

Influence of yttrium additions on the hot tearing susceptibility of magnesium–zinc alloys

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ABSTRACT

The influence of Y additions on the hot tearing behaviour of Mg–Zn alloys was investigated in this study. In permanent mould castings and in direct chill cast ingots, alloying of a few wt.% Y results in a significant reduction of hot tearing susceptibility. The reduced susceptibility is attributed to the effect of Y on the solidification path at the terminal period of solidification: it increases the solidus temperature and thus shortens the solidification path, which in turn reduces the terminal freezing range. Via thermodynamic calculations it is shown that this is caused by the formation of the ternary phase Mg_3YZn_6 . Using a simplified version of Clyne and Davies' model, the influence of the terminal freezing range on hot tearing susceptibility is clearly illustrated.

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1. Introduction

Hot tearing (HT), also known as hot cracking, hot shortness or hot brittleness, is a major defect which can arise during solidification. It is defined as failure occurring in the mushy zone of a freezing alloy, i.e. at solid fraction $f_s < 1$. Numerous publications and industrial experience regarding the hot tearing phenomenon show that HT occurs in the terminal stages of solidification when the solid fraction exceeds 0.85–0.95. According to Eskin et al. [1] four stages of solidification characterise the permeability of the solid network: (1) mass feeding, where the liquid and the solid can freely move; (2) interdendritic feeding, where the dendrites start to form a solid network and the liquid must flow through the network; (3) interdendritic separation, where the liquid network becomes fragmented; and (4) interdendritic bridging, where the structure develops moderate strength. The last two stages are important for the occurrence of HT. Here, with increasing solid fraction, the permeability of the solid network becomes very low and liquid feeding ceases. Because thermal contraction occurs simultaneously, strains may develop. If the strain (and the strain rate) imposed on the solid network is greater than a critical value, hot tearing occurs. Thus, it is mainly during the 3rd stage, i.e. interdendritic separation, where the structure is vulnerable to HT. However, the extent to which this happens depends strongly on the temperature dependence of

the volume fraction, f_s , in the temperature range at the terminal period of solidification, $f_s(T)$ for $f_s > 0.9$. According to Djurdjevic and Schmid-Fetzer [2] this partial freezing range near termination of solidification, or “terminal freezing range” (TFR), may be taken as the freezing range from 90% to 98% solid fraction, $\Delta T^{90/98}$. It indicates the TFR of the “almost” last 10% of the solidifying liquid. This value is assumed to be more relevant than $\Delta T^{90/100}$ because at $f_s \geq 0.98$ the structure develops considerable strength and solid-state creep can compensate the strain caused by thermal contraction [3]. Since the degree of thermal contraction is proportional to the TFR and here the structure is susceptible to HT, it seems reasonable to view the TFR as a rough measure of an alloy's hot tearing susceptibility (HTS). With regard to the HTS of magnesium alloys, various papers describe the effect of the respective chemical composition and relate it partly to the solidification path at the end of solidification [4] and to the time period where the solidifying alloy is vulnerable to HT [5–10], which in turn correspond approximately to the TFR.

In the course of producing Mg–Zn–Ca(–Y) alloys via the direct chill casting route [11–13] the authors of this study observed a remarkable influence of the yttrium content on the alloy's HTS. Even small Y additions to Mg alloys containing 2–3 wt.% Zn resulted in a significant reduction of the HTS. In this paper we investigate this effect in more detail by comparing the HTS with the TFR of Mg–Zn3–Y alloys with systematically varied Y content. The purpose of the study is to examine the HTS of these alloys in permanent mould and direct chill casting, and to correlate it to the specific TFR.

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2. Experimental procedure

2.1. Casting experiments – permanent mould and direct chill casting

The evaluation of the HTS of Mg–Zn3–Y alloys was carried out by means of industry-relevant casting experiments. The first experiment was performed using a permanent star-shaped steel mould (PSM), similar to that described in [1]. The geometry of the cast component is shown in Fig. 1. The rod length variations (head to head distance) were as follows: 25, 45, 65, 95, 125 and 175 mm; all were 10 mm in diameter. The rods' dog-bone shape prevented free contraction during solidification. For each alloy composition five casting trials were performed. Prior to each 5-trial series the mould was coated with BN. For all casting experiments the mould was pre-heated to a temperature of $250 \pm 5^\circ\text{C}$. Independent of the alloys' chemical composition, the pouring temperature was $700 \pm 5^\circ\text{C}$. As shown below, the liquidus temperature of all alloys was about 640°C , i.e. the superheat was approximately 60°C . The average cooling rate in the temperature range between 600°C and 300°C was about 30 K s^{-1} . The mould was opened around 5 min after pouring, and the castings were examined for cracks with the naked eye and using a $10\times$ magnifying glass.

The second experiment was a direct chill casting (DCC) process. Billets were produced at LKR using a MAGNUMCAST automated casting machine with hot-top technology [14]. The melt was heated to $700 \pm 5^\circ\text{C}$ in an electric furnace with a capacity of 600 kg. A protective gas mixture of 1.5% HFC134a and N_2 was deployed. Cylindrical billets of 152 mm in diameter and an average length of 1800 mm were cast, at a cooling rate of about 10 K s^{-1} . For each alloy composition one billet was produced and inspected.

For both the PSM and the DCC experiments, Mg alloys with the following nominal chemical composition were used (in wt.%): Mg–Zn3–Zr0.5, Mg–Zn3–Zr0.5–Y0.4, Mg–Zn3–Zr0.5–Y0.8. The exact chemical compositions of the components produced, measured by spark source optical emission spectroscopy, are given in Table 1. Zirconium was added for grain refinement and its amount was kept constant for all alloys. In this study it will not be considered as an element influencing HTS, and will for reasons of clarity not be incorporated into the thermodynamic calculations.

2.2. Characterisation

The microstructures of all samples were investigated using optical microscopy (OM) and scanning electron microscopy (SEM; Hitachi SU-70, operated at 15 kV). For phase identification two techniques were deployed: X-ray diffraction (XRD) and energy

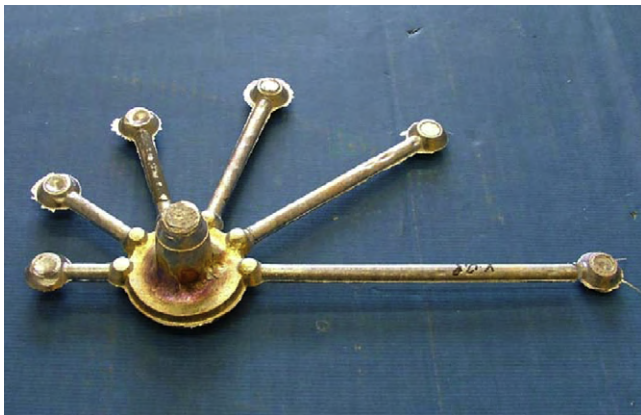


Fig. 1. Component cast in permanent star-shaped steel mould for evaluation of HTS.

Table 1

Chemical composition (alloying elements in wt.%; Mg remainder) of the PSM rods (average of five trials) and DCC billets (average of two trials).

	Zn	Zr	Y
Mg–Zn3–Zr0.5			
PSM	3.17 ± 0.05	0.54 ± 0.03	–
DCC	2.91 ± 0.04	0.48 ± 0.01	–
Mg–Zn3–Zr0.5–Y0.4			
PSM	2.94 ± 0.02	0.43 ± 0.04	0.43 ± 0.05
DCC	2.88 ± 0.04	0.46 ± 0.02	0.35 ± 0.02
Mg–Zn3–Zr0.5–Y0.8			
PSM	3.20 ± 0.03	0.47 ± 0.03	0.79 ± 0.04
DCC	2.83 ± 0.05	0.43 ± 0.01	0.67 ± 0.01

dispersive X-ray analysis (EDX). XRD measurements were conducted using a PANalytical X'Pert PRO-MPD diffractometer (Cu $\text{K}\alpha_1$ source operated at 37 kV and 45 mA); EDX measurements (Oxford Instruments) were performed at 5 kV. The volume fraction of the intermetallic phases was determined by means of optical analysis of OM images (analysis FIVE – Digital Imaging Solutions) and of SEM backscattered electron images (ImageJ image processing [15]). The solidus temperatures were measured by means of differential scanning calorimetry (DSC 220CU, Seiko Instruments) operated at a heating rate of 20 K min^{-1} under a constant Ar flow of 50 ml min^{-1} . Thermodynamic calculations were performed using the simulation software tool PANDAT with the PanMg8 database [16].

3. Results

The PSM castings were examined optically and a number representing the hot tearing susceptibility (HTS_{PSM}) as allocated to each alloy. This number was obtained by examining each rod and assigning a value between 0 and 1 according to the following scheme: 1 for completely broken rods; 0.5 for obviously cracked rods; 0.25 for rods with cracks detectable only with the magnifying glass; and 0 if no cracks were observed. The final HTS_{PSM} represents the average value of all five trials (note: $\text{HTS}_{\text{PSM}} = 6$ is the theoretical upper limit if all six rods are completely broken, while $\text{HTS}_{\text{PSM}} = 0$ represents the “best case” if the alloy is not susceptible to HT under the given casting conditions).

The DCC billets were cut into four segments at positions of 1000 mm and 1300 mm from the bottom of the billets. The cross-sections of the segments were metallographically prepared (ground) and examined optically for hot cracks. Since the alloys show only surface cracks but no evidence of centre cracks, and since the average crack length (a_c) is of the same order of magnitude for all alloys and trials ($a_c = 11.3 \pm 2.8\text{ mm}$, $12.9 \pm 1.6\text{ mm}$, $9.8 \pm 1.2\text{ mm}$ for Mg–Zn3–Zr0.5, Mg–Zn3–Zr0.5–Y0.4 and Mg–Zn3–Zr0.5–Y0.8, respectively) the average number of surface cracks was chosen as a measure of the alloy's hot tearing susceptibility (HTS_{DCC}).

Fig. 2 shows the ranking of the alloys according to their hot tearing susceptibility, HTS_{PSM} and HTS_{DCC} . It is obvious that the Y content significantly influences the alloy's solidification performance. Even a slight increase in Y additions results in reduced hot tearing. Although HTS_{PSM} and HTS_{DCC} reflect susceptibility only from a qualitative point of view, the advantage of adding Y seems to be more significant in the DCC experiment.

4. Discussion

4.1. Effect of Y addition on HTS

Clyne and Davies [17] proposed a cracking susceptibility coefficient (CSC) for the estimation of compositional effects on the hot

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