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Wang, Z.; Huang, Y.; Srinivasan, A.; Zhen, L.; Kainer, K.U.; Hort, N.:

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Materials Science Forum, Light Metals Technology Conference, LMT 2013 (2013)
Trans Tech Publications

DOI: 10.4028/www.scientific.net/MSF.765.306

Materials Science Forum *Online: 2013-07-31*
ISSN: 1662-9752, Vol. 765, pp 306-310
doi:10.4028/www.scientific.net/MSF.765.306

Influences of Y Additions on the Hot Tearing Susceptibility of Mg-1.5wt.%Zn Alloys

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Keywords: Mg-Zn-Y alloys, Casting, Hot tearing, Solidification, Microstructure

Abstract. The influences of Y (0.2, 2 and 4 wt.%) additions on the hot tearing behaviour of Mg-1.5Zn alloys were investigated using a constrained rod casting (CRC) apparatus equipped with a load cell and data acquisition system. The initiation of hot tearing was monitored during CRC experiments. It corresponds to a drop in load on the hot tearing curves. The experimental results indicate that, the hot tearing susceptibility defined by the total crack volume, which was measured by the wax penetration method, decreases with increasing the content of Y at a mould temperature of 250 °C. The reduced susceptibility is attributed to the effect of Y on the solidification behaviour: it shortens the freezing range and reduces the grain size. The highest susceptibility is observed for Mg-1.5Zn-0.2Y alloy. It is caused by its coarse microstructure and relatively larger solidification range. In contrast, the lowest susceptibility is observed for Mg-1.5Zn-4Y alloy with a small equiaxed grain microstructure. In addition, the healing of hot cracks by the subsequent refilling of the remained liquid at the later stage of solidification is also beneficial for the alleviation of hot tearing susceptibility in Mg-1.5Zn-4Y alloy.

Introduction

Hot tearing is a spontaneous failure of a metal during its solidification and remains one of the most severe defects in casting processes. Previous studies have revealed that this phenomenon occurs in the terminal stages of solidification when the solid fraction exceeds 0.85-0.95 [1]. The factors dominating the formation and susceptibility of hot tears include alloying elements, freezing range, amount of eutectic phases and solidification rate [2]. So far, the investigated alloys are mainly Mg-Al series [3-6].

Recently, Mg-Zn-Y alloys have received significant interests as a promising wrought magnesium alloy. Previous investigations on them were performed mainly on their microstructures and mechanical properties. However, the investigations on their castability, especially hot tearing, are very limited [7-8]. In this work, the effects of Y content on the hot tearing susceptibility (HTS) of Mg-1.5wt.%Zn alloy was investigated using an constrained rod casting (CRC) apparatus attached with a load cell and data acquisition system. The hot tearing formation was explored by monitoring the contraction force vs. temperature during casting. The influences of Y content on HTS are discussed.

Experimental Procedures

Ternary Mg-1.5Zn-xY alloys (x=0.2, 2 and 4 wt.%) were prepared. 350 g of magnesium was melted in a steel crucible under a protective gas mixture of high pure Ar+0.2 % SF_6. Pure Y and Pure Zn were added to the melt at 700 °C. After stirring at 80 rpm for 2 min. and holding for 5 min.

at pouring temperature 750 °C, the molten alloys were cast into a (CRC) mould, which was coated with a thin layer of boron nitride. The mould was preheated to a temperature (T_{mould}) of 250 °C. The castings were extracted from the mould after solidification and then examined for cracks. Each test was repeated for 3 times. To detect the initiation of hot tearing, a quantitative method based on the measurement of contraction load was developed [9]. The system consists of a constrained rod casting (CRC) mould, a contraction force measurement system with a load cell, a data logging unit and a data recording program. The force, mould temperatures at different positions and temperature of the solidifying casting at the junction of sprue and rod were recorded. The force curve (force vs. time) and cooling curve (temperature vs. time) were used for analyzing the hot tearing.

The grain morphology and cracks were investigated on the rod near the sprue-rod junction. They were observed using Reichert-Jung MeF3 optical microscope. A Zeiss Ultra 55 (Carl Zeiss GmbH, Oberkochen, Germany) Scanning Electron Microscope (SEM) was used to observe the fracture surfaces. The volume of hot cracks was measured using the wax injection method [9].

Results and Discussion

Fig. 1. shows the experimental curves of Mg-1.5Zn-xY alloys with different contents of Y. The detailed descriptions about the characteristics of hot tearing curves, including the definition of hot tearing initiation temperature (T_i) and crack propagation, can be found elsewhere [10-11]. On the hot tearing curves of Mg-1.5Zn-0.2Y and Mg-1.5Zn-4Y alloys, a slight reduction in the load is observed at the beginning of pouring. This is possibly due to the molten melt pressure exerted on the stud that connects to the load cell – as the melt enters from the sprue into the rod relatively fast and due to the sudden change in the cross-section it hits the stud.

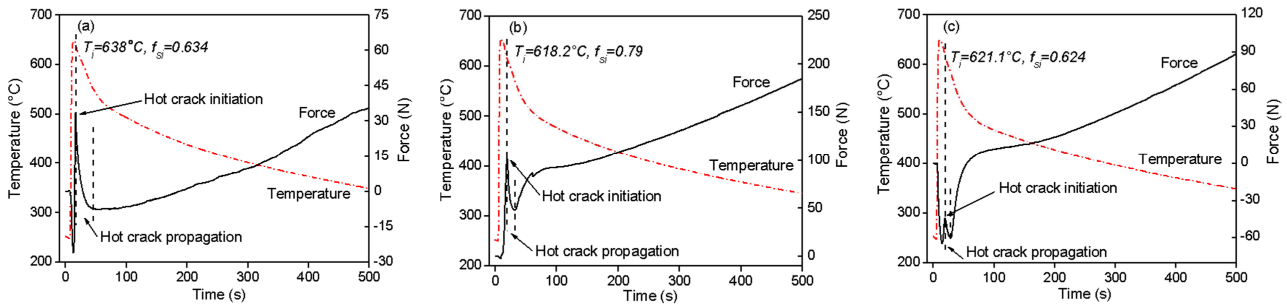

Fig. 1. Typical curves of contraction force as a function of solidification time at a mould temperature of 250 °C: (a) Mg-1.5Zn-0.2Y, (b) Mg-1.5Zn-2Y, (c) Mg-1.5Zn-4Y.

As shown in Fig. 1, the load evolutions during solidification are generally similar for all alloys, but some differences are still found at the beginning of the solidification. With the solidification proceeding, the load increases, reaching a maximum and then decreases for a while and further increases again. This drop in force indicates the initiation of the hot tearing in the casting, caused by the force release due to the formation of these hot cracks. The temperature corresponding to the beginning of the force drop is considered as the hot tearing initiation temperature. The different Mg-1.5Zn-Y alloys have different hot tearing initiation temperatures. For Mg-1.5Zn-0.2Y alloy, the hot cracks initiate at 638 °C, which corresponds to a solid fraction of 0.634. This value is obtained by the thermodynamic calculations with Pandat software using Scheil model (Fig. 1a). For Mg-1.5Zn-2Y alloy, the hot cracks initiate at 618.2 °C, at which the solid fraction is 0.79 (Fig. 1b). On both the hot tearing curves of Mg-1.5Zn-0.2Y and Mg-1.5Zn-2Y alloys, the forces drop very sharply once the hot cracks are formed. The sharper the force drop is, the larger the crack size is. Unlike the two aforementioned alloys, the force does not drop sharply at the beginning of solidification for the Mg-1.5Zn-4Y alloy. The initiation temperature of hot tearing for this alloy is 621.1 °C. This temperature corresponds to a solid fraction of 0.624. In a recent review [1], Eskin indicated that the solid fraction at which the hot tearing initiates is in the range from 0.85 to 0.95.

However, the present measured values of critical solid fraction change from 0.634 to 0.79 (Fig. 1). Due to the fact that the solidification is a complex process, it is very difficult to measure this value accurately.

Fig. 2. shows the total crack volume measured by the wax injection method and macro-photos of hot cracks. The total crack volume depends on the content of Y. The additions of Y in the Mg-1.5 wt.% Zn alloy have a very positive effect on alleviating its hot tearing susceptibility. The volumes of hot crack continuously decrease with increasing content of Y. When the content of Y reaches to 4 wt.%, the hot crack volume is much less with a value of only 0.006 cm^3. As shown by the macro-photos of hot cracks located on the surfaces of the restrained rods for different Mg-1.5Zn-xY alloys, the compositions of alloys largely influence the amount of hot cracks. No apparent macro-cracks are found near the junction of the Mg-1.5Zn-4Y alloy. In contrast, the macro-cracks are clearly observed near the junctions of both the Mg-1.5Zn-0.2Y and Mg-1.5Zn-2Y alloys. The cracks on the surface of the former alloy have a much wider opening than that of the latter, indicating that Mg-1.5Zn-0.2Y has the largest hot tearing susceptibility among all these three alloys.

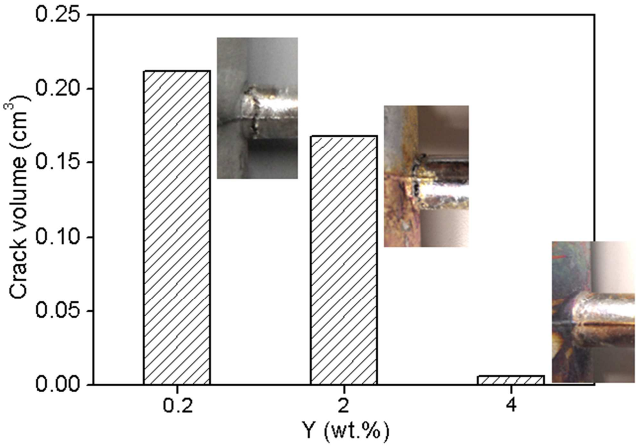

Fig. 2. Total crack volume measured by wax injection method as a function of Y content in Mg-1.5Zn-xY alloys.

Fig. 3 shows the optical micrographs of ternary Mg-1.5Zn-xY alloys taken near the junction of the sprue and the horizontal rod. With increasing content of Y the microstructure is changed from columnar grains to equiaxed grains. Mg-1.5Zn-0.2Y alloy exhibits the largest grain size amongst all the alloys. Small equiaxed grains are dominant in the Mg-1.5Zn-4Y alloy. This fine microstructure facilitates more paths for the remaining liquid to flow so that the refilling ability at the later stage of solidification is improved and the hot crack susceptibility reduces.

Fig. 3. Optical microstructures of ternary Mg-1.5Zn-xY alloys showing the grains: (a) x=0.2, (b) x=2, (c) x=4.

Fig. 4 shows both the low and high magnified optical micrographs of hot crack propagations and refilling. The hot cracks are formed at grain and dendritic boundaries and propagate along them. Some of the formed hot cracks can be healed by the subsequent refilling of the remaining liquid. The increment in the Y content increases the amount of eutectic phases. It is helpful for the improvement of flow ability and feeding ability of the liquid at the last stage of solidification. There exist coarse river-like structures connecting with a peripheral skeleton-like structure in

Mg-1.5Zn-4Y alloy (Fig. 4d). The formation of this special microstructure is due to the fact that a hot tearing separation is refilled by the remaining liquid at the last stage of solidification. After the hot cracks occur, the regions near them have a negative pressure [8,29]. The liquid can be inhaled again into these regions due to the negative pressure. This makes it possible to refill and heal the previously formed hot cracks. Owing to easy refilling and healing of hot cracks, no apparent drop in load is found on the hot tearing curve of Mg-1.5Zn-4Y alloy.

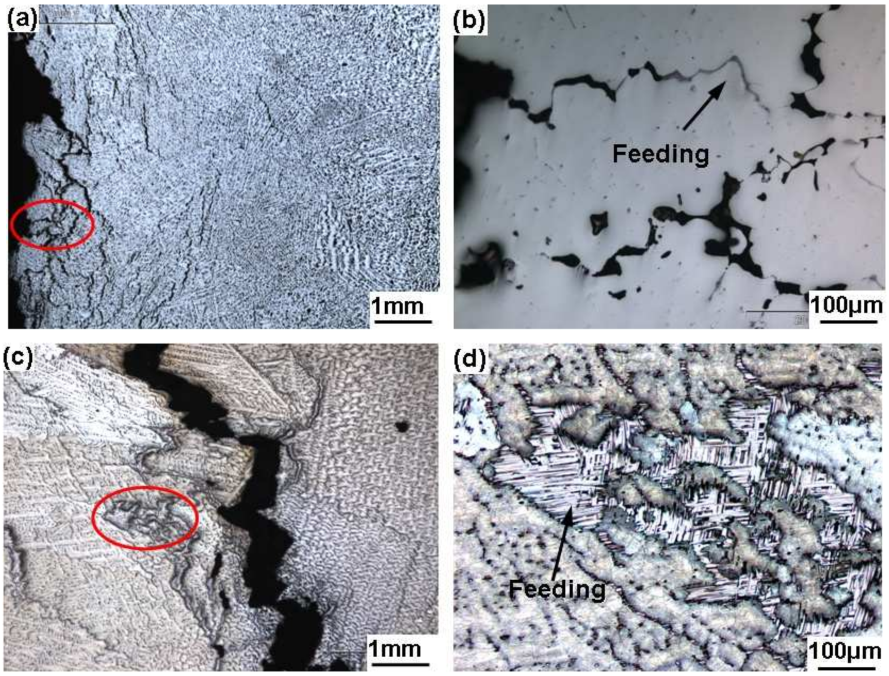

Fig. 4. Optical micrographs showing the hot crack propagation and refilling in alloys: (a) and (b) Mg-1.5Zn-2Y, (c) and (d) Mg-1.5Zn-4Y.

Normally, the hot tearing susceptibility is proportional to the solidification range, especially the vulnerable solidification region with solid fraction of 0.9 to 0.99 [12], which is defined as follows:

$$\Delta T = T_{0.9} - T_{0.99} \quad (1)$$

where ΔT is the temperature difference between the temperatures at a solid fraction of 0.9 ($T_{0.9}$) and 0.99 ($T_{0.99}$). The large value of ΔT could lead to severe hot tearing. Table 1. lists the ΔT values obtained by thermodynamic calculations with Pandat software using the Scheil model. Apparently, the vulnerable solidification region depends on the alloy compositions. Mg-1.5Zn-0.2Y alloy has a lager freezing range than other two alloys. Thus, the time the solidifying metal spends in the vulnerable solidification zone is much longer, demonstrating that its possibility of hot cracking susceptibility is high. This result is in agreement with that obtained by experimental measurements (Fig. 2).

Table 1. Prediction of vulnerable temperature ranges for Mg-1.5Zn-xY alloys.

Alloy	$T_{0.9}$ [°C]	$T_{0.99}$ [°C]	ΔT [°C]
Mg-1.5Zn-0.2Y	610.1	345.2	264.9
Mg-1.5Zn-2Y	593.0	581.0	12.0
Mg-1.5Zn-4Y	581.9	566.9	15.0

Fig. 5 shows the fracture surfaces of hot cracks for Mg-1.5Zn-0.2Y and Mg-1.5Zn-2Y alloys. In Mg-1.5Zn-0.2Y alloy, the fracture surface is quite smooth without transgranular tears. The dendrite-like bumps on the fracture surface can be observed (Fig. 5a). It indicates that a significant amount of interdendritic liquid was still present at the initiation of hot tearing. In the aforementioned results, the liquid fraction is 0.366 when the hot cracks initiate in the Mg-1.5Zn-0.2Y alloy. This is enough to allow the formation of dendrite-like bumps on the fracture surface. In Mg-1.5Zn-2Y alloy, the dendrite-like bumps are still observed on the fracture surfaces. Interestingly, besides them the transgranular tears are also found, indicating that the interconnections of dendrites have happened before the initiation of hot tearing. Compared with Mg-1.5Zn-0.2Y alloy, the liquid fraction at the initiation of hot cracks is less with a value of about 20 % in this alloy. With a smaller amount of remained liquid, the intergranular liquid film is thin. The formed bumps are therefore not so high as that observed in Mg-1.5Zn-0.2Y alloy (Fig. 5b).

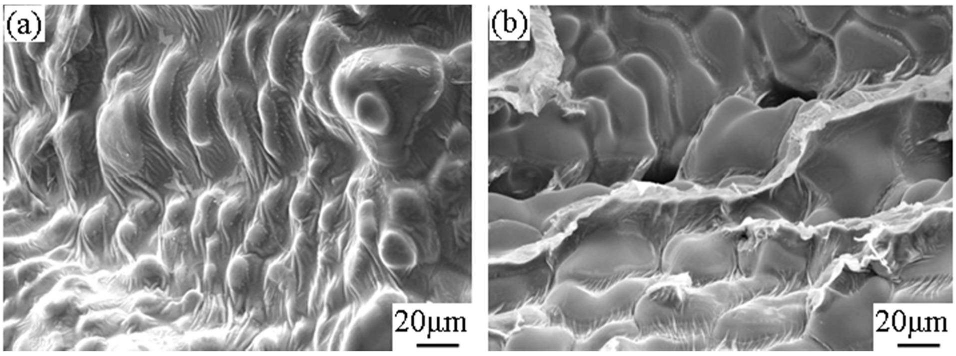

Fig. 5. SEM micrographs of hot tear surfaces of (a) Mg-1.5Zn-0.2Y and (b) Mg-1.5Zn-2Y alloys.

Conclusions

The hot tearing susceptibility of ternary Mg-1.5Zn-xY system has been investigated. The conclusions are summarized as follow:

(1) The hot tearing susceptibility of Mg-1.5Zn-xY alloys decreases with increment in Y content at a mould temperature of 250 °C.

(2) Both the initiations and propagations of hot cracks are influenced by alloy compositions, grain morphology and solidification range. The maximum hot tearing susceptibility is obtained in Mg-1.5Zn-0.2Y alloy which is due to its large grain size and a wide solidification range.

(3) Some of hot cracks can be healed by the subsequent refilling of remained liquids.

Acknowledgement

The authors would like to thank Mr. G. Meister for the technical support and Mrs. Petra Fischer for SEM observations. Financial supports from CSC-Helmholtz scholarship for Wang′s PhD study in HZG are gratefully acknowledged.

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