Effects of spherical quasi-crystal on microstructure and mechanical properties of ZA155 high zinc magnesium alloy

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Abstract: Effects of spherical quasi-crystal contained in Mg-Zn-Y-Mn master alloy on the microstructure and as-cast mechanical properties of ZA155 high zinc magnesium alloy have been investigated by means of optical microscopy, XRD, SEM, EDS, tensile test, impact test and hardness test. Experimental results show that the addition of spherical quasi-crystal contained in the Mg-Zn-Y-Mn master alloy into the ZA155 high zinc magnesium alloy resulted in grain refinement of the matrix, changing the morphologies of φ-$Al_2Mg_5Zn_2$ phase and τ-$Mg_{32}(Al,Zn)_{49}$ phase from continuous net-like structures to discontinuous strip-like structure and blocky one, respectively. In the present research, the best comprehensive mechanical properties of reinforced ZA155 high zinc magnesium alloy has been obtained when 5.0wt% spherical quasi-crystal was introduced from the Mg-Zn-Y-Mn master alloy into the target alloy system. In such case, the room-temperature tensile strength reached 207 MPa, about 23% higher than that of the base alloy; the impact toughness peaked at 5.5 J/cm^2, about 40% higher than that of the base alloy; and the elevated-temperature tensile strength reached 203 MPa, indicating improved heat resistance.

Key words: magnesium alloy; quasi-crystal strengthening; microstructure; mechanical properties
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Magnesium alloy, one of the lightest metallic materials as engineering structure materials nowadays, has been used in communication, automobile and aerospace industries. Owing to its low strength and poor heat resistance, the application of magnesium alloy under elevated-temperature conditions is limited. Although a class of high zinc magnesium alloys from recent research featured low cost and high heat resistance, their relatively low impact-toughness made them undesirable for practical industrial applications [1-5].

Therefore, the purpose of this investigation was to take quasi-crystal as the reinforcing phase [2] to improve the as-cast microstructure and mechanical properties of ZA155 magnesium alloy. This should provide theoretical foundations as well as new technical approach for potential applications of high zinc magnesium alloy.

1 Experimental details

The studied alloys were prepared in a crucible furnace according to the designed compositions given in Table 1.

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Magnesium (99.9wt.%), zinc (99.9wt.%), aluminum (99.9wt.%), Al-4%Be master alloy and Al-10%Mn master alloy were used as raw materials. Different amounts (0%, 1%, 3%, 5%, 7% by weight) of spherical quasi-crystal contained in Mg-Zn-Y-Mn (SQCM) master alloy [4] were added into the alloy system at temperatures ranging from 730 ℃–760 ℃. The melt was held for 10–30 min to ensure its complete meltage and homogeneous composition. After refinement, the melt was held for 30–50 min and then poured into metal mold. The microstructures were examined using optical microscope, scanning electron microscope (SEM) and energy dispersive spectroscope (EDS), and the phase analyses using X-ray diffractometer. Hardness was measured with a Brinell hardness tester (HB-3000B), while the impact-toughness was determined with an impact tester and tensile strength with a WE-10B hydraulic universal testing machine.

Table 1: The designed compositions of magnesium alloys with SQCM master alloy (wt.%)

No.	Mg	Zn	Al	Mn	Be	SQCM
1#	Bal	15.00	5.00	0.25	0.02	0
2#	Bal	15.00	5.00	0.25	0.02	1.0
3#	Bal	15.00	5.00	0.25	0.02	3.0
4#	Bal	15.00	5.00	0.25	0.02	5.0
5#	Bal	15.00	5.00	0.25	0.02	7.0

2 Results and discussion

2.1 Effect of SQCM master alloy addition on microstructures of ZA155 magnesium alloy

The XRD analysis results of as-cast microstructures of ZA155 magnesium alloy with and without SQCM master alloy addition are shown in Fig.1. It can be seen that the microstructure of alloy 1# consists of α-Mg phase, φ-$Al_2Mg_5Zn_2$ phase and τ-$Mg_{32}(Al, Zn)_{49}$ phase [see Fig.1(a)]. A new peak was found in the XRD pattern of alloy 4# because of the SQCM master alloy addition. This indicates that the microstructure of alloy 4# is composed of α-Mg phase, φ-$Al_2Mg_5Zn_2$ phase, τ-$Mg_{32}(Al, Zn)_{49}$ phase and $Mg_{45}Zn_{47}Y_3Mn_5$ quasi-crystal phase. Since the $Mg_{45}Zn_{47}Y_3Mn_5$ quasi-crystal phase has a relatively high melting point (about 627 ℃) [5-9], it cannot be melted completely in the range of the processing temperature (730 ℃–760 ℃). Hence, small quasi-crystal particles still exists in the melt and are inherited in the as-cast microstructure of the ZA155 magnesium alloy.

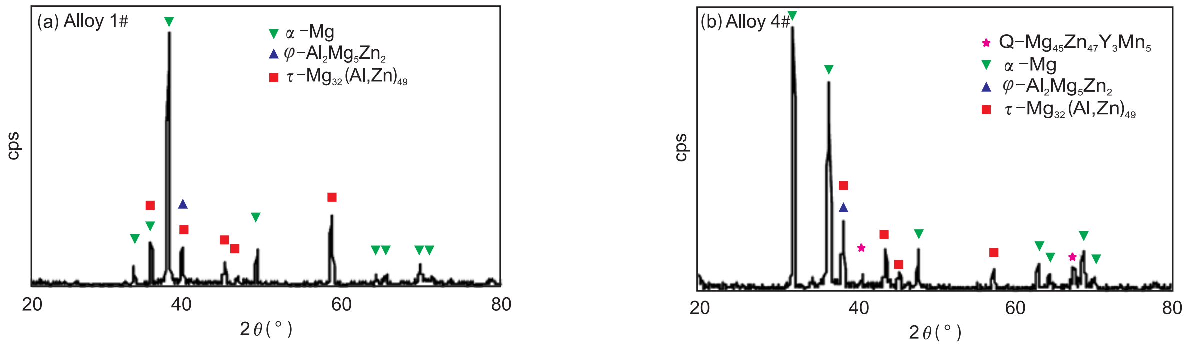


Fig.1: XRD patterns of ZA155 magnesium alloy with and without SQCM master alloy addition

Figure 2 shows the microstructures of ZA155 magnesium alloys with different additions of SQCM master alloy. It is apparent that the matrix microstructure of ZA155 magnesium alloy was gradually refined with increase of the SQCM master alloy addition (up to 5%). This was due to that, in the solidification process, the quasi-crystal phase existing in the ZA155 magnesium alloy melt was pushed forward to the front of growing interface of the primary α-Mg, hindering the diffusion of Al and Zn atomics, retarding the growth of α-Mg dendrites, and thus refining the grains and matrix microstructure. The as-cast microstructure of the base alloy consists of grey α-Mg phase, φ-$Al_2Mg_5Zn_2$ phase and white bright eutectic τ-$Mg_{32}(Al, Zn)_{49}$ phase which is mainly distributed at the grain boundaries [Fig. 2(a)]. It can be seen from Fig.2(b), 2(c) and 2(d) that when SQCM master alloy addition increased from 1% to 5%, not only was the grain size of matrix reduced, but also τ-$Mg_{32}(Al, Zn)_{49}$ phase got refined remarkably. Its morphology changed, to a certain extent, from continuous net-like structure to discontinuous strip-like one, and some of τ-$Mg_{32}(Al, Zn)_{49}$ phase appeared in granules dispersedly distributed at the grain boundaries. A granular black compound phase was also observed. When the addition of SQCM master alloy reached 7%, the enrichment of Q phase restrained so much the diffusion of Al, Zn atomics that α-Mg dendrites tended to grow more freely, leading to a coarsened matrix microstructure [Fig. 2(e)].

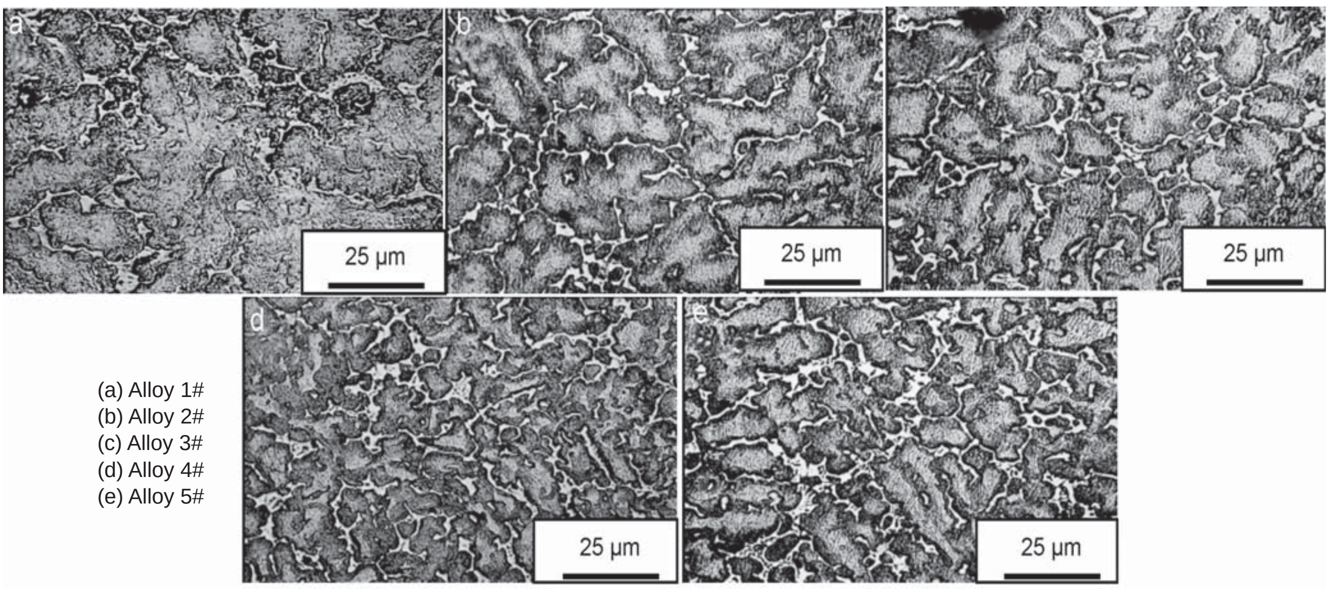
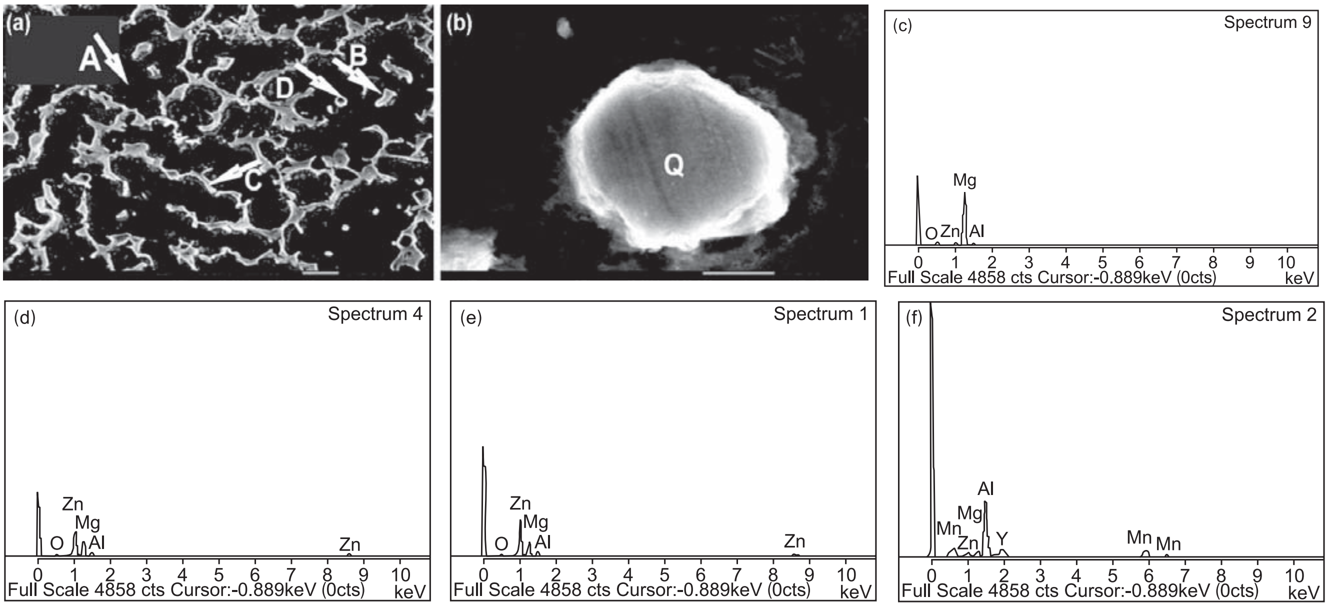


Fig.2: The microstructures of ZA155 high zinc magnesium alloys with different additions of SQCM master alloy

The SEM and EDS analysis results of alloy 4# are shown in Fig.3. From Fig.3(a), it is clear that the black phase (by arrow A) is α-Mg phase, the irregular blocky phase (by arrow B) is φ-$Al_2Mg_5Zn_2$ phase, the strip-like phase (by arrow C) is τ-$Mg_{32}(Al, Zn)_{49}$ phase, and a few granular bright spots (by arrow D) are the spherical quasi-crystal granules inherited by SQCM master alloy. As shown in Fig.3(a), these tiny quasi-crystal particles served as the strengthening phase which dispersedly distributed in α-Mg matrix and in or around strip-like τ-$Mg_{32}(Al, Zn)_{49}$ phase. Figure 3(b) is the magnified SEM image of the remaining quasi-crystal particle (by arrow D) in Fig.3(a). It can be seen that the Q-$Mg_{45}Zn_{47}Y_3Mn_5$ phase in SQCM master alloy still existed in spherical form. The quasi-crystal has dispersion strengthening effect on the ZA155 magnesium alloy and prevents the growth of dendrite, which is in favor of the refinement of grain and matrix microstructure. Figure 3(c),(d),(e) and (f) are the EDS analysis results of points A, B, C and D in Fig. 3(a) respectively, which confirm the existence of quasi-crystal phase.



(a): SEM morphology of alloy 4#; (b): Enlarged SEM image of D in Fig.(a); (c), (d), (e) and (f): EDS spectrum of A, B, C and D in Fig.(a)

Fig. 3: SEM morphology and EDS spectrum of alloys 4#

2.2 Effects of SQCM master alloy addition on room-temperature mechanical properties of ZA155 magnesium alloy

Figure 4 shows the effect of addition level of SQCM master alloy on the mechanical properties of ZA155 magnesium alloy. It is clear that after the addition of SQCM master alloy, the impact toughness of ZA155 magnesium alloys is improved significantly. When the addition level of SQCM master alloy was raised to 5%, the impact toughness peaked at 5.5 J/cm^2. This change pattern was mainly attributed to: (A) the refining of grains in matrix due to the SQCM master alloy addition; and (B) the change of morphologies of φ-$Al_2Mg_5Zn_2$ phase and τ-$Mg_{32}(Al, Zn)_{49}$ phase from continuous net-like structures to discontinuous strip-like and blocky ones, promoting a relatively high toughness. The addition of SQCM master alloy has also affected the tensile properties significantly. When adding 5% SQCM master alloy, the tensile strength at room temperature reached the peak – 207 MPa, about 23% higher than that of alloy 1# (no adding SQCM master alloy).

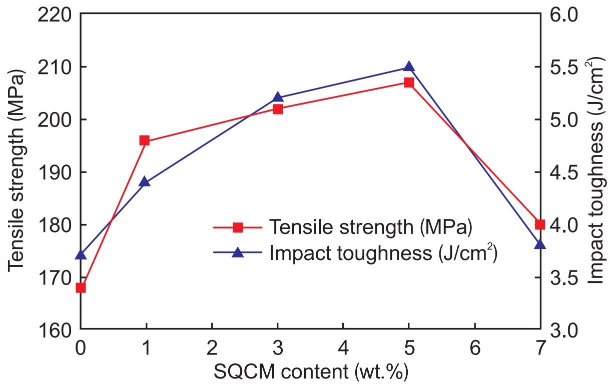


Fig. 4: Effect of SQCM master alloy addition on mechanical properties of ZA155 magnesium alloy

2.3 Effects of SQCM master alloy addition on elevated-temperature mechanical properties of ZA155 magnesium alloy

Table 2 shows the mechanical properties of the base alloy and ZA155 magnesium alloy reinforced by 5.0% SQCM master alloy. As compared with the room-temperature tensile strength values, the elevated temperature tensile strength of alloy 1#

and alloy 4# decreased by only 5% and 2%, respectively. This slight decrease in tensile strength at elevated temperature may be explained as follows. Like many other metals, apart from the softening of matrix, the heat-resistance of grain-boundary phases at elevated temperature has a great influence on high-temperature stability of microstructure of ZA155 alloy. In the solidification process, dystectic τ-$Mg_{32}(Al, Zn)_{49}$ phase is formed and distributed at the grain boundaries. Since it is difficult to deform, the possibility of grain boundary sliding is very low, ensuring the alloy with relatively high heat resistance. The effect of SQCM master alloy addition is perhaps more important. The remaining Q-$Mg_{45}Zn_{47}Y_3Mn_5$ quasi-crystal phase with high melting point (627 ℃) in ZA155 magnesium alloy is dispersedly distributed in the matrix and at the grain boundaries, which is beneficial to the strengthening of matrix. In addition, stable quasi-crystal particles with regular dispersive distribution can prevent the grain boundary from sliding and dislocation movement in the matrix and pin up the grain boundaries. Therefore, the high-temperature strength of the alloy is improved.

Table 2: Mechanical properties of ZA155 magnesium alloys

Alloy	Room temp.		200 ℃	
	R_m (MPa)	A (%)	R_m (MPa)	A (%)
ZA155 (1#)	168	1.3	160	1.6
ZA155 + 5.0%SQCM (4#)	203	2.5	196	3.2

3 Conclusions

(1) Through the addition of SQCM master alloy, the grains of matrix microstructure of ZA155 magnesium alloy can be refined, leading to the change of morphologies for τ-$Mg_{32}(Al, Zn)_{49}$ phase and φ-$Al_2Mg_5Zn_2$ phase from continuous net-like structures to discontinuous strip-like structure and blocky one, respectively.

(2) When adding 5% SQCM master alloy, the room-temperature mechanical properties can be improved significantly: 207 MPa in tensile strength (23% higher than that of un-reinforced alloy) and 5.5 J/cm^2 in impact toughness (a 40% increase). In addition, the elevated-temperature mechanical property is also improved markedly.

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