Quantitative Analysis of Hot-Tearing Susceptibility of New High-Temp Magnesium Alloys Using Neutron Diffraction

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Introduction

The automotive industry has renewed interest in magnesium alloys. Magnesium alloys are about 35% lighter than aluminium and about 80% lighter than steel. As a result, incorporation of magnesium alloy castings in new vehicles plays a critical role in reducing the vehicle's weight and increasing its fuel efficiency. Further, magnesium alloys show excellent specific properties, castability and recycling potential. However, when magnesium alloys are processed via high-pressure die-casting (HPDC) or permanent mold casting (PMC), they show high susceptibility to hot tearing.

Thermal and mechanical stress, strain and feeding, that is, interdendritic liquid flow of a given alloy are known to be the key parameters affecting the onset of hot tearing. Theoretical criterion functions based on these concepts were developed with the aim of predicting the onset of hot tearing. However, experimental validation of these criterion functions remains a challenge, because the currently available test methods often involve intrusive probes, which alter the casting solidification profile, or indirect estimations of the stress or strain conditions.

Solidification stresses arise in a casting due to thermal gradients causing inhomogeneous casting contraction during solidification. Further, when a casting solidifies within a rigid steel mold, as in the case of HPDC or PMC processes, the casting contraction is opposed by the rigid mold and consequently mechanical stresses develop in the semi-solid alloy. Measurement of casting residual stresses at the onset of hot tearing using neutron diffraction (ND) has not yet been reported in literature.

In this research, two magnesium alloys were studied: (1) AZ91D (9 wt%Al – 1 wt%Zn) magnesium alloy; AZ91D has excellent castability and room temperature mechanical properties, and is currently used in the automotive industry; (2) AE42 (4 wt%Al – 2 wt%RareEarths) magnesium alloy; AE42 is known for its excellent high-temperature strength in comparison to traditional magnesium alloys, such as AZ91 or AM60, and thus has a high potential for future use, for example in engine components.

Both of these alloys are susceptible to hot tearing. In order to control the severity of hot tearing in the current experiments, the mold temperature was increased from 140°C to 390°C. Figure 1a shows the casting geometry and the region where hot tears typically nucleated. Figure 1b,c illustrate the effect of mold temperature on hot tearing in the critical region. Residual strain for (100), (002), (101) and (102) crystallographic reflections was measured on two castings for each alloy: one with a hot tear, one without a hot tear. The edge of the casting, where hot tears were typically observed, corresponded to location of *x=0*.

In summary, this research involved measurement of the total, that is, thermal and mechanical, residual strains in castings with various degrees of hot tearing. Also, the solidification history and microstructure of the castings was analyzed, thus correlating these fundamental parameters to the onset of hot tearing.

Results

Analysis of the residual strain profiles along the length of the horizontal bar (i.e., strain variation in *x*-direction) revealed that the reflections (100) and (002) did not show significant strain development for ε_x, ε_y and ε_z. However, reflections (101) and (102) exhibited a definite ε_x strain variation along the length of the bar: higher tensile strain in the sprue region, followed by a decreased strain in the horizontal bar.

AZ91D

The *x*-direction contraction of the horizontal bar induced tensile strain in the horizontal bar and was responsible for initiation of hot tears in the casting. Casting contractions in the *y*- and *z*-directions were not restricted and thus resulted in compressive residual strains. Figure 2 shows the distribution of ε_x strains along the length of the horizontal bar for the (101) reflection in the cracked and non-cracked castings, respectively.

In the case of a casting with a hot tear, the ε_x strain in the sprue region ($x < 0$ mm) was tensile: 0.00051 mm/mm. Residual strains were relieved in the area of the crack, as indicated by a drop in the strain profile in Figure 3a. The ε_x in the horizontal bar to right of the 90° junction was tensile 0.00018 mm/mm ($15 < x < 25$ mm). In the case of a casting without a hot tear, Figure 3b, the ε_x strain in the downsprue was also tensile: 0.00044 mm/mm. However, contrary to the cracked casting, the region to the right of the 90° junction ($15 < x < 25$ mm) possessed compressive ε_x strain of 0.00011 mm/mm. The strains in the casting became tensile only far away from the 90° junction.

The difference in the ε_x strain profile was related to the feeding of the casting. At high mold temperatures, intergranular liquid feeding was possible for a longer period of time. Thus, the volumetric contraction of the horizontal bar was compensated by incoming liquid metal feed, and the developing strains were continuously alleviated. However, for low mold temperatures, the horizontal bar solidified and contracted rapidly without compensation by liquid metal from the downsprue. Thus, inadequate compensation of casting contraction resulted in the development of significant tensile strains, which aided in separation of dendrites and crack nucleation.

AE42

The relative uniformity of the measured strain values suggests that the horizontal bar solidified rapidly along its entire length, unlike in the case of the AZ91D alloy, where the casting solidified slowly from the restraint towards the sprue. The measurements indicate that the HCP crystals in the AE42 alloy experienced a significant strain, as shown in Figure 3.

Prior to reaching the onset conditions, a casting without a hot tear developed tensile strains between 0.006 – 0.007 mm/mm. Upon nucleation of a hot tear, the tensile strains were relieved and reduced to nearly zero. The basal planes (002) retained some of the tensile strains, even after hot tearing occurred. This observation suggests that the basal planes in the AE42 alloy were stiffer than the prismatic or pyramidal planes. A possible reason for this observation is the formation of Mg-Al$_x$RE$_y$ precipitates on the basal planes and their ability to resist dislocation motion during high temperature deformation. For the directions (101) and (102), a marginal reversal of the strain condition (from tensile to compressive) was recorded with the onset of hot tearing, as shown in Figure 3. This is in agreement with reported studies on high-temperature deformation of magnesium and its alloys, which have shown that the critical resolved shear stress (CRSS) at room temperature is considerably higher for non-basal slip than for the dominant basal slip. However, Agnew *et al.* [1] suggested that the relative strength and hardening response of a variety of slip and twinning systems control the deformation of magnesium alloys at elevated temperatures. At elevated temperatures, reorientation of the basal planes occurs, thus activating additional non-basal slip systems and accelerating bulk deformation. In particular, deformation along the (101) and (102) crystallographic directions was seen to dominate.

Conclusions

Neutron diffraction analysis in conjunction with thermal analysis and microscopic characterization enabled a better understanding of casting behaviour at the onset of hot tearing. The measurement of casting residual strain at the onset of hot tearing was successfully carried out and yielded information previously unavailable.

At high solidification rates (~ 15 °C/s), the AZ91D castings developed hot tears, since the downsprue was not able to sufficiently feed the horizontal bar. As a result, the horizontal bar's contraction was not compensated by incoming liquid metal feed, tensile ε_x strain of 0.00018 mm/mm developed in the horizontal bar, to the right of the 90° junction. For an AZ91D casting without a hot tear the solidification rate was low enough (~ 10 °C/s) to enable liquid metal feed to the contracting horizontal bar. As a result, the ε_x strain at the 90° junction remained compressive (0.00011 mm/mm) and hot tearing did not occur.

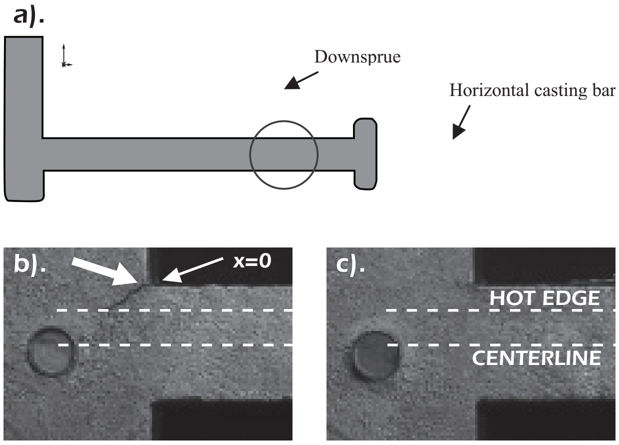

Fig. 1 *AE42 magnesium alloy castings: (a) casting geometry and "critical region" where hot tears formed, (b) casting with a hot tear (340 °C mold temperature), and (c) casting free of hot tears (390 °C mold temperature). The white dashed lines show the location of two of the four line scans performed to map the map the residual strain.*

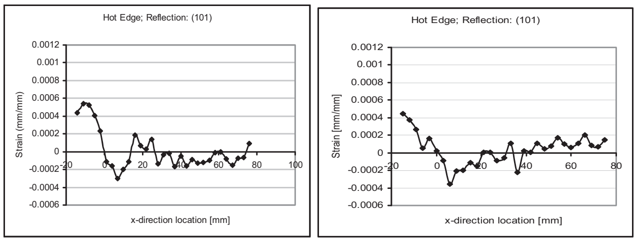

Fig. 2 ε_x *residual strain hot-edge profiles for AZ91D castings with (a) and without (b) a hot tear.*

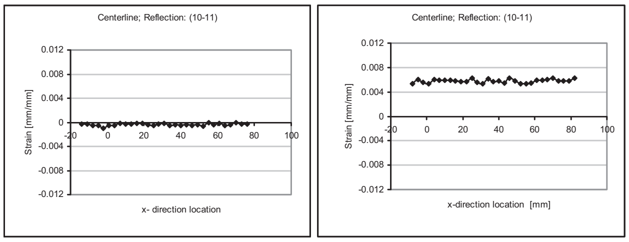

Fig. 3 ε_x *residual strain centerline profiles for AE42 castings with (a) and without (b) a hot tear.*

References

[1] Agnew, S. R., Tome, C. N., Brown, D. W., Holden, T. M. and Vogel, S. C., Scripta Materialia. 2003. 48: 1003-1008