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ARTICLE

Effect of Ultrasonic Impact Treating on Wear Resistance and Microhardness of AZ91D Magnesium Alloy

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Abstract: The surface of AZ91D magnesium alloy was treated using a HJ-III type ultrasonic impact treating (UIT) machine and the microstructures on the treated surface was investigated by an optical microscope and a High Resolution Transmission Electron Microscope. The wear resistance of AZ91D magnesium alloy was experimentally studied both for the treated and un-treated samples. The effects of UIT on the worn surfaces and microhardness were also investigated using SEM and microhardness tester. The results indicate that the severe plastic deformation in the surface of AZ91D is formed by UIT, and the thickness of the plastic deformation layer is approximately 120 μm. The grains on the top surfaces of AZ91D are highly refined. The wear resistance and microhardness of the treated surface layer of AZ91D alloy could be enhanced significantly compared to that of the un-treated sample. The longer the impact time and the higher the impact current, the greater the wear resistance and the microhardness of the treated surface layer of AZ91D would be. When the UIT time is 9 min and the current is 1.5 A, the microhardness and wear resistance of the treated specimen is about 112.5% and 57.39% higher than those of the untreated specimen, respectively.

Key words: ultrasonic impact treating; AZ91D magnesium alloy; microstructure; hardness; wear resistance

Magnesium alloys, owing to their low density and high strength-to-weight ratio, are gaining increasing importance as a structural material for applications in which weight reduction is critical[1,2]. Magnesium is about 33% lighter than aluminum[3]. It exhibits similar melting point and strength levels as that of aluminum[4]. Despite these good properties, magnesium alloys exhibit poor wear resistance and low hardness, limiting their application in automotive, locomotive vehicles, aerospace, and so on[5-7]. In certain applications, lightweight alloys and composites are subjected to sliding motion including automotive brakes, and engine components (piston and cylinder bores). Sliding wear is also an important consideration in material processing by rolling, extrusion, forging etc., from the point of view of understanding the changes in the deformation microstructure at the work-tool interface and the associated heat generation. Tests of various approaches have been used to enhance the wear resistance of magnesium alloys, for example laser surface modification[8], reinforcement of the metal matrix with ceramic particles[2] and fibers[6], ion implantation[9], plasma electrolytic oxidation (PEO)[10] and physical vapor deposition (PVD)[11].

A modern treatment technique, ultrasonic impact treatment (UIT), is a possible way to effectively improve the wear resistance, corrosion performance, fatigue properties of metals and their alloys[12,13]. Compared to traditional surface cold working, UIT is claimed to be more efficient involving a complex effect of strain hardening and grain refinement to increase the strength and hardness of the metal surface and also a compressive residual stress distribution in the metal surface[14]. Although the UIT method has been developed for actual application, there is little research about the effect of UIT on wear resistance and microhardness of magnesium and its alloy especially for AZ91D alloy. AZ91D is one of the widely used magnesium alloys and it possesses a good

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combination of mechanical and physical properties[15]. However, high friction and poor wear resistance are critical issues seriously limiting its practical application. In most cases, material failures occur on the surface due to wear, corrosion and fatigue. These failures are very sensitive to the microstructure and properties of the material surface [16,17]. Hence, optimization of the surface microstructure of the materials can be an effective approach to improve their properties and service life. In the present paper, the experimental work was designed to study the effect of UIT on the wear resistance and microhardness of AZ91D magnesium alloy and the wear mechanism was also discussed.

1 Experiment

The material studied was cast Mg-Al-Zn alloy (AZ91D). The chemical composition and mechanical properties of the AZ91D alloy is given in Table 1 and Table 2.

The impact tests were carried out with a HJ-III type ultrasonic impact machine (made by SUNBOW, China). The ultrasonic generator could generate oscillation signal of about 18~27 kHz that was converted to P-wave mechanical vibration energy through a transducer. The frequency and line speed of the vibration was 20 kHz and 2~3 m/s, respectively. The acceleration was equivalent to 30 000 times gravity acceleration. Single-punch diameter is generally 8 mm, and multi-punch's punch ranged side by side with a diameter of 2.5~3.5 mm. UIT comprises a handheld tool and an electronic control box containing the ultrasonic generator. The tool is easy to operate and provides a better work environment with negligible noise and vibration. the diameter UIT tool and pins is 3 mm.

In this test, the UIT current was 1.2, 1.5 A, and the UIT time was 3, 6, and 9 min. The treated and un-treated surface of AZ91D plate is shown in Fig.1. The plate shape was a rectangle with size 210 mm ×180 mm ×8 mm.

The microstructures on the surface of AZ91D alloy after UIT was investigated by an optical microscope (OM, Zeiss Germany), and a JEM-2100 High Resolution Transmission Electron Microscope (JEOL, Japan). The effect of UIT on the surface grain refining of AZ91D alloy was discussed. The microhardness on the top surface of AZ91D alloy was tested using an XHV-1000Z type hardness tester (CANY, China) with a load of 100 g and duration of 10 s. The worn surfaces of the specimens were examined with a SJM-6360LA scanning electron microscope (JEOL, Japan).

The wear tests were carried out using a wear test machine of M-2000 model (Xuanhua, China) under dry wear condition. The external load was 300 N. The rotating speed of down wear specimen was 200 r/min. All wear tests were performed at room temperature and 60% humidity.

2 Results and Discussion

2.1 Microstructure and hardness

Fig.2 shows the cross-sectional optical microscope observations of the treated and un-treated samples. Obviously, the microstructure morphology of the treated surface layer is quite different from that in the inner part. Evidences of severe plastic deformation are seen in the surface layer, in which grain boundaries can't be clearly identified as they can be seen in the inner part. After UIT, severe plastic deformation is produced in the top surface of AZ91D alloy. With increase of the impact time and current, the depth of the severe plastic deformation layer becomes bigger and bigger, as shown from Fig.2a to Fig.2e. The maximum depth of the plastic deformation layer is approximately 120 μm, as shown in Fig. 2f. Fig.2g shows the microstructure of the base metal.

Fig.3 shows the TEM bright-field image of the specimen after UIT. It is seen from the TEM image that fine grains in the surface layer are obtained, and the grain sizes in some places are less than 200 nm (see the place at arrow tip A). At the same time, high-density dislocation tangles and walls are formed (arrows B and C). The plastic deformation during UIT process includes crystal plane slip, twin, grain boundary movement, diffusion creep and so on.

The microhardness on the surface of treated and un-treated AZ91D alloy was measured by the microhardness tester of XHV-1000Z type with a 100 g load for 10 s. Table 3 illustrates the microhardness test results of the specimens for different UIT parameters. Every sample was measured three times and took their average. Fig.4 shows the relationship between the microhardness and UIT time. From Table 3 and Fig.4 it can be seen that the microhardness values of the treated specimens are markedly increased compared to the un-treated specimens. Among the treated specimens, the microhardness values correspond quite well with the impact current and impact time during the UIT process.

The results of microhardness tests show that when the impact time is 9 min, and the impact current is 1.2 A, the mean microhardness HV value is 1514 MPa; when the impact time is 9 min, the impact current is 1.5 A, the mean microhardness HV value is 1615 MPa. Compared to the untreated specimen which presents a microhardness HV value of 760 MPa, the microhardness of treated specimens is about 99.21% and 112.50% higher than that of the untreated specimens when the current is 1.2 and 1.5 A, respectively with the UIT time 9 min. The increase of hardness in the UIT processes can be attributed to both grain refinement and

Table 1 Chemical composition of AZ91D

Element	Al	Zn	Mn	Be	Si	Cu	Fe	Ni	Mg
Content/wt%	9.03	0.64	0.33	0.0014	0.031	0.0049	0.0011	0.0003	Balance

Table 2 Physical and mechanical properties of AZ91D at room temperature

Density/g cm^{-3}	$HV_{0.5\ kg}$/MPa	*E*/GPa	$\sigma_{0.2}$/MPa	δ/%
1.79	760	43.1	93.6	6.96

Note: *E*-Young's modulus, δ -elongation at fracture

Fig.1 Treated and un-treated surface

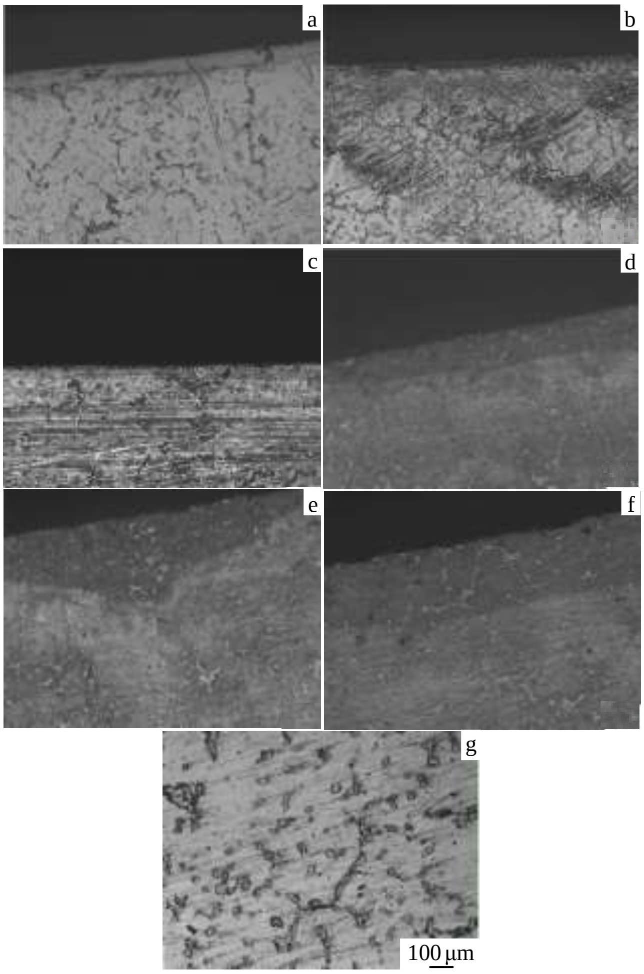

Fig.2 Microstructures of treated surface with different UIT current and time: (a)1.2 A/3 min, (b) 1.2 A/6 min, (c) 1.2 A/9 min, (d) 1.5 A/3 min, (e) 1.5 A/6 min, (f) 1.5 A/9 min, and (g) un-treated base metal

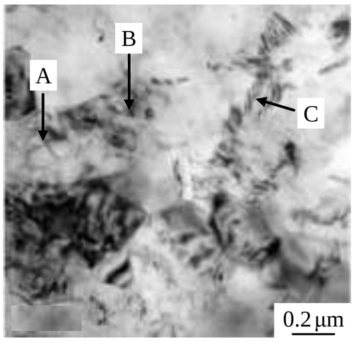

Fig.3 TEM bright field image of the specimen after UIT

work-hardening effects on the surface layer following the Hall-Petch relationship[18]. This relationship gives an empirical description of grain boundary strengthening in many metals and alloys and it is expressed as follows:

$$H = H_0 + kd^{-1/2} \quad (1)$$

where, *k* is a constant for a given material, H_0 is an appropriate constant associated with the hardness measurements, and *d* is the mean grain size. This relationship has been confirmed in both theory and practice in many metallic materials with grain size in the micrometer scale[19]. The physical basis of this behavior is not fully understood, but it is believed to be associated with the inhibition of dislocation movement across grain boundaries and stress multiplication due to dislocation pile-up. Also, this relationship has been elucidated by several models such as the pile-up of dislocations ahead of grain boundaries, the grain boundary acting as a source of dislocations, and the effect of grain size on the dislocation density where dislocation density is inversely proportional to grain size[17].

The grain size strengthening effect in AZ91D Mg alloy, which has the hexagonal close-packed (hcp) crystal structure, is highly relative to those of other metals with the body-centered cubic (bcc) and the face-centered cubic (fcc) crystal structures since Mg has a large Taylor factor[20]. As noted before, higher impact current and longer time during the UIT process result in higher hardness compared with lower impact current and shorter time because of dislocation movements within the crystal structure of the material.

2.2 Wear performance

Fig.5 shows the shape and dimensions of wear test specimens. The upper specimens were made of tested materials both for treated and un-treated, with a size of 17 mm ×8 mm ×30 mm which were cut from the treated and un-treated area on the rectangle plate shown in Fig. 3. The discs were made of GCr15 alloy steel, with *Φ*40 mm in the outside diameter, *Φ*16 mm in the inner circle diameter, 10 mm in thickness, and a hardness of 61 ±2 HRC after quenching and low temperature tempering.

Table 3 Vickers hardness test results of AZ91D alloy

Current/A	Time/min	Sample	Test (1), HV/MPa	Test (2), HV/MPa	Test (3), HV/MPa	Average HV/MPa
0	0	0#	702	825	753	760
1.2	3	1#	1372	1343	1314	1343
	6	2#	1362	1490	1536	1462
	9	3#	1532	1532	1478	1514
1.5	3	4#	1516	1490	1611	1539
	6	5#	1631	1509	1505	1548
	9	6#	1584	1627	1635	1615

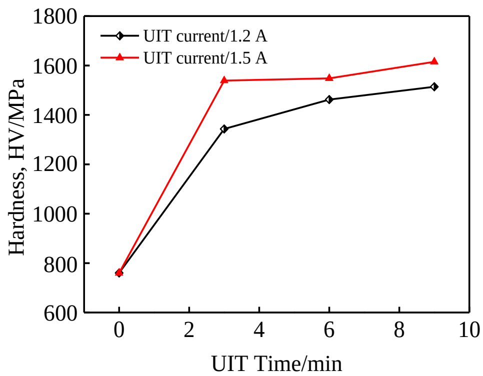

Fig.4 Relationship between hardness and UIT time

Table 4 Wear test results of AZ91D specimen

Current/A	Time/min	Measured mass loss/ $\times10^{-3}$g	Average mass loss/ $\times10^{-3}$g
0	0	5.2, 6.7, 5.3, 5.8	5.750
1.2	3	4.4, 4.4, 4.7, 4.0	4.375
1.2	6	3.4, 3.5, 3.4, 3.5	3.450
1.2	9	2.9, 3.0, 2.9, 2.9	2.925
1.5	3	2.6, 2.8, 2.6, 2.7	2.675
1.5	6	2.6, 2.5, 2.6, 2.6	2.575
1.5	9	2.4, 2.5, 2.4, 2.5	2.450

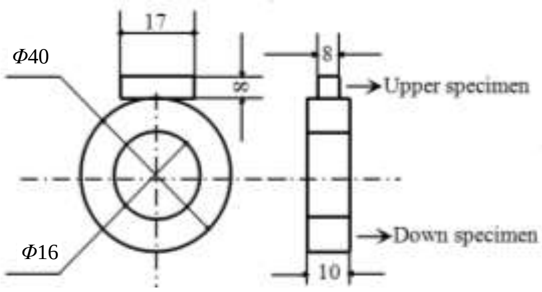

Fig.5 Shape and dimensions of wear test specimen

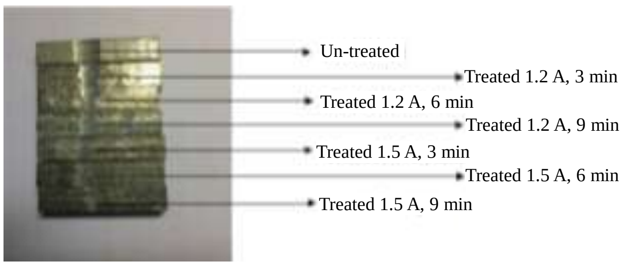

Fig.6 Worn surfaces of specimens after wear testing

All specimens were pre-weared for 3 min and then cleaned in acetone. The mass of wear specimens were measured using a scale of TG-328 model with a precision of 10^{-4} g. Table 4 shows the wear test results. It has been seen that with the increase of impact time and current, the wear of all treated specimens decreases gradually. For a certain impact current, longer in impact time results in increase in surface hardness and decrease in wear loss. Also, for certain impact time, higher in impact current leads to increase in hardness and so decrease in wear loss. The wear resistance of the specimens strengthened by UIT were remarkably improved, especially for the specimen treated with the impact current of 1.5 A and impact time of 9 min, whose wear resistance has been increased by about 57.39% compared to the un-treated specimen.

Fig.6 shows the worn surfaces of the tested specimens with different UIT time and current. It has be found that the wear scar width on the macro-wear surface becomes narrower and narrower followed by increasing the UIT time and current.

SEM images of the typical worn surfaces of the treated and un-treated specimens are shown in Fig.7. It can be seen that there are many parallel grooves in the worn surface of the treated and un-treated specimens. The morphology indicate the wear mechanism is abrasive wear. In the case of the un-treated specimen Fig.7a, the grooves on the worn surface presented the widest. Furthermore, the treated specimens, which were processed at a higher impact current and longer impact time, have much narrower wear grooves width. With the increase of the UIT time and current, the width of the wear grooves decreases significantly. Wear grooves of all the treated specimens are narrower compared to those of the untreated specimens. The experimental results show that the

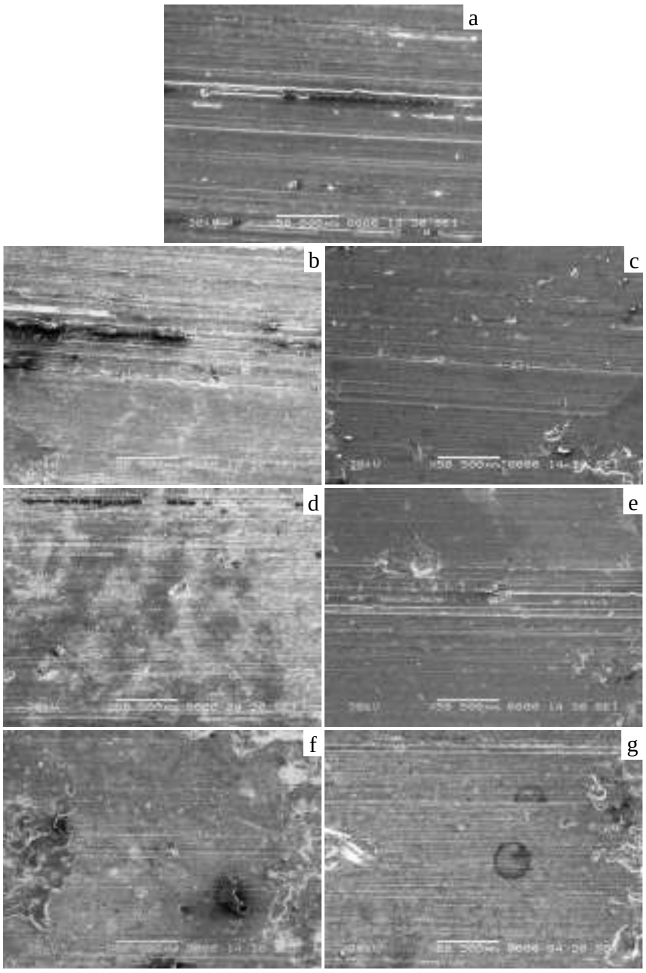

Fig.7 SEM images of the typical worn surfaces of the specimens with different UIT current and time: (a) un-treated, (b) 1.2 A/3 min, (c) 1.2 A/6 min, (d) 1.2 A/9 min, (e) 1.5 A/3 min, (f) 1.5 A/6 min, and (g) 1.5A /9 min

wear resistance of AZ91D alloy could be improved by the UIT process. The specimen whose hardness is the highest has been worn least among all the specimens, and it has the best wear resistance, and lowest wear loss (Fig.7g). The tested mass loss data shown in Table 4 confirmed the microscopic observations shown in Fig.7.

The improvement in wear resistance of the treated specimens can be interpreted by Holms and Archards adhesive wear theory[21] as:

$$V = PW / H \tag{2}$$

It is applied to adhesive and abrasive wear, where V is the wear volume loss per unit sliding distance, W is the applied load, H is the hardness of the materials, and P is the wear constant related to the wear mechanisms and the materials of the wear members. The wear loss obtained can be directly correlated to the hardness of the surface. Fine grain structure and compressive residual stress improves the surface strength of the material[22]. The compressive residual stress and high strength of fine grain material at the treated surface increase the wear resistant properties compared to the untreated samples.

3 Conclusions

1) The microstructures on the treated surface of AZ91D alloy can be refined by UIT. After UIT process, severe plastic deformation was produced in the surface of AZ91D, and the maximum depth of the plastic deformation layer is about 120 μm.

2) The microhardness of AZ91D could be greatly improved via the UIT process. The microhardness of the treated specimens is about 99.21% and 112.5% higher than that of the untreated specimens when the UIT time is 9 min and the current is 1.2 and 1.5 A, respectively.

3) The wear resistance of AZ91D could be increased by the UIT process. When the UIT current is 1.5 A, and the time is 9 min, the wear resistance has been increased by about 57.39% compared to that of the un-treated specimens.

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超声冲击对 AZ91D 镁合金耐磨性能及显微硬度的影响

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摘 要：采用 HJ-III 型超声冲击设备对 AZ91D 镁合金表面进行了冲击处理，利用光学显微镜和高倍透射电子显微镜研究了超声冲击表层的微观组织。对经超声冲击处理和未冲击处理的 AZ91D 镁合金的耐磨性能进行了对比研究。用扫描电镜和显微硬度计研究了超声冲击处理对磨损表面形貌和显微硬度的影响。结果表明，超声冲击使 AZ91D 镁合金的表面出现了严重的塑性变形，塑变层深度约为 120 μm，表面组织明显得到细化。超声冲击可极大的提高 AZ91D 镁合金的耐磨性能和显微硬度。耐磨性能和显微硬度随超声冲击电流的增加和冲击时间的延长而提高。与未冲击试样相比，在冲击时间为 9 min，冲击电流为 1.5 A 时，冲击试样的显微硬度和耐磨性分别提高了 112.5% 和 57.39%。

关键词：超声冲击；AZ91D 镁合金；微观组织；硬度；耐磨性能

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