Effect of the Extrusion Ratio on the Mechanical Properties of As-Forged Mg-8Al-0.5Zn Alloy

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This paper demonstrates the effect of the extrusion ratio on the mechanical properties of the as-forged Mg-8Al-0.5Zn alloy. Three extruded Mg bars with the extrusion ratio of 9:1, 16:1, and 25:1 are prepared in the same extrusion condition, which are applied to the warm forging test to obtain the different microstructure with respect to the degree of extrusion effect in Mg alloys. The extrusion ratio over 16:1 has little effect on the mechanical properties of the as-extruded bars since the average grain size and amount of precipitates hardly change. The forgeability of the highly extruded bar is improved around flange area while the mechanical properties are slightly enhanced. The rod-type and particle-type precipitates tend to be favored in the as-forged microstructure with the extrusion ratio over 16:1.

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1. Introduction

Magnesium (Mg) alloys have been of great interest in transportation and electronics industries to make a light-weight design although they show limited formability and strong tension-compression symmetry in plastic flow at the ambient temperature.¹⁻⁶ Most of applications with magnesium alloys have been produced by the die casting process since it guarantees high productivity and sufficient strength. However, casting defects and porosities in the die casting process do not only reduce ductility but also degrade mechanical properties of the final product, inevitably.⁷ To overcome these drawbacks, warm forging process with wrought Mg alloys such as extruded bars has been applied extensively to a bulk forming for steering knuckles, control arms, and high-strength road wheels,⁸ which considerably improves strength and ductility of the final forged product. Skubisz et al.⁹ demonstrated the closed-die forging to test forgeability with Mg-Al-Zn magnesium alloys in a complex state of stress and strain. Shan et al.¹⁰ proposed a complex shape forging technology by adopting fully enclosed die forging and a combined female die. Wang et al.¹¹ have intended to induce dynamic recrystallization (DRX) to the initial billet by imposing a pre-strain, which enables AZ80 alloy wheels and AZ31 alloy brackets being forged successfully for near-net-shape forming.

During warm forging process with extruded Mg bars, mechanical properties of the final product are substantially influenced by the quality of as-cast ingot such as the grain size and uniformity of the

grain structure depending on the extrusion conditions. However, it is not possible to increase the extrusion ratio tremendously because it does not only require huge facilities for extrusion process but also increases the production cost exponentially. Furthermore, it is not necessary to increase the extrusion ratio excessively in mass production since insufficient extrusion ratio in the extruded bar is able to be compensated by the subsequent plastic forming with dynamic recrystallization (DRX) during the warm forging process. Therefore, it is quite interesting to correlate the extrusion ratio with the mechanical properties of the forged product, which is able to suggest appropriate extrusion ratio in the warm forging process with Mg alloys.

Many researches concerning the effect of the extrusion ratio have been focused on the microstructure and variation of mechanical properties of the extruded bars with respect to various extrusion ratios. Tong et al.¹² showed that the volume fraction of DRXed grains remarkably increases with the increase of the extrusion ratio, but the average DRXed grains size is almost unchanged. It is also noted that the extrusion ratio had only little effect on the tensile properties of the as-extruded bars due to the similar strengthening effect from the unDRXed and DRXed grains. Wen et al.¹³ conducted various hot extrusions with the ratios of 11:1, 25:1 and 44.4:1 in which they showed that the increase of the extrusion ratio enhances the ductility and tensile strength of Mg-Nd-Zn-Zr magnesium alloy. Chen et al.¹⁴ demonstrated that the ultimate tensile strength (UTS) and yield strength

(YS) of AZ31 alloy increase obviously with extrusion ratio increasing to 24, then the UTS and YS are little influenced by further increasing extrusion ratio. Uematsu et al.¹⁵ have investigated grain refinement and fatigue behavior with respect to the extrusion ratio. Chang et al.¹⁶ examined the effect of the grain size and texture effect on compression behavior of hot-extruded Mg-3Al-1Zn alloys at room temperature.

However, it has not been studied for the effect of the extrusion ratio on the microstructure and mechanical properties of the forged Mg product, directly. In this paper, the extruded Mg-8Al-0.5Zn bars with the ratio of 9:1, 16:1, and 25:1 were manufactured in the same extrusion conditions, which were provided into the warm forging process. Depending on the various extrusion ratios, the microstructure and mechanical properties of the forged Mg-8Al-0.5Zn product are investigated in terms of grain structure with the optical microscopy and the yield, ultimate tensile strengths in the uniaxial tensile tests, which can suggest optimum extrusion ratio in the Mg warm forging process.

2. Experimental Procedures

2.1 Extrusion Process

To obtain three different extrusion ratios of 9:1, 16:1, and 25:1, as-cast Mg-8Al-0.5Zn ingots (Table 1) with the diameter of 155 mm and length of 300 mm are prepared. Table 2 indicates the extrusion conditions in which the container and as-cast ingot temperature remain 573K and ram speeds are controlled adaptively such as 1.7, 0.9, and 0.6 mm/sec depending on the extrusion ratio to fix the outlet velocity of the material flow which influences the extrusion temperature considerably. Fig. 1 shows the extrusion facility and three kinds of extruded bars depending on the extrusion ratios. The final diameters of the extruded Mg-8Al-0.5Zn bars are 54, 40, and 32 mm with respect to the extrusion ratios of 9:1, 16:1, and 25:1, which are applied to the warm forging process at the temperature of 523K as introduced in the Section 2.2 after mechanical machining into the same diameter.

Microstructures of the extruded specimens have investigated along the extrusion direction with the optical microscopy. The microstructures of the extruded bars according to various extrusion ratios were investigated with optical micro-scope (OM) using a NIKON EPIPHOT200 in which there is no substantial difference in the average grain size as shown in Figs. 2(b) and 2(d) while the as-cast bar shows huge grains and Mg₁₇Al₁₂ precipitates¹⁷ near grain boundaries as depicted in Fig. 2(a).

Fig. 2 demonstrates comparison of the microstructures between the as-cast and as-extruded with respect to various extrusion ratios in which the average grain size is over 40 μm in the as-cast. Due to the DRX, it reduces to the average grain size of 10–12 μm with the extrusion ratio of 9:1 as shown in Fig. 2(b). However, there is no dramatic reduction in the grain size with increase of the extrusion ratio up to 25:1, then it is recrystallized to 5–8 μm since the rate of recrystallization becomes saturated in the extrusion ratio around 25:1 as depicted in Figs. 2(c) and 2(d).

In order to evaluate the mechanical properties of the extruded bars with respect to the various extrusion ratios, tensile tests are conducted with the strain rate of 0.001/sec at room temperature as shown in Fig. 3. Three tensile specimens are fabricated from the extruded bars with the extrusion ratio of 9:1, 16:1, and 25:1 along the extrusion direction with the standard in ASTM B557M. The YS and UTS of the extruded

bars are enhanced gradually as the extrusion ratio increases while they dramatically increase compared with those of the as-cast ingot. The YS and UTS of the extruded bars are little influenced by further increasing

Table 1 Chemical composition of Mg-8Al-0.5Zn ingot

Mg alloy	Chemical composition (%)			
	Al	Zn	Mn	Si etc.
AZ80	8.6	0.58	0.30	0.013 Bal.

Table 2 Extrusion conditions

Extrusion ratio	Ram speed (mm/sec)	Extrusion rate(mm/sec)	Final Diameter(mm)
9:1	1.7 $\pm$ 0.5	15	54
16:1	0.9 $\pm$ 0.5		40
25:1	0.6 $\pm$ 0.5		32

Fig. 1 Extrusion facility and as-extruded bar

Fig. 2 Comparison of initial microstructures; (a) As-Cast ingot (b) As-Extruded (9:1) (c) As-Extruded (16:1) (d) As-Extruded (25:1)

Fig. 3 Comparison of tensile test results with respect to extrusion ratio at room temperature

extrusion ratio over 16 as shown in Fig. 3. It is because the variation of the average grain sizes and amount of precipitates are comparably small with respect to the extrusion ratio of 9:1, 16:1, and 25:1 in the extrusion process as shown in Figs. 2(b) and 2(d).

2.2 Warm Forging of Extruded Bar

During warm forging process,¹⁸ the extruded Mg bars tends to undergo the DRX which considerably affects the mechanical properties of the final product since it reduces the grain size, dislocation density, and the accumulated energy to facilitate plastic deformation.^{2,19,20} In order to investigate the effect of extrusion ratio on the subsequent plastic deformation, warm forging process is carried out with the three extruded Mg bars with three extrusion ratios of 9:1, 16:1, and 25:1.

It is required to design the punch and die-set for the warm forging test with Mg alloys in a small scale since it consumes huge amount of billet and time to conduct experiment. Fig. 4 demonstrated the layout of the punch and die-set for the type of tensile specimen forging, which is able to induce complex plastic deformation into the extruded Mg bars as well as preserve the shape of the tensile specimen after warm forging since it is machined into the tensile test specimen for evaluating mechanical properties of the forged one as shown in Fig. 5. The warm forging tests are conducted in a 200-ton hydraulic press and the working temperature is set to 523K by the heating chamber as depicted in Fig. 4(a). Table 3 indicates the warm forging conditions with the extruded Mg bars. It takes 1.5 minutes to elevate the temperature of the initial specimen to 523K right after it is placed on the pre-heated die-set. Then, it is pressed when the current temperature from the attached thermocouples on the die-set guarantees the target temperature of 523K.

Fig. 6 shows the comparison results of the test specimens forged at 523K with extruded bars according to the extrusion ratio of 9:1, 16:1, 25:1 and as-cast ingot. While severe cracks around the flange area are investigated distinctly in the forged specimen with as-cast ingot, flange and sharp corner are precisely forged when applying the extruded bars with higher extrusion ratio as shown in Figs. 6(c) and 6(d). It is noted

that a sound forged part in terms of good forgeability and net-shape can be produced with the extruded bars with extrusion ratio over 16:1.

3. Results and Discussions

In order to evaluate the mechanical properties of the as-forged Mg-8Al-0.5Zn alloys according to the extrusion ratios, Vickers hardness and tensile tests are conducted in test specimens which are obtained from the warm forging test in Section 2.2. Fig. 7 shows the variation of Vickers hardness with respect to extrusion ratio for as-extruded and as-forged

Fig. 5 Test procedure for evaluating mechanical properties from complex shape forging

Table 3 Warm forging conditions

Materials	Mg-8Al-0.5Zn
	As-Cast, As-Extruded (9:1, 16:1, 25:1)
Specimen size (mm)	Ø15.0×124.0 mm (cylinder type)
Temperature (K)	523
Head speed (mm/sec)	30
Facility	200ton hydraulic press
Lubrication	Graphite

Fig. 4 Layout of punch and die for complex shape forging at the elevated temperature; (a) Heating chamber (b) Punch and die

Fig. 6 Comparison of test specimen forged at 523K; (a) As-Cast (b) As-Extruded (9:1) (c) As-Extruded (16:1) (d) As-Extruded (25:1)

where they show the saturated hardness for the extrusion ratio over 9:1.

Fig. 8 shows the comparison results of tensile test for the as-extruded and as-forged in which the increases of the YS are 80, 85, and 83 MPa and, for the UTS, 57, 48, and 46 MPa with respect to extrusion ratio of 9:1, 16:1, 25:1, respectively. While the fracture elongations are not critically influenced by the extrusion ratio over 9:1, they decrease from 8.5% to 6% from the warm forging effect. During the warm forging process, it does not only experience the DRX but also has large amount of precipitates, which accelerate the inhomogeneity in terms of grain size distribution and various phases such as α , β , and $\alpha+\beta$. That is why the elongation-to-failure tends to be degraded in the as-forged specimens. Especially, a big difference in grain size between as-received and recrystallized tends to decrease the elongation-to-failure even though the average grain size reduces from the DRX at the elevated forming temperature.

OM investigation in the as-forged has been performed on the axial direction of the specimen as shown in Fig. 6. As shown in Fig. 9, it demonstrates microstructure in the as-forged at the elevated temperature, it slightly reduces to the grain size between $5\mu\text{m}$ and $8\mu\text{m}$ in the extrusion ratio of 9:1 while decreasing $4\mu\text{m}$ with the extrusion ratio over 16:1 including 25:1 (Figs. 9(c) and 9(d)).

Fig. 9 shows the microstructures forged at 523K in OM investigation with respect to extrusion ratio in which the larger fraction of recrystallized fine grains and precipitates are observed as the higher

Fig. 7 Variation of Vickers hardness with respect to extrusion ratio for as-extruded and as-forged at 523K

Fig. 8 Comparison of tensile test results for as-extruded and as-forged with respect to extrusion ratio

extrusion ratio is applied. Wang et al.²¹ and Braszczynska-Malik¹⁷ have examined the evolution of precipitates of Al-Mg alloys for the T5 heat

Fig. 9 Comparison of microstructures forged at 523K in OM investigation with respect to extrusion ratio; (a) As-Cast (b) 9:1 (c) 16:1 (d) 25:1

Fig. 10 Comparison of microstructures forged at 523K in SEM investigation with respect to extrusion ratio; (a) As-Cast (b) 9:1 (c) 16:1 (d) 25:1

treatment where the discontinuous rod-type α precipitates dominantly nucleates and grow around grain boundaries which are the main diffusion paths at the lower aging temperature while volume diffusion plays an important role inside the α -grain for the continuous particle-type β precipitates at the higher aging temperature. It is worth mentioning that the discontinuous rod-type and the continuous particle-type β precipitates are favored simultaneously in the microstructure forged with extruded bar with the extrusion ratio over 16:1 as shown in Figs. 10(b) and 10(c) while the continuous particle-type β precipitates are dominantly produced with the extrusion ratio of 9:1 as shown in Fig. 10(a), which are identified to β -Mg₁₇Al₁₂ intermetallic compounds since these chemical compositions have Mg of 61.83% and Al of 38.17%, Mg of 59.73% and Al of 40.27% based on the energy dispersive spectrometer (EDS) analysis as shown in Fig. 11. It is interpreted that the discontinuous rod-type precipitates tend to be favored easily when the larger fraction of the grain boundaries is produced from the higher degree of extrusion ratio.

4. Conclusions

This paper demonstrates the effect of the extrusion ratio on the mechanical properties of the as-forged Mg alloy, which is able to suggest appropriate extrusion ratio when using extruded Mg bars in the warm forging process. Three extruded Mg bars with the extrusion ratio of 9:1, 16:1, and 25:1 are prepared in the same extrusion condition, which are applied to the warm forging test and compared with each other in terms of microstructure using OM and SEM and mechanical properties in the tensile tests.

Based on close examination, following conclusions can be drawn:

(1) As the extrusion ratio increases, mechanical properties of the as-extruded bars are slightly enhanced. Especially, the extrusion ratio over 16:1 has little effect on the mechanical properties of the as-extruded bars since the average grain size and amount of precipitates hardly change.

(2) When using the extruded bar with higher extrusion ratio over 16:1, the forgeability at the elevated forming temperature is noticeably improved around flange area while the mechanical properties are slightly enhanced.

(3) The fracture elongation of the as-forged Mg part is hardly affected by the degree of the extrusion ratio of the extruded bars.

(4) The discontinuous rod-type and the continuous particle-type β precipitates are favored simultaneously in the microstructure forged with extruded bar with the extrusion ratio over 16:1 since the fraction of grain boundaries which are the main diffusion path increases as the extrusion ratio increases.

Fig. 11 EDS analysis on precipitates in forged microstructure

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