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INVESTIGATIONS ON HOT TEARING OF MG-ZN-(AL) ALLOYS

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Abstract

Mg-Zn alloys are widely used as wrought alloys such as ZM, ZK and ZE series. They are reportedly to be prone to hot tearing due to the presence of Zn. The present work first evaluates the hot tearing susceptibility (HTS) of binary Mg-Zn alloys using quantitative experimental methods and thermodynamic simulations based on Clyne's model, and then further investigate the addition of aluminum on the HTS in the ternary alloys Mg-Zn-Al. The results show that the curve of the HTS vs. the content of Zn has a typical "λ" shape. With increasing the content of Zn, the HTS increases firstly, reaches the maximum at 1.5% Zn and then decreases again. The addition of Al in Mg-Zn alloys influences the HTS. In the Mg-Zn-Al ternary system, the HTS decreases with the increase of Al content. The curve of the HTS as a function of Zn content in the ternary Mg-Zn-Al system is a little different from that observed in the binary Mg-Zn alloys. Two peaks are obtained: one is approximately at 1.0 to 1.5 wt.% Zn, another at 3.0 wt.% Zn.

Introduction

The hot tearing, also called hot cracking, is often a major defect in casting of alloys. It occurs during solidification due to obstructed contraction of the solidifying alloy, often at hot spots where the casting finishes solidifying or at locations with a sudden change in cross sections. Hot tearing is a complex solidification phenomenon that is still not fully understood, though various mechanisms and criterion have been proposed [1-4]. The factors dominating the formation and susceptibility of hot tears include alloying elements, freezing range, amount of eutectic phases and initial mold temperature.

For hot tearing susceptibility of magnesium alloys, most of previous inspections were performed only for Mg-Al series. They surveyed the effect of alloying elements such as RE, Ca and Sr on the hot tearing susceptibility of Mg-Al alloys [5-8]. The additions of these alloying elements more or less deteriorate the castability and increase the tendency for hot tearing. Mg-Zn alloys are most widely used as the wrought magnesium alloys, which is a basic composition of ZK series commercial alloys. Previous investigations were mainly performed on their corrosion behavior, age-hardening behavior and microstructure, but there are very limited investigations on their hot tearing. Clyne et al. carried out the preliminary investigations on the hot tearing of Mg-Zn alloys and concluded that the largest hot tearing susceptibility can be observed with 2% Zn [3]. The present work investigates the influence of Zn content and mold temperature on the hot tearing susceptibility for Mg-Zn binary alloys and Mg-Zn-Al ternary alloys using thermodynamic modeling and quantitative experimental measurements.

Experimental procedures

Thermodynamic calculations based on Clyne's model

The hot tearing criterion proposed by Clyne and Davies [2, 3] is based on the assumption that the strain applied during the earlier stage of liquid and mass feeding is accommodated without problem by the casting. When the dendrites are no longer free to move easily, the liquid mass feeding can not accommodate the strains developed during this stage. The last stage of freezing is considered the most susceptible to hot tearing in this criterion. The cracking susceptibility coefficient (CSC) is defined by the ratio of t_V, the vulnerable time period where hot tearing may develop, and t_R, the time available for the stress-relief process where mass feeding and liquid feeding occur. The CSC reads:

$$CSC = \frac{t_V}{t_R} = \frac{t_{f_L=0.01} - t_{f_L=0.1}}{t_{f_L=0.1} - t_{f_L=0.6}} \qquad \text{Equation 1}$$

where $t_{f_L} = 0.01$ is the time when the liquid fraction, f_L, is 0.01, $t_{f_L} = 0.1$ is the time when f_L is 0.1 and $t_{f_L} = 0.6$ is the time when f_L is 0.6. The CSC values were calculated using Pandat and PanEngine thermodynamic software based on the thermodynamic database PanMg 8.0. The detailed description about the calculation of CSC can be found in the previous paper [9].

Melting and quantitative setup to characterize hot tearing

A cylindrical mild steel crucible coated with BN was used for melting in an electrical resistance furnace. Pure magnesium (99.9 wt. %), zinc (99.6 wt. %) and aluminum (99.6 wt. %) were used as staring materials. About 700g of pure magnesium was melted in the crucible under a protective gas of high pure Ar + 0.2% SF6 to minimize the formation of oxide films on the melt surface. When the temperature of melt reached about 700°C, pure zinc and aluminum were added to the melt. The melt was stirred manually for 2 minutes and then held at the pouring temperature for about 5 minutes before pouring. The pouring temperature was set at 80°C above the liquidus temperature. The melt was poured into a permanent mold with a thin layer of BN. For a certain pouring temperature for each Mg-Zn alloy, five different initial mold temperatures ranging from 200 to 450°C were selected.

To detect the initiation of hot tearing, a quantitative method based on the contraction stress measurement principle was developed [10-12]. The system consists of a constrained rod casting (CRC) mold, a contraction force measurement system with a load cell, a data logging unit and a data recording program. During solidification, the contraction of the horizontal bar is restrained by both the sprue and the flange. This restraint can cause hot tears to form. The hot tears always occurred at the junction of the sprue and the horizontal bar. Once the casting started, the force measurement system was activated. The force and temperatures of the mold at different positions and temperature at the hot spot area were recorded by computer during casting. A computer-based data acquisition system, including ALTHEN load cell (ADBBPS), was used to record the temperature and force during solidification. The force curve (force vs. time) and cooling curve (temperature vs. time) were used for analyzing the hot tearing.

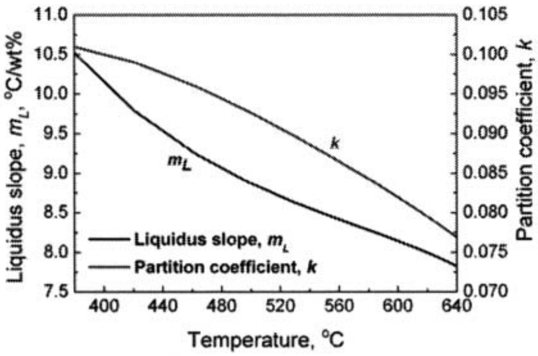

Figure 1. Calculated values m_L and k as a function of temperature.

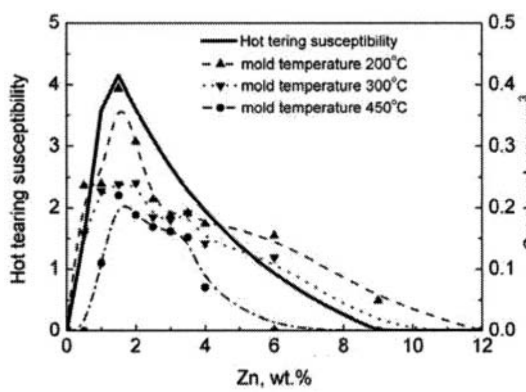

Figure 2. Comparison of hot tearing susceptibility obtained by thermodynamic calculations and crack volume by experimental measurement for Mg-Zn alloys at different mold temperatures.

Crack volume measurement

In the previous investigations, the hot crack size was normally used as the index of hot tearing susceptibility. The larger the crack size, the higher the hot tearing susceptibility. Besides that, either the total size or the width of crack was quantified instead of the crack size. In fact, due to the complexity of crack pattern and the fact that the depth of crack was not considered, the large errors become inevitable when using these methods. In order to reduce the system error and increase the precise of evaluation, the present work takes the volume of total cracks as an index to quantitatively describe hot tearing susceptibility. The detailed descriptions about the measurement of the crack volume can be found in Ref. [10-12].

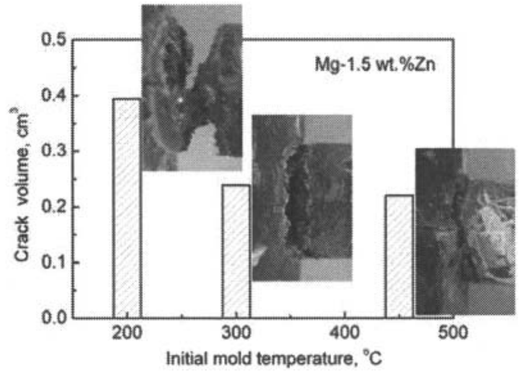

Figure 3. Influence of the initial mold temperature on the hot tearing susceptibility of Mg-1.5Zn alloy.

Results and discussion

Hot tearing susceptibility of Mg-Zn binary alloys

Influence of the Zn content on hot tearing susceptibility. In the present thermodynamic calculations, some modifications have been done for the parameters "liquidus slope m_L" and "partition coefficient k". These two parameters were considered to be constant in the previous Clyne's method. In fact, they vary with temperature, as shown in Figure 1. The liquidus slope m_L increases from 7.8 to 10.5 as the temperature decreases from 648°C (melting point of Mg) to 340°C (eutectic temperature of binary Mg-Zn alloys). The partition coefficient k also changes from 0.076 to 0.1 in the temperature range from 640°C to 340°C.

Figure 2 shows the prediction of CSC as a function of the content of Zn for the binary Mg-Zn alloys. The curve shows a typical "λ-shape". The CSC value first increases with the content of Zn, reaches the maximum at about 1.5 wt.% Zn, and then decreases again with further increasing Zn content. The measurements of crack volume for the hot tearing samples show the same tendency in the variation of hot tearing susceptibility with Zn content (Figure 2). It also indicates that the maximum hot tearing susceptibility occurs at about 1.5 wt%. Zn. Good agreement is obtained between the current thermodynamic predictions and the experimental measurements of crack volume. However, it is noticed that the present thermodynamic calculations cannot predict the effects of mold temperature on the hot tearing susceptibility (Figure 2), although they can give a satisfied result in predicting the influence of the content of Zn on the hot tearing susceptibility. Actually, with the mold temperature increasing, the hot tearing susceptibility decreases (More details are given later). To optimize the alloy composition from the considering of hot tearing susceptibility, the thermodynamic calculations based on Clyne and Davies' model would still be helpful and valuable.

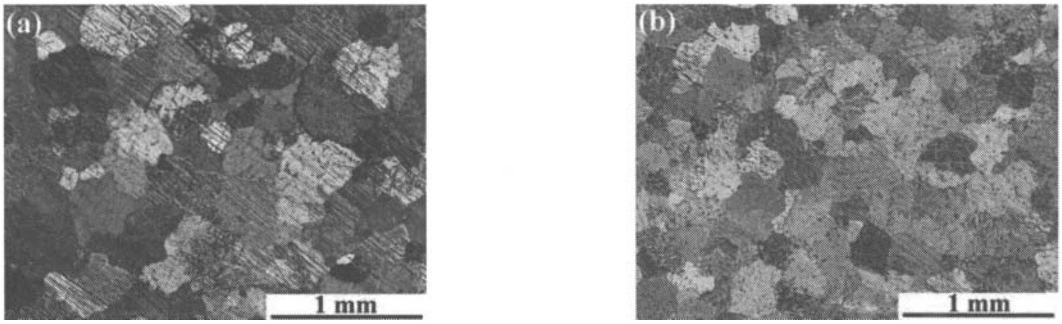

Figure 4. Morphologies of grains for alloys with mold temperature 300°C, (a) Mg-1.5 Zn and (b) Mg-6.0 Zn.

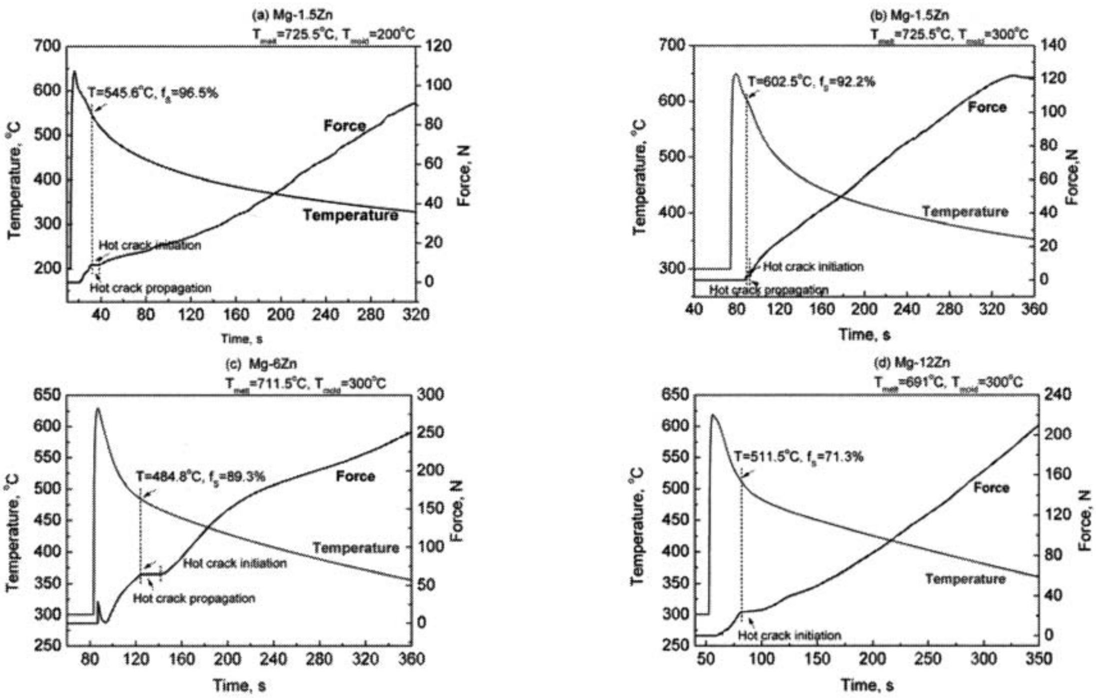

Figure 5. Typical curves of contraction force as a function of solidification time, (a) Mg-1.5Zn, mold temperature 200°C; (b) Mg-1.5Zn, mold temperature 300°C; (c) Mg-6Zn, mold temperature 300°C; and (d) Mg-12Zn, mold temperature 300°C.

Although the detailed mechanism about the effect of primary alloying elements on the hot tearing is unclear, the following explanations are more or less helpful to understand the role of primary alloying elements. The resultant microstructure such as the dendrites and the amount of eutectic phases are associated with the content of primary alloying elements. At a lower content of Zn, the amount of eutectic phases is less. With increasing Zn content, the amount of Zn-containing intermetallics increases due to the non-equilibrium solidification. This may lead increasing tendency of hot tearing when the Zn content increases. At higher Zn content, the dendrite size decreases [13]. On the other hand, the amount of low melting point eutectic phases increases, and that improves the fluidity of liquid. The refilling of the hot cracks by these liquids may proceed at the later stages of solidification, and the tendency of hot tearing is alleviated. Due to the complexity of hot tearing [4], there is still much work to do to clarify the mechanism. For example, at the later stages of solidification, the segregation of impurities at the dendritic and grain boundaries may also influence the hot tearing susceptibility [4].

Influence of mold temperature. The cooling rate significantly affects the solidification process, and has a considerable influence on the hot tearing susceptibility. It is easy to obtain different cooling rates by changing the mold temperatures. Figure 3 illustrates the crack volume in castings prepared under different initial mold temperatures from 200 to 500°C for the Mg-1.5 wt.% Zn alloy. It is clearly shown that the increment in the initial mold temperature decreases the hot tearing susceptibility. The crack volume of the sample with the initial mold temperature at 450°C is smaller than that at an initial mold temperature of 200°C. More data for the other alloys is shown in Figure 2. For each alloy, both the hot tearing susceptibility and measured crack size increase with decreasing initial mold temperature. In addition, the critical value of the initial mold temperature to suppress the occurrence of the hot tearing is different when the Zn content is different (Figure 2). For example, the crack is hardly observed when the initial mold temperature is 450°C for the Mg-6wt.% Zn alloy. With further increases in Zn content to 12 wt.%, no visible crack is observed even with an initial mold temperature at 200°C.

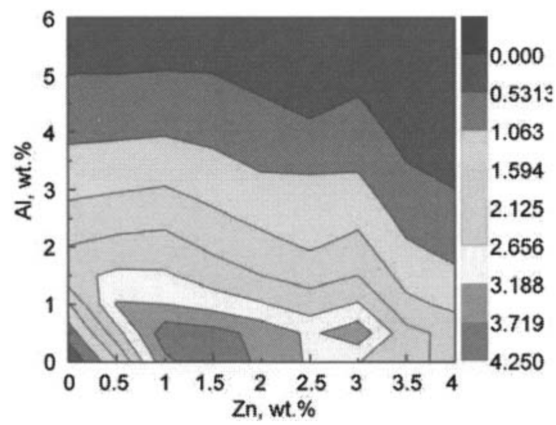

Figure 6. Influence of the content of Zn and Al on the hot tearing susceptibility of Mg-Zn-Al ternary alloys.

Different initial mold temperatures can lead to different cooling rates in the casting. Hot tearing is a defect normally formed in the hot spot areas, where the lattermost solidification takes place. For an irregularly shaped casting, a higher cooling rate will generate larger temperature gradients, thus resulting in more severe hot spots. At the same time, the larger temperature gradient leads to higher thermal stresses in the casting [4]. Therefore, the hot tearing susceptibility is higher when the cooling rate is high, i.e. the initial mold temperature is low. The fact that the critical initial mold temperature to suppress the hot tearing decreases with the increment in the content of Zn, is attributed to the following possible reasons:

(1) With increasing Zn content, the liquidus temperature of Mg-Zn alloys reduces.
(2) The fluidity of liquid improves due to the increment in the content of Zn.
(3) The size of dendrites and grains decreases when the content of Zn increases (Figure 4).

Initiation and propagation of hot cracks. Some typical experimental curves for Mg-Zn binary alloys with different initial mold temperatures are summarized in Figure 5. The analyses of these curves can satisfactory explain the hot tearing response that occurred during solidification [10-12]. The sudden drop was observed on the force curves. The peak point of the drop corresponds to the initiation of hot tearing. These peak positions are affected by both the initial mold temperature and the Zn content. As shown in Figure 5(a), the hot crack initiated at 545.6°C for Mg-1.5 wt.%Zn alloy with the initial mold temperature 200°C. This corresponds to a solid fraction of 96.5%, according to the thermodynamic calculation by Pandat software using the Scheil model. This solid fraction value is close to the well-established criterion that hot tearing normally occurs at the late stages of solidification with the solid fraction in the range from 85% to 95% [1, 14, 15]. With the initial mold temperature increasing from 200°C to 300°C, the onset temperature increases from 545.6°C to 602.5°C (Figure 5(b)). This corresponds to a solid fraction decreasing from 96.5% to 92.2%. For Mg-6 wt.% Zn and Mg-12 wt.% Zn with the mold temperature 300°C, the onset temperature is 484.8°C and 511.5°C, respectively (Figure 5(c),(d)), corresponding to a solid fraction of 89.3% and 71.3%, respectively. Therefore, with increasing Zn content, the solid fraction decreases at which the hot tearing happens during solidification. The cause is the same as that mentioned above, i.e. the higher Zn content leads to a higher amount of eutectic phases and improves the liquid fluidity. Besides the information about the initiation of hot tearing, more information such as the propagation of hot crack can also be obtained by further analyzing the experimental curves. During the propagation of a hot crack, the force releases as marked in Figure 5(a), (b) and (c) with a dashed line. In Figure 5(d), no apparent drop is observed on the curves, indicating that no visible hot cracks exist in Mg-12 wt.% Zn alloy with the initial mold temperature of 300°C. This is in good agreement with the experimental observation of hot crack (Figure 2). However, it should be noted that, although the apparent force drops are not observed, the curve slope greatly reduces after some time (see the position of the dashed line in Figure 5(d)), indicating that the accumulated force is released in some ways. This may proceed with the formation of micro-hot tears [9]. The formation of these micro-hot tears decreases the rate of force accumulation, and in the subsequent solidification they could be healed by liquid refilling because this sample has a higher Zn content and the amount of eutectic phases is higher.

Hot tearing susceptibility of Mg-Zn-Al ternary alloys

Thermodynamic calculations. The contour plot of hot tearing susceptibility for Mg-Zn-Al ternary alloys with thermodynamic calculation is shown in Figure 6. The maximum hot tearing susceptibility occurs at the composition of around 1.5 wt.% Zn and <0.5 wt.%Al. The data from the two sections in this contour plot are compared with the experimental data in Figure 7. The hot tearing susceptibility at the section with a fixed content of Zn (1.5 wt.%), i.e. the Mg-1.5Zn-yAl (y=0.5,3,6) alloys, decreases with increasing Al content (Figure 7 (a)). Both the thermodynamic calculations and experimental measurement of crack volume show that the hot tearing susceptibility decreases when the content of Al increases in Mg-1.5 Zn-y Al ternary alloys. This indicates that the thermodynamic calculations on the hot tearing susceptibility based on Clyne and Davies' model are also suitable for the composition design of ternary alloy system from the consideration of castability. When the content of Al is fixed at 0.5 wt.% Al, i.e. the Mg-xZn-0.5Al (x=0.5, 1.5, 2.5, 4) alloys, good agreement for the hot tearing susceptibility as a function of Zn content is also observed between the thermodynamic calculations and experimental measurements (Figure 7(b)). As shown in Figure 7(b), in the investigated range of Zn content two peaks are observed: one is at about 1.0 to 1.5 wt.% Zn, another at about 3.0 wt.%.

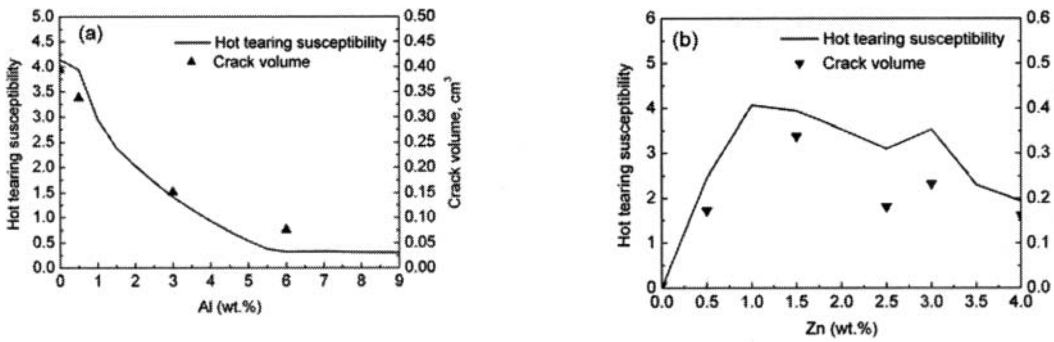

Figure 7. Comparison of the hot tearing susceptibility obtained by thermodynamic calculations and the crack volume by experimental measurement which is proportional to the hot tearing susceptibility for Mg-Zn-Al ternary system, (a) with a fixed value of 1.5 wt.% Zn; and (b) with a fixed value of 0.5 wt.% Al.

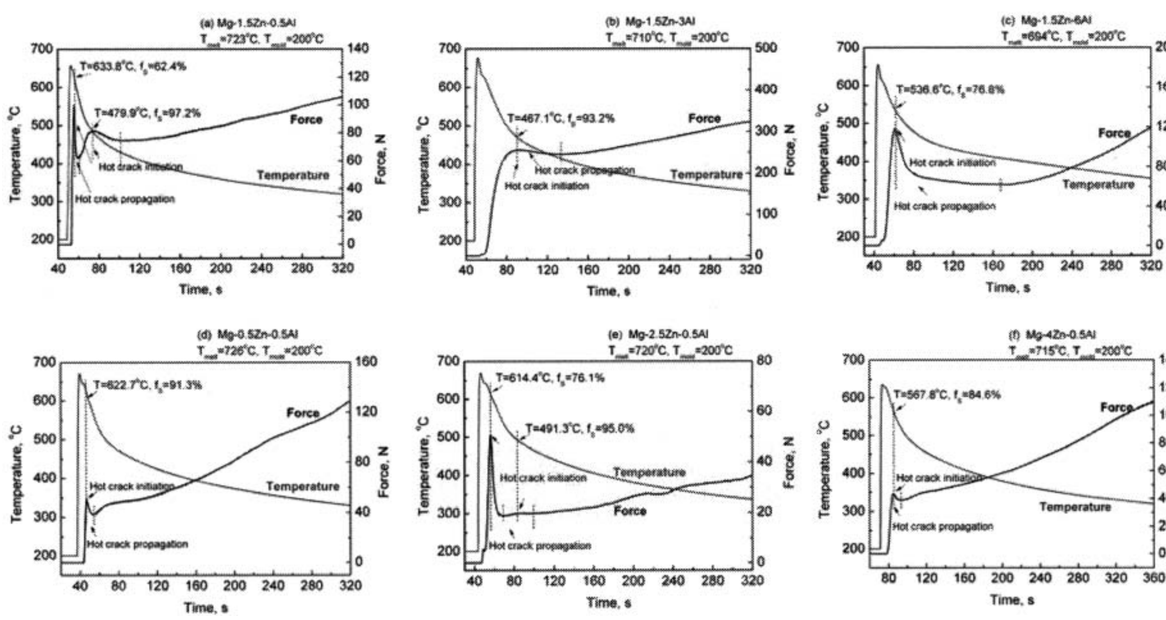

Figure 8. Typical curves of contraction force as a function of solidification time at mold temperature 200°C, (a) Mg-1.5Zn-0.5Al; (b) Mg-1.5Zn-3Al; (c) Mg-1.5Zn-6Al; (d) Mg-0.5Zn-0.5Al; (e) Mg-2.5Zn-0.5Al and (f) Mg-4.0 Zn-0.5Al.

Figure 8 shows typical curves of contraction forces as a function of solidification time for Mg-1.5Zn-yAl and Mg-xZn-0.5Al alloys at a mold temperature of 200°C. A clear drop in the contraction force is observed in all curves, indicating that the hot tears form in all these samples. For Mg-1.5Zn-0.5Al alloy, two peaks exist on the curve (Figure 8(a)). The first peak occurs at temperature 633.8°C which corresponds to a solid fraction of 62.4%. The second peak is located at 479.9°C which corresponds to a solid fraction of 97.2%. This sample contains 1.5 wt.% Zn and 0.5 wt.% Al. The investigations of the binary Mg-Zn alloys (Figure 2) and Mg-Al alloys [11] illustrate that when the content of Zn is 1.5 wt.% and Al 0.5 wt.% the hot tearing susceptibility is very large. The formation of two peaks on the contraction force curve may also depict that this alloy has a large hot tearing susceptibility. When the first hot tear occurs at 633.8°C, the solid fraction is relatively low with a value of 62.4%. A large amount of liquid still remains and the formed dendritic network does not so densely contact each other. The liquid still has a chance to flow into the first formed hot tears and repair them. With the solidification proceeding, the force increases again. When it reaches a critical value, new hot tearing occurs and the force drops again (second peak in Figure 8(a)). The same situation is also observed for alloy Mg-2.5Zn-0.5Al, indicating that this alloy has a large hot tearing tendency.

As observed for the binary Mg-Zn alloys, the initiation of hot tears and their propagation can also be reflected by the curves of contraction force for the ternary Mg-Zn-Al alloys (Figure 8). Based on the peak position and its corresponding temperature, the critical solid fraction at which the hot tear occurs can be calculated with the thermodynamic calculations. The hot tearing occurs at a higher sold fraction similar to that observed for the binary Mg-Zn alloys, normally more than 90%. Due to the complexity of hot tearing, at this moment it is not easy to explain the recorded curves completely and clearly both for the binary and ternary alloys. More investigations are needed in the future. In spite of this, it seems that with increasing Al content, the critical solid fraction decreases for the ternary Mg-Zn-Al alloys (Figure 8).

Conclusions

The hot tearing susceptibility of binary Mg-Zn system and ternary Mg-Zn-Al system has been investigated by thermodynamic calculations and experimental methods. The conclusions are summarized as follow:

(1) Both the measurements of hot crack volume and thermodynamic calculations show that the hot tearing susceptibility as a function of Zn content follows the "λ" shape. The HTS first increases with Zn content, reaches the maximum at about 1.5 wt.% Zn and then decreases with further increasing the Zn content. The thermodynamic calculations on HTS, based on Clyne and Davies' model, are helpful and valuable for the optimal design of compositions for magnesium alloys from the considerations of hot tearing susceptibility. However, this model cannot predict the influence of other parameters on HTS, such as the initial mold temperature.

(2) With increasing the initial mold temperature, the hot tearing susceptibility decreases, because the higher initial mold temperature results in a lower cooling rate.

(3) In the Mg-Zn-Al ternary system, the HTS decreases with increasing Al content. The curve of the HTS as a function of Zn content in the ternary Mg-Zn-Al system is a little different from that observed in the binary Mg-Zn alloys. Two peaks are obtained: one is at about 1.0 to 1.5 wt.% Zn, another at about 3.0 wt.%.

(4) The recorded contraction force-temperature-time curves can supply some useful information about the initiation of hot tears, the corresponding solid fraction, propagation of hot tears, and load release by the formation of macrocracks or microcracks.

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References

1. J. Campbell, *Castings* (Oxford: Butterworth-Heinemann, 2003), 205-231.

2. T.W. Clyne, and G.J. Davies, "Comparision between Experimental Data and Theoretical Predictions Relating to Dependence of Solidification Cracking on Composition", Solidification and casting of metals, edited by Sheffield, UK, 1977, 275-278.

3. T.W. Clyne, and G.J. Davies, "The Influence of Composition on Solidification Cracking in Binary Alloy Systems", *Brit. Foundryman*, 74 (1981), 65-73.

4. D.G. Eskin, Suyitno, and L. Katgerman, "Mechanical Properties in the Semi-Solid State and Hot Tearing of Aluminium Alloys", *Progress in Materials Science*, 49 (2004), 629-711.

5. G. Cao, I. Haygood, and S. Kou, "Onset of Hot Tearing in Ternary Mg-Al-Sr Alloy Castings", *Metallurgical and Materials Transactions A*, 41 (2010), 2139-2150.

6. G. Cao, and S. Kou, "Hot Tearing of Ternary Mg-Al-Ca Alloy Castings", *Metallurgical and Materials Transactions*, 37A (2006), 3647-3663.

7. Y.S. Wang, Q.D. Wang, C.J. Ma, W.J. Ding, and Y.P. Zhu, "Effects of Zn and RE Additions on the Solidification Behavior of Mg-9Al Magnesium Alloy", *Materials Science and Engineering A*, 342 (2003), 178-182.

8. W. Zheng, S. Li, B. Tang, D. Zeng, and X. Guo, "Effect of Rare Earths on Hot Cracking Resistant Property of Mg-Al Alloys", *Journal of Rare Earths*, 24 (2006), 346-351.

9. L. Zhou, Y.D. Huang, P.L. Mao, K.U. Kainer, Z. Liu, and N. Hort, "Influence of Composition on Hot Tearing in Binary Mg-Zn Alloys", Proceedings of the 8th Pacific Rim International Conference on Modeling of Casting and Solidification Processes, edited by J. K. Choi, H. Y. Hwang and J. T. Kim, Incheon, Korea, 2010, 97-104.

10. Z.S. Zhen, N. Hort, Y.D. Huang, N. Petri, O. Utke, and K.U. Kainer, "Quantitative Determination on Hot Tearing in Mg-Al Binary Alloys", *Light Metals Technology 2009*, 618-619 (2009), 533-540.

11. Z.S. Zhen, N. Hort, Y.D. Huang, O. Utke, N. Petri, and K.U. Kainer, "Hot Tearing Behaviour of Binary Mg-1Al Alloy Using a Contraction Force Measuring Method", *International Journal of Cast Metals Research*, 22 (2009), 331-334.

12. Z.S. Zhen, N. Hort, O. Utke, Y.D. Huang, N. Petri, and K.U. Kainer, "Investigations on Hot Tearing of Mg-Al Binary Alloys by Using a New Quantitative Method", *Magnesium Technology 2009*, (2009), 105-110.

13. D.H. StJohn, M. Qian, M.A. Easton, P. Cao, and Z. Hildebrand, "Grain Refinement of Magnesium Alloys", *Metallurgical and Materials Transactions*, 36A (2005), 1669-1679.

14. D. Eskin, and L. Katgerman, "A Quest for a New Hot Tearing Criterion", *Metallurgical and Materials Transactions A*, 38 (2007), 1511-1519.

15. Suyitno, V. Savran, L. Katgerman, and D. Eskin, "Effects of Alloy Composition and Casting Speed on Structure Formation and Hot Tearing During Direct-Chill Casting of Al-Cu Alloys", *Metallurgical and Materials Transactions A*, 35 (2004), 3551-3561.