Hot tearing susceptibility of $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys and mechanism

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Abstract: The hot tearing susceptibility of $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ ($x = 0.5, 1, 2, 4, 6$) alloys was evaluated using Clyne–Davies' theoretical model and a constrained rod casting (CRC) apparatus equipped with a load cell and data acquisition system. The results obtained from these two approaches were in good agreement, illustrating that the hot tearing susceptibility of the investigated alloys is in the order of $\text{MgZn}_{4.5}\text{Y}_1\text{Zr}_{0.5} > \text{MgZn}_{4.5}\text{Y}_{0.5}\text{Zr}_{0.5} > \text{MgZn}_{4.5}\text{Y}_2\text{Zr}_{0.5} > \text{MgZn}_{4.5}\text{Y}_4\text{Zr}_{0.5} > \text{MgZn}_{4.5}\text{Y}_6\text{Zr}_{0.5}$. The microstructure and morphology of hot tearing regions were observed by means of X-ray diffraction and scanning electron microscopy. The function curves on variation of contraction force and temperature versus time were recorded by a computer during solidification of the $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys in a "T" type mold after A/D (Analog to digital) conversion. Results show that both the amount and morphology of the second phases have a great relationship with the hot tearing susceptibility. But the former plays a more important role on that of $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys. The role of low-melting point eutectic phases on the hot tearing susceptibility of $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys changes gradually with different Y contents. When $Y \leq 1\text{wt.}\%$, it is mainly a damaging effect on intergranular bonding force; when $Y > 1\text{wt.}\%$, it is mainly an intergranular feeding effect on formed separated dendrites.

Key words: hot tearing susceptibility; Mg-Zn-Y-Zr alloys; second phases; liquid film

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Magnesium alloys are known as the "21st Century Green Engineering Materials" because of their many advantages such as low density, high specific strength and stiffness, excellent castability and machinability^[1-3]. They are widely used in many areas including aerospace, military equipment, vehicles, optical devices and communication facilities. However, magnesium alloys often show high hot tearing susceptibility during casting process, due to the wide solidification region and high solidification shrinkage stress^[4]. Thus, hot tearing has increasingly become one of the "bottlenecks", hampering magnesium alloy castings from becoming more thin-walled and complicated^[5]. Recently, Mg-Zn-Y-Zr alloys have been extensively considered for their characteristics of high strength and high ductility. Consequently, rare earth (RE) metals have been proven to be important alloying elements for magnesium alloys^[6]. It has been shown that adding a small amount of Y elements to magnesium alloys could increase mechanical properties of the alloys both at room

and elevated temperatures, as well as to improve their corrosion-resistance^[7, 8]. Adding a certain amount of Y to Mg-Zn alloys can improve their castability, change the aging precipitation and increase high-temperature strength. Therefore, the Mg-Zn-Y system should be an ideal candidate for developing high performance magnesium alloys^[9]. Huang et al.^[10, 11] investigated the solidification path of Mg-Zn-Y alloys when Zn/Y ratio is between 0.33–3.33, and they found that Mg-Zn-Y alloys contain generally three kinds of ternary phases, which are the I-phase ($\text{Mg}_3\text{Zn}_6\text{Y}$, quasicrystal structure), W-phase ($\text{Mg}_3\text{Zn}_3\text{Y}_2$, cubic structure) and X-phase (Mg_{12}ZnY) according to different Zn/Y ratios. Meanwhile, Huang et al.^[10, 11] found that adding a certain amount of Zr to the Mg-Zn-Y alloys could reduce their hot tearing susceptibility. Recently, Liu et al.^[12] conducted a systematic study on hot tearing behavior of $\text{MgZn}_{2.5}\text{Y}_x\text{Zr}_{0.5}$ alloys with different proportions between Zn and Y from 0.42 to 5. They found that the second phases formed during solidification had a significant effect on the hot tearing susceptibility of the studied alloys.

In order to optimize research findings on hot tearing behavior of Mg-Zn-Y-Zr alloys, different ratios of Zn to Y from 0.75 to 9 were studied when Zn content was 4.5wt.%. The aim of the present work is to evaluate the hot tearing susceptibility of $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys,

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including investigation of the relationship between the different yttrium contents and the hot tearing susceptibility through the changes of the second phase, to determine the temperature and time when hot cracks initiate and to analyze the effects of the solid fraction and contraction stress on hot tearing susceptibility of $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys.

1 Experimental procedure

The $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ ($x = 0.5, 1, 2, 4, 6$) alloys were prepared by melting Mg (99.95wt.%), Zn (99.7wt.%), Mg-25wt.% Y and Mg-30 wt.% Zr master alloys.

A crucible-resistance furnace with a Si temperature controller was used for melting the alloys. The protective gas mixture of high purity $\text{N}_2+0.2\% \text{SF}_6$ was applied during the melting process. Pure Mg preheated to 200 °C was melted in a steel crucible. Pure Zn, Mg-Y master alloy and Mg-Zr master alloy were added to the same crucible during melting at 700 °C. The

melt was stirred for 5 min and then held at 720 °C for 30 min to ensure that the alloying elements were dissolved and diffused completely^[12]. Then, the molten alloy was poured at 720 °C into the "T" shaped mold preheated to 200 °C. Before pouring, the inner surface of the "T" shaped mold was sprayed with boron nitride (BN) coatings, making the fully solidified casting strip from the mold readily. The schematic of the experimental setup is shown in Fig. 1(a). A Ni-Cr/Ni-Si thermocouple was placed to the center of the hot spot in the mold prior to pouring for measuring the temperature where hot cracks generate, as shown in Fig. 1(b). A load sensor was connected with the mold by a 120 mm long, 4 mm diameter elongated steel rod for measuring the contraction force formed during solidification process. The acquired analog signals were transmitted to the signal conversion module at the beginning of the pouring simultaneously. Then the signal conversion module converted the analog signal into the digital signal and transferred it to a computer. Finally, the signals were shown in the form of data and charts by Lab View software.

Fig. 1: (a) Schematic of experimental setup, (b) position of thermocouple

Hot tearing susceptibility of $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys was evaluated using cracking susceptibility coefficient (CSC) method of Clyne-Davies' theoretical model^[13, 14]. The expression of CSC is as follow:

$$\text{CSC} = \frac{t_v}{t_R} = \frac{t_{0.01} - t_{0.1}}{t_{0.1} - t_{0.6}} \quad (1)$$

where t_v is the corresponding solidification time when the liquid fraction is between 0.01 and 0.1; t_R is the corresponding time when the liquid solidification fraction is between 0.1 and 0.6.

When the liquid fraction is between 0.1 and 0.6, the feeding effect on separated dendrites is great due to sufficient liquid, and the corresponding solidification time was defined as t_R . The region with liquid fraction between 0.01 and 0.1 was known as the vulnerable region, and the corresponding solidification time was defined as t_v . In this region, the interdendrite spacing was difficult to be fed because of limited available liquid, which made hot tearing susceptibility of the alloys become increased. The ratio of t_v and t_R was defined as the cracking susceptibility coefficient (CSC), a parameter to evaluate the hot tearing susceptibility of the alloys^[13, 14]. The higher value of CSC means the higher hot tearing susceptibility of the alloys. t_v and t_R could be measured in the fractional time vs. liquid fraction curve, as shown in Fig. 2.

Fig. 2: Determination method of t_R and t_v in curve of fractional time vs. liquid fraction^[12-14]

2 Results and discussion

2.1 Assessment and measurement

The predicted CSC values used to characterize the hot tearing susceptibility of $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys are shown in Fig. 3. The CSC values of $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys in descending order are as follow: $\text{MgZn}_{4.5}\text{Y}_1\text{Zr}_{0.5} > \text{MgZn}_{4.5}\text{Y}_{0.5}\text{Zr}_{0.5} > \text{MgZn}_{4.5}\text{Y}_2\text{Zr}_{0.5} > \text{MgZn}_{4.5}\text{Y}_4\text{Zr}_{0.5} > \text{MgZn}_{4.5}\text{Y}_6\text{Zr}_{0.5}$. The hot tearing susceptibility of $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys appears in a rising trend from Y = 0.5wt.% to Y = 1wt.% with the Zn/Y ratio decreasing, and

Fig. 3: Predicted CSC values and hot crack volumes for $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys

reaches the peak in $\text{MgZn}_{4.5}\text{Y}_1\text{Zr}_{0.5}$ alloy when $\text{Zn/Y} = 4.5$; and then gradually decreases with increasing Y content.

In order to determine the effect of Zn/Y ratio on the hot tearing susceptibility of the tested alloys, the hot crack volumes for $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys were characterized by wax penetration method. The samples were put into molten wax in the vacuum state. The main principle of this method is to measure the sample weight before and after wax penetration in vacuum. Then, the crack volume can be calculated using equation $V_{\text{cr}} = M_2 - M_1 / \rho_{\text{wax}}$, where V_{cr} is crack volume; M_2 is weight after wax penetration; M_1 is weight before wax penetration; ρ_{wax} is the density of wax. Figure 3 shows the hot crack volumes for $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys. The crack volume is 0.137 cm^3 when the Zn/Y ratio is 9. The max volume is 0.144 cm^3 when Zn/Y ratio is 4.5, indicating that the hot tearing susceptibility of the $\text{MgZn}_{4.5}\text{Y}_1\text{Zr}_{0.5}$ alloy is the highest. Then, as the Y content further increases, the crack volumes decrease, which are 0.131 cm^3 when Zn/Y ratio is 2.25 and 0.111 cm^3 when Zn/Y ratio is 1.125, respectively. The crack volume is 0.092 cm^3 when Zn/Y ratio is 0.75, which illustrates the hot tearing susceptibility of the alloy is the lowest. From Fig. 3, it can be found that the trends of CSC values and hot crack volume for investigated alloys are consistent, implying the good accuracy of the CSC prediction on the hot tearing susceptibility of $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys.

2.2 Phase compositions

According to solidification theory, at the beginning stages of solidification, elements such as Zn and Y are discharged to the outside of the grains as the α -Mg primary crystals nucleate and grow up^[15, 16]. As the alloy solidifies continuously, the contents of Zn and Y constantly increase in the residual liquid between α -Mg dendritic crystals. The ternary phases containing elements Mg, Zn and Y as well as the eutectic phases are formed through the eutectic reaction at a certain temperature. The type and amount of ternary phase depend on Zn, Y content in alloys. The XRD pattern of $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys is shown in Fig. 4. I-phase ($\text{Mg}_3\text{Zn}_6\text{Y}$) is formed when the Zn/Y ratio is 9 and 4.5. The formed I-phase is limited because of low Y content. It has not much positive impact on feeding to the interdendrite spacing. This is the main factor leading to high hot tearing susceptibility of $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys when value of Zn/Y ratio is high. Both I-phase ($\text{Mg}_3\text{Zn}_6\text{Y}$) and W-phase ($\text{Mg}_3\text{Zn}_3\text{Y}_2$) form when the Zn/Y ratio is 2.25. As the content of Y element increases, the second phase enriching at the grain boundaries increases, which could increase the intergranular bonding and decrease the hot tearing susceptibility of the alloy^[12]. Only W-phase is formed when the ratio of Zn/Y ratio is 1.125. It is known that W-phase gradually exists with grid-like structure at the grain boundaries when Zn/Y ratio is closed to 1^[17]. According to previous studies^[10-12], W-phase could result in the difficulties of interdendritic feeding because its grid-like morphology could hamper the free flow of residual liquid between the dendrites. However, compared to the hot crack volumes when Zn/Y ratio is 9, 4.5 and 2.25, the formed cracks are smaller than the ones when Zn/Y ratio is 1.125. It demonstrates that the amount of formed W-phase in $\text{MgZn}_{4.5}\text{Y}_4\text{Zr}_{0.5}$ alloy is sufficient to form eutectic networks at the grain boundaries due to high Y content, providing a better condition for feeding effect of the residual liquid. This is the reason why the hot tearing susceptibility decreases when Zn/Y ratio is 1.125. Both W-phase and X-phase (Mg_{12}ZnY) are formed when the Zn/Y ratio is 0.75. The hot tearing susceptibility of $\text{MgZn}_{4.5}\text{Y}_6\text{Zr}_{0.5}$ alloy is the lowest because a large amount of second phases is formed and

Fig. 4: XRD patterns of $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys

the morphology of X-phase is propitious to feeding effect on separated dendrites^[11].

2.3 Fracture analysis

The SEM micrographs of the $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys are shown in Fig. 5. The crack initiates from the surface of the casting^[17]. The internal dendrites separate under solidification shrinkage stress. The separating direction is perpendicular to the direction of crack propagation. Figures 5(a) and 5(b) show the microstructure of $\text{MgZn}_{4.5}\text{Y}_{0.5}\text{Zr}_{0.5}$ alloy and $\text{MgZn}_{4.5}\text{Y}_1\text{Zr}_{0.5}$ alloy, respectively. The smooth feeding channels at the grain boundaries could not form due to that only a small amount of low-melting point eutectic phases is formed, which causes the more probability of the hot tearing emergence at low Y content. However, the crack is not connected into pieces or propagates through the whole casting. The reason is that bridges are formed between the two adjacent grains when dendrites separate.

Formed bridges can hinder the propagation of cracks^[17]. Figures 5(c), 5(d) and 5(e) show the microstructure of $\text{MgZn}_{4.5}\text{Y}_2\text{Zr}_{0.5}$, $\text{MgZn}_{4.5}\text{Y}_4\text{Zr}_{0.5}$ and $\text{MgZn}_{4.5}\text{Y}_6\text{Zr}_{0.5}$ alloy, respectively. According to the feeding theory during the solidification process^[4], when the dendritic growth reaches the interference point, as the temperature decreases, the feeding mechanism in the solidification process is changed gradually from the overall feeding to the interdendritic feeding^[12]. With Y content increases, the amount of low-melting point eutectic phase increases and the eutectic networks form gradually, which means more and more continuous feeding channels are formed to significantly reduce the flowing obstruction and improve feeding ability. The residual liquid makes separated dendrite re-healed and plays an important role on hampering crack propagation and reducing the crack volumes. Thus, the hot tearing susceptibility of these three alloys decreases with increasing Y content.

Fig. 5: SEM micrographs of $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys

The morphology of fracture for $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys is shown in Fig. 6. A certain thickness of liquid film covering the grains has been formed in the end of solidification, which is the low-melting point eutectic phases. According to theory of liquid film^[18, 19], the formation of hot cracks is determined by two factors, the existence of formed liquid film and

solidification shrinkage resistance. The composition of alloys is a crucial factor affecting the thickness and strength of liquid film. The morphology of fracture for $\text{MgZn}_{4.5}\text{Y}_{0.5}\text{Zr}_{0.5}$ alloys is shown in Fig. 6(a). The wrinkles of the film covering grains are fewer, implying the film is thinner. It is due to the fact that the formed low-melting point eutectic phases near solidus are

Fig. 6: Morphology observation of fracture for $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys

limited because of low Y content. The morphology of fracture for $\text{MgZn}_{4.5}\text{Y}_1\text{Zr}_{0.5}$ alloy is shown in Fig. 6(b). The formed grains become clear because the continuous film forms due to increasing Y content. However, it is still too thin to resist the stretching action of solidification shrinkage stress though the liquid film is thicker than that of $\text{MgZn}_{4.5}\text{Y}_{0.5}\text{Zr}_{0.5}$ alloy. The thin film is one of the factors causing the high hot tearing susceptibility when Zn/Y ratio is high. The morphology of fracture for $\text{MgZn}_{4.5}\text{Y}_2\text{Zr}_{0.5}$ alloy is shown in Fig. 6(c). The grains separate and move toward opposite direction under solidification shrinkage stress. The film moves with grains and continues to be stretched. Although the film becomes thicker, the tearing phenomenon is observed when solidification shrinkage stress acting on the grains is greater than the tension of film. The morphology of the fracture for $\text{MgZn}_{4.5}\text{Y}_4\text{Zr}_{0.5}$ alloy is shown in Fig. 6(d). High solid shrinkage rate leads to the formation of great intergranular micro-voids^[20]. If they are not refilled opportunely, macro-cracks will form^[21]. It can be seen that the thick film existing around micro-voids increases the intergranular bonding. The main micro-voids do not propagate to the surrounding to create more little cracks, suggesting low hot tearing susceptibility of the alloy. In Fig. 6(e), thicker liquid film and more wrinkles are observed in $\text{MgZn}_{4.5}\text{Y}_6\text{Zr}_{0.5}$ alloy because more low-melting point eutectic phases form. They could be able to improve intergranular

bonding greatly for enhancing anti-hot tearing property of the alloy.

The comprehensive analysis in Figs. 5 and 6 shows that the low-melting point eutectic phase exiting at grain boundaries is not enough to form a continuous feeding channel at low Y content, so residual liquid is difficult to feed to the separated dendrites. A layer of continuous film forms at grain boundaries when the Zn/Y ratio is 4.5. However, it is easy to tear under greater solidification shrinkage stress when it is too thin. Thus, the formed eutectic phase is destructive to intergranular bonding significantly, but the feeding extent on separated dendrite is very small, leading to the result that the hot tearing susceptibility of $\text{MgZn}_{4.5}\text{Y}_1\text{Zr}_{0.5}$ alloy is the highest among $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys. Although the formed film is the thinnest when the Zn/Y ratio is 9, it is still not complete and continuous. This phenomenon implies that the original intergranular bonding still plays a certain role on hampering initiation of cracks. It signifies that the damaging effect of eutectic phases on intergranular bonding does not reach the acme. Therefore, the hot tearing susceptibility of the $\text{MgZn}_{4.5}\text{Y}_{0.5}\text{Zr}_{0.5}$ alloy is lower than that of the $\text{MgZn}_{4.5}\text{Y}_1\text{Zr}_{0.5}$ alloy. In contrast, the intergranular bridge is important to hinder the development of cracks. According to theory of intergranular bridge^[22], intergranular bridges improve binding force between dendrites during the late stage of solidification. It implies

more maintaining bridges in $\text{MgZn}_{4.5}\text{Y}_{0.5}\text{Zr}_{0.5}$ alloy than that in $\text{MgZn}_{4.5}\text{Y}_1\text{Zr}_{0.5}$ alloy. When Zn/Y is less than 4.5, the more continuous eutectic networks form gradually owing to the more formed eutectic phases. They tend to form the more smooth channels at the grain boundaries. Thus, more and more sufficient feeding makes the hot tearing susceptibility of the alloys drop down gradually with increasing Y content. In addition, intergranular bridges are not easily observed because initiated and propagated micro-cracks could be re-filled by residual liquid or eutectic phases opportunely. In summary, the role of low-melting point eutectic phases on the hot tearing susceptibility of $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys is shifting gradually with different Y content^[23, 24]. When Y is not more than 1 wt.%, the role of low-melting point eutectic phases is mainly a damaging effect on intergranular binding force; when Y is more than 1wt.%, it is mainly an intergranular feeding effect on formed separated dendrites.

2.4 Hot tearing curves

Figure 7 shows the contraction force and temperature as function of time for $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys. The force value is zero in time-force function curves at the beginning of solidification due to the fact that the formed solid is not enough to establish strength of the alloys. The contraction force begins to increase dramatically as the alloys solidify continuously. A decline appears on the time-force function curve when stress relaxation generates, which implies macro-cracks occur at the junction of the "T" shaped bar. As the solid fraction increases constantly, the size of the cracks tends to be stabilized. Figure 7(a) displays the contraction force and temperature as a function of time for $\text{MgZn}_{4.5}\text{Y}_{0.5}\text{Zr}_{0.5}$ alloy. A decline occurs on the time-force function curve when the temperature is 359.9 °C and the corresponding solid fraction is 96.3%, which means the

hot macro-cracks are formed in the alloy. As the solidification of the alloy continues, another decline appears on the time-force function curve when the temperature is 349.8 °C and the corresponding solid fraction is 97.3%, suggesting that the hot macro-cracks are formed in the alloy for the second time. Figure 7(b) shows the contraction force and temperature as a function of time for $\text{MgZn}_{4.5}\text{Y}_1\text{Zr}_{0.5}$ alloy. The declines occur on the time-force function curve when the temperature is 414.2 °C and the corresponding solid fraction is 96.9%, and when the temperature is 337.5 °C and the corresponding solid fraction is 99.0%, respectively. With a low Y content, continuous feeding channels are not formed, which makes the residual liquid flow difficultly. Formed crack sources could not be re-filled promptly and propagated into larger cracks rapidly. Because of poor anti-tearing capability, micro-cracks are formed early when the solid fraction is low. With contraction force becomes gradually greater, the formed thin film or intergranular bridges could not resist stretching intention, which results in the second hot-tearing appearance. It is obvious that fluctuating amplitude of the time-force function curve is the greatest because of the least intergranular binding force and the poorest feeding capacity when Zn/Y ratio is 4.5. Figure 7(c), 7(d) and 7(e) show contraction force and temperature as a function of time for $\text{MgZn}_{4.5}\text{Y}_2\text{Zr}_{0.5}$ alloy, $\text{MgZn}_{4.5}\text{Y}_4\text{Zr}_{0.5}$ alloy and $\text{MgZn}_{4.5}\text{Y}_6\text{Zr}_{0.5}$ alloy, respectively. The macro-cracks appear when the temperature is 343.8 °C and the corresponding solid fraction is 99.4%, when the temperature is 390.3 °C and the corresponding solid fraction is 99.2%, and when the temperature is 353.7 °C and the corresponding solid fraction is 99.3%, respectively. With a high Y content, very low melting point eutectic phases form thick film, which could enhance the intergranular binding force and resist the great contraction force. Thus, the macro-cracks emerge when the solid fraction is high and the secondary

Fig. 7: Contraction force and temperature as function of time for $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys

hot tearing does not happen. It can also be seen that fluctuating amplitudes of the time-force function curves are small from $w(Y) = 1 \text{ wt.}\%$ to $w(Y) = 6 \text{ wt.}\%$. The reason is that residual liquid reheals the separated dendrite easily due to the formation of more smooth feeding channels.

3 Conclusions

(1) The hot tearing susceptibility of $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys can be given in descending order as follows: $\text{CSC}(\text{MgZn}_{4.5}\text{Y}_1\text{Zr}_{0.5}) > \text{CSC}(\text{MgZn}_{4.5}\text{Y}_{0.5}\text{Zr}_{0.5}) > \text{CSC}(\text{MgZn}_{4.5}\text{Y}_2\text{Zr}_{0.5}) > \text{CSC}(\text{MgZn}_{4.5}\text{Y}_4\text{Zr}_{0.5}) > \text{CSC}(\text{MgZn}_{4.5}\text{Y}_6\text{Zr}_{0.5})$. In other words, $\text{MgZn}_{4.5}\text{Y}_1\text{Zr}_{0.5}$ alloy exhibits the highest hot tearing susceptibility and $\text{MgZn}_{4.5}\text{Y}_6\text{Zr}_{0.5}$ alloy shows the lowest among the investigated alloys.

(2) Both the amount and morphology of the second phases have a great relationship with the hot tearing susceptibility. But the former plays a more important role on that of $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys. The grid-like W-phase does not hinder the feeding flow of residual liquid greatly because its quantity is high enough to form feeding networks.

(3) The role of low-melting point eutectic phases on the hot tearing susceptibility of $\text{MgZn}_{4.5}\text{Y}_x\text{Zr}_{0.5}$ alloys shifts gradually with different Y contents. When Y is not more than 1 wt.%, it is mainly a damaging effect on intergranular binding force; when Y is more than 1 wt.%, it is mainly an intergranular feeding effect on formed separated dendrites.

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