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EFFECTS OF HIGH-TEMPERATURE SHOT PEENING ON SURFACE CHARACTERISTICS AND FATIGUE PROPERTIES OF FORGED AZ31 MAGNESIUM ALLOYS

Yuki Ichihara[1], Masafumi Noda[2], Kunio Funami[2]
[1]Graduate School of Engineering, Chiba Institute of Technology,
2-17-1 Tsudanuma, Narashinoshi, Chiba 275-0016, Japan
[2]Department of Mechanical Science and Engineering, Chiba Institute of Technology,
2-17-1 Tsudanuma, Narashino, Chiba, 275-0016, Japan

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Abstract

In this present study, the effects of high-temperature shot peening (HSP) on the surface characteristics and fatigue properties of forged AZ31 magnesium alloys were investigated. The HSP process was performed with a low-carbon steel ball under a shot pressure of 0.2 MPa and time of 6 s at a temperature of 523 K. Gradable microstructures were formed in the near-surface region, about 150 μm from the surface edge. These were composed of an ultra-fine-grained region, a residual working strain region, and a twin region. The HSP-processed material showed increased fatigue strength compared with the non-HSP-processed material. From the measurement of the crack-propagation rate, it was found that the improvement in fatigue properties led to a delay in the crack-propagation rate in the ultra-fine-grained region and the residual working strain region.

Introduction

The magnesium alloy used here is one of the most light-weight metals in practical use. Since it has many excellent properties such as its specific strength, damping capacity, and machinability, it has started to be utilized for transport machine components in automobile and railroad vehicles. However, until now, its practical use was limited to the parts on which only a comparatively light load would act, such as in electric devices [1-3]. In recent years, the application of plate materials (which have excellent mechanical properties compared with casting materials, in which defects such as blowholes are a concern) to structural members has been considered.

However, the magnesium alloy has strong anisotropy in the crystal itself, showing unique mechanical properties in the texture formed by plastic working processes such as rolling and extrusion [4]. Therefore, in terms of fatigue properties, different modes of action of the applied stress have been reported to give rise to particular behaviors [5,6]. Moreover, it has also been reported that the initiation/propagation characteristics of a crack depend on the crystal grain size or orientation [7-10]. Therefore, full examination of the relationship between the structure and the fatigue characteristics is necessary for the application of Mg alloy expansile materials in structural members.

Traditionally, shot peening (SP) has been used to improve the fatigue characteristics of steel. In recent years, it has been reported for aluminum and titanium alloys that nanoscale fine-grained structures can be formed on the surface through shot peening [11,12]. However, if SP is performed on a magnesium alloy at room temperature, cracks occur easily on the SP surface because the deformation ability is low. To address this problem, we performed SP at various processing temperatures, and found that a graded-structure material with a fine-grained structure layer on the material surface can be produced without crack initiation [13,14].

In this present study, we investigate the relationship between the surface and fatigue characteristics of AZ31 magnesium alloys with surface gradable structures, which were produced by the high-temperature SP process.

Materials and Experimental Procedure

The materials used were obtained from a commercial AZ31 Mg alloy extrusion material forged with multiaxial forging processing (forging temperature: 1-pass: 543 K, 2-pass: 513 K, 3-pass: 473 K; reduction ratio: 30%; compression speed: 2 mm/min). Recrystallization heat treatment at 523 K with 20-min holding was performed for structure homogenization. Herein, this material is referred to as the Non-SP material. Through this refinement process, the average grain size became 18 to 12 μm, and the random crystalline structure and anisotropy of the proof stress on the tensile side and compression side caused by the texture formed by extrusion was no longer observed. The inverse pole figure (IPF) map of the Non-SP material is shown in Figure 1. The high-temperature SP process used air-type sandblast, and it was performed with a shot pressure of 0.2 MPa and a time of 6 s with a low-carbon steel ball. SP processing was performed at 523 K with 20-min holding in order to homogenize the structure. This material, after the high-temperature SP process, is referred to herein as the HSP material. Tensile tests were carried out at room temperature with a tension speed of 0.5 mm/min. The tensile specimen was cut down by electrical-discharge machining to give a parallel portion (11 mm in length, 5 mm in width, and 1 mm in thickness). SP was carried out on only two faces of the board.

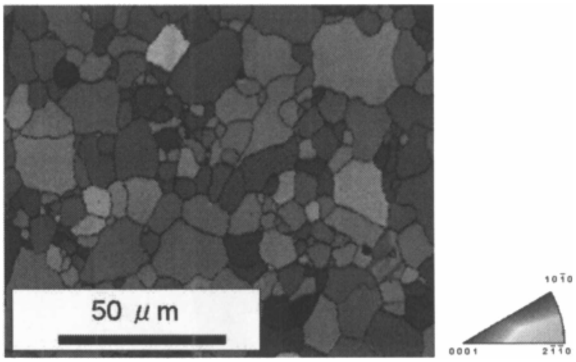

Figure 1 IPF map of AZ31 magnesium alloy structure processed by forging and heat treatment (Non-SP)

Using a servo-type fatigue machine with a capacity of 9.8 kN, we performed fatigue testing at room temperature with a test frequency of 10 Hz and a stress ratio, R, of −1.0. To determine the fatigue strength, we carried out high-cycle fatigue testing; the specimen used was a round bar specimen of 4 mm in diameter and with a parallel portion 12 mm in length. The crack-observation specimen was a form with a U-shaped notch (6 mm in diameter) attached to a plate (55 mm in height, 12 mm in width, and 5 mm in thickness), with a stress-concentration factor of 2.6. Lathe processing or electrical-discharge machining from the forging material, such that the length direction and the direction of extrusion became equal, produced two kinds of specimen shape. The surfaces of the specimens were machine-polished with emery papers #180 to #2000, and then buff-finished. SP processing was carried out over the parallel portion of the specimen for fatigue testing. For the crack-observation specimen, SP processing was performed only on the side of the U-shaped notch in order to facilitate the observation of the crack. In addition, the replica method was used for crack observation with optical microscopy and scanning electron microscopy (SEM).

Results and Discussion

Surface characteristics of the high-temperature shot-peening materials

Figure 2 shows IPF maps obtained by electron backscatter diffraction (EBSD) of the surface layers of the HSP material (b), and the relation between the distance from the surface and the residual stress (a). It was found from Figures 2 (a) and (b) that the graded-structure zone of about 200 μm on the surface was divided into three zones according to the HSP process: a recrystallized zone, a severe residual strain zone, and a twin zone. It seems that the formation of this graded structure is related to the strain distribution of the SP process and the cooling rate. Moreover, the diameter of a crystal grain in the recrystallization layer was about 1 μm, as determined from the transmission electron microscopy (TEM) images shown in Figure 3 (a). This was further confirmed from the pole figure of the HSP material, and the results for the Non-SP material in Figures 3 (b) and (c) show that the degree of random orientation in the HSP process is stronger than in the static recrystallization process.

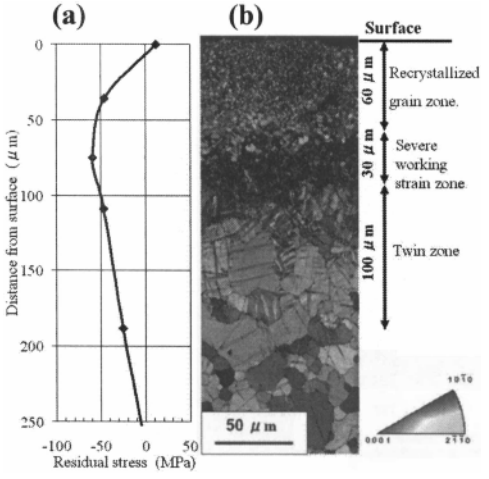

Figure 2 Relation between distance from surface and residual stress of HSP material (a), and IPF map of surface structure of HSP material at 523 K (b)

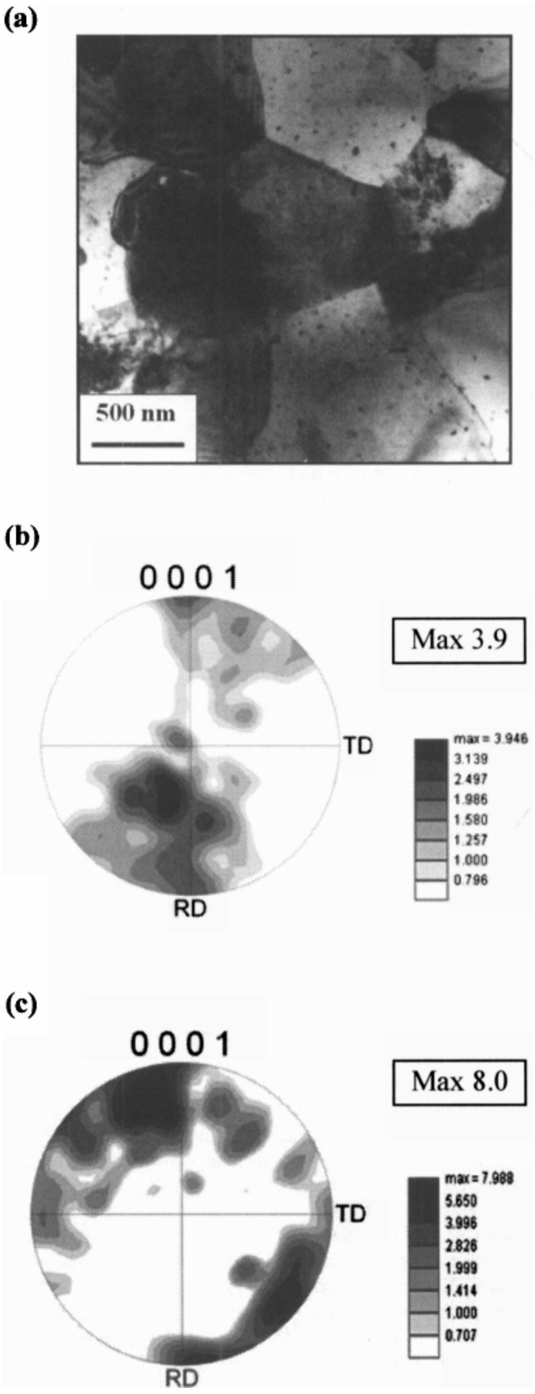

Figure 3 TEM micrographs and pole figure of HSP and Non-SP materials. TEM microstructure of recrystallized grain zone of HSP material (a), pole figure of recrystallized grain zone of HSP material (b), and pole figure of non-SP material (c)

Mechanical characteristics of HSP material

The tensile and fatigue test results are shown in Table 1. From the tensile test results, it is found that there is an improvement in strength and elongation with HSP processing. This is considered to arise from the effect of grain refinement and the random orientation seen in Figure 3. Furthermore, the fatigue-testing results showed a 5 MPa improvement in the fatigue limit with HSP processing. SEM micrographs of the fracture surfaces of the HSP and Non-SP materials fractured by a stress amplitude of 120 MPa are shown in Figure 4. In the fracture surface of the HSP material, a ratchet mark is seen, indicated by the arrow in Figure 4 (a). On the other hand, for the Non-SP materials shown in Figure 4 (b), such a trace is not observed. Therefore, from the fracture form of the HSP material, it is thought that two or more cracks are initiated and propagated, resulting in the fracture of the materials.

On the basis of detailed SEM observations, it was confirmed that crack initiation was promoted by the stress concentration in the peening dimples formed by the SP process. Therefore, we suppose that the crack-propagation process is a factor in the improvement of the fatigue characteristics of HSP materials.

Table 1 Mechanical characteristics of non-SP and HSP materials

	Tensile test			Fatigue test
	Tensile strength (MPa)	Proof stress (MPa)	Elongation (%)	Fatigue limit ($5 \cdot 10^6$)
Non-SP	248	128	22	90
HSP	258	135	27	95

Fatigue crack-propagation properties of HSP materials

Figure 5 shows the relation between the crack length and the number of cycles for the HSP and Non-SP materials. This figure shows that the HSP material has a short lifetime to crack initiation compared with the Non-SP material. As described above, it is considered that the stress concentration originates in a peening dimple. Moreover, a delay in the fatigue-crack growth rate is seen in a zone with a surface crack length of about 70 μm. This is in agreement with the length of the recrystallization layer shown in Figure 2. Moreover, SEM micrographs of fatigue crack in the HSP materials (stress amplitude: 120 MPa; number of cycles: 3200) are shown in Figure 6. This figure shows that a crack in the recrystallization layer propagates in a zig-zag form. It has been reported that crack propagation of the polycrystalline AZ31 magnesium alloy progresses remarkably along a grain boundary, and that the fatigue-crack growth rate changes by a factor of about five with the crystal direction [15]. Therefore, the delay in the fatigue-crack growth rate is considered to be caused by the grain boundary increasing on the crack route (which is, in turn, due to the grain refinement by the HSP process) and the random grain orientation . Next, the IPF maps of the microstructures of the twin layer and fatigue crack are shown in Figure 7. This figure shows that the crack does not necessarily propagate along the boundary between the twin and base materials. It has been reported that, although double twin formation leads to crack initiation, however the {10-12} twins do not contribute directly to fatigue failure [9]. Subsequently, direction analysis was carried out in the twin layer of Figure 2. All the twins in this twin layer were {10-12} twins. From this fact, it seems that there was no delay or participation in the fatigue-crack growth rate within the twin layer. Therefore, as shown in Figure 5, the lifetime to crack initiation decreases with the HSP process, but it is thought that, through the delay in crack propagation in the recrystallization layer, this leads to an improvement in fatigue strength. Moreover, further improvement in fatigue strength is expected with suppression of the formation of peening dimples.

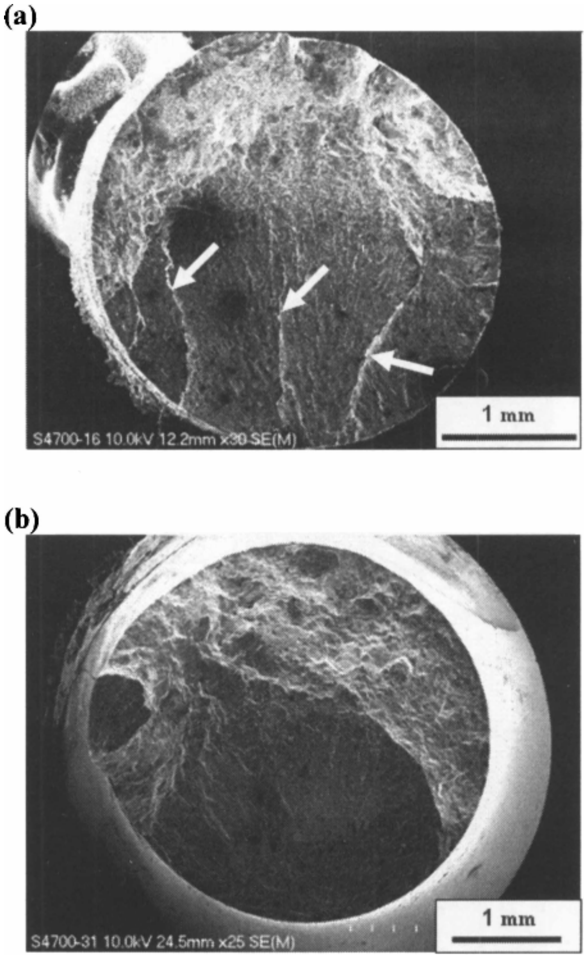

Figure 4 SEM micrographs of fracture surface. (a) HSP material (stress amplitude is 120 MPa); (b) Non-SP material (stress amplitude is 120 MPa)

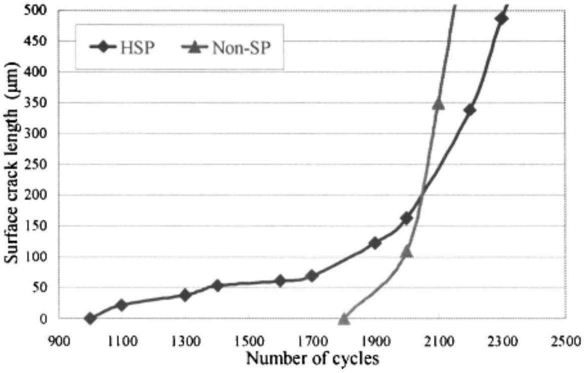

Figure 5 Relation between surface crack length and number of cycles

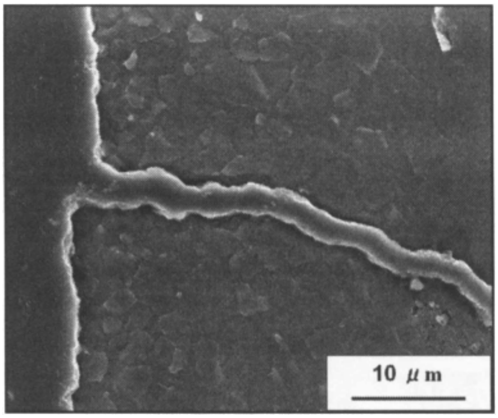

Figure 6 SEM micrographs of the fatigue crack of the HSP material

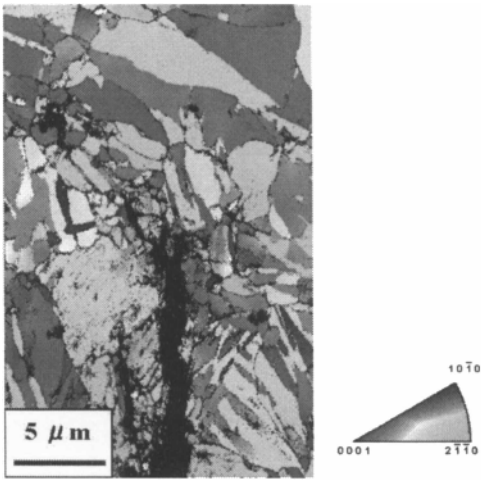

Figure 7 IPF map of the microstructure near the fatigue-crack tip in the twin zone

Conclusion

In this present study, the effects of high-temperature shot peening (HSP) on the surface characteristics and fatigue properties of forged AZ31 magnesium alloys have been investigated. It has been shown that a graded microstructure consisting of three layers (a recrystallization layer of about 1-μm grain size, a severe working strain layer, and a twin layer) can be formed by the HSP process. Moreover, because of the grain refinement and random orientation in the recrystallization layer, there is an improvement in the tensile strength, elongation, and fatigue strength.

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