tear was present along the middle of the horizontal bar, as shown in Fig. 2a. Addition of 0.02 wt% Ti significantly reduced the severity of cracking, as only a small tear was present at the sprue–bar junction (Fig. 2b). The reason for the difference in the location of the hot tear is addressed later. Finally, addition of 0.05 wt% Ti resulted in a complete elimination of surface hot tears (Fig. 2c). As a result, the correlation between the degree of hot tearing and residual strain was investigated.

2.3. Casting microstructure analysis

Following neutron diffraction experiments, the castings were sectioned and samples were prepared for metallographic analysis. These samples were ground using varying levels of SiC papers (i.e. 120 grit, 320 grit and 600 grit) and subsequently polished using 5 μm alumina, 3 μm diamond suspension and finally 1 μm diamond suspension. The samples were then etched for grain size using Keller's reagent. Grain size measurements were performed on a stereomicroscope in conjunction with Buehler OmniMet® image analysis