Arch. Metall. Mater. **68** (2023), 1, 97-101

DOI: https://doi.org/10.24425/amm.2023.141479

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EFFECTS OF SPD BY BIAXIAL ALTERNATE FORGING ON THE TENSILE PROPERTIES AND MICROSTRUCTURE OF AZ31B MAGNESIUM ALLOY

The forming limit of AZ31 alloy, a representative Mg-Al-Zn-based wrought alloy, and the effect of severe plastic deformation (SPD) by examining the microstructure change caused by dynamic recrystallization led by high temperature and high dislocation density at 300°C using a biaxial alternate forging (BAF) were investigated in this study. As a result of BAF test for AZ31 Mg alloy, significant cracks on the ends of workpieces occurred after 7 passes. The microstructure of as-extruded specimen showed the non-uniform distribution of the relatively coarse grains and the fine grains considered to be sub-grains. However, as the number of passes increases, the area of coarse grains gradually disappeared and the fine grains became more dominant in the microstructures. The result of tensile test for workpieces with each forging pass showed an increase in strength depending on pass number was shown with a slight increase of elongation. The Electron Backscatter Diffraction (EBSD) results exhibited that, the microstructure showed the presence of coarse grains and twins after only 1 pass, while the grains appeared to be significantly refined and uniformly distributed after 3 pass, at which the strength and elongation began to increase, simultaneously.

Keywords: Forging; Magnesium alloy; Grain refinement; Severe plastic deformation; Tensile properties

1. Introduction

As the lightest structural metals, Magnesium and its alloys have a specific gravity of about 1.74 g/cm^3, which is equivalent to 2/3 of the aluminum alloys [1]. Also, since they have the highest specific strength and many excellent physical properties such as high damping ability, it is suitable for structural parts requiring weight reduction. On the other hand, since their hexagonal close-packed crystal structure allows only limited slip systems, Mg alloys have a poor formability at room temperature [1]. However, it has been reported that the formability can be significantly improved by warm forming at the temperature range from 200 to 300°C because non-basal slip is activated in addition to basal slip [2]. It is also known that a plastic deformation by hot forging leads to grain refinement and improves the mechanical properties of forgings at room temperature.

Recently, a biaxial alternate forging (BAF) was proposed to systematically evaluate the forging properties of light metal alloys by Shin et al. [3]. The BAF was designed to assess forging limits and mechanical properties of forgings, simultaneously, following certain amounts of strain. A desired amount of strain can be applied to workpiece by repeated forging passes using the BAF dies with an octagonal cross-sectional cavity. With increasing the forging passes, the strain is gradually concentrated on the core of workpiece, and consequently severe plastic deformation (SPD) can be imparted to the workpieces.

The purpose of this study is to investigate the forming limit of AZ31 alloy, a representative Mg-Al-Zn-based wrought alloy, and the effect of SPD by examining the microstructure change caused by dynamic recrystallization led by high temperature and high dislocation density at 300°C using BAF die system mentioned above [3].

2. Experimental

The initial material examined in this study was an AZ31B alloy cast billet subjected to a homogenization heat treatment at 400°C for 10 h. The billet was provided by NICE LMS Co., Ltd. in South Korea (former EMK, taken over by NICE Group). In order to destroy the cast structure of the billet, an extrusion to ∅21 mm bar with a extrusion ratio of 7.4 was carried out. Forging workpieces (∅19×108 mm, round 6 mm) were machined from the extruded bars and preheated at 300°C in an electric

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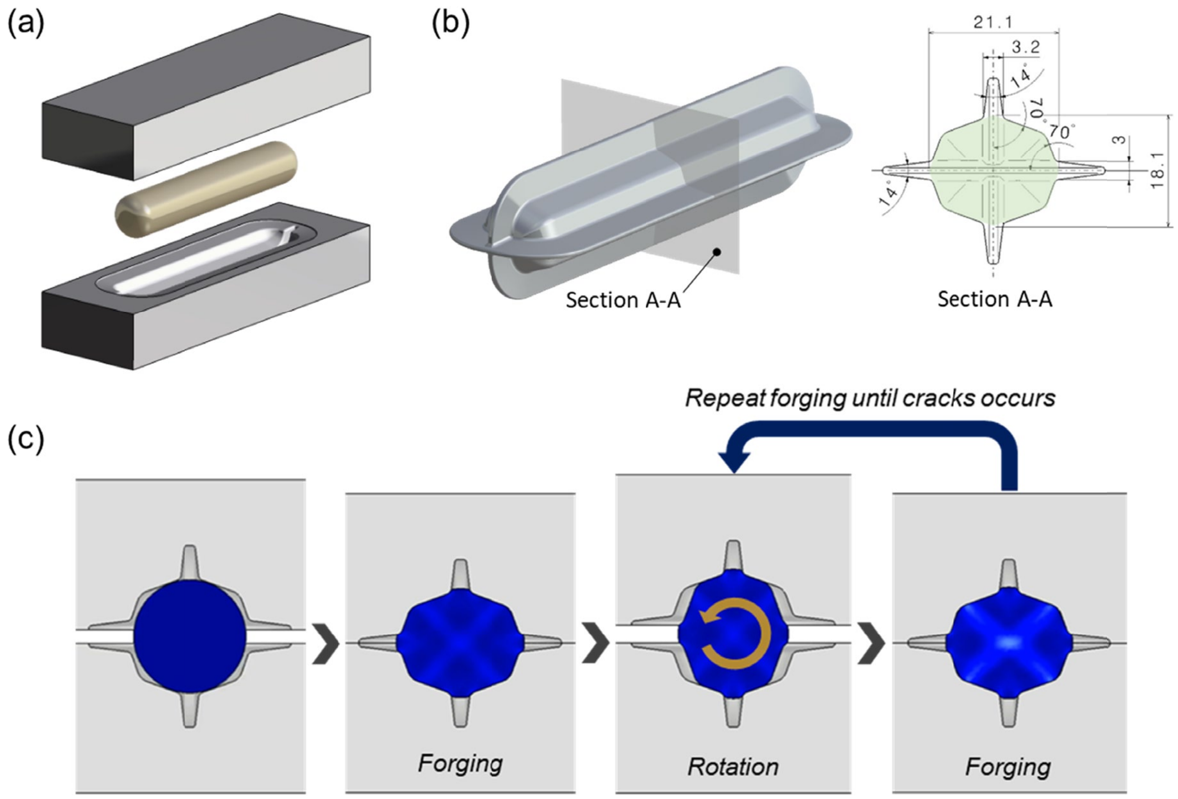

Fig. 1. Schematic 3D views of (a) dies and workpiece for multi-forging, (b) die cavity shape, and (c) biaxial alternate forging process

furnace prior to the biaxial alternate forging. The die set was also preheated at 300°C by electric heating rods inserted inside for isothermal forging. Through the die set installed in a hydraulic press with a capacity of 150 ton, the forging was carried out while rotating at an angle of 90° and continued until cracks occurred at both ends of the work-pieces. The forging speed from the upper die was set to about 1.2 mm/s. Schematic 3D views of dies and workpiece for multi-forging, die cavity shape, and biaxial alternate forging process are shown in Fig. 1.

To evaluate the tensile properties depending on the forging pass, tensile specimens with a diameter of 9 mm were taken from the forged workpieces and machined according to the 'Small-Size Specimens Proportional to Standard' of ASTM: B557M-10 [4]. The tensile test on one specimen for each condition was conducted at a strain rate of 0.004/s and room temperature. The cross section of the forged workpieces was ground, micro-polished, and etched using a mixture of 80 ml Ethanol, 10 ml distilled water, 10 ml acetic acid, and 4.8 g picric acid for 8 to 20 seconds to observe the microstructure for each forging pass. And then, the microstructures were taken by an optical microscope. Electron Backscatter Diffraction (EBSD) was performed on the samples fabricated under selected process conditions. The obtained EBSD data were analyzed with TSL software (version 8.6), which used a tolerance angle of 5° and a confidence index value >0.1. The EBSD scanned area of samples was 200 × 200 μm. And the EBSD step size was 0.25 μm. The EBSD samples were prepared with mechanical grinding and a final polishing step that used a 0.04 mm colloidal silica suspension.

3. Results and discussion

Fig. 2 shows appearance of the workpieces after the forging at 300°C. As shown in Fig. 2(b), significant cracks occurred after 7 passes. As mentioned above, it was considered that the formability was significantly increased at 300°C due to the activation of non-basal slip system. Fig. 3 demonstrates the microstructure change depending on the pass number in the center of the cross

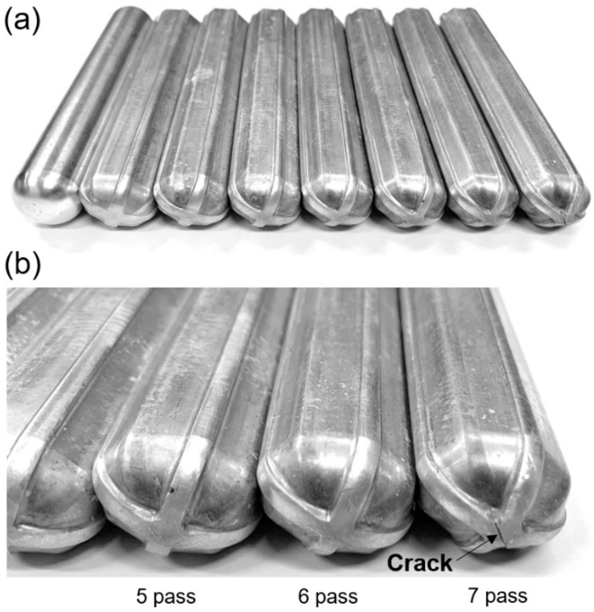

Fig. 2. Appearance of workpieces depending on the number of forging passes after forging at 300°C

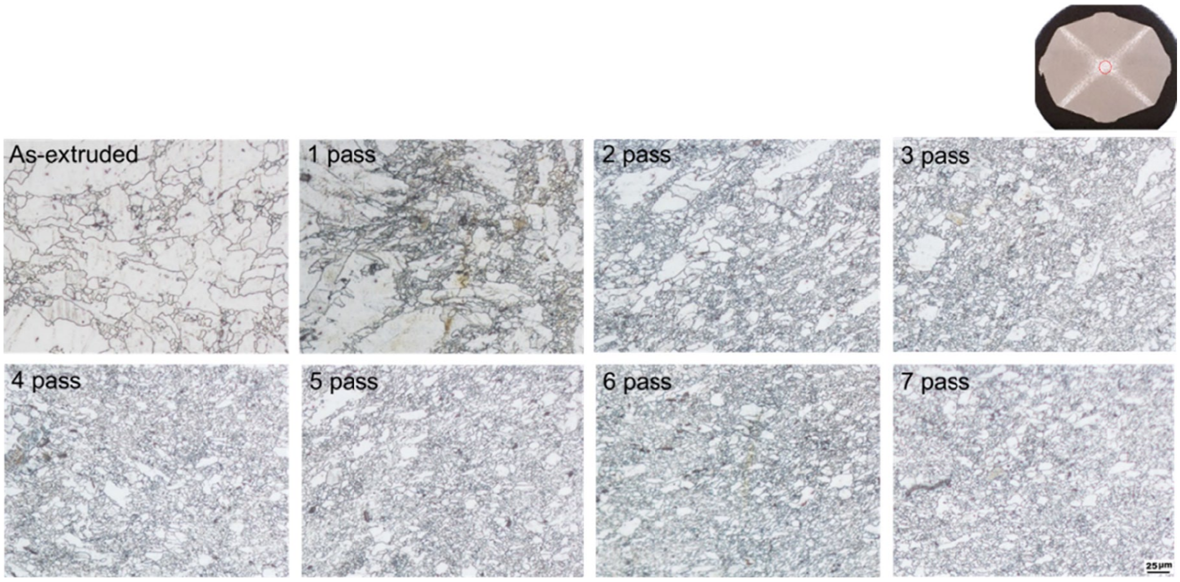

Fig. 3. OM microstructures of AZ31 workpiece cross-sections after forging at 300°C

section of workpieces. The microstructure of the as-extruded specimen can be explained as the non-uniform distribution of the relatively coarse grains and the fine grains considered to be sub-grains. However, the further refinement of sub-grains and existence of their area were observed even after the forging of 1 pass.

As the number of forging passes continuously increases, the area of coarse grains gradually disappeared, while the fine grains became more dominant in the microstructures. Therefore, it was thought that the forging condition examined in this study possibly worked for the refinement of microstructures by the dynamic recrystallization. The engineering tensile stress-strain curves and tensile properties for each forging pass were graphed as shown in Fig. 4(a) and (b). In general, it can be said that the tensile strengths increased with increasing the pass number. A relatively significant increase in strength appeared to occur after the 4 passes. However, there is no dramatic increase of

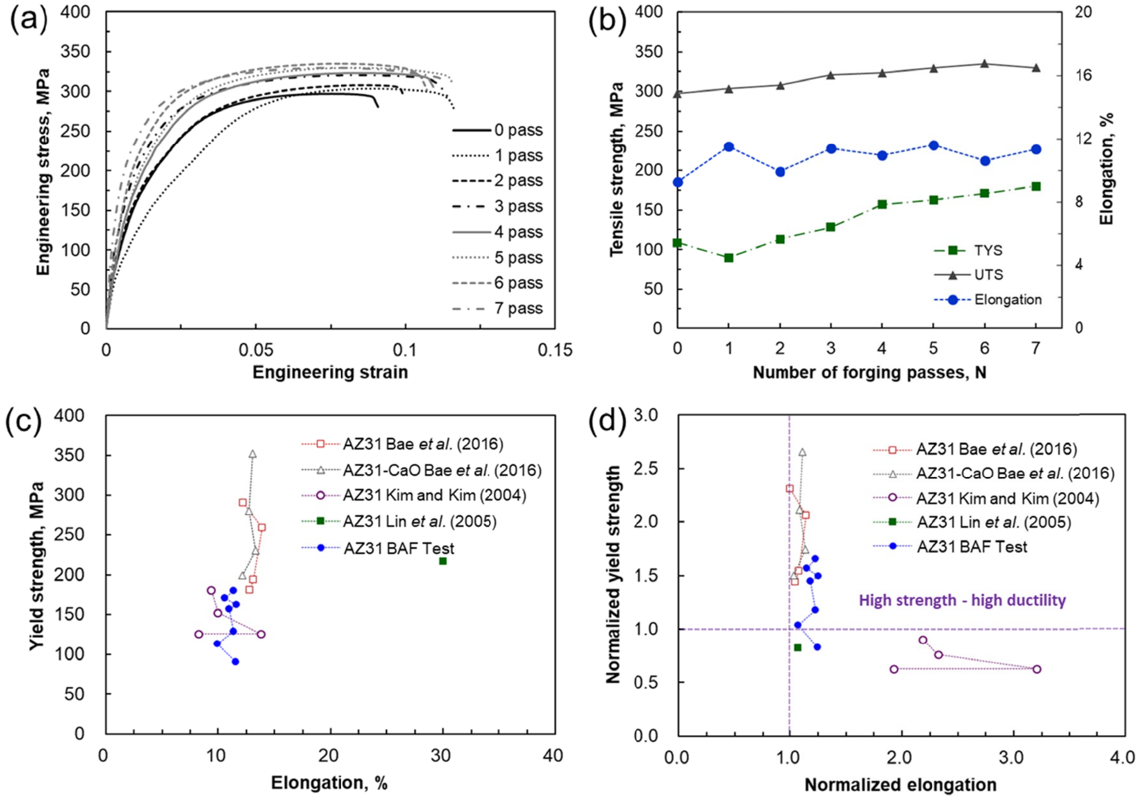

Fig. 4. (a) Engineering tensile stress-strain curves of AZ31B workpieces after BAF test at 300°C and (b) variation of tensile properties depending on forging passes. Quantitative representation of strength-elongation relationship from tensile test results of the current and previous studies; (c) absolute values and (d) their normalized representation

strengths throughout the entire forging conditions. Fig. 4(c) shows the variation of yield stress and elongation relationship of forged workpieces as the number of forging passes increases. For comparison, the results from literatures for the tensile properties of AZ31 alloy are also presented [5-7]. The variation of yield stress and elongation relationship normalized by dividing yield stress and elongation of forged workpieces by those of the initial material before forging is also shown in Fig. 4(d) in order to examine a change of strength-elongation relationship only by SPD without considering effects of initial tensile properties [8-9]. In the test values in this study, which is referred to as BAF Test, the strength increases as the forging pass increases with no reduction of elongation, indicating the characteristics of SPD effect on mechanical properties. However, when compared to those of ECAP (Equal Channel Angular Pressing) conducted by Bae et al. [5], the strength improvement in BAF Test was less significant. The strength increase by work hardening is attributed to the increase of dislocation density. Considering that the ECAP by Bae et al. [5] was conducted at lower temperatures, the SPD in this study possibly has a less effect on the strengthening. Therefore, it is considered that a significant strengthening effect cannot be obtained only by grain refinement. Temperature increase leads to thermal activation of dislocation motion, which causes the rearrangement and annihilation of dislocations. Consequently, it is considered that the reduction of dislocation density decreased the work hardening effect.

A slight increase of elongation depending on pass number shown in Fig. 4 is possibly associated with the slip system and grain size of Mg alloy. Simultaneous increase of strength and elongation has been found in previous studies on SPD effect in Mg alloys [10-11]. Fig. 5 shows the EBSD results of forged AZ31B workpieces examined in this study. After only 1 pass,

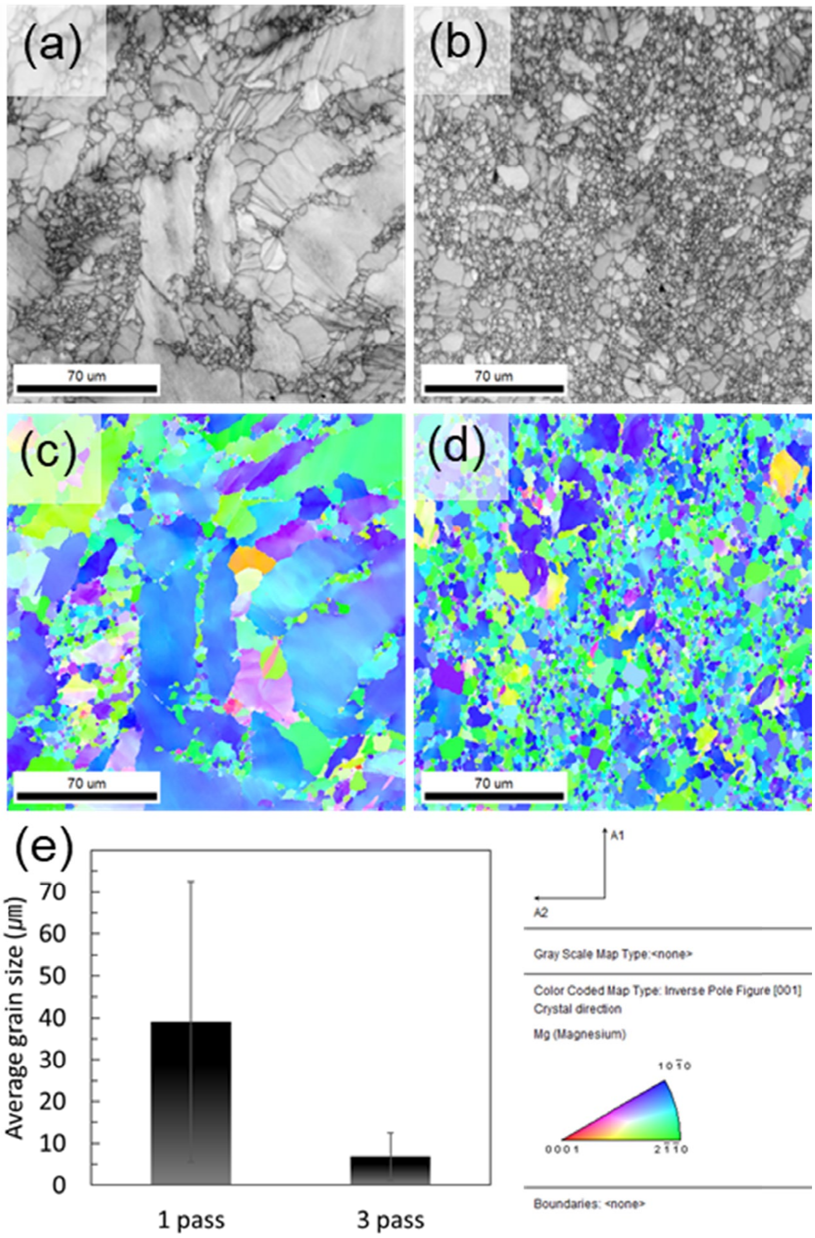

Fig. 5. EBSD results of forged AZ31B work-pieces. IQ maps after (a) 1 pass and (b) 3 pass, IPF maps after (c) 1 pass and (d) 3 pass, and (e) average grain size determined from (c) and (d)

the microstructure showed the presence of coarse grains and twins, while the grains appeared to be significantly refined and uniformly distributed after 3 pass, at which the strength and elongation began to increase, simultaneously. In the deformation of Mg alloys with HCP, twinning plays an important role because of their limited slip systems. According to previous reports on the deformation of Mg alloys, strain can be applied through the formation of {10-12} tension twin at room temperature. On the other hand, the basal slip within the twins would be easier following the formation of {10-11} contraction twin and {10-11}-{10-12} double twin, leading to the increase of dislocation density [12-14]. The agglomeration of dislocations possibly induces a stress concentration and cracking, and consequently reduces the elongation. However, since a relatively high stress is required to activate twinning in fine grains, the grain refinement can lead to the formation of less twins. As shown in Fig. 5(e), the grain size dramatically decreased after 3 pass. Therefore, simultaneous increase of strength and elongation after 3 pass is attributed to a significant refinement of grains.

4. Conclusions

As a result of BAF test for AZ31 Mg alloy, significant cracks occurred after 7 passes, indicating that the formability was significantly increased at 300°C due to the activation of non-basal slip system. The microstructure of as-extruded specimen showed the non-uniform distribution of the relatively coarse grains and the fine grains considered to be sub-grains. However, as the number of forging passes increases, the area of coarse grains gradually disappeared and the fine grains became more dominant in the microstructures following the dynamic recrystallization. In the tensile properties of workpieces for each forging pass, an increase in strength depending on pass number was shown with a slight increase of elongation. However, there was no dramatic increase of strengths throughout the entire forging conditions. From the EBSD results, it was considered that a simultaneous increase of strength and elongation after 3 pass is attributed to a significant refinement of grains and suppressed deformation twinning. Based on the results of this study, it is thought that it is possible to evaluate the forming limit of materials having low formability such as Mg alloys and to realize grain refinement by applying SPD at high temperature.

Acknowledgments

This work was supported by the Korea Institute of Industrial Technology (EH210004, Development of Intelligent Quality-Control Platform for Plastic Forming Process)

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