In-Situ Study on Deformation Behavior of ZK60 Alloy Processed by Cyclic Extrusion and Compression

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The effects of cyclic extrusion and compression (CEC) on the deformation behavior and failure of ZK60 alloy were examined using in-situ scanning electron microscope (SEM) uniaxial tensile testing at room temperature. Fracture surface was analyzed by SEM. Result shows that the tensile elongation of the extruded ZK60 alloy is obviously increased by CEC deformation. The change in fracture modes has been attributed to the suppression of twinning and the activation of non-basal slips due to the grain refinement and texture modification induced by CEC deformation. [doi:10.2320/matertrans.MC201405]

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1. Introduction

The use of magnesium alloys in industrial fields, such as the automotive and bicycle industries, has gained much attention due to their energy-efficient properties including low density and high specific strength.1,2 However, the application of magnesium alloy is greatly limited for its relatively low strength and plasticity.3 An effective way to improve the mechanical properties of magnesium alloy is to refine the grains.4,5 In recent years, severe plastic deformation (SPD)5,6 has been widely used to fabricate ultrafine grained Mg alloys. As a kind of continuous SPD technique, cyclic extrusion and compression (CEC) is very suitable to refine grains of hard-deformation metals because the materials are imposed by three-dimensional compression stress during the CEC processing.7,8 Previous studies on the CEC processed Mg alloys revealed that the microstructure was effectively refined and the room temperature ductility was significantly enhanced by CEC processing.2-7,9 However, there are few reports on the deformation behavior of the fine-grained Mg alloys fabricated by CEC. In this study, the effects of the CEC processing on the deformation behavior and failure of ZK60 alloy were examined using in-situ SEM uniaxial tensile testing at room temperature.

2. Experimental Procedure

The extruded ZK60 (Mg–5.5 mass%Zn–0.5 mass%Zr) alloy bar with a diameter of 29.5 mm was used. The CEC procedure was described elsewhere.7 The CEC processing was conducted up to 8 passes at 350°C. Microstructures along CEC extrusion direction were observed by optical microscopy. Flat, dog-bone shape in-situ tensile specimens were cut by electric-discharged machining (EDM) from the extruded bar along longitudinal direction, with a gauge section of 14 mm x 3 mm x 1.5 mm. Macro picture of the specimen is shown in Fig. 1. The specimen surfaces were mechanically polished to eliminate the produced scratches during machining, and then were etched in a solution of 1 ml nitric acid + 1 ml acetic acid + 1 g oxalic acid + 150 ml water for the microstructure observation. In-situ tensile tests were carried out using a Shimadzu Super Scan SS-550 SEM equipped with a tensile test device at room temperature. After failure, the fracture surfaces were observed by SEM in vacuum. Transmission electronic microscopy (TEM) observation was performed with a JEOL 2010 microscope operated at 200 kV.

3. Experimental Results and Discussion

The longitudinal microstructures of the as-extruded and 8 passes CEC processed ZK60 alloy are shown in Fig. 2. It shows that the grain size of the ZK60 alloy was effectively refined from ~17 µm down to ~5 µm by CEC processing. Typical uniaxial tensile engineering stress–strain curves for the ZK60 alloy at room temperature before and after CEC processing are shown in Fig. 3. It is impressive that the tensile elongation of the extruded ZK60 alloy obviously
increase from about 15% to about 33% by CEC deformation, due to the microstructure refinement and texture modification. Similar results have been found in other CEC processed Mg alloys.\(^2,7,8\) In order to examine the effects of CEC deformation on the plastic deformation and fracture mechanisms of the ZK60 alloy, the changes in the surface morphology during tensile plastic deformation is observed.

Figure 4 shows the microstructure evolution of the surface morphologies of the as-extruded ZK60 alloy during in-situ tensile testing. Since no obvious changes were observed in the elastic stage, three strain stages in the plastic region were chosen to observe the changes in the surface morphology. At the early stage of the plastic deformation (Fig. 4(a)), the slipping deformation should be activated, but no obvious slip lines were observed with deformation of 0.7%. With the
increase of strain (Fig. 4(b)), slip lines appear in most grains. The slip lines are parallel to each other and perpendicular to the loading direction. It should be the basal sliding, which is the dominant slip system for magnesium alloy at room temperature. In some hard orientation grains, the basal slip is difficult to be activated due to the low Schmid factor, for instance in grain A (Fig. 4(b)). High angle grain boundaries will act as obstacle against slip deformation, then large stress concentrations are caused by the impingement of slip lines towards grain boundaries. When the stress locally exceeds a threshold value, the microcrack appears (marked as arrow in Fig. 4(b)). As the strain continues to rise (Fig. 4(c)), the slip lines become thick, the number of microcracks increases and the width of the detachment becomes larger.

Besides the basal slip, twinning is known to be an important deformation mechanism in Mg alloys because of an insufficient number of independent slip systems. Two types of twins are frequently observed in Mg alloys: \(\{10\bar{1}2\}\{10\bar{1}1\}\) c-axis extension twins and \(\{10\bar{1}1\}\{10\bar{1}2\}\) c-axis contraction twins. Compared to the contraction twinning, the extension twinning occurs more easily due to its lower critical resolved shear stress (CRSS). As shown in the Fig. 4(b), the \(\{10\bar{1}2\}\{10\bar{1}1\}\) extension twins form in some coarse grains to accommodate the strain incompatibility caused by localized basal dislocation slip. In addition, the microcracks are more easily to be initiated from twin boundaries.

The microstructure evolution of the CEC processed ZK60 alloy obtained by \textit{in-situ} SEM tensile testing is shown in Fig. 5. At the relatively low strain level (Fig. 5(a)), the amount of slip lines is much larger than that of the as-extruded samples. The uniform distributed slip lines imply that the uniform plastic deformation occurs. At the relatively high strain level (Fig. 5(b)), grains are badly elongated along the tensile direction and grain boundaries are undistinguishable. The multiple and intersection slip lines indicate that the major deformation mechanism is changed from single-slip to multi-slip, due to the grain refinement and texture modification induced by the CEC deformation. In addition, the coarse \(\{10\bar{1}2\}\{10\bar{1}1\}\) twins is apparently suppressed by grain refinement due to the increasing stress required for twin nucleation (i.e., twin nucleation stress). Whereas, the \(\{10\bar{1}1\}\{10\bar{1}2\}\) contraction twins is observed in the CEC processed sample with tension deformation 10% at room temperature, as shown in Fig. 6.

The fracture fractography of the \textit{in-situ} specimens are shown in Fig. 7. In the as-extruded specimen (Fig. 7(a)), the fracture surface contained typical cleavage facets and cleavage steps, which formation has been related to the cracking of twinning. In contrast, an obviously uniform deformation character is exhibited for the CEC processed ZK60 alloy after tensile fracture (Fig. 7(b)). The fracture surface of this sample shows a typical ductile characteristic with many dimples. The change in fracture modes can be attributed to the change in the deformation mechanism of the CEC processed ZK60 alloy, in other words, the twinning is suppressed and the non-basal slips, including prismatic slip and pyramidal slip are activated due to the grain refinement and texture modification.

4. Conclusions

(1) The tensile elongation of the extruded ZK60 alloy dramatically increased from about 15% to about 33% by 350°C/8-passes CEC deformation.
(2) The multiple and intersection slip lines demonstrate that the major deformation mechanism is changed from single-slip to multi-slip, i.e., the non-basal slips are activated due to the grain refinement and texture modification caused by the CEC deformation.

(3) The \{10\overline{1}1\}\{10\overline{1}2\} contraction twinning is observed in the CEC processed sample with tension deformation 10%, whereas the \{10\overline{1}2\} twinning is suppressed.

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