Effect of Shot Peening on Surface Characteristics and Fatigue Properties of T5-Treated ZK60 Alloy

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The effects of shot peening on surface characteristics and high cycle fatigue (HCF) performance of T5-treated high-strength magnesium alloy ZK60 (named after ZK60-T5) were investigated. The glass bead with an average diameter of 0.35 mm was adopted for shot peening and the Almen intensity was arranged from 0.02 to 0.40 mmN. The surface microstructure and texture of ZK60-T5 are greatly changed by shot peening, and residual compressive stress is produced in the surface deformation layer. The magnesium alloy ZK60-T5 shows a pronounced overpeening effect. A marked improvement in fatigue life is obtained at low Almen intensities, namely the fatigue strength (at 10^7 cycles) increases from 150 to 195 MPa at the optimum Almen intensity of 0.05 mmN. The fatigue crack nucleation site of ZK60-T5 is also found from surface regions to the subsurface. [doi:10.2320/matertrans.MRA2008415]

(Received November 7, 2008; Accepted January 26, 2009; Published March 25, 2009)

Keywords: shot peening, high-cycle fatigue (HCF), ZK60, surface

1. Introduction

Magnesium alloys are very attractive as structural materials, because they are extremely light, possessing excellent specific tensile strength, excellent machinability, good castability, good stiffness, and good vibrational absorption.¹⁾ Due to their energy and weight saving characteristics, magnesium alloys are considered to be good candidates for material in the automotive industry to improve fuel efficiency and reduce emissions. For these automotive components under the combined actions of fluctuating loads and corrosive environment, fatigue fracture is one dominant failure mode, and it is necessary to understand the fatigue properties of magnesium alloys. However, in comparison with aluminum alloy and steel, the researches on fatigue properties of magnesium alloys are still limited. Some researches^{2,3)} have showed that fatigue properties of magnesium alloys are poor, and thus make it difficult to apply the alloys for load-bearing parts in automobiles. Therefore, how to improve the fatigue properties of magnesium alloys becomes a vital research subject.

It is well known that the fatigue cracks always initiate from surface layer (especially from surface stress concentration zone), so enhancing the surface strength and improving the surface stress state by means of surface mechanical treatment such as shot peening is thought of as an effective method to increase their fatigue life and fatigue strength for various metal alloys, including magnesium alloy.^{4,5)} Recent work by P. Zhang and Wagner⁶⁻⁸⁾ has reported that the fatigue life of magnesium alloys can be improved by shot peening: compared to the reference specimens (EP), the fatigue strength of magnesium alloy AZ80 increases from 100 to 160 MPa and its fatigue life is improved approximately by two orders of magnitude after shot peening under the optimum Almen intensity. Till to now, the research on the

effect of shot peening is limited in magnesium-aluminum alloys and the specific characteristics of the surface deformation layer are still not very clear.

As a wrought magnesium alloy, ZK60 has high tensile strength and excellent plasticity among commercial magnesium alloys.⁹⁾ Its microstructure, mechanical properties, deformation treatment, and the effects of alloy elements and microelements are well studied.¹⁰⁾ At present, the researches on ZK60 magnesium alloy is mainly focused on plasticity, superplasticity¹¹⁾ and ZK60 based composite.¹²⁾ As mentioned in the first paragraph, ones of the main drawbacks encumbering the application of ZK60 magnesium alloy in automotive industry are its comparatively poor fatigue properties and wear resistance.^{13,14)} The ZK60 alloy after being extruded and T5-treated (ZK60-T5) has its best mechanical properties.¹⁵⁻¹⁷⁾ Therefore, alloy ZK60-T5 are chosen for shot peening aiming to improve its fatigue properties. The effects of shot peening on surface characteristics and high cycle fatigue (HCF) performance of alloy ZK60-T5 will be investigated systematically.

2. Experimental

Chemical composition of the studied alloy is listed in Table 1. Alloy ZK60 were melt from high purity magnesium (Mg, 99.95%), zinc (Zn, 99.9%), and Mg-30Zr (mass%) master alloys in an electric resistance furnace protected by a mixed gas of CO₂ and SF₆ with the ratio of 100 : 1, and cast to some billets (100 mm in diameter and 350 mm in length) in a steel mold. The cast billets were homogenized at 400°C for 14 h, and then hot extruded to some cylindrical bars (26.8 mm in diameter) with an extrusion ratio of 14 at 390°C. T5 (150°C/24 h) treatment was applied to the extruded cylindrical bars. Specimens for mechanical testing were machined with the load axis parallel to extrusion direction (ED) of ZK60-T5 bars. Tensile tests were performed on sheet

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Table 1 Chemical composition of magnesium alloy ZK60-T5.

Material	Composition (mass%)		
	Mg	Zn	Zr
ZK60-T5	Balance	5.54	0.56

Table 2 Tensile results on magnesium alloys ZK60-T5.

Material	Testing direction	TYS/MPa		UTS/MPa		EL (%)	
		$\bar{v}$	S	$\bar{v}$	S	$\bar{v}$	S
ZK60-T5	ED	273	4.4	329	3.2	16.5	0.9

$\bar{v}$ and S refer to average value and standard deviation respectively.

Table 3 Parameters of the peening medium.

Peening medium	Composition (mass%)	Diameter (μm)	Hardness (HRC)	Density (gcm^{-3})
Glass beads	73%SiO ₂ , 8%CaO,	250–400	49	2.4–2.6
	4%MgO, 13%Na ₂ O,			
	2%Al ₂ O ₃			

specimens with 15 mm gauge length, 3.6 mm width and 2 mm thickness at the initial strain rate of $5 \times 10^{-4} \text{ s}^{-1}$. Tensile test results are shown in Table 2.

For fatigue testing, hour-glass shaped round specimens (5.8 mm gage diameter) were used. After machining, a layer with thickness of about 200 μm was removed from the surface of the specimens by electrolytically polished (EP) in order to avoid the influence of machining on the fatigue results. Shot peening (SP) was performed with an injector type machine using glass beads. The detail parameters of the peening medium are listed in Table 3. The distance between the nozzle tip and the specimen surface was about 100 mm. To determine the optimum shot peening condition with regard to high cycle fatigue (HCF) properties, specimens were shot peened to full coverage by using Almen intensities in the range of 0.02–0.40 mmN.

Fatigue tests were performed under rotating beam loading ($R = -1$) at a frequency of about 100 Hz in air. The stress amplitude ranged from 140 to 300 MPa.

The surface properties of shot peened specimens were determined by roughness measurements through profilometry, measurements of the microhardness-depth profiles and residual stress measurements by means of a successive surface layer removal from the top of the peened specimen. Crystallographic textures were characterized by X-ray diffraction using Ni-filtered Cu-K α radiation. Analyses of the chemical compositions of the microstructure, and fracture surfaces after fatigue failure were analyzed using scanning electron microscopy (SEM, Philip-505).

3. Results and Discussion

3.1 Microstructures and texture of plastic deformation layer

Figure 1 shows X-ray diffraction patterns of peened and unpeened ZK60-T5. The peaks in the peened and unpeened ZK60-T5 can be indexed as α -Mg, MgZn₂ and MgZn. In

Fig. 1 XRD analysis of ZK60-T5 before and after shot peening. a: unpeened ZK60-T5; b: peened ZK60-T5.

Fig. 2 Microstructure of ZK60-T5 before and after shot peening: (a) unpeened ZK60-T5; (b) peened ZK60-T5.

addition, it can be seen that the diffraction peaks of peened ZK60-T5 (Fig. 1(b)) are weaker than those of ZK60-T5 (Fig. 1(a)), and the diffraction peaks of peened ZK60-T5 broaden as a result of lattice distortion and dislocation introduced by plastic deformation in the process of shot peening.

Figure 2 shows the microstructures of unpeened and peened ZK60-T5 at Almen intensity of 0.10 mmN in a plane parallel to the ED. As seen from Fig. 2(a), the microstructures of unpeened ZK60-T5 consisting of fine grains (about 9 μm) in the region A and banded microstructure in the region B are the same as typical magnesium alloy extruded structures, appearing as parallel layers and marking out the deformation flow-lines evidently.^{18,19} Analysis of the composition of each layer was done using EDX analysis. The region A is composed of 95.5Mg-3.4Zn-1.1Zr (at%, primary α -Mg), and the region B consists of a mixture of the intermetallic phase of 54.8Mg-35.5Zn-9.7Zr (at%) and α -

Fig. 3 Section topographies of peened ZK60-T5 at different Almen intensities: (a) 0.05 mmN; (b) 0.10 mmN; (c) 0.30 mmN; and (d) 0.40 mmN.

Mg. Figure 2(b) shows a micrograph of the layer in a depth of about 30 μm from the top surface layer of shot-peened specimen. Compared to unpeened ZK60-T5, the grains of shot-peened ZK60-T5 break up and grain boundaries are poorly defined because of the dislocation movement and incomplete recrystallization. Therefore, the banded microstructures in the deformation layer of peened ZK60-T5 are inconspicuous and flexuose. In addition, the microstructures of cross-section of peened ZK60-T5 at different Almen intensities are shown in Fig. 3. It can be seen that the increase in Almen intensity does not change significantly the grain size of the surface layer, but increases the thickness of plastic deformation layer.

Crystallographic textures ($\{0001\}$ pole figure and $\{10\bar{1}0\}$ pole figure) of ZK60-T5 and deformation layer of peened ZK60-T5 were shown in Fig. 4. As seen from Fig. 4(a), (b), it is evident that $\{0001\}$ basal plane and $\langle 10\bar{1}0 \rangle$ crystallographic direction in most grains are distributed parallel to the ED. That is, the ZK60-T5 magnesium alloys exhibits an ED // $\langle 10\bar{1}0 \rangle$ fiber texture. Similar tendency of basal planes lying parallel to the ED after direct extrusion has been observed by other investigators^{20–22} in other magnesium alloys. Figure 4(c), (d) shows $\{0001\}$ pole figure and $\{10\bar{1}0\}$

Fig. 4 $\{0001\}$ and $\{10\bar{1}0\}$ pole figures of ZK60-T5 before and after shot peening.

pole figure of peened ZK60-T5, compared to unpeened ZK60-T5, it can be seen that great changes have taken place in crystal preferred orientation of ZK60-T5 after shot peening, and fiber texture of ZK60-T5 was decomposed by shot peening, the pole figure intensity decrease and the diffuse degree of texture increase.

In the process of shot peening, as glass beads with high energy impacting on the surface of sample from different directions, elastic and plastic deformation is introduced. As the result, grains are refined and hence become equiaxial.^{23,24} Moreover, the volume fraction of grain boundaries increases. The refined grains and high volume fraction of boundaries make grains easy to rotate in further deformation, through which the textures are randomized in the uppermost surface of samples. Therefore, the peened ZK60-T5 magnesium alloy showed evident broadening diffraction peaks (Fig. 1(b)) and weak texture (Fig. 4(c), (d)).

3.2 Surface characteristics

The typical surface topography of the specimens after shot peening is shown in Fig. 5. It can be seen that shot peening results in considerable surface damage in magnesium, e.g. small pits, even at much lower Almen intensity of 0.05 mmN. The unacceptable severe defects in surface such as overlaps and microcracks were observed when the Almen intensity is higher than 0.15 mmN. Figure 6 shows the results of the surface roughness measurement. It is found that the increase in Almen intensity leads to a marked increase of the surface roughness, which is consistent with Fig. 3.

Figure 7 shows the microhardness-depth profile after shot peening with different Almen intensities from 0.02 to 0.40 mmN. Owing to plastic deformation induced by shot

Fig. 5 Surface topographies of peened ZK60-T5 at different Almen intensities: (a) 0.05 mmN; (b) 0.10 mmN; (c) 0.30 mmN; and (d) 0.40 mmN.

Fig. 6 Surface roughness values (R_a , R_y) vs. Almen intensity.

Fig. 7 Microhardness-depth profile of peened ZK60-T5.

peening, there is a significant increase in microhardness in the near-surface region. Stronger Almen intensity leads to deeper plastic deformation, approximately, the plastic deformation layer increases from 40 to 140 μm with the increase of Almen intensity from 0.02 to 0.40 mmN. The same trend is also found in optical microscope (OM) micrograph as shown in Fig. 3.

Fig. 8 Residual stress-depth profile of peened ZK60-T5.

Fig. 9 Fatigue life vs. Almen intensity of peened ZK60-T5 at stress amplitudes of $\sigma_a = 185$ and 200 MPa.

Figure 8 shows the residual stress distribution in ZK60-T5 after shot peening, in which it can be seen that the shot peening induces compressive residual stresses in magnesium alloy. The maximum compressive residual stress increases with the increase in the Almen intensity. According to the Almen intensities varying from 0.02 to 0.40 mmN, the maximum compressive stresses appear from 40 to 80 μm below surface and increase from 56 to 113 MPa. Certainly, increasing the Almen intensity also leads to the surface quality loss (Fig. 5).

3.3 High cycle fatigue

Figure 9 shows the fatigue life as a function of Almen intensity for ZK60-T5 at different stress amplitudes of $\sigma_a = 185$ and 200 MPa. Compared to the reference unpeened specimens, the fatigue life is improved by shot peening. One can see that the fatigue life depends on the Almen intensity at all tested stress amplitudes. Especially at the stress amplitude of 185 MPa, the dependence is more evident, i.e. with increase in the Almen intensity, the fatigue life first dramatically increases, then decreases drastically. The decrease is a result of overpeening. An improvement in the fatigue life by approximately one to two orders of magnitude is obtained by shot peening with the Almen intensities between 0.02 and 0.10 mmN at the stress amplitude of 185 MPa. With regard to the fatigue performance, the Almen intensity of 0.05 mmN is taken as the optimum.

Fig. 10 S-N curves of ZK60-T5 magnesium alloy after optimum shot peening.

The stress-life (S-N) curve at the optimum condition (Almen intensity of 0.05 mmN) for shot peening is shown in Fig. 10. Compared to the reference unpeened specimens the fatigue strength (at 10^7 cycle) increases from 150 to 195 MPa after shot peening, i.e. the improvement of 30% in fatigue strength has been achieved. In addition, for ZK60-T5 the optimum shot peening (0.05 mmN) increases the fatigue life by roughly one point five order of magnitude in the HCF-regime.

3.4 Fractography

Overall fracture surfaces of unpeened and peened specimens are shown in Fig. 11. It is found that overall fracture surface can be divided into three regions (shown in Fig. 11(a), (c)), i.e. crack initiation region (Region 1), steady crack propagation region (Region 2) and tearing region

Fig. 11 Overall fracture surfaces and Region 1 of ZK60-T5 (SEM): (a) and (b) unpeened ZK60-T5; (c) and (d) peened ZK60-T5, 0.05 mmN; (e) peened ZK60-T5, 0.30 mmN. Arrows indicate the crack initiation sites.

Fig. 12 SEM image from Region 2 of ZK60-T5 (SEM): (a) unpeened ZK60-T5 (in Fig. 11(a)); (b) peened ZK60-T5 (in Fig. 11(c)), 0.05 mmN.

Fig. 13 SEM image from Region 3 of ZK60-T5 (SEM): (a) unpeened ZK60-T5 (in Fig. 11(a)); (b) peened ZK60-T5 (in Fig. 11(c)), 0.05 mmN.

(Region 3). Figures 11–13 present the high magnification SEM images of Region 1, 2 and 3. In Region 1, the fatigue crack of unpeened specimen initiated at the surface, as seen from Fig. 11(b), since the surface experiences the maximum tension stress during rotating beam loading fatigue. In addition, due to the lack of constraint in grains at free surface, the glided dislocations during deformation may result in a microscopically irregular surface, which makes the surface as a prevailing site for crack initiation. In contrast, subsurface fatigue crack initiation is observed in peened specimen of the ZK60-T5 magnesium alloy under optimum peening condition (Fig. 11(d)). The depth of the crack nucleation site is about 40 μm deep below the surface, which is in agreement with the depth of plastic deformation estimated by the microhardness measurements. With an increase in Almen intensity, a significantly higher number of fatigue cracks and crack initiation sites can be seen, and this increase in Almen intensity from 0.02 to 0.40 mmN shifted the fatigue crack initiation site in ZK60-T5 from subsurface regions to the surface (Fig. 11(e)). Presumably, the limited deformability of the hexagonal crystal structure of the magnesium alloy leads to the development of critical microcracks under stronger shot peening and thus, to crack growth from the surface into the interior. Moreover, numerous secondary cracks which were hindered to propagate are found, particularly on specimens shot peened with higher intensities (Fig. 11(e)), indicating a pronounced effect of surface roughness on the resistance to fatigue crack nucleation. In Region 2, the fracture surface of unpeened

ZK60-T5 shows a typical cleavage feature, which consists of lots of lamellar cleavage planes (Fig. 12(a)). This result indicates that the fatigue crack propagates along the cleavage plane in ZK60-T5 at the beginning of propagation. In addition, the characteristic of fracture surface of peened ZK60-T5 in Region 2 (Fig. 12(b)) is similar to that of unpeened ZK60-T5 (Fig. 12(a)). Compared with Region 1 and 2, the fracture surfaces of unpeened and peened ZK60-T5 in Region 3 are all rather rough and many micro cracks and dimples can be observed, as shown in Fig. 13(a, (b)).

In order to examine the interaction between crack initiation and propagation behaviours and the microstructure of the specimen, the fatigue experiment was conducted on the specimens whose microstructure was pre-revealed by etching. The result of OM observations on an unpeened specimen surface as detected by the replica method during fatigue at stress amplitude of 170 MPa is shown in Fig. 14. As seen from Fig. 14, a crack initiates at the banded layer as region B in Fig. 2(a), and in this region the crack path is straight, showing characteristic transgranular fracture. Then the fatigue crack propagates into the neighbouring regions as region A in Fig. 2(a), and in this region the path of fatigue crack growth is mainly intergranular.

The fatigue performance of peened ZK60-T5 magnesium alloy is dependent on the combined effects of surface roughness, strain hardening, and residual compressive stresses produced by shot peening. Surface roughening accelerates the nucleation and early propagation of cracks, while strain hardening retards the propagation of cracks by increasing the

Fig. 14 LOM observation on the unpeened specimen's surface as detected by the replica method during fatigue at stress amplitude of 170 MPa.

resistance to plastic deformation and the residual compressive stress provides a corresponding crack closure stress that reduces the driving force for crack propagation.^{25–27} In the present study, the reason for fatigue life improvement by shot peening can be attributed to retardation of microcrack growth, owing to the positive effect on fatigue life induced by residual compressive stress field. The positive effect clearly overcompensates the reduction in fatigue life caused by earlier crack nucleation as a consequence of shot peening induced high surface roughness.^{7,28} As residual compressive stresses can decrease the tensile stress induced by the externally applied forces, fatigue cracks do not initiate or propagate easily, thus improvements in fatigue strength are achieved. The stronger shot peening not only results in lower near surface residual compressive stresses, but also increases roughness and induces microcracks.⁷ For magnesium alloys, due to the limited deformability of HCP crystal structure at room temperature, surface damages are aggravated. At the lower Almen intensities (0.02–0.10 mmN), the life benefit outweighs the debit due to additional surface damages. However, with the increases in Almen intensity (>0.10 mmN), more severe defects such as overlaps and microcracks occur, and the life improvement dramatically decreases. i.e. ZK60 magnesium alloy shows a marked overpeening effect. Similar overpeening effects have also been observed in other materials by other researchers.^{7,8,29–31}

4. Conclusions

The influence of shot peening on microstructure and texture of surface deformation layer, and HCF performance of high-strength wrought magnesium alloy ZK60-T5 was studied. Results obtained can be summarized as follows:

- (1) Great changes have taken place in surface microstructure and texture of ZK60-T5 after shot peening. Grains in plastic deformation layer are refined prominently, and grain boundaries are poorly defined because of dislocation movement and incomplete recrystallization. Extruded fiber texture of ZK60-T5 is decomposed after shot peening, and the pole figure

intensity is decreased and the diffuse degree of texture is increased.

- (2) A pronounced overpeening effect is observed in ZK60-T5. The fatigue life first dramatically increases with the increase of Almen intensity compared to an unpeened specimen, and then drastically drops as the intensity further increased. This overpeening effect is associated with the limited deformability of the hexagonal crystal structure of magnesium at room temperature. The fatigue strength increases from 150 to 195 MPa after shot peening with the optimum Almen intensity of 0.05 mmN, i.e. the improvement of 30% in fatigue limit has been achieved.
- (3) The residual compressive stress in plastic deformation layer produced by shot peening transfer the fatigue crack nucleation site from surface regions to the subsurface in ZK60-T5 specimen. With an increase in Almen intensity, a significantly higher number of fatigue cracks and crack nucleation sites can be seen. Fracture surface shows a typical cleavage feature, which consists of lots of lamellar cleavage planes.

Acknowledgments

The project sponsored by National Ministry of Science and Technology (Grant No. 2007CB613703), Shanghai Pujiang Program (Grant No. 06PJ14062) and the Scientific Research Foundation for the Returned Overseas Chinese Scholars, State Education Ministry.

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