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Residual stresses near the hot sprues of as-cast Mg-Zn alloys investigated by STRESS-SPEC neutron diffractometer

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Abstract. Residual strains near the sprues of ingots with different contents of Zn (6 wt. % and 9 wt. %) were measured using neutron diffraction. The results showed that the increase of Zn content decreases the residual stress in the hot sprue region. These results are in good agreement with those obtained by the measurement of hot tearing susceptibility.

Introduction

The hot tearing or hot cracking is often a major defect in casting of alloys. All thermal contraction associated with decreasing temperature and the changing state of material exerts thermal stress during casting. Thermal stress involves different consequences such as distortion, crack, hot tear, and residual stress [1]. Hot tearing is a complex solidification phenomenon which is still not fully understood, though various mechanisms have been proposed [2]. All of them have significant effects on the quality of casting products. For subsequent processing or service, those components are preferred which are free of casting defects and contain very low residual stresses.

Research on magnesium alloys is getting more attractive in recent years due to their potential in 3C (consumer, computer, communication) and automotive industries [1]. Most previous studies on hot tearing susceptibility were carried out on Mg-Al alloys [2, 3]. Different from aluminum alloys and steels, magnesium alloys have low elastic constants. Therefore, a very small residual stress can cause the distortion of casting components. Laboratory characterizations on hot tearing of Mg-Al alloys have shown that casting defects such as hot cracks could occur at the sprue due to accumulation of thermal stresses during solidification.

The primary aim of the present investigations is to quantify the distribution of residual stress in the casts of Mg-Zn alloys using neutron diffraction. AZ31 is the most commonly applied alloy. Other Mg-Zn alloys are still subjects of research. Ref. 4 is one of our papers on Mg-Al hot tearing. Neutron diffraction for stress analysis is preferred because of its high penetration depth and flexible gauge volume choices for coarse grained as-cast ingots. Furthermore, it is also possible to perform an *in situ* strain study during the solidification process at high flux neutron source. The obtained thermal stress distribution is used to evaluate the formation of hot tearing in Mg-Zn alloys in combination with previous experimental results which are published elsewhere [2-4].

Experimental

The ingots for the neutron diffraction measurement were prepared using the setup of hot tearing evaluation system which was discussed in detailed elsewhere [4]. A cylindrical mild steel crucible coated with BN was used for melting in an electrical resistance furnace. High purity Ar + 0.2% SF_6 mixed protective gas was used for melt protection. Pure magnesium (99.9 wt.%.) and zinc (99.6 wt.%) were used as starting materials. They were heated and melted at 700°C. The melt was stirred for 5 min manually. Then the melt was held at the pouring temperature for about 5 min before casting. The pouring temperature was set at 80 ^{o}C above the liquid temperature. The melt was poured into a mould coated with a thin layer of BN, which was preheated to a temperature between 250°C and 500°C. The casting ingot is shown in Fig. 1 (a) and the head was later machined for the diffraction. The microstructure of the ingot is shown in Fig. 1 (b) which has an average grain size of 180 µm. In this study, two Zn contents (6 wt.% and 9 wt.%) with two mould temperatures of 200 °C and 300 °C were selected. The stress-free reference sample was machined from the sprue as a cylinder of Ø2×2 mm^2 from each Mg-Zn alloy.

Neutron diffractometer STRESS-SPEC at FRM II was used to measure the residual strain [5]. A wavelength of 0.205 nm produced by Ge (311) monochromator was selected to measure the peak position variation of (10.3) planes of Mg. The investigated gauge volume 2×2×2 mm^3 was controlled using a primary and a radial collimator, as shown in Fig. 2 (a), with the red dashed lines representing the neutron beam path and the blue line with an arrow designating the direction of measured strain (radial). Due to large grains of cast ingot, the sample was oscillated around Ω with amplitude of ± 5°.

Triaxial strain scanning (radial, hoop, and axial) was carried out with a step size of 2 mm: along the central line through the casting junction (designated with B) and along two lines 6 mm above and below the central line (designated with line A and C, end at the junction (Fig. 2 (b)), respectively. The lattice strain (ε_{hkl}) for the *hkl* reflection at a constant wavelength was calculated by,

$$\varepsilon_{hkl} = \frac{d_{hkl} - d^0_{hkl}}{d^0_{hkl}} = \frac{\sin\theta^0_{hkl}}{\sin\theta_{hkl}} - 1 \tag{1}$$

where d_{hkl} is the lattice spacing of *hkl* planes in the residual stressed materials and θ_{hkl} the corresponding diffraction angle, d^0_{hkl} is the lattice spacing of *hkl* planes in the stress-free materials and θ^0_{hkl} the corresponding diffraction angle. Then with Hooke's law the principal residual stress components (radial, hoop, and axial) are calculated using constant elastic Young modulus E_x= 45 GPa and Poisson ratio v= 0.286.

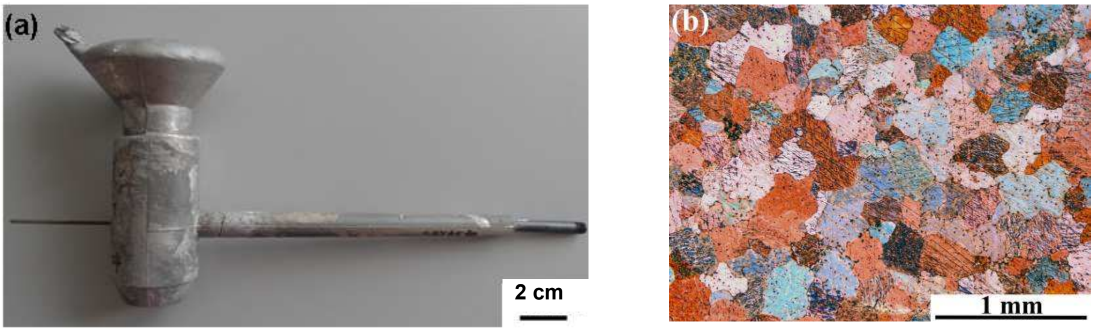

Fig. 1 (a) An Mg-Zn ingot; (b) optical microstructure of as-cast Mg-6Zn alloy prepared under a mold temperature of 300°C (observation area at the region near the junction).

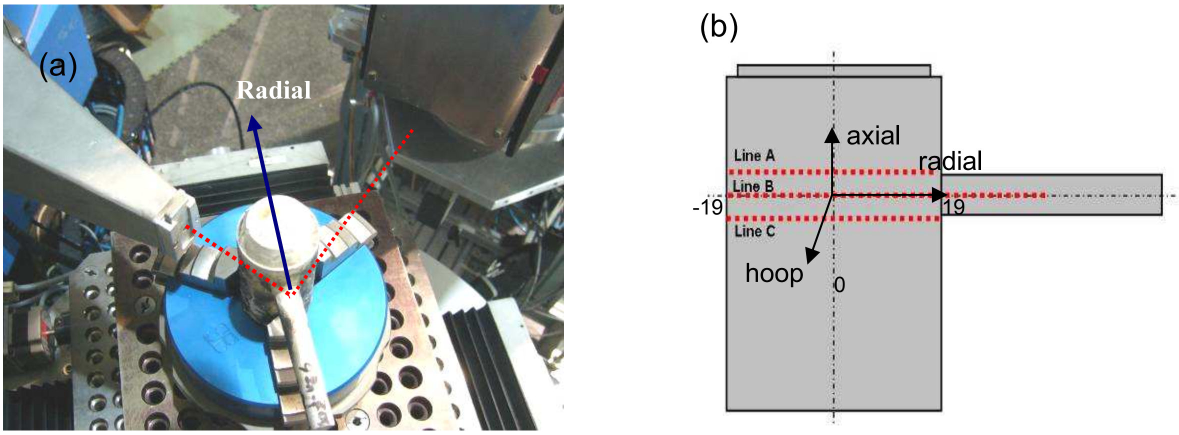

Fig. 2 (a) Instrumental setup for the measurement of radial direction strain in materials; (b) schematic diagram showing the scanning points of neutron diffraction along line A, B, and C, respectively.

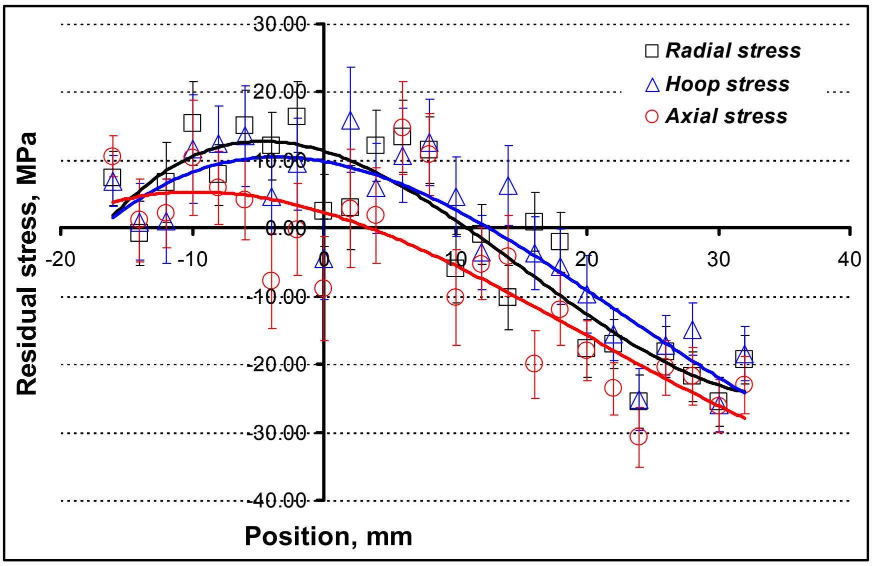

Fig. 3 Residual stress distribution along the central line B of Mg-9Zn using 200ºC cast mold.

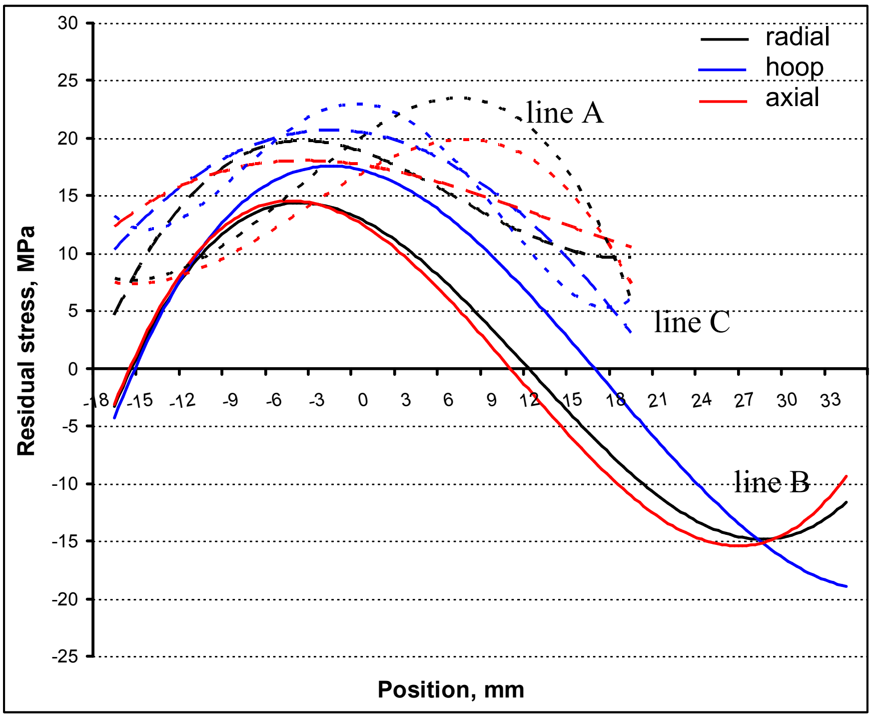

Fig. 4 Residual stress distributions along the lines A, B, and C in Mg-9Zn with a mold temperature of 300ºC.

Results and discussions

The distribution of triaxial residual stresses (radial, hoop, and axial) along the central line B for Mg-9Zn alloy with a mold temperature of 200 ºC is plotted in Fig. 3. Both the radial and hoop stresses show similar variations from left to right. From left surface to the junction there exists a residual tensile stress. It increases from the left surface (position= -18 mm) to the maximum around the center (position= 0 mm), and then decreases from the center to the junction (position= 20 mm). The measured maximum tensile stress is about 20± 8 MPa. Near the junction, the sign of residual stresses changed from tension to compression. The compressive residual stress monotonously decreases from the junction to the region far from the junction. The maximum compressive residual stress is about 25± 10 MPa. Comparing residual stresses in the three coordinate directions, the axial residual stress appears to be the lowest.

Fig. 4 shows the evolution of triaxial residual stress state along the lines A, B, and C in the as-cast Mg-9Zn alloy with a mold temperature of 300 ºC, respectively. A similar residual stress evolution along line the B is found in the Mg-9Zn alloy for both mold temperatures, 300°C as well as 200°C. The present mold temperatures (200°C and 300°C) seem not to influence the residual stress value so much. Comparing the residual stress evolution along the central line B with those along the lines A and C, a little difference is found. First, the residual stresses along the lines A and C show higher value than those along the line B. The cooling rates at the junctions in the lines A and C are larger than that in the line B. Consequently, at these places the residual stresses are higher. The previous experimental results have indicated that the hot cracks normally initiated at the junctions, and then propagated along the dendritic or grain boundaries [6, 7]. Second, a wider range with tensile stress is observed for the residual stresses along the lines A and C, demonstrating that at these places possibility of hot cracks formation is higher. In general, the hot cracks are formed by interdendritic separation with the assistance of tensile stresses.

Fig. 5 illustrates the stress evolution along the central line B in Mg-Zn alloys with different Zn contents of 6 % and 9 %, respectively. Results show that both, the Mg-6Zn and Mg-9Zn alloys develop similar stress distributions. However, the magnitude of tensile residual stress is higher in the Mg-6Zn alloy. This means that a high Zn content can help to decrease the hot tearing tendency.

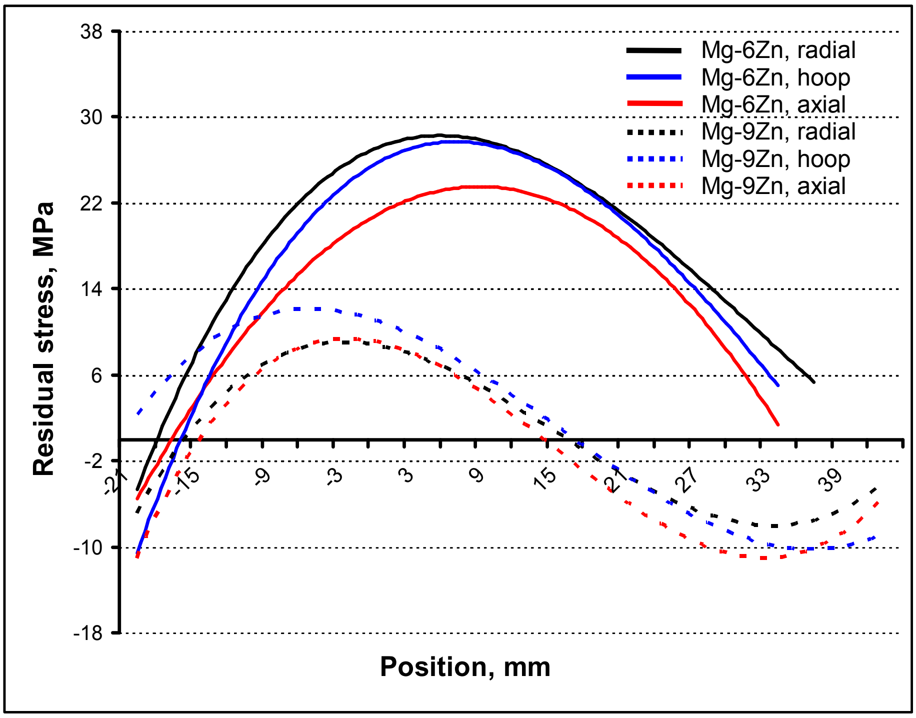

Fig. 5 Residual stress distribution along the central line B in Mg-6Zn and Mg-9Zn alloys with a mold temperature of 300 °C.

The influence of Zn content on the hot tearing susceptibility of Mg-Zn alloys has been investigated by experimental methods (Fig. 6) and thermodynamic calculations [6, 7]. Both of them show that the hot tearing susceptibility as a function of Zn content follows the “Λ” shape. The hot tearing susceptibility increases with the content of Zn, reaches the maximum at about 2 wt.% Zn and then decreases with further increasing the Zn content. As shown in Fig. 6, at a mold temperature of 300°C, the hot tearing susceptibility of Mg-6Zn alloy is higher than that of Mg-9Zn alloy. In Mg-9Zn alloys, no apparent cracks were observed after casting.

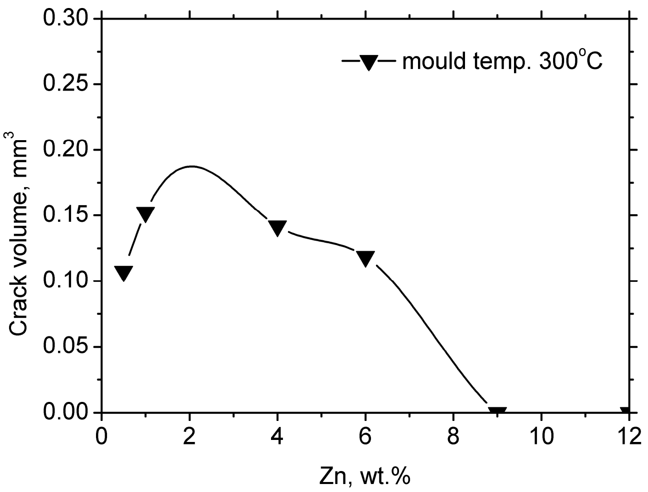

Fig. 6 Crack volume as a function of the content of Zn, mold temperature 300°C.

It also noted that the triaxial residual stresses of the above investigated three lines (A, B and C) are non-equilibrium. The main reason should be due to the segregations from surface to the sample centre. The residual stress balance around the junction could be related along the whole cast cylinder. Therefore residual stress mapping is suggested and will be done in future.

Summary

From the left surface to the junction there exists a residual tensile stress. It increases from the left surface to a maximum stress near the center, and then decreases from the center to the junction. Near the junction, the residual stress changes from tension to compression. Increasing of Zn content decreases the residual stress in the junction region. These results are in good agreement with those obtained by the measurement of hot tearing susceptibility.

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