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Hot tearing susceptibility of binary Mg–Y alloy castings

Zhi Wang [a,b,*], Yuanding Huang [a], Amirthalingam Srinivasan [a], Zheng Liu [b], Felix Beckmann [a], Karl Ulrich Kainer [a], Norbert Hort [a]

[a] Institute of Materials Research, Helmholtz-Zentrum Geesthacht, Max-Planck-Str. 1, 21502 Geesthacht, Germany
[b] School of Materials Science and Engineering, Shenyang University of Technology, Shenyang 110870, China

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ABSTRACT

The influence of Y content on the hot tearing susceptibility (HTS) of binary Mg–Y alloys has been predicted using thermodynamic calculations based on Clyne and Davies model. The calculated results are compared with experimental results determined using a constrained rod casting (CRC) apparatus with a load cell and data acquisition system. Both thermodynamic calculations and experimental measurements indicate that the hot tearing susceptibility as a function of Y content follows the "λ" shape. The experimental results show that HTS first increases with increase in Y content, reaches the maximum at about 0.9 wt.%Y and then decreases with further increase the Y content. The maximum susceptibility observed in Mg–0.9 wt.%Y alloy is attributed to its coarsened columnar microstructure, large solidification range and small amount of eutectic at the time of hot tearing. The initiation of hot cracks is monitored during CRC experiments. It corresponds to a drop in load increment on the force curves. The critical solid fractions at which the hot cracks are initiated are in the range from 0.9 to 0.99. It is also found that it decreases with increasing the content of Y. The hot cracks propagate along the dendritic or grain boundaries through the interdendritic separation or tearing of interconnected dendrites. Some of the formed cracks are possible to be healed by the subsequent refilling of the remained liquids.

1. Introduction

Hot tearing (or hot cracking) is known as one of the most fatal solidification defects commonly encountered during casting. Previous studies have revealed that this phenomenon occurs in the mushy zone of a freezing alloy and the solid phase of casting is formed by a continuous network of grains. Although it has been investigated for decades, the understanding still stands at a qualitative stage [1,2]. The factors dominating the formation and susceptibility of hot tears include alloying elements, freezing range, amount of eutectic phases and solidification rate [3]. So far, the investigations on hot tearing are mainly focused on the steels and aluminum alloys [4,5]. A comprehensive review on hot cracking of aluminum alloys has been published by Eskin et al. [2]. In contrast, only few works have been reported on the hot tearing of Mg alloys.

Investigations on the castability of Mg alloys indicated that castings are often prone to hot tearing defects. The selected alloys for the investigations of hot tearing are mainly Mg–Al series [6–11]. Wang et al. [12] used a quantifying method to monitor the temperature at which the hot tearing occurs. They concluded that the occurrence of eutectic induces the hot tearing of AZ91 alloy. After the addition of rare earths (cerium-rich mischmetal) to AZ91 alloy, the hot tearing susceptibility reduces [13]. Cao et al. [6,7] also surveyed the effects of alloying elements such as Ca and Sr on the hot tearing susceptibility of Mg–Al alloys. Their results demonstrated that these two alloying elements improve the castability and decrease the hot tearing susceptibility of Mg–Al alloys. Recently, Zhou et al. [14,15] used thermodynamic calculations and a quantitative method to evaluate the hot tearing of binary Mg–Zn alloys, which are the base alloys to be used for the development of wrought Mg alloys such as Mg–Zn–RE (rare earths). They found that the hot tearing of these alloys is largely influenced by both the content of Zn and mold temperature. The influence of Zn content on the hot tearing susceptibility follows the "λ" shape. It is also found that the addition of Y to Mg–Zn alloys alleviate the hot tearing [16]. The beneficial effects are attributed to the facts that Y addition increases the solidus temperature, shorten the terminal solidification path and reduce the terminal freezing range. Besides the investigations on the influences of respective chemical compositions on HTS, the effects of casting conditions such as the effect of cooling rate on HTS were also sometimes explored in these above mentioned works such as the effect of cooling rate [14,15].

Considering the fact that the Y element plays a very important role in modifying the properties of Mg alloys [17–19], the

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* Corresponding author at: Institute of Materials Research, Helmholtz-Zentrum Geesthacht, Max-Planck-Str. 1, 21502 Geesthacht, Germany. Tel.: +49 (0) 4152 87 1966; fax: +49 (0) 4152 87 1909.

E-mail address: zhi.wang@hzg.de (Z. Wang).

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investigations on the effects of Y on HTS of Mg alloys should be very interesting. The addition of Y not only improves the mechanical properties but also increases the corrosion resistance [20]. Mg–Zn–Y alloys have recently been reckoned as one of the most promising wrought Mg alloys for practical applications. However, the effects of Y on the castability of Mg alloys such as hot tearing is not yet well understood. The related mechanisms of hot tearing in Mg alloys containing Y still remain somewhat unclear. Therefore, the present work investigates the hot tearing susceptibility of binary Mg–Y alloys, and the influences of Y content on HTS of Mg alloy will be discussed.

2. Prediction of crack susceptibility coefficient based on Clyne and Davies model

The hot tearing criterion proposed by Clyne and Davies is based on the assumption that the liquid feeding cannot accommodate the strains developed during solidification [21,22]. The last stage of freezing is considered as a critical stage to hot tearing. In their model, a cracking susceptibility coefficient (CSC) was proposed, which is defined by the ratio of t_V, the vulnerable time period where the hot tearing may develop, and t_R, the time available for the stress relief process where both the mass feeding and liquid feeding occur (Fig. 1). The CSC reads:

$$\mathrm{CSC} = \frac{t_V}{t_R} = \frac{t_{0.99} - t_{0.9}}{t_{0.9} - t_{0.4}} \tag{1}$$

where $t_{0.99}$ is the time when the volume fraction of solid, f_S is 0.99, $t_{0.9}$ is the time when f_S is 0.9 and $t_{0.4}$ is the time when f_S is 0.4. The larger CSC value means the higher tendency of hot tearing.

As shown in the above Eq. (1) and Fig. 1, in order to calculate the CSC, the variant fractional time at a specified solid fraction or liquid fraction should be known. This can be done by the following steps:

(1) With using Scheil's modeling, the volume fraction of solid phase as a function of temperature is first calculated using thermodynamic software Pandat and PanMg 8.0 thermodynamic database. In Clyne and Davies model, the Scheil's assumption was considered to be reasonable for the solidification conditions encountered during castings.
(2) The second step is the determination of temperature profile as a function of time, i.e. the cooling curve.

In order to predict the variation of the cracking susceptibility coefficient with alloy composition, it is necessary to design a series of alloys with different Y contents. The range of Y content considered is from 0.2 to 8.0 wt.% which is less than its maximum solubility in Mg at the eutectic temperature [23,24]. The volume fraction of solid phase as a function of temperature is shown in Fig. 2. The content of Y has a large influence on the freezing range and the melting point. Above 610–640 °C the solid fraction reduces quickly, and below 610–640 °C it changes slowly. The specified temperature above which the solid fraction changes quickly closely depends on the content of Y. The melting points of Mg–Y alloys change from 650 to 632 °C when the content of Y increases from 0.2 to 8.0 wt.%.

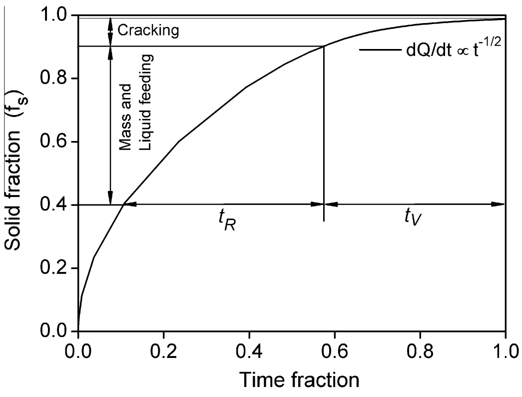

Fig. 1. Schematic diagram of liquid fraction vs. fraction time showing the calculation of CSC.

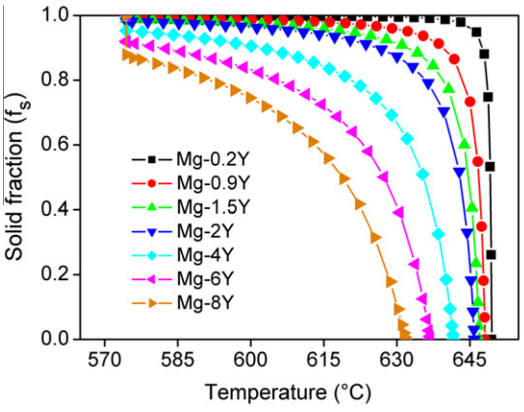

Fig. 2. Solid fraction vs. temperature for the binary Mg–Y alloys calculated using non-equilibrium (Scheil) modeling.

In Clyne and Davies investigations, for calculating cooling curve, constant partition coefficient and liquidus slope were used [21,22]. Also it was assumed that both the liquidus and solidus were approximately linear. Actually, this may not be true. The liquidus and solidus lines in the phase diagram are not linear. In order to improve the accuracy of calculated results, in the present calculation the partition coefficient and liquidus slope were calculated using PanEngine module in Pandat software based on thermodynamic database PanMg 8.0. PanEngine is a collection of C++ classes, which performs some related thermodynamic and equilibrium calculations [25]. The calculated partition coefficient and liquidus slope of the Mg–Y alloy is shown in Fig. 3, which clearly indicates that both the partition coefficient k and liquidus slope m_L vary with temperatures. The value of the partition coefficient increases from 0.19 to 0.27 as the temperature decreases from 650 to 632 °C. The liquidus slope also changes from 6.8 to 8.5 in the temperature range from 650 to 632 °C.

The cooling curves could be estimated using three different modes: mode 1 with a constant cooling rate, dT/dt = constant; mode 2 with a constant heat flow, dQ/dt = constant and mode 3 with a heat flow proportional to the square root of time, $dQ/dt \propto t^{-1/2}$ [21]. The typical calculated cooling curves for Mg–1.5 wt.%Y alloy under these three cooling conditions are shown in Fig. 4. After comparing the experimental results, the calculated results using the mode 3 are found close to the realistic situation. Thus, all CSC values are calculated using the mode 3 cooling condition in the present investigation. Fig. 5 shows the calculated CSC value as a function of the content of Y for the binary Mg–Y alloys. The curve follows the typical "λ" shape. The hot tearing susceptibility first increases with the content of Y, reaches a maximum at 1–2 wt.%Y and then decreases with further increasing the content of Y.

3. Experiments

3.1. Melting

Binary Mg alloys containing 0.2, 0.9, 1.5 and 4 wt.%Y were prepared for the present study. 350 g of Mg was molten in a mild steel