Fabrication of Single Crystal of Mg Alloys Containing Rare Earth Elements

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Abstract—Single crystals of Magnesium alloys such as Mg-1Al, Mg-1Zn-0.5Y, Mg-3Li, and AZ31 alloys were successfully fabricated in this study by employing the modified Bridgman method. Single crystals of pure Mg were also made in this study. To determine the exact orientation of crystals, Laue back-reflection method and pole figure measurement were carried out on each single crystal. Dimensions of single crystals were 10 mm in diameter and 120 mm in length. Hardness and compression tests were conducted and the results revealed that hardness and the strength strongly depended on the orientation. The closer to basal one the orientation was, the higher hardness and compressive strength were. The effect of alloying was not higher than that of orientation. After compressive deformation of single crystals, the orientation of the crystals was found to rotate and to be parallel to the basal orientation.

Keywords—Compressive strength, Hardness, Mg alloys, Modified Bridgman method, Orientation, Pole figure, Single crystal.

I. INTRODUCTION

MAGNESIUM is the lightest metal that can be employed for structural use [1]. Magnesium alloys are becoming more attractive for engineering applications because of their particularly low density, excellent damping capacity, good recycling capacity and machinability [2]. However, the number of commercially available Mg alloys is still limited especially for application at elevated temperature [3]. The poor cold rolling response of Mg is generally attributed to its hexagonal crystallography and the basic symmetry of hexagonal close-packed (HCP) crystals has the effect of limiting the number of independent slip systems and making twinning an important deformation mechanism [4]. The general result in wrought polycrystalline aggregate is a more or less sharply developed texture which underlies a strong anisotropy in mechanical behavior. Knowing how the one influences the other is essential background for the use of such materials.

Magnesium is well known to undergo unique plasticity transition in the neighborhood of 200°C [5, 6]. At lower temperatures, plastic deformation before fracture in polycrystalline material is limited, while at higher temperatures extensive deformation is possible. The transition temperature commonly determines the lower limit of the range in which Magnesium is worked. Plastic working of Mg alloys is, therefore, generally performed at above 250°C.

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Considering productivity including manufacturing expenditure, however, it needs to develop a new alloy system or a new technology for the plastic working at lower temperature than 250°C [7]. In this regards, the origin of plasticity transition and the exact deformation mechanisms of Mg and its alloy are very important to be systematically understood. In the present work, single crystals of pure Mg, Mg-1Al, Mg-1Zn-0.5Y, Mg-3Li, and AZ31 alloys were fabricated and their compressive deformation behaviors were measured.

II. EXPERIMENTAL PROCEDURES

Single crystals of Mg and Mg alloys used in this study were grown by directional solidification, using a modified Bridgman method. Ingots of pure Mg, Mg-1Al, Mg-1Zn-0.5Y and Mg-3Li alloys were prepared by conventional casting and machined into rods, 10 mm in diameter and 120 mm in length with one end pointed to fit into a split graphite mould. Commercial plate of AZ31 alloy was used. The mould, carefully tightened with Kanthal wire, was then placed in a vertical quartz tube. The tube was surrounded by three independently controllable heating elements and was water cooled in the bottom end to give proper temperature gradient for crystal growth. The maximum temperature was set at 760°C near the central zone of the furnace. After the rod was completely melted, the mould was driven downward by a motor at the rate of ~ 13 mm per hour. The apparatus used in this study is schematically illustrated in Fig. 1. Figure 2 shows the split graphite mould used and a typical as-grown single crystal.
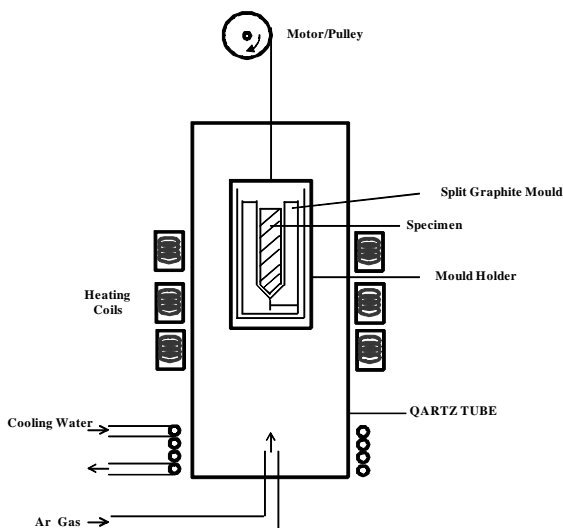

Fig. 1 Schematically illustrated apparatus for single crystal growth

Fig. 2 Graphite mould used in this study and as-grown crystal of pure Mg

A quick examination by etching in a NaOH solution occasionally revealed a few very small stray grains on the surface, but they were always removed from gauge section during machining process. Laue back reflection diffraction patterns were taken from a few spots of the bottom and top sections. The identity of the patterns confirmed them as single crystals. The pole figures of the single crystal specimens were also measured on planes normal to the solidification direction. (0002), $(10\bar{1}0)$, $(10\bar{1}1)$ and $(10\bar{1}2)$ pole figures were measured to analyze the orientations of single crystals grown in this study using X-ray reflection method up to a reflection angle of 70°. Micro-hardness and compression tests were carried on the single crystals at room temperature. Compression tests were conducted up to 50 % reduction at room temperature under the strain rate of 5×10^{-4} s^{-1}. Cylindrical specimens with a diameter of 8 mm and a height of 10 mm were used. After compression tests, pole figures were measured on the same plane to compare with the initial orientations of single crystals.
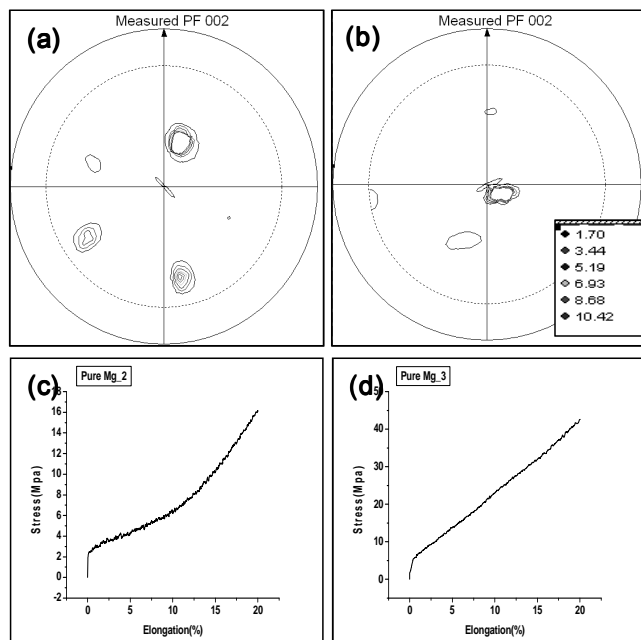
III. RESULTS AND DISCUSSION

Fig. 3 (0002) pole figures of pure Mg single crystal No.2 (a) and No.3 (b) and the compressive flow curves of crystal No.2 (c) and No. 3 (d), respectively

Figure 3 shows (0002) pole figures of pure Mg single crystals with different orientations and compressive flow curves of them. Single crystals were designated by No. 2 and No. 3 in this study. As shown in Fig. 3(a) and (b), while orientation of the crystal No.3 was very near to the normal of basal plane, that of No.2 appeared to move somewhat away from basal orientation.

It is very interesting to note from Fig. 4(c) and (d), flow stress and strain hardening rate of crystal No.2 are much lower than those of No.3. In the case of crystal No.2, well known easy glide behavior is observed in the early stage of compression test. The yield strength of crystal No.3 is much higher than that of No. 2, which indicates that the closer to basal one the orientation is, the higher hardness and compressive strength are.
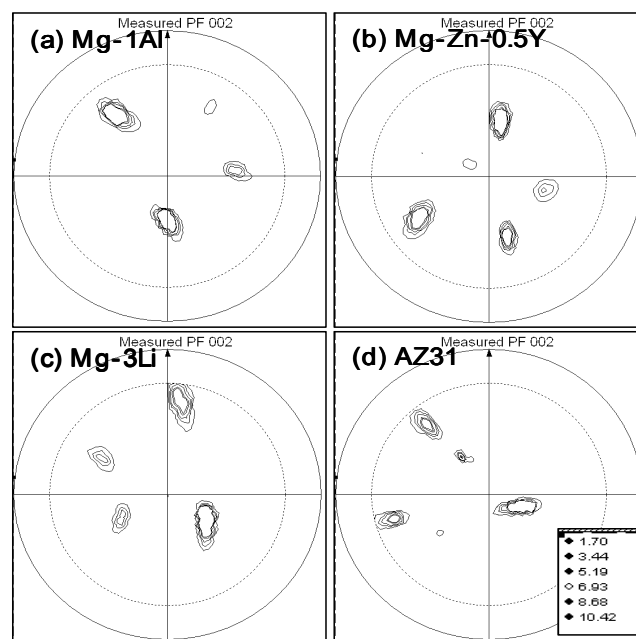

Fig. 4 (0002) pole figures measured on the single crystals of Mg-1Al (a), Mg-Zn-0.5Y (b), Mg-3Li (c) and AZ31 (d) alloys

Figure 4 shows (0002) pole figures measured on the single crystals of Mg-1Al, Mg-Zn-0.5Y, Mg-3Li and AZ31 alloys, of which the orientations are very similar to that of pure Mg single crystal No.2.

Fig. 5 shows compressive flow curves measured on the single crystals of Mg alloys grown in this study. Although the yield strength of Mg alloys are somewhat higher than that of pure Mg single crystal No. 2, shape of flow curves is very similar to that except AZ31 alloy.

Yield strength of Mg-3Li alloys single crystal is very low and easy-glide behavior clearly appeared. It is very interesting to note from Fig. 5(d), the strain hardening rate of AZ31 single crystal is very high and the evidence of plastic instability is observed. Yield strength of Mg-1Zn-0.5Y alloy is highest of all. The highest value of micro-hardness was, on the other hand, obtained in AZ31 single crystal.
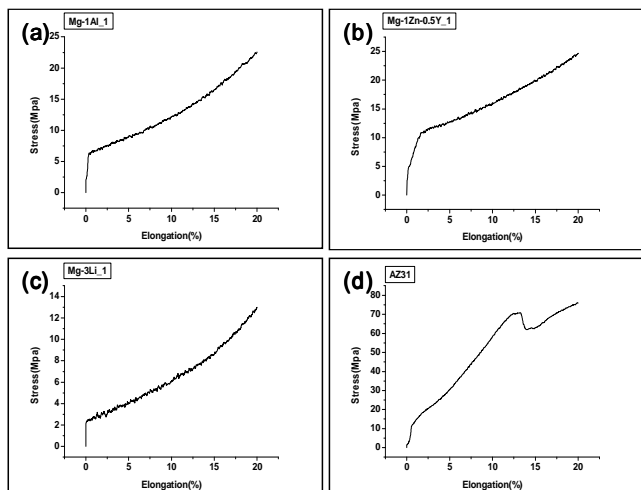
Fig. 5 Compressive flow curves of the single crystals of Mg-1Al (a), Mg-Zn-0.5Y (b), Mg-3Li (c) and AZ31 alloys (d) grown in this study.
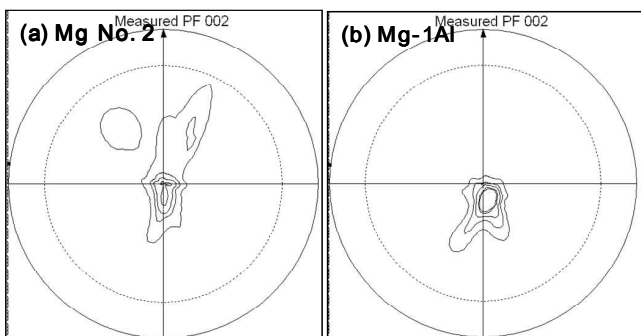
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Fig. 6 (0002) pole figures measured after 50% compressive reduction on the pure Mg single crystal No.2 (a) and Mg-1Al alloy single crystal.

As shown in Fig. 6, interestingly, the orientation of the crystal was found to rotate and to be parallel to the basal orientation after compressive reduction of 50% both in pure Mg and Mg-1Al alloys.

IV. CONCLUSIONS

Single crystals of pure Mg, Mg-1Al, Mg-1Zn-0.5Y, Mg-3Li, and AZ31 alloys were successfully fabricated in this study by employing the modified Bridgman method. To determine the exact orientation of crystals, Laue back-reflection method and pole figure measurement were carried out.

Hardness and compression tests were conducted and the results revealed that hardness and the strength strongly depended on the orientation. The highest value of micro-hardness was, on the other hand, obtained in AZ31 single crystal. The closer to basal one the orientation was, the higher hardness and compressive strength were.

The effect of alloying was not higher than that of orientation. After compressive deformation of single crystals, the orientation of the crystals was found to rotate and to be parallel to the basal orientation.