

Reduction of Hot Tears: Alloy and Casting Process Optimization Using Neutron Diffraction

2010-01-0748

Published
04/12/2010

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ABSTRACT

The continued need of vehicle weight reduction provides impetus for research into the development of novel automotive casting alloys and their processing technologies. Where possible, ferrous components are being replaced by aluminum (Al) and magnesium (Mg) alloy counterparts. This transition, however, requires a systematic optimization of the alloys and their manufacturing processes to enable production of defect-free castings. In this context, prevention of hot tears remains a challenge for Al and Mg alloy thin-wall castings.

Hot tears form in semi-solid alloy subjected to localized tensile stress. Classical methods of stress measurement present numerous experimental limitations. In this research, neutron diffraction (ND) was used as a novel tool to obtain stress maps of castings and to quantify the effect of two processes used to eliminate hot tears in permanent mold castings: 1) increasing of the mold temperature during casting of Mg alloys, and 2) grain refinement of Al alloys.

In case of the AZ91D Mg alloy, the ND results indicate that increasing the mold temperature effectively decreased the level of tensile strain in a casting region with a geometric stress concentration, thereby preventing nucleation of hot tears. In the case of the B206 Al alloy, hot tearing was alleviated by the addition of 0.05 wt% Ti-B grain refiner and the ND mapping revealed a decrease in the stress level along with enhanced stress uniformity across the casting.

INTRODUCTION

Manufacturing processes such as casting, forming, heat treatment, machining and joining add value to alloys and extend their range of application [1]. In the case of magnesium (Mg) and aluminum (Al) alloys, the automotive and electronics industries require parts with superior mechanical properties and favorable process economy. These requirements continue to drive fundamental and applied research into processing and optimization of these alloys. Specifically, the effect of the manufacturing process on the microstructure and the mechanical performance, wear resistance and dimensional stability of the cast products are subject to extensive research.

In the case of Mg and Al components, casting is one of the primary manufacturing routes. During the solidification of a casting, temperature distribution and homogeneity must be carefully controlled to ensure continuous and appropriate feeding of liquid metal to solidifying parts of the casting. When uniform solidification is absent, high thermal gradients may induce thermo-mechanical and residual stresses. Thermal stresses result from non-uniform temperature distribution during solidification (resulting in shrinkage) and thermal contraction of a casting subsequent to solidification. Mechanical stresses develop when a casting solidifies within a rigid mold, which limits its solidification shrinkage and thermal contraction. Cracks resulting from ensuing material are typically referred to as hot tears. Once a hot tear forms, the casting must be scrapped [2].

The hot tearing susceptibility of an alloy depends on various factors. For example, the level of solute concentration significantly affects hot tearing tendency. An example of a λ -curve (indicating the length of a hot tear as a function of solute concentration) for Al-Mg alloy is presented in [Figure 1](#), along with the Al-Mg phase diagram.

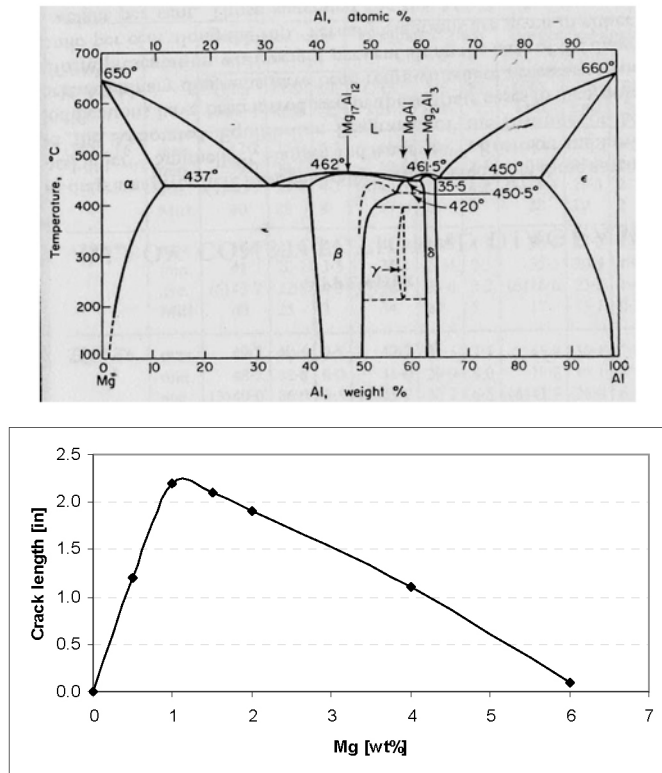


Figure 1. (a) Al-Mg phase diagram, (b) Al-Mg alloy λ -curve [3].

The initial increase in the crack length (i.e., severity of hot tearing) with increasing solute concentration (from zero to approximately 1 wt% Mg) is related to the widening of the solidification range. The maximum hot tearing susceptibility coincides with the maximum solidification range of the alloy. Subsequent increase of solute concentration typically results in the formation of eutectic microconstituents, which extend interdendritic feeding at late stages of solidification and decrease the alloy's hot tearing susceptibility.

Attempts to quantify the hot tearing susceptibility of alloys have achieved only limited success. For example, in order to determine the stress and strain conditions in the alloy during solidification, load cells, LVDT's and push-rods were installed in molds. However, these intrusive probes altered the natural casting solidification profile, thus making the final results questionable. Similarly, theoretical criterion functions based on solidification theories were developed, along with computer models; however, validation of these theoretical criterion functions and computer models was successful only

for simple casting geometries and a few alloys (e.g., iron plate castings). To this date, there is no universal formula relating the development of alloy strength to hot tearing [4].

Extensive research has been carried out on the effect of grain refinement on hot tearing [5, 6, 7, 8]. 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 [5, 6]. 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 [7, 8]. 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 residual stresses (ex-situ) in castings with distinct levels of hot tearing. Thus, the research quantified the impact of increasing mold temperature in Mg alloy casting on hot tearing, as well as the impact of grain refinement on hot tearing of Al alloys.

EXPERIMENTAL PROCEDURE

AZ91D and B206 alloy castings were produced via the permanent mold casting (PMC) process. The casting cavity consisted of a downsprue and a 260 mm long horizontal bar with an end restraint, as shown in [Figure 2](#). All hot tears in the AZ91D castings were observed near the 90° corner at the junction of the downsprue and the horizontal bar. For magnesium alloy experiments, the severity of hot tearing was manipulated by adjusting the mold temperature between 140 °C and 380 °C. By increasing the mold temperature, the solidification rate decreased, allowing time for interdendritic feeding and homogeneous temperature distribution. As a result, hot tearing decreased with increasing mold temperature, as expected. The pouring temperature was held constant at 720 °C.

For B206 aluminum alloy experiments, hot tears were observed in the midsection of the horizontal bar. 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. The alloys were poured at 710 °C with a constant mold temperature of 380 °C.

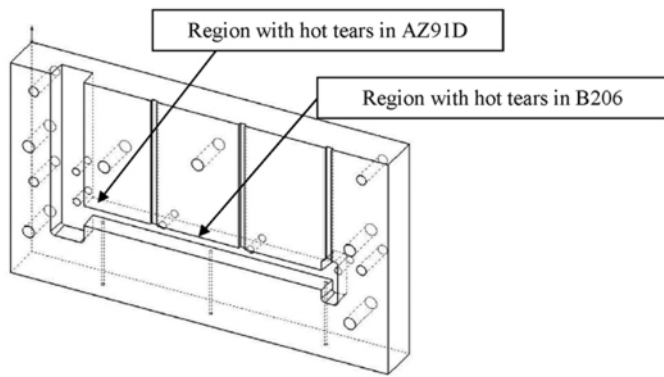


Figure 2. Custom-designed permanent mold.

The magnesium alloys used in this research were obtained as 10kg ingots from Meridian Technologies, Inc. In the case of the B206 aluminum alloy, ingots were obtained from Alcan Inc. The actual alloy compositions as obtained from an emission spectrometer are presented in [Table 1](#) and [2](#), respectively. All castings were made with virgin ingot material (i.e., no recycled alloy was used).

Table 1. Composition of AZ91D alloy (wt%).

Mg	Al	Zn	Mn	Si	Cu	Fe	Ni	Be
90.53	8.61	0.60	0.23	0.017	0.003	0.0038	0.0014	0.0012

Table 2. 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.

In order to determine the process parameters corresponding to the onset of hot tearing, a series of trial-and-error experiments were performed. The objective was to manipulate the pouring and mold temperatures to produce castings with distinct degrees of hot tearing. This systematic manipulation of the process temperatures enabled visual determination of the onset conditions for hot tearing in each alloy.

Neutron diffraction strain mapping was performed at the Canadian Neutron Beam Centre in Chalk River, Canada. Neutron diffraction closely parallels X-ray diffraction in methodology and analytical assessment. Neutrons interact with nuclei of atoms, which constitute a small fraction of the atom, enabling penetration depths nearly a thousand times greater than in the case of X-rays (for the wavelength range of $0.7 < \lambda < 4 \text{ \AA}$) [9]. In addition, ND can be carried out in controlled environments (e.g., furnaces or sample containers) thus yielding accurate information about the properties of the material.

When a material is subjected to a tensile load, the lattice spacing of its crystal structure, d , increases in the tensile loading direction with respect to its stress-free value, d_o . The lattice spacing can be accurately measured experimentally

using Bragg's law. Similarly, the lattice spacing decreases for compressive loads. Thus, the strain, ϵ , experienced by the material can be expressed using the peak-shift method as:

$$\epsilon = \frac{d - d_o}{d_o} \quad (1)$$

The experiments were carried out with a monochromatic beam of neutrons ($\lambda = 2.371 \text{ \AA}$), and a first-order diffraction ($n = 1$) analysis was performed. In the case of AZ91D Mg alloy, the (hkl) planes of interest were the prismatic $(10\bar{1}0)$, basal (0002) and pyramidal $(10\bar{1}1)$ and $(10\bar{1}2)$ planes. For B206 Al alloy, the (hkl) planes of interest were the close-packed (111) and the (200) plane. For both alloys, a reference stress-free sample was obtained from the downsprue of respective castings. The downsprue was free to contract (under very low cooling), and thus contained minimal residual stress. Further, by machining the stress-free sample to $3 \times 3 \times 20 \text{ mm}$ size, remaining residual stresses were relieved.

Strain measurements were performed on two castings for AZ91D: one casting made at 210°C mold temperature (i.e., a casting with a hot tear) and one casting made at 250°C mold temperature (i.e., casting without a hot tear). 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 3](#). The linescan was 4 mm below the top edge of the horizontal bar.



Figure 3. Linescan location (drawing not to scale).