Mechanical Properties and Resonant Characteristics of Friction Stirred AZ31-Mg Alloy

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An annealed AZ31-Mg specimen (AZ31-O) was given a FSP (friction stir process) to obtain a AZ31-FSP specimen, whose tensile and vibration fracture mechanisms are examined in this study. As a result of FSP, the structure of the stirred zone (SZ) separated into two zones: (1) the SZ-top had a finer structure and (2) the grain size of the SZ-bottom was like the AZ31-O specimen. Because the basal plane (0002) had pressed close to the trace surface of the onion structure in the SZ, the recrystallization of FSP increased the elongation of the specimens at room temperature, but the refined grains had no contribution to tensile strength and had an unusual Hall-Petch effect. Notably, the vibration deformed resistance of the AZ31-FSP specimen was higher than that of the AZ31-O specimen. The FSP specimen not only possessed finer structures but also had a preferred orientation in the stirred zone. This led to an increase in the crack tortuosity, which in turn increased the crack propagation resistance and the vibration life. [doi:10.2320/matertrans.MRA2008167]

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1. Introduction

The friction stir process (FSP) is an innovative process that developed from friction stir welding (FSW). FSP was adopted in this study because the friction rotation between the tool and specimen can produce a plastic deformation flow to obtain finer recrystallized grains and improve the material characteristics. FSP, Equal-Channel Angular pressing (ECAP) and hot rolling result in finer recrystallized grains. The equipment of FSP is simple and used widely. It is worth noting that FSP can induce continuous dynamic recrystallization, and causes the friction stir zone to possess fine recrystallized grains.

Mg-Al-Zn (AZ system) alloy has excellent casting properties, good mechanical properties and corrosion resistance. Because of its hexagonal close-packed structure (HCP), it is hard to work at room temperature. FSP can refine the grains and improve the workability. Many reports of Mg alloys have revealed that fine recrystallized grains with a high density of dislocations possess better hardness, tensile properties and toughness. Magnesium alloys have been used extensively in the auto industry. Given that failure may occur due to vibration, the vibration fracture resistance should be taken into consideration in the design of FSP-Mg alloys. However, the vibration life of many engineering materials cannot be assessed from the tensile mechanical properties, and the relationship between the grain refinement and vibration behavior of the friction stirred AZ31-Mg alloy has still not been clarified, especially under resonant conditions. This study uses AZ31-Mg alloy not only to analyze the characteristics of the stirred zone (SZ), but also to investigate the deformation fracture mechanism under tensile testing and vibration testing.

2. Experimental Procedure

Commercially rolled Mg alloy (AZ31B-H24) plates (thickness of about 3.1 mm) were used in this study. To obtain identical structures, the specimens were given heat-treatment at 620 K for 12 h followed by furnace cooling to room temperature to obtain fully annealed specimens (hereafter designated as AZ31-O) before FSP. The AZ31-O matrix presents an equiaxed grain structure with an average grain size of 7.6 µm (Fig. 1).

A tool (non-thread pin) rotation speed of 1600 rpm was chosen for FSP modified testing (hereafter designated as AZ31-FSP). The specimens after FSP were air-cooled to room temperature. A schematic illustration of the FSP, rotational tool and the dimensions of the specimens are shown in Fig. 2. The direction of friction stir was parallel to...
the direction of rolling. During FSP, a water-cooled backing plate was used to enhance the cooling rate and avoid grain growth. Tool moving speeds were fixed at 15 mm min\(^{-1}\) with 1.5° of tool angle and the downward push force was held at 21.7 MPa.

OM and SEM were used for microstructural evolution and analysis of the dynamic recrystallization, and an image analyzer was used to measure the average grain size in the stir zone. To understand the tensile mechanical properties of the stirred zone of the FSP specimens at room temperature with equiaxed grain structure, the gauge of the specimens parallel to the direction of stirring was chosen for tensile testing. The dimensions and the related location of the tensile specimens are shown in Fig. 3. In addition, the tensile test results of each sample had a constant strain rate of 8 \times 10^{-4} \text{s}^{-1}.

For vibration testing, a simple cantilever beam vibration system was used for the vibration experiments (Fig. 4(a)). The test specimens (Fig. 4(b), (c)) were rectangular with dimensions 70 mm \times 10 mm \times 1.5 mm. The specimens were mounted and fixed on end to the vibration shaker. Two circular-notches near the clamp were made for observing
On the vibration frequency vs. the deflection amplitude curve, the maximum deflection amplitude always occurs at resonant frequency. The resonant frequency is taken as the frequency leading to the largest deflection and is determined by varying the vibration frequency continuously. Each analysis datum was the average of at least 3–7 test results.

3. Results and Discussion

Figure 1 shows the microstructure of the full-annealed AZ31-O specimen. The structures in the ND, RD and TD directions were equiaxed grain structures with an average grain size of 7.6 μm. After FSP (Fig. 5(a)), the equiaxed grain matrix had refined and the stirred zone (SZ) had separated into two zones according to the grain size: (1) the SZ-top had a finer structure (Fig. 5(b)) and (2) the grain size of the SZ-bottom (Fig. 5(c)) was like the AZ31-O specimen. In addition, the average thickness of the SZ-top region was 0.5 mm and that of the SZ-bottom region was 2.6 mm. The average grain size of the SZ-top was 2.8 μm and that of the SZ-bottom was 7.2 μm (The AZ31-O specimen had an average grain size of 7.6 μm, Fig. 1). After polishing, the total thickness of SZ region was 1.5 mm (SZ-top: 0.4 mm and SZ-bottom: 1.1 mm). So, the ratio of both regions is 0.37:1. For the reason mentioned above, the FSP led to finer recrystallized grains.

Figure 6 shows a comparison of the tensile results of the FSP specimens and AZ31-O specimen at room temperature. The results show that the tensile strength of the AZ31-O
specimen was higher than that of the FSP specimens, while it had an inverse tendency towards elongation. For the FSP specimen, the refined grains had no contribution to tensile strength. According to our previous report\(^1\) and relevant studies,\(^2\) FSP specimens exhibit more retained stress than AZ31-O specimens and there is an orientation effect. In addition, onion structures had formed in the SZ and the basal plane (0002) of Mg alloy had pressed close to the trace surface of the onion structures allowing cracks to propagate under mechanical property testing. Thus it can be seen that a change in orientation\(^2\) and retained stress\(^1\) (FSP specimen > AZ31-O specimen) were induced after FSP, and the softening effect due to texture much greater than the hardening effect due to retained stress, resulted in an unusual Hall-Petch effect (\(\sigma = \sigma_0 + kd^{1/2}\)). Meanwhile, the AZ31-FSP specimen showed significantly refined grains (the average grain size of the specimen including SZ-top and SZ-bottom was 3.4\(\mu m\), which was about fifty percent of the AZ31-O specimen). This specimen was given resonant testing to understand the deformation behavior of recrystallized grains formed by FSP.

This study avoided the effect of damping capacity by controlling the vibration force and measured the D-N curves (deflection amplitude versus number of vibration cycles) of the specimens under constant initial deflection conditions. An initial deflection of 1.08 mm (on the Y-axis) was selected as a standard for the specimens, and the resonant frequencies of the two specimens did not change; the values were 71 \(\pm\) 1 Hz. Figure 7 shows the D-N curves of the specimens under resonant frequency and a constant initial deflection amplitude.\(^{15-17,20,21}\) The D-N curve can be divided into an initial stage with ascending deflection amplitude, a second stage in which deflection remains constant, and a final stage with a descending deflection amplitude. The ascending and constant deflection amplitudes within Stage I and Stage II can be attributed to the effect of strain hardening in competition with crack generation and linking within this region. The descending deflection amplitude in Stage III is due to the deviation of the actual vibration frequency from the resonant frequency caused by the inward propagation of major cracks. In Fig. 7, the AZ31-O curve shows an obvious Stage I, revealing that strain hardening was active during initial vibration. There is a visible contraction of Stage II in the AZ31-O specimen, and the AZ31-O curve immediately enters Stage III. As for the FSP curve, the effect of strain hardening of Stage I is lower, followed by a longer Stage II (II-O < II-FSP), which continues for an extended period before finally entering Stage III.

A previous study revealed that a AZ31 specimen had a nearly 3 Hz deviation between the actual vibration frequency and the resonant frequency when the deflection amplitude was decreased to 94% of the maximum value. Therefore, the vibration life in this study was defined as the vibration cycle number when the deflection amplitude was reduced to 95% (0.95\(D_{\text{max}}\)) of the maximum value. Based on this definition, Fig. 7 shows that the effect of FSP caused the vibration life to increase. To understand the vibration fracture behavior, a diagram of observation direction is shown in Fig. 8 and SEM was used to examine the characteristics and mechanisms of vibration fracture. Figure 9 and Fig. 10 show the vibration fractures of the specimens under a constant initial deflection amplitude of 1.08 mm. Comparing Fig. 9(a) and 9(b), we find that the vibration crack propagation of the AZ31-O specimen showed little tortuosity, however...
that of the AZ31-FSP specimen exhibited more tortuosity. In other words, FSP was able to increase the vibration crack tortuosity, which in turn increased the crack propagation resistance. After etching, transgranular fractures can also be seen in the image in Fig. 10(a). Both at the SZ-top (Fig. 10(b)) and SZ-bottom (Fig. 10(b)) of the AZ31-FSP specimen, the results reveal that both intergranular and transgranular fractures occurred during vibration deformation. This explains how the finer recrystallized grains of FSP affected crack propagation during vibration.

According to Fig. 8, the vibration fracture subsurfaces were observed, as shown in Fig. 11. The roughness of the vibration subsurface was lower (Fig. 11(a)). Notably, a large number of splintery characteristics were observed on the...
subsurface of the vibration fracture of the FSP specimen (Fig. 11(b)). From observation of vibration-deformed structures, we see that both intergranular and transgranular fractures can deplete the vibration energy and lengthen the vibration life. FSP allows intergranular fractures to form easily during vibration. So, the finer recrystallized grains had greater vibration fracture resistance than the AZ31-O specimen. The FSP makes a contribution to the vibration life and causes intergranular fractures to occur easily. This shows that the effect of refined grains was obviously active in the FSP specimen and the splinterly characteristics had an obvious tendency to increase the vibration life.

4. Conclusions

After FSP, the equiaxed grain matrix had become more fine in the stirred zone and the grain size of SZ increased from the stirred surface to subsurface. For tensile testing, the orientation and retained stress of the refinement grains made no contribution to tensile strength. Under constant initial deflection amplitude, the finer recrystallized grains of FSP were able to restrain the vibration crack propagation and lengthened the vibration life.

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