Solidification pathways and hot tearing susceptibility of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys

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Abstract: Hot tearing is known as one of the most serious solidification defects commonly encountered during solidification. It is very important to study the solidification path of alloys. In the work, thermal analysis with cooling curve was used for the investigation of microstructure evolution with different Zn contents during solidification process of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys. Thermal analysis results of $\text{MgY}_4\text{Zr}_{0.5}$ alloys revealed one distinct phase precipitation: α -Mg. Three different phase peaks were detected in the Zn-containing alloys: α -Mg, Z-phase (Mg_{12}YZn) and W-phase ($\text{Mg}_3\text{Y}_2\text{Zn}_3$). In addition, for the present $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys, the freezing ranges of these alloys from large to small were: $\text{MgZn}_{1.5}\text{Y}_4\text{Zr}_{0.5} > \text{MgZn}_{3.0}\text{Y}_4\text{Zr}_{0.5} > \text{MgZn}_{0.5}\text{Y}_4\text{Zr}_{0.5} > \text{MgY}_4\text{Zr}_{0.5}$. The effect of different contents of Zn (0, 0.5, 1.5, 3.0wt.%) on hot tearing behavior of $\text{MgY}_4\text{Zr}_{0.5}$ alloy was investigated using a constrained rod casting (CRC) apparatus equipped with a load cell and data acquisition system. The experimental results show that the addition of Zn element significantly increases hot tearing susceptibility (HTS) of the $\text{MgY}_4\text{Zr}_{0.5}$ alloy due to its extended freezing range. Some free dendrite-like bumps and ruptured liquid films on the fracture surfaces were observed in all the fracture surfaces. These phenomena proved the fact that the hot tearing formation was caused by interdendritic separation due to lack of feeding at the end of solidification.

Key words: $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys; microstructure; thermal analysis; hot tearing susceptibility

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Hot tearing is considered as a serious defect in castings, especially in those alloys with large freezing ranges^[1, 2]. The hot tearing mainly occurs due to the lack of compensation and stresses exceeding the critical strength in the mushy zone^[3, 4]. In other words, the hot tearing is very complex phenomenon which is associated with solidification path, feeding ability and strength of the solid phase^[5]. The hot tearing phenomenon has been investigated for a long time, but the mechanism of hot tearing has been yet not clearly understood^[6]. Most researchers worked on prevention of hot tearing defects and explored hot tearing mechanisms^[7-10]. Recently, Song et al. reviewed hot tearing criterion, experimental set-ups and factors influencing hot tearing of Mg alloys^[4].

Many commercial Mg alloys are based on the Mg-Zn system alloys with addition of minor rare earth (RE). As one of the most important rare earth elements, Yttrium (Y) has been widely used in the production of Mg alloys to improve the comprehensive mechanical properties

^[11,12]. Besides, Y can improve casting properties, such as the decrease of gases, impurities and grain size. In the past two decades, Mg-Zn-Y alloys have received more attention due to their high strength, high creep resistance, good corrosion resistance and other outstanding processing techniques^[13-15]. The high strength of Mg-Zn-Y alloys is attributed to the formation of icosahedral quasicrystalline phase (I phase), which shows a high thermal stability and a strong interface bonding with the matrix. It has been reported that the yield strength of Mg-Zn-Y alloys increases with increasing volume fraction of I-phase^[16]. The study by Xu et al. indicated that Mg-Zn-Y-Zr alloys with Zn/Y ratios of 5 and 10 were mainly composed of I-phase and α -Mg matrix^[17]. For Mg-Zn-Y-Zr system, the researchers mainly focused on the investigation of microstructure and mechanical properties. The hot tearing susceptibility Mg-Zn-Y-Zr alloys was rarely studied, which may greatly influence their practical applications. Previously, the effects of Y addition on the hot tearing susceptibility of ternary Mg-1.5Zn-xY ($x=0.2, 2$ and 3 wt.%) and Mg-4.5Zn-xY ($x=0.4, 0.9$ and 2 wt.%) were studied using an instrumented constrained rod casting (CRC) apparatus, and the hot tearing susceptibility of Mg-1.5Zn-xY and Mg-4.5Zn-xY alloys decreased with increasing Y content. In this study, the effects of Zn content on the hot tearing susceptibility of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ ($x=0, 0.5, 1.5, 3$

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wt.%) were explored using the same setup. Meanwhile, several important temperatures in the mushy zone of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys were measured by a double-thermocouple testing system, such as liquidus temperature, phase formation temperature and solidus temperature.

1 Experimental procedures

1.1 Hot tearing tests

The hot tearing tests were performed using a hot tearing test apparatus that was developed by our research team based on the measurement of contraction force during solidification [18]. As shown in Fig.1, the whole apparatus consisted of a CRC permanent mold, a contraction force measurement system and a data acquisition system. In order to investigate the process of hot tearing initiation and propagation, the evolutions of contraction force and temperature were monitored during solidification. Once a hot tearing occurred during the solidification process, the contraction force was released, and hence a sudden drop could be obtained on the force curve.

The required $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys were prepared in a cylindrical steel crucible which was coated with boron nitride (BN) and put in an electric resistance furnace. Three hundred and fifty grams of purity Mg was melted under mixture of high

purity $\text{Ar}+0.2\%\text{SF}_6$ gas. Required amounts of purity Zn, Mg-30wt.%Y and Mg-35wt.%Zr master alloys were added to the melts at 700 °C. The molten metal was manually stirred for 2 minutes in order that the addition elements were completely dissolved before the ingot was cast. The pouring temperature was 720 °C, and the mold of the hot tearing tests was preheated to 200 °C. Each hot tearing test was conducted three times for each composition in order to ensure the result reliability.

The hot tearing susceptibility of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys was characterized by the measurements of crack volume using the wax penetration method. The advantages of this method are simplicity and speed, without damaging the samples. The principle of the method was based on measurement of the sample weight differences before and after penetration wax, and then divided by wax density to obtain the crack volumes. The details of the apparatus can be obtained from Ref. [3]. The volume of the cracks can be determined using the following equation:

$$V_{\text{cr}} = \frac{M_2 - M_1}{\rho_{\text{wax}}}$$

where V_{cr} is the volume of cracks; M_1 and M_2 are the weight of the magnesium casting before and after the injection of wax, respectively; ρ_{wax} is the density of the paraffin wax, and $\rho_{\text{wax}}=0.90 \text{ g}\cdot\text{cm}^{-3}$.

Fig. 1: Schematic of hot tearing test setup: (a) whole setup, (b) device for detecting temperature and force during the solidification, (c) thermocouple position for obtaining temperature at hot spots

1.2 Thermal analysis

Thermal analysis is one of the most useful in situ methods to investigate the solidification characteristics of alloys during casting process, which was developed by Backerud et al. [19]. The $\text{Mg}-x\text{Zn}-4\text{Y}-0.5\text{Zr}$ alloys were remelted in an electric resistance furnace with a graphite crucible. When the melt was 700 °C and held for 30 min, the crucible with the melt was taken out from the furnace. The top and bottom of the crucible were covered with fiberfrax to ensure Newtonian heat transfer. Then, two K-type thermocouples were inserted into the melt, where one was placed close to wall, the other was located at the center of the crucible, as shown in Fig. 2, and they were kept at the same depth in the melt to ensure the reliability of the results. Thermal analysis records the temperature/time data during the solidification process by one data acquisition system, as shown in Fig. 2. Each thermal analysis was conducted two times for each composition in order to ensure the result reliability.

Fig. 2: Schematic of thermal analysis system with data acquisition system

1.3 Microstructure analysis

A longitudinal section of the sprue-horizontal rod junction was chosen for the tear and microstructural studies due to hot tears happening near the junction. The microstructures and hot tearing morphologies were studied using an optical microscope

(OM). The samples were grounded with SiC waterproof papers up to 2,000 grit size, and then polished on an abrasive finishing machine with 0.5 μm diamond polishing paste. The polished samples were chemically etched in a solution of 16 g picric acid, 10 mL acetic acid, 20 mL distilled water and 200 mL ethanol. The phase identification of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys was characterized by X-ray diffraction (XRD).

2 Results and discussions

2.1 XRD results

Figure 3 shows the XRD patterns of as-cast $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys with different content of Zn. The as-cast Zn-free $\text{MgY}_4\text{Zr}_{0.5}$ alloy mainly contains $\alpha\text{-Mg}$. In contrast, some additional diffraction peaks were observed for the Zn-containing alloys. Following comparison with the International Centre for Diffraction Data, such peaks were identified as Z-phase (Mg_{12}YZn) and W-phase ($\text{Mg}_3\text{Y}_2\text{Zn}_3$). It can be found that the Z-phase (Mg_{12}YZn) forms in the Zn-containing alloys. Both the Z-phase (Mg_{12}YZn) and W-phase ($\text{Mg}_3\text{Y}_2\text{Zn}_3$) form in $\text{MgZn}_{1.5}\text{Y}_4\text{Zr}_{0.5}$ and $\text{MgZn}_{3.0}\text{Y}_4\text{Zr}_{0.5}$ alloys.

Fig. 3: XRD patterns of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys

2.2 Thermal analysis tests

The thermal analysis results of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys are shown in Fig. 4. It shows several important curves of mushy zone in $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys measured by double-thermocouple testing system, such as the cooling curve, baseline and first derivative curves. The baseline is first derivative of the cooling curve. It is assumed that no phase transforms during solidification. The released latent heat can be arrested by arrest points on the cooling curve and related to the phase precipitation on the cooling curve. Therefore, enhancement of slope on the cooling gradient curves is related to the solidification reactions for different phases. In order to calculate solid fraction during progressive solidification, the baseline was estimated by peak fitting square function curve between the onset and the end of solidification in the first derivative curve. The solid fraction at each time frame included the area between the first derivative

and the baseline. The solid fraction can be calculated using the following equation [4]:

$$f_s = \frac{\int_0^{t_s} [(dT/dt)_{cc} - (dT/dt)_{bl}] dt}{\int_0^{t_s} [(dT/dt)_{cc} - (dT/dt)_{bl}] dt}$$

where cc and bl denote cooling curve and baseline, respectively.

As shown in Fig. 4(a), for $\text{MgY}_4\text{Zr}_{0.5}$ alloy, only one obvious peak is observed in the first derivative curve which corresponds to the critical temperature of 647.0 °C. There is only one phase, that is, $\alpha\text{-Mg}$, according to the XRD results. This is consistent with the observed microstructure, as shown in Fig. 4(b). Moreover, as shown in Fig. 4 (d), the amount of second phases increases with increasing Zn content. Two peaks are observed in Fig. 4 (c). They represent the $\alpha\text{-Mg}$ phase formation and the $\text{L} \rightarrow \alpha\text{-Mg} + \text{Z-phase}$ (Mg_{12}YZn) eutectic reactions, which correspond to the temperatures of 644.9 °C and 530.0 °C, respectively. The microstructures are also composed of $\alpha\text{-Mg}$ and Z-phase, which agrees well with the thermal analysis results. With the increase in Zn content, $\text{MgZn}_{1.5}\text{Y}_4\text{Zr}_{0.5}$ alloy has three peaks observed in the first derivative curve, which correspond to the critical temperatures of 638.0, 530.6 and 506.6 °C, respectively. These three peaks represent the $\alpha\text{-Mg}$ phase formation, the $\text{L} \rightarrow \alpha\text{-Mg} + \text{Z-phase}$ (Mg_{12}YZn) eutectic reaction, and $\text{L} \rightarrow \alpha\text{-Mg} + \text{W-phase}$ ($\text{Mg}_3\text{Y}_2\text{Zn}_3$) eutectic reaction. This agreed well with the results of X-ray diffraction and microstructure observation. Accordingly, the microstructure of $\text{MgZn}_{1.5}\text{Y}_4\text{Zr}_{0.5}$ alloy is mainly composed of $\alpha\text{-Mg}$, Z-phase and W-phase at the grain boundaries. The solidification pathway can be described as follows: after $\alpha\text{-Mg}$ formation, Z-phase formation occurs by a eutectic reaction, and then W-phase formation. Analysis of cooling and first derivative curves of $\text{MgZn}_{3.0}\text{Y}_4\text{Zr}_{0.5}$ alloys also shows similar peaks with $\text{MgZn}_{1.5}\text{Y}_4\text{Zr}_{0.5}$ alloy, since there also are three identical phases, which are $\alpha\text{-Mg}$, Z-phase, and W-phase in the as-cast state. These phases are also identified in the as-cast microstructures.

The transformation sequences during solidification of these studied alloys are listed in Tables 1 and 2. In addition, several important temperatures of mushy zone for $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys measured by double-thermocouple testing system, such as the liquidus temperature, the phase formation temperature and the solidus temperature are summarized in Table 3.

In order to determine the freezing range, according to thermal analysis results, the evolution of liquidus and solidus with Zn content for $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys are shown in Fig. 5. It can be found that the liquidus temperature slowly decreases with increasing Zn content. The solidus temperature first quickly decreases with increasing the Zn content, reaches the minimum at 1.5wt.%Zn, and then slightly increases with an increase further in Zn content to 3.0wt.%. Thus, the freezing ranges of $\text{MgZn}_{0.5}\text{Y}_4\text{Zr}_{0.5}$ and $\text{MgY}_4\text{Zr}_{0.5}$ alloys changed narrowly, which are 129.4 and 54.0 °C, respectively. In contrast, the freezing ranges of $\text{MgZn}_{1.5}\text{Y}_4\text{Zr}_{0.5}$ and $\text{MgZn}_{3.0}\text{Y}_4\text{Zr}_{0.5}$ alloys changed widely, which are 146.4 and 144.0 °C, respectively. As the

Fig. 4: Thermal analysis results and SEM micrographs of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys: (a) and (b) $x=0$, (c) and (d) $x=0.5$, (e) and (f) $x=1.5$, (g) and (h) $x=3$

Table 1 : Solidification path of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys

ID No.	Transformation
L	Onset of $\alpha\text{-Mg}$ nucleation (liquidus): $\text{L} \rightarrow \alpha\text{-Mg} + \text{L}$
1	End of the nucleation and the growth of $\alpha\text{-Mg}$
2	Z-phase formation by pseudobinary eutectic reaction: $\text{L} \rightarrow \alpha\text{-Mg} + \text{Z-phase}$
3	W-phase formation by pseudobinary eutectic reaction: $\text{L} \rightarrow \alpha\text{-Mg} + \text{W-phase}$
S	End of solidification (solidus)

Table 2 : Transformation sequences of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys during solidification

Alloys	Transformation
$\text{MgY}_4\text{Zr}_{0.5}$	$\text{L} \rightarrow \alpha\text{-Mg}$
$\text{MgZn}_{0.5}\text{Y}_4\text{Zr}_{0.5}$	$\text{L} \rightarrow \alpha\text{-Mg} + \text{L}; \text{L} \rightarrow \alpha\text{-Mg} + \text{Z-phase}$
$\text{MgZn}_{1.5}\text{Y}_4\text{Zr}_{0.5}$	$\text{L} \rightarrow \alpha\text{-Mg} + \text{L}; \text{L} \rightarrow \alpha\text{-Mg} + \text{Z-phase}; \text{L} \rightarrow \alpha\text{-Mg} + \text{W-phase}$
$\text{MgZn}_{3.0}\text{Y}_4\text{Zr}_{0.5}$	$\text{L} \rightarrow \alpha\text{-Mg} + \text{L}; \text{L} \rightarrow \alpha\text{-Mg} + \text{Z-phase}; \text{L} \rightarrow \alpha\text{-Mg} + \text{W-phase}$

Table 3: Thermal analysis results for characteristic temperatures (°C) for all investigated alloys

Alloys	L (°C)	1 (°C)	2 (°C)	3 (°C)	S (°C)
$\text{MgY}_4\text{Zr}_{0.5}$	650.3	647.0	-	-	596.3
$\text{MgZn}_{0.5}\text{Y}_4\text{Zr}_{0.5}$	649.2	644.9	530.0	-	519.8
$\text{MgZn}_{1.5}\text{Y}_4\text{Zr}_{0.5}$	644.1	638.0	530.6	506.6	497.7
$\text{MgZn}_{3.0}\text{Y}_4\text{Zr}_{0.5}$	642.9	637.4	530.7	508.4	498.9

Fig. 5: Evolution of liquidus and solidus with Zn content for $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys from thermal analysis

alloy solidifies continuously, the molten alloy enters into the slurry and mushy zone when the temperature drops below the liquidus, and then the liquid is difficult to move freely, which may be caused by the larger mushy zone of the alloy, and the more developed dendrite growth [20]. In that case, the dendrites start to form a solid skeleton and the liquid has to flow through the dendrite network. The liquid flow is blocked and cannot be feeding well when the dendrites form a continuous network structure. Therefore, the hot tearing may occur. Generally, the hot tearing susceptibility is proportional to the freezing range. For the present $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys, the freezing ranges of these alloys from large to small are: $\text{MgZn}_{1.5}\text{Y}_4\text{Zr}_{0.5} > \text{MgZn}_{3.0}\text{Y}_4\text{Zr}_{0.5} > \text{MgZn}_{0.5}\text{Y}_4\text{Zr}_{0.5} > \text{MgY}_4\text{Zr}_{0.5}$.

2.3 Hot tearing tests

The typical and important results of the hot tearing tests are the temperature-force-time curves. Figure 6 shows such curves of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys with different content of Zn at a mold temperature of 200 °C. The red line and black line are temperature and contraction force measured near the sprue-rod junction during solidification, respectively. With the alloy solidification proceeding, the force increased due to the contraction occurred in the casting. Except for Zn-free

$\text{MgY}_4\text{Zr}_{0.5}$ alloy [Fig. 6(a)], the force leveling off or suddenly dropping indicates that hot tearing formed in the casting, and the temperature corresponding to the onset of the force drop or level off is the temperature of hot tearing initiation (T). For $\text{MgY}_4\text{Zr}_{0.5}$ alloy, although no obvious force leveling off or dropping is found from the temperature-force-time curves, the hot tearing indeed occurs through macro-photos observation. The reason might be small hot tearing formation, which is beyond the detection limit for the hot tearing test apparatus. The temperature-force-time curve of $\text{MgZn}_{0.5}\text{Y}_4\text{Zr}_{0.5}$ alloy is shown in Fig. 6(b), one force leveled off is observed at the temperature of 552.4 °C and the correspondence to the solid fraction is 96.3%, which means the hot tearing initiation in the alloy. With an increase in Zn content to 1.5wt.%, one obvious force drop is observed at the temperature of 507.6 °C and the correspondence to the solid fraction is 96.9%. In addition, the force of $\text{MgZn}_{1.5}\text{Y}_4\text{Zr}_{0.5}$ alloy is dropping greatly, which means the hot tearing is initiating and propagating more seriously than other alloys. For $\text{MgZn}_{3.0}\text{Y}_4\text{Zr}_{0.5}$ alloy, the hot tearing initiated at 519.3 °C and the correspondence to the solid fraction is 91.7%.

The macro-photos of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys exhibiting the hot tearing susceptibility are shown in Fig. 7. It can be clearly seen that the hot tearing susceptibility is significantly influenced by the Zn addition at a mold temperature of 200 °C. The length and width of the hot tearing firstly increases with increasing the Zn content, reaches the maximum at 1.5wt.% Zn, and then decreases with further increase in the Zn addition. The hot tearing susceptibility of these alloys from high to low are: $\text{MgZn}_{1.5}\text{Y}_4\text{Zr}_{0.5} > \text{MgZn}_{3.0}\text{Y}_4\text{Zr}_{0.5} > \text{MgZn}_{0.5}\text{Y}_4\text{Zr}_{0.5} > \text{MgY}_4\text{Zr}_{0.5}$.

Figure 8 shows total crack volumes and freezing ranges of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys with different content of Zn. It can be observed that the total crack volumes and freezing ranges of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys are remarkably influenced by the Zn content. The total crack volumes of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys increase with the addition of Zn content. Meanwhile, the freezing ranges of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys are enlarged from 54.0 °C to 146.4 °C by the addition of Zn, reach the maximum at 1.5wt.% Zn. Especially, $\text{MgZn}_{1.5}\text{Y}_4\text{Zr}_{0.5}$ alloy shows the largest

Fig. 6: Temperature-force-time curves of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys at a mold temperature of 200 °C: (a) $x=0$, (b) $x=0.5$, (c) $x=1.5$, (d) $x=3$

Fig. 7: Macro-photos of casting showing the hot tearing susceptibility

Fig. 8: Total crack volumes and freezing ranges of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys with different Zn contents

freezing range over other alloys which leads to the serious hot tearing susceptibility. These results substantiate the statement that the large freezing range corresponds to a large hot tearing susceptibility.

Figure 9 shows OM micrographs of hot tears for $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys. The black area is hot tears. It can be found that the hot tears initiate at the dendrites or grain boundaries and propagate along them. Another interesting phenomenon is that, for $\text{MgZn}_{0.5}\text{Y}_4\text{Zr}_{0.5}$ alloy, some feeding traces can be observed around the main hot tears. The formation of these feeding traces is due to the fact that a hot tearing separation was refilled by the remaining liquid at the end of the solidification stage. After the hot tears occur, the regions near them have a negative pressure [21]. This negative pressure causes the liquid to be sucked back,

Fig. 9: OM micrographs of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys showing hot tear areas: (a) $x=0$, (b) $x=0.5$, (c) $x=1.5$, (d) $x=3$

refilling the hot tears.

2.4 Fracture surfaces

The typical fracture surfaces of the hot tears regions were observed in $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys, as shown in Fig. 10. Evidence of some free dendrite-like bumps and ruptured liquid films on the fracture surfaces were observed in all the shown fracture surfaces. These phenomena prove the fact that the hot tearing formation is caused by interdendritic separation due to lack of feeding at the end of solidification. According to liquid film theory, two factors determine the hot tearing formation: the liquid film thickness and the solidification contraction resistance. Normally, the alloy composition can influence the thickness of liquid film. Figure 10(a) shows the fracture surfaces of Zn-free $\text{MgY}_4\text{Zr}_{0.5}$ alloy. A large number of ruptured liquid films are observed on the fracture surfaces, which is enough to resist the tensile stress of solidification contraction. This also indicates that a lot of liquid existed when the hot tearing happened. Therefore, the hot tearing susceptibility of Zn-free $\text{MgY}_4\text{Zr}_{0.5}$ alloy is lower than that of the other alloys. In contrast, the amount of ruptured liquid films decreased for $\text{MgZn}_{0.5}\text{Y}_4\text{Zr}_{0.5}$ and $\text{MgZn}_{1.5}\text{Y}_4\text{Zr}_{0.5}$ alloys, as shown in Fig. 10 (b) and (c). In addition, some large dendrite-like bumps are observed on the fracture surface of $\text{MgZn}_{1.5}\text{Y}_4\text{Zr}_{0.5}$ alloy. It means that some dendrites are separated due to the serious hot tearing susceptibility. As shown in Fig. 10(d), a large amount of ruptured liquid films appeared in $\text{MgZn}_{3.0}\text{Y}_4\text{Zr}_{0.5}$ alloy which decreased the hot tearing susceptibility.

3 Conclusions

The solidification pathways and hot tearing characteristics of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloy castings were investigated by experimental methods. Addition of Zn has significant influence on the microstructure, phase precipitation, freezing ranges and hot tearing behaviors of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys. The following conclusions have been drawn:

(1) Thermal analysis results of Zn-free $\text{MgY}_4\text{Zr}_{0.5}$ alloy revealed one distinct phase precipitation: α -Mg. Three different phases were detected in the Zn-containing alloys: α -Mg, Z-phase (Mg_{12}YZn) and W-phase ($\text{Mg}_3\text{Y}_2\text{Zn}_3$). In addition, for $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys, the freezing ranges from large to small were: $\text{MgZn}_{1.5}\text{Y}_4\text{Zr}_{0.5} > \text{MgZn}_{3.0}\text{Y}_4\text{Zr}_{0.5} > \text{MgZn}_{0.5}\text{Y}_4\text{Zr}_{0.5} > \text{MgY}_4\text{Zr}_{0.5}$.

(2) Experimental results show that the length and width of the hot tearing firstly increased with increasing the Zn content, reached the maximum at 1.5wt.% Zn and then decreased with further increases in the Zn addition. The hot tearing susceptibility of these alloys from high to low was: $\text{MgZn}_{1.5}\text{Y}_4\text{Zr}_{0.5} > \text{MgZn}_{3.0}\text{Y}_4\text{Zr}_{0.5} > \text{MgZn}_{0.5}\text{Y}_4\text{Zr}_{0.5} > \text{MgY}_4\text{Zr}_{0.5}$. The addition of Zn element significantly increases HTS of the $\text{MgY}_4\text{Zr}_{0.5}$ alloy due to its extended freezing range.

(3) Some free dendrite-like bumps and ruptured liquid films on the fracture surfaces were observed in all the fracture surfaces. These phenomena proved the fact that the hot tearing formation was caused by interdendritic separation due to lack of feeding at the end of solidification.

Fig. 10: SEM micrographs of tear surfaces of $\text{MgZn}_x\text{Y}_4\text{Zr}_{0.5}$ alloys: (a) $x=0$, (b) $x=0.5$, (c) $x=1.5$, (d) $x=3$

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