Verification of Optimum Temperature on Tensile Ductility Improvement of Friction Stir Processed AZ31 at Warm Temperature Range up to 300°C

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AZ31 Mg alloy in a friction stir processed condition was deformed in tension at temperatures ranging from room temperature to 300°C in comparison with the same alloy in an extruded condition. It was found that friction stir processed AZ31 possesses excellent ductility at a comparatively low thermal exposure temperature (100°C) and a significant difference of strain hardening behavior compared with as extruded one. These results show that the formability of friction stir processed specimens is better than that of as extruded samples due to the differences in texture and microstructural features. In order to confirm these findings, the present study conducted tensile tests from room temperature to 300°C and verified the improvement in ductility. The effect of exposure temperature on formability will be discussed as well.


(Received January 13, 2011; Accepted March 28, 2011; Published May 25, 2011)

Keywords: magnesium alloy, friction stir process, formability, uniform elongation

1. Introduction

Friction stir process (FSP) is a method for grain refinement and texture control to improve the formability of magnesium alloys. A special region (i.e., stir zone, SZ) is characterized by fine and equiaxed recrystallized grains and randomized texture. Due to its uniqueness, previous investigations have tried to clarify the effects of the above-mentioned factors on tensile ductility improvement pertaining to subsequent stamping or hydroforming processing.

With regard to reducing the weight of structural components, AZ31 Mg alloy is the most attractive candidate alloy for applications of transportation and mobile electronics. Consequently, it has been extensively used while the insufficient ductility of extruded AZ31 alloy for cold working has limited its process design. In addition, the mechanical properties of AZ31 alloy often do not meet the requirements such as tensile strength, ductility and fatigue properties. However, AZ31 alloy possesses particularly favorable predominance in weight specific values so that this alloy is used in various applications.

Based on our previous experimental study, the tensile ductility of extruded AZ31 alloy at room temperature is rather poor due to its (0002) laid parallel to the extrusion direction, which is not favorable for [1012] twinning and suppresses the occurrence of deformation twins. It should be noted that a homogeneous grain refinement can be acquired with only one pass friction stir process. Though the tensile strength of friction stir processed samples is significantly lower than that of extruded ones, an improvement in tensile ductility as well as effective work hardening rate should be considered.

In regard to the formability of AZ31 Mg alloy, its deformation behavior has been widely discussed. In general, twinning shear plays an important role in retaining strain compatibility, especially when strained at room temperature. Two twinning systems [1012][1011] and [1011][1012] are expected in AZ31 Mg alloy, the former is a “tension twin” that is associated with tensile loading along the c-axis, and the latter is a “compression twin” that corresponds to compressive loading along the c-axis.

As mentioned above, an extruded specimen usually possesses a texture in which basal planes tend to align parallel to the extrusion direction while a friction stir processed specimen usually results in a more complex texture in which basal planes tend to surround the stirring pin. Although this texture feature of the friction stir processed specimen actually improves its tensile ductility at room temperature, the aim for further improvement in ductility is still needed. Therefore, one goal of our exploration was to analyze the twinning system as a function of texture. Another goal was to contrast the contribution of different twinning and slip systems on improving the accommodating ability including tensile ductility, work hardening rate and uniform elongation at the warm temperature range from 100°C to 300°C.

In this investigation, the contribution of textural feature and twinning factor on the improvement in tensile ductility will be the main focus of examination. Another aim is to explore the possibility of lowering the temperature to around 100°C and see whether AZ31 still possesses sufficient tensile ductility and observe the microstructural evolution during tensile deformation.

2. Experimental Procedures

AZ31 Mg alloy with nominal chemical composition of (in mass%) 3.3 Al, 0.6 Zn, 0.6 Mn was selected in this investigation. An as-received billet with above-mentioned composition was extruded to 6-mm thickness and 350-mm width at 400°C. Some extruded plates were machined as the substrates for friction stir processing. The processing direction (PD) was parallel to the extrusion direction (ED), with a
stirring tool which was 1.5° backward from the process direction under a constant tool rotation speed (1600 rpm). The pin of the stirring tool had a diameter of 5.5 mm and depth of 3 mm.

The gauge length section dimension of the tensile specimen was $15\times3.7\times1.7$ mm, and the tensile direction was parallel to both extrusion and process direction. The gauge length portion of the friction stir processed specimen was completely located within the stir zone. Uniaxial tensile tests were carried out at a constant initial strain rate of $8.3\times10^{-4}$ s$^{-1}$ from room temperature to 300°C. All tensile data were obtained from more than 3 samples.

3. Experimental Results

3.1 Effect of FSP on microstructural feature, texture randomization and tensile deformation behavior at warm temperature

Figure 1 shows a significant difference in microstructures between the as extruded (AE) and the friction stir processed (AF) samples. The former reveals a coexistence of coarse incipient grains and fine dynamic recrystallized grains while the latter possesses comparatively homogeneous equiaxed grains. AE has an average grain size of 184μm in the transverse direction and 110μm in the normal direction. Compared to the coarser microstructure of AE, AF shows a finer and more equal-axial grain structure with 8-μm average grain size; hence the conspicuously heterogeneous extrusion feature of AE could be homogenized efficiently by FSP.

X-ray diffraction patterns of the normal and transverse sections are demonstrated in Fig. 2(a) and 2(b) for AE and AF respectively. The result of the TD section in AE indicates high (0002) intensity while the ND section indicates higher $<10\bar{1}0>$ and $<1\bar{1}10>$ intensity. Thus AE possesses a texture in which basal planes tend to align parallel to the extrusion direction as illustrated in Fig. 2(a). For the AF specimen, the diffraction data of the TD section were collected separately from the vicinity of the center portion and designated as sections A, B and C. Compared with two end sides as sections A and C, the diffraction result of section B indicates high $<10\bar{1}0>$ and $<11\bar{2}0>$ intensity and also indicates a lower $<1\bar{1}10>$ intensity in the center portion (Fig. 2(b)). Therefore a texture randomization can be recognized in the friction stir processed sample that gave rise to a texture of basal planes tending to surround the stirring pin as shown in Fig. 2(b). This means that the included angle between the basal planes and process direction tended to be non-zero in AF while the basal planes of AE were parallel to the extrusion direction.

It is well known that the formability of metals can be correlated with their texture pertaining to the microstructural feature. The well developed basal texture is responsible for the yield phenomenon of AZ31 Mg alloy.$^{13,14}$ Based on experimental results as shown in Fig. 3, the decreasing of the basal plane component induced by FSP results in the low tensile strength of the AF samples, and it also contributes to the improvement in tensile ductility in the AF specimens. It can be noted from Fig. 4 that the work hardening rate of AF is significantly smaller than AE starting from the initial
stage of tensile deformation. Furthermore, the significantly lower flow stress in the AF specimen was found to be due to the unique texture of (0002) roughly surrounding the rotation direction while in the AE specimen the basal planes are almost parallel to the tensile direction (extrusion direction).

Based on tensile flow curves, the variations in tensile data along with the test temperatures of the AE and AF samples are illustrated in Fig. 3. It is demonstrated that the AF samples are characterized by a significantly lower tensile deformation resistance and higher elongation to failure. With regard to the tensile deformation resistance given in Fig. 3(a), although FSP is a well-known process utilized to refine and homogenize the microstructure, the improvement of UTS and 0.2% proof stress at elevated temperatures up to 300°C cannot be achieved even though the microstructure is refined and homogenized. According to the textural randomization data as shown in Fig. 2, it can be inferred that the inhibition of the enhanced tensile deformation resistance of the friction stirred material can be attributed to the difference in textural feature.

3.2 Thermal exposure effect on the tensile ductility

The work hardening rate data abstracted from tensile flow curves are plotted in Fig. 4. At any given temperature, it is clear that the work hardening rate of the AE specimen rises more significantly in the initial tensile deformation stage than that of AF, subsequently the work hardening rate of AE is followed by a sharp drop with increasing strain. It should be noted that the strain hardening region before the maximum stress point of the AF specimen is obviously prolonged especially at 100°C. In addition, from Fig. 3(b) the AF specimen exhibits better tensile ductility than that of the AE samples from room temperature to 300°C, and in particular the maximum tensile elongation (35%) of the AF sample can be acquired at 100°C. If we compare the microstructural differences of the deformed specimens as shown in Fig. 5, deformation twins are a shared microstructural feature. The work hardening rate of AF is significantly smaller than that of AE in the initial strain stage, as indicated in Fig. 4, but a plateau stage could be significantly extended while the AE specimen indicates a tendency to decline. From the microstructural feature as shown in Fig. 5, it is fairly safe to say that the variations in the work hardening rate are mainly caused by the preponderance of twinning.

Figure 6 illustrates the tensile deformation structure in the vicinity of the fracture surface as the test temperature is raised up to 200 and 300°C. For the AE specimen, most grains in the deformed microstructure are elongated accompanied with a small amount of equiaxed DRX grains with an average grain size of 2 μm and 5 μm at 200°C and 300°C respectively. This partial occurrence of DRX grains causes
the decrease in uniform strain. When the test temperature was further raised to 300°C, an obvious decrease occurred in the uniform elongation of the AF specimen due to the enhanced inter-granular slip and cracking as indicated in Fig. 7.

4. Discussion

Many previous investigations have mentioned that AZ31 alloy tested at a higher temperature actually possesses higher tensile elongation,\textsuperscript{10,16} which means that the material does not fracture easily and possesses better formability. Experimental results of forming limit tests agree well with the tensile ductility data.\textsuperscript{16} However, an increase in total elongation at elevated temperatures is usually accompanied by a loss of uniform strain since dynamic recrystallization and grain boundary sliding dominate the deformation behavior of Mg alloy at elevated temperatures. This can be confirmed from Fig. 3(b) and Fig. 7(c) as increasing the test temperature can effectively raise the total elongation of AE, but its uniform elongation drops obviously in comparison with that at room temperature.

The present study confirms that the friction stir processed specimen exhibits an excellent uniform elongation at 100°C,
and its uniform elongation can even reach to 34% as shown in Fig. 3(b). We can infer that the friction stir processed AZ31 alloy can also acquire excellent formability even if only exposed to a warm ambient temperature of 100 °C. This ability to resist necking can be attributed to the work hardening effect becoming significant as the ambient temperature rises to 100 °C. Compared to the rapid drop in work hardening rate of as extruded samples, the work hardening coefficient of the friction stir processed samples can maintain a longer duration at room temperature and 100 °C. Therefore, its notorious limited ductility at room temperature due to its hexagonal close packed (HCP) structure can be improved by FSP. Consequently it is also very important to confirm the microstructural evolution of FSPed AZ31 alloy at around 100 °C by clarifying the microstructural evolution.

Figure 3(a) indicates that AE and AF have different yield phenomena. The yield stress of AF is quite low in contrast to that of AE, and the effect of increasing temperature on decreasing the yield stress of AF is not as obvious as that of AE. The basal planes of AE are almost parallel to the tensile direction, which results in high flow stress due to the activity of non-basal slips; meanwhile this texture is also favorable for (1011) compression twins. In AF, its basal planes and tensile direction have a non-zero included angle, which is more favorable for basal slip and (1012) tension twins. As mentioned above, the texture factor dominates the yield phenomena and affects the microstructure during tensile deformation as well.

From Fig. 3(b), the ascending uniform elongation from the lower temperature side can be attributed to the difference of the microstructural evolution pertaining to the twinning feature during tensile deformation. In our recently study, we found (1012) tension twins in the tensile microstructure of FSPed AZ31 Mg alloy at room temperature, and their occurrence was suggested to be another influential factor. It is indicated that the appearance of (1012) tension twin is beneficial to increasing the work hardening rate, which results in the higher work hardening rate of AF at room temperature and 100 °C. On the other hand, (1011) compression twins have no similar effect on improving the work hardening rate. Thus it makes sense that the work hardening rate of AE drops rapidly.

A combination of lower tensile flow stress and higher work hardening rate in the friction stir processed samples can be inferred to be the cause of the improved tensile ductility. In addition, one common factor responsible for the decreasing of uniform elongation at elevated temperature (200–300 °C) is the onset of dynamic recrystallization as shown in Fig. 6 and 7. In these figures, almost no deformation twins can be observed in the deformed microstructure, which implies that twinning deformation became a minor factor on the compatibility of tensile deformation at 200–300 °C.

Comparing the grain size of new DRX grains with the original grains of AE, new DRX grains are quite small (~5 μm) in contrast to the matrix (~100 μm). As DRX occurs, new grains nucleate on the grain boundaries of the original ones and multiply inward until the matrix is covered by DRX grains. Therefore, heterogeneity will be induced as the coarse grains and the fine grains are not perfectly identical in their deformation behavior, which results in necking induced fracturing during tensile deformation. The difference in grain size causes the total elongation of AE less than that of AF at 200 and 300 °C. Figure 6 reveals that some cracking occurs in the vicinity of the fracture surface in AF. Though the total elongation of AF at 300 °C is close to that at 200 °C, the cracks at 300 °C are not limited to the vicinity of the fracture surface. It should be noted that 200 and 300 °C are not suitable forming temperature for friction stir processed AZ31 alloy due to the high frequency of cracks in the deformed microstructure at these two temperatures.
5. Conclusions

The conclusion can be summarized as follows:

(1) The present study demonstrates an optimum temperature for the improvement in tensile ductility of friction stir processed AZ31 alloy. Depending on the initial dynamic recrystallized fine grains acquired by friction stir processing, different strain hardening behaviors could be recognized, which in turn affected the subsequent tensile elongation before maximum stress.

(2) Friction stir processed specimens exhibited a remarkable increase in tensile ductility at elevated temperatures of up to 300°C, in which the uniform tensile elongation was even able to reach 34% when deformed at 100°C. A significant difference in the strain hardening behavior between the as extruded and FSPed specimen which resulted from the differences in the microstructural feature was identified.

(3) FSPed specimens demonstrated a lower work hardening rate in the initial tensile deformation stage and maintained a prolonged strain hardening region before reaching the ultimate tensile stress when the specimens were tested at a warm temperature of 100°C.

Acknowledgement

This work was supported by the Chinese National Science Council (Contracts: NSC 94-2216-E-006-023), for which we are grateful.

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