Microstructures and Mechanical Properties of Mg$_{96}$Zn$_2$Y$_2$ Alloy Prepared by Extrusion of Machined Chips

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1. Introduction

Recently, it has been reported that an Mg$_{97}$Zn$_1$Y$_2$ (at%) alloy prepared by rapidly solidified powder metallurgy (RS P/M) processing exhibited high 0.2% proof strength ($\sigma_{0.2}$), more than 600 MPa and elongation ($\delta$) of 5% at room temperature. Furthermore, this alloy also exhibited strain-rate-supersaturation with a maximum $\delta$ of 700–800% at high strain rates of 0.1–0.2 s$^{-1}$ at 623 K. The Mg$_{97}$Zn$_1$Y$_2$ alloy was found to have fine Mg grains and a uniform distribution of 10 nm Mg$_2$Zn$_5$ particles. The Mg$_{97}$Zn$_1$Y$_2$ phase with 18R-type long period ordered (LPO) structure was known as the $\gamma_1$ phase in ternary Mg-Zn-Y phase diagrams, and several periods such as 18R-, 10H-, 14H-, and 24R-type were found in the Mg-Zn-Y alloys. The Mg$_{97}$Zn$_1$Y$_2$ phase is believed to suppress the growth of Mg grains at high temperatures, and is known to have a strong oxidation effect.

Because the refinement of Mg grains led to higher strength and good workability at higher temperatures, extrusion of rapidly solidified Mg alloy powder has been investigated. The Mg-Al-Zn, Mg-Zn-Zr and Mg-Y-RE (RE = rare earth metals) alloys produced by the P/M technique had small grain size of 0.5–3 $\mu$m, and exhibited a high $\sigma_{0.2}$ of 400–530 MPa at room temperature and superplasticity in the high strain rate range of $10^{-2}$–$10^{-1}$ s$^{-1}$ at 523–673 K.

Thus, RS P/M processing is considered an effective method for producing fine grains. However, from an engineering point of view, rapidly solidified Mg alloy powder is considered to have a high production cost. Recently, Mabuchi et al. reported extrusions processed from AZ91 Mg alloy machined chips at 573 and 673 K had mean grain sizes of 7.6 and 15.4 $\mu$m, and showed a good combination of a high $\sigma_{0.2}$ of 220–300 MPa and a $\delta$ of 5–12% at room temperature. Moreover, the extrusions processed from machined chips showed superplastic behavior with a maximum $\delta$ of 150–310% and high m values of 0.4–0.5 with a strain rate range on the order of $10^{-5}$–$10^{-4}$ s$^{-1}$ at 573 K. Further, it was also reported that the extrusions processed from the AM50, AZ31, and AE42 magnesium alloy chips formed mean grain sizes of 9.6, 10.3, and 12.1 $\mu$m, respectively, by dynamical crystallization through the extrusion. Consequently, the extrusions showed superplastic behavior with high m values of 0.35–0.59 at high temperatures (653–698 K). Therefore, extrusion of machined chips is considered to be an appropriate method for obtaining fine-grained Mg alloys. Moreover, Mabuchi et al., also suggested that the extrusion of machined chips can be an effective processing method for recycling Mg machined chips. Yamaguchi et al. reported the preparation of fine-grained, consolidated Mg$_{96}$Zn$_2$Y$_2$ (at%) alloy bars through continuous consolidation of chips using a newly developed single screw extrusion machine; the bars exhibited high yield strength at room temperature and superplasticity at 723 K. This process is considered to be a useful engineering process for obtaining fine-grained Mg alloy consolidation. However, little is known about the microstructures and mechanical properties of the extruded Mg-Zn-Y alloy processed from machined chips. In this paper, we report the microstructures and mechanical properties of the extruded Mg$_{96}$Zn$_2$Y$_2$ (at%) alloy prepared from machined chips. In particular, the relationships between the microstructure and tensile properties will be discussed in connection with the superplastic behavior of the extruded Mg$_{96}$Zn$_2$Y$_2$ alloy.

2. Experimental Procedures

An alloy ingot of Mg$_{96}$Zn$_2$Y$_2$ (at%) 26 mm in diameter and 180 mm long was prepared by furnace melting in an
extruded Mg in Fig. 1(d) and (e). Compound B had higher Zn content different Zn compositions marked in Fig. 1(c), are detected (f), respectively. Two types of compounds, A and B, with the same area of Fig. 1(c) are shown in Fig. 1. (d), (e), and cavities of less than 5 μm in the Mg matrix. Although a few cavities in the Mg matrix, are observed in the Mg matrix, rather than compound A. Oxygen distributions shown in (f) do not correspond to those of Zn and Y, but rather to cavities indicated by the white circles in (c), suggesting that some Mg oxides segregate around cavities. The Mg oxides are considered to be formed when machined chips are prepared from bulk ingot, and cavities form due to difficulties in consolidating machined chips covered with oxides. X-ray diffraction patterns of the cross section of extruded Mg alloy processed at 623 K showed that the Mg12ZnY and Mg3Zn2 phases were formed in α-Mg. From these results, compounds A and B are identified as the Mg12ZnY and Mg3Zn2 phases, respectively. These two phases are already known as stable phases in Mg6Zn2Y cast alloy. The amount of Mg oxides is considered to be small because reflection of oxides is not recognized in the XRD pattern.

Figure 2 shows a TEM image of the Mg phase in the extruded Mg6Zn2Y2 alloy. Mg grains with diameter of 200–700 nm are observed. The average Mg grain diameter is about 450 nm. It is considered that the fine Mg grains are formed by dynamic crystallization through the extrusion process at 623 K. Further, the Mg12ZnY phase with fine lamellar structure, indicated by the arrows in Fig. 2, is frequently observed inside Mg grains. Draugelates et al. reported extrusions from machined chips that were prepared from AM50, AZ31, and AE42 types Mg alloys, and consequently obtained a fine grain diameter of 3–15 μm by dynamic crystallization through the extrusion process. The Mg grain size obtained in the present study is less than 1 μm, which is lower than that of several extruded Mg alloys processed from machined chips. Mabuchi et al. reported that magnesium oxide (MgO) in the extruded Mg alloy suppresses growth of Mg grains. However, the Mg12ZnY phase, rather than MgO, was frequently observed inside Mg grains in the extruded alloy. It is known that the Mg12ZnY and Mg phases in the Mg6Zn2Y2 cast alloy are formed with the same orientation relationships, and the Mg12ZnY phase grows.
along the a-axis of adjoining Mg grains. It is concluded that the Mg_{12}ZnY phase inside Mg grains suppresses growth of Mg grains in the extruded alloy. The proof strength (σ_{0.2}), ultimate tensile strength (σ_{UTS}), and elongation (δ) are 495 MPa, 500 MPa, and 3%, respectively, at room temperature. The specific yield strength defined by the ratio σ_{0.2}/ρ is 2.6 × 10^5 Nm/kg, which is comparable to that of commercial Ti6Al4V alloy. The low δ value is caused by cavities as shown in Fig. 1(b) and a relatively high volume fraction of the Mg_{3}Zn_{3}Y_{2} phase, which is brittle in nature.

Figure 3 shows nominal stress-strain curves at several strain rates and temperatures. The elongation increases rapidly with increasing test temperature. At a strain rate of 2 × 10^{-3} S^{-1}, flow stress and elongation are 52 MPa and 300% at 623 K, and 9 MPa and 450% at 723 K, respectively. Such a large elongation is called superplasticity. Further, large elongations of 190% and 206% are observed from the stress-strain curves of 2 × 10^{-2} S^{-1} (623 K) and 2 × 10^{-1} S^{-1} (723 K), respectively. That is, the extruded alloy exhibits high-strain-rate-superplasticity, is a phenomenon in which a large elongation appears at a high strain rate (more than 10^{-2} S^{-1}). High strain rate superplasticity has several advantages for the manufacturing process because this deformation speed is equivalent to a practical working speed. The strain sensitivities (m), defined as the slope of the double logarithmic plot of flow stress versus strain rate, are estimated to be 0.40 (m = 2 × 10^{-4} S^{-1}) and 0.46 (m = 2 × 10^{-3} S^{-1}) at 623 K and 723 K, respectively. The high value of m suggests that grain boundary sliding of Mg grains is the dominant deformation mechanism in this deformation condition of the extruded alloy.

Figure 4(a) shows an SEM image taken around the fracture area after deformation to 450% of the Mg_{96}Zn_{2}Y_{2} extruded alloy. The Mg_{12}ZnY phase deformed along the tensile direction, and numerous voids of 5–20 μm are observed in the Mg matrix and at the interfaces of the Mg and Mg_{12}ZnY phases. It is reasonable to consider that the cavities observed in Fig. 1(c) developed during superplastic flow at 723 K. This suggests that excessive cavity formation is responsible for the low elongation of the extruded alloy. Since the Mg_{12}ZnY phase deformed along the tensile direction, it is considered that the Mg_{12}ZnY phase is detrimental to the superplasticity of the extruded alloy.

Figure 4(b) shows TEM image of Mg phase (dark contrast area) in Fig. 4(a). Although a fine Mg grain of about 200 nm is observed, the average grain size is about 1 μm which is slightly larger than that of the extruded alloy.
Most of the Mg grains seem equiaxed, and some Mg grains include the Mg$_{12}$ZnY phase, as indicated by arrows. From these results, we concluded that grain boundary sliding makes a substantial contribution to superplastic deformation. Undeformed and fractured tensile specimens are shown in Fig. 4(c), where a maximum elongation of 450% was obtained at $2 \times 10^{-3}$ S$^{-1}$ (723 K). In spite of the high test temperature of 723 K, no distinct color change appears on the surface between deformed and undeformed specimens. The reason for high oxidation resistance at high temperature in the extruded alloy is attributed to the addition of the Y element at 2%.

Inoue et al. reported that the RS P/M Mg$_{97}$Zn$_1$Y$_2$ alloy exhibited superplasticity with large elongation of 700–800% at a high strain rate of $2 \times 10^{-1}$ S$^{-1}$ at 623 K. These results originate from the successful production of the RS P/M Mg$_{97}$Zn$_1$Y$_2$ alloy with Mg grains of 100–150 nm, without a secondary phase at the boundary of the Mg grains. Furthermore, the RS P/M Mg$_{97}$Zn$_1$Y$_2$ alloy eliminated factors inimical to superplasticity, such as cavities and oxidation from closed processing. However, the extruded alloy processed from the machined chips incorporates factors such as cavities and secondary phases. The Mg$_{12}$ZnY and Mg$_3$Zn$_3$Y$_2$ phases are considered to add strength at high temperature, and cavities seems to be the origin of fractures. These factors lead to low elongation of the extruded alloy compared with the RS P/M Mg$_{97}$Zn$_1$Y$_2$ alloys. Therefore, superplasticity of the extruded alloy appears at a higher temperature than it does for the RS P/M Mg$_{97}$Zn$_1$Y$_2$ alloys. However, from an engineering standpoint, because of the low production cost and recycling of material, extrusion of machined chips is considered to be a practical method for obtaining a fine-grained consolidated Mg alloy with good mechanical properties.

4. Conclusion

Microstructures and mechanical properties of the extruded Mg$_{96}$Zn$_2$Y$_2$ alloy processed from machined chips were investigated. The results are summarized as follows.

(1) The extruded Mg$_{96}$Zn$_2$Y$_2$ alloy was composed of the $\alpha$-Mg, Mg$_{12}$ZnY, and Mg$_3$Zn$_3$Y$_2$ phases, and the Mg grains had a mean grain size of 450 nm. The Mg$_{12}$ZnY phase was frequently observed inside Mg grains.

(2) The extruded Mg$_{96}$Zn$_2$Y$_2$ alloy exhibited a high 0.2% proof strength of 495 MPa, ultimate tensile strength of 500 MPa, and elongation of 3%, at room temperature. Further, the extruded alloy also exhibited superplasticity at temperatures of 623 and 723 K. Large elongations of 450% and 206% were observed at strain rates from $2 \times 10^{-1}$ S$^{-1}$ to $2 \times 10^{-3}$ S$^{-1}$ at 723 K. From TEM observations, it was concluded that grain boundary sliding of Mg grains was the dominant deformation mechanism for the extruded alloy at high temperature.

REFERENCES

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