Forgeability and Flow Stress of Mg-Zn-Y Alloys with Long Period Stacking Ordered Structure at Elevated Temperatures

Ryo Matsumoto¹, Michiaki Yamasaki², Masaaki Otsu² and Yoshihito Kawamura²

¹Division of Mechanical Engineering, Graduate School of Engineering Science, Osaka University, Toyonaka 560-8531, Japan

²Department of Materials Science and Engineering, Graduate School of Science and Technology, Kumamoto University, Kumamoto 860-8555, Japan

To develop a forging process for high strength Mg-Zn-Y alloys with a long period stacking ordered (LPSO) structure, the forgeability and flow stress of Mg₉₇Zn₁Y₂ (at%) alloys were investigated with the upsettability test at an initial strain rate of 0.55 s⁻¹. As-cast and extruded Mg₉₇Zn₁Y₂ alloys can be successfully forged without fracture up to 0.5 and 1.0 respectively of average equivalent strain at a forging temperature of 773 K. To remove the influence of the temperature change during upsetting from the experimentally obtained flow stress curve, the isothermal flow stress curve was estimated by combining experimental results with finite element analysis. Furthermore, the mechanical properties of the forged Mg-Zn-Y alloys were measured, and the influence of microstructure on the forging properties was discussed.

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1. Introduction

Magnesium alloys are increasingly used in the automotive and electronics industries for lightweight structural and functional parts. As the common process for mass production, die casting or thixoforming is used.¹⁾ Since these manufacturing processes are low productivity ones, it is desirable to produce Mg alloy parts by higher productivity processes, especially, forging. Furthermore, the strength and toughness of forged products are higher than those of cast ones. In order to investigate the possibility of precision forging of Mg alloys, fundamental forging tests for commercial wrought Mg alloys such as AZ31 (Mg-3 mass%Al-1 mass%Zn) and ZK60 (Mg-6 mass%Zn-0.5 mass%Zr) have been carried out.²⁻⁴⁾

Recently, a rapidly solidified powder metallurgy (RS P/M) Mg-Zn-Y alloy has been developed by Kawamura *et al.*⁵⁾ The alloy consists of a fine-grained α -Mg matrix and an 18R-type long period stacking ordered (LPSO) structure, and has excellent mechanical properties of 610 MPa in tensile yield strength and 5% in elongation at room temperature.^{6,7)} Moreover, it was reported that 18R and 14H-type LPSO structures were formed not only in the rapidly solidified alloy but also in ingot metallurgy (I/M) Mg-Zn-rare earth alloys.⁸⁻¹³⁾

The excellent properties of the LPSO phase containing I/M Mg-Zn-Y alloy make it desirable for use as structural parts in industry. However, the coarse-grained α -Mg matrix in I/M Mg-Zn-Y alloy limits the strengthening ability of LPSO phase. On manufacturing light structural parts from this alloy, forging or that after extrusion may be effective not only for strengthening of matrix but also in productivity. In a process design of the industrial forging, it is essential to know the properties under dynamic deforming conditions, but the known properties have mainly been measured under static conditions, i.e. at a low strain rate.

In industry, finite element simulation is carried out for designing of forging process. In the simulation, flow stress curve of material obtained by compression test are used as

one of input data for the simulation. In the test, the influence of temperature rise during the test on flow stress is not taken into account, however, the calculation is conducted with accuracy in the cases of forging of steels or aluminum alloys. On the other hand, a few Mg alloys have been forged in the practical use and a number of forging simulation of Mg alloys is not so large. In many cases of finite element simulation of forging processes, flow stress for input data includes the influence of the temperature rise during forming. To carry out the simulation with accuracy, the influence should be removed from the flow stress used in the simulation since flow stress of Mg alloys is sensitively affected by forming temperature. Although, Kada *et al.*¹⁴⁾ have suggested the method of calculating the isothermal flow stress obtained by removing the influence of temperature rise during forming from the flow stress, isothermal flow stresses of Mg-Zn-Y alloys have not been calculated yet.

In this study, the forgeability and flow stress curves of LPSO phase containing Mg-Zn-Y alloys were investigated by combining experimental results from an upsettability test with finite element analysis. Particular attention was paid to the isothermal flow stress curves under high strain rate compression, in order to discuss the flow stress curves without the influence of the temperature change during upsetting. The isothermal flow stress curves under high strain rate compression targeting practical forging are obtained. The mechanical properties of the forged Mg-Zn-Y alloys were measured, and the influence of microstructure on the forging properties is discussed.

2. Material

The material tested was Mg₉₇Zn₁Y₂ (at%) alloy. An ingot was prepared by high-frequency induction melting in an Ar atmosphere followed by homogenizing at 773 K for 10 h. The cast ingot was cut into a rod with a diameter of 29 mm and a length of 80 mm, and was extruded with an extrusion ratio of 5 (equivalent strain of 1.6) at a temperature of 623 K or 723 K with a ram speed of 2.5 mm·s⁻¹.

(a) As-cast

(b) 623 K-extruded

(c) 723 K-extruded

Fig. 1 Microstructures of as-cast and extruded $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ alloys.

Figure 1 shows the microstructures of as-cast and extruded $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ alloys before forging. The as-cast alloy consisted of two phases, an α -Mg matrix and an 18R-LPSO phase corresponding to the lamellar contrast in the optical micrograph, with a grain size in the range of 260–340 μm . In the alloys extruded at 623 K and 723 K, there were three regions, the dynamically recrystallized α -Mg grain region, the hot-worked α -Mg grain region and the kink-deformed 18R LPSO phase region. Grain size of the recrystallized α -Mg grains in the 623 K-extruded alloy was in the range of submicron to 5 μm . However, grain growth of dynamically recrystallized α -Mg grains occurred in the 723 K-extruded alloy, the grain size of recrystallized α -Mg grains reached about 9 μm . Furthermore, the area of recrystallized α -Mg grains in the

Fig. 2 Calculated equivalent strains by FEM in upsettability test.

723 K-extruded alloy was larger than that in the 623 K-extruded alloy.¹⁵⁾

3. Upsettability Test

3.1 Experimental conditions

In order to examine the workability of the $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ alloy, the upsettability test¹⁶⁾ was carried out. In the test, a cylindrical billet was compressed with concentrically grooved flat tools to restrict the end surfaces of the billet, so that the influence of friction between the billet and the tool during the test was removed. The billet deformed to a barrel shape and the equivalent strain in the billet was not distributed uniformly, as shown in Fig. 2 (calculated by FE analysis). The forging limit (forgeability) was defined as the reduction in height of the billet when a crack was first observed on the surface of the compressed billet. Average flow stress was obtained from the load-stroke data in the upsettability test.¹⁷⁾ The average flow stress and average equivalent strain were calculated by a finite element simulation from the measured load and reduction in height in the experiment. Since it was possible to measure the flow stress curve up to an average equivalent strain of about 2.5 under a high strain rate corresponding to the value in forging process by mechanical press, the test is a practical one for developing forging processes in industry.

The initial shape of billet was cylinder with a diameter d_0 of 10 mm and a height h_0 of 15 mm. In extrusion rod, its axis is corresponded to the billet axis. The billets were heated in a furnace without protective gas and were compressed in the temperature range of $T_s = 473\text{--}773\text{ K}$. To prevent the heated billet from rapidly cooling on the tool, the tools were heated to a temperature of 523 K when the testing temperatures were higher than $T_s = 523\text{ K}$. For the case of $T_s = 473\text{ K}$, the tools were heated to a temperature of 473 K.

The upsettability test was conducted on a material testing machine (Shimadzu Autograph, AG-250kNISE). The compression speed was $8.3\text{ mm}\cdot\text{s}^{-1}$; the initial strain rate at the beginning of compression was about 0.55 s^{-1} .

3.2 Forgeability

The as-cast and extruded $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ specimens after upsetting are shown in Fig. 3. In upsetting of the as-cast

Fig. 3 Photographs of as-cast and extruded $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ specimens after upsetting.

Fig. 4 No-crack limit in forging of as-cast and extruded $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ alloys in upsettability test.

alloy, a shear type fracture was caused and the barreled surface of the specimen was rough due to the large grain size as shown in Fig. 1. In upsetting of the extruded alloy, the specimen was separated by a shear type fracture at a low reduction in height of $\Delta h/h_0 = 17\%$ at $T_s = 523$ K. On the other hand, the ductility was improved at $T_s = 773$ K and a ductile type fracture was caused at $\Delta h/h_0 = 58\%$.

Figure 4 shows the forging limit without fracture of the as-cast and extruded $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ alloys in the upsettability test. The forging limit of the as-cast alloy was low, i.e. $\Delta h/h_0 = 32\%$ at $T_s = 773$ K. Coarse grains and networking of the LPSO phase in the grain boundaries and dendrite arm boundaries may cause a decline in forgeability. On the other hand, in upsetting of the 623 K-extruded alloy, a shear type fracture occurred at less than $\Delta h/h_0 = 20\%$ irrespective of the forging temperature. Local grain-refinement and the formation of hot-worked grains in the α -Mg phase, and the

dispersion of the LPSO phase, occurred in extrusion and are thought to be responsible for the low forging limit. In upsetting of the 723 K-extruded alloy, although the forging limit was low at below $T_s = 623$ K, the ductility changed discontinuously between $T_s = 623$ K and 723 K, and the fracture mode changed from the shear type to the ductile type. In comparison with the 623 K-extruded alloy after forging, the recrystallization of α -Mg phase in the 723 K-extruded specimen was accelerated with improving the forgeability. Thus it is found that the forgeability is sensitively affected by the extrusion temperature of the specimen before forging.

3.3 Flow stress curve

Figure 5 shows the average flow stress curves of the as-cast and extruded $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ alloys obtained from the load-stroke data in upsetting, prior to the occurrence of a crack in the billet, at various forging temperatures. At the same initial billet temperature, the flow stress values of the extruded billets (Fig. 5(b), (c)) were higher than those of the as-cast ones (Fig. 5(a)), and the peak value of the flow stress of the extruded billets changed considerably with temperature. In the $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ alloy, it was confirmed that the grain refinement by extrusion as shown in Fig. 1 is highly effective to strengthening at low temperature and to ductility improvement at high temperature. Especially, the ductility improvement of 723 K-extruded billet at high forging temperature as shown in Figs. 4 and 5 may be due to expansion of recrystallized α -Mg matrix region and then grain growth of recrystallized grains during extrusion.

3.4 Vickers hardness

Figure 6 shows the Vickers hardness of the as-cast and extruded $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ specimens after forging at $T_s = 723$ K. The Vickers hardness was measured at the center of the

Fig. 5 Natural flow stress curves of as-cast and extruded $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ alloys.

Fig. 6 Vickers hardness of as-cast and extruded $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ specimens after forging at $T_s = 723$ K.

cross-section in the forging direction. In compression up to an average equivalent strain of 0.8, the hardness of the as-cast and extruded specimens increased to 90 HV and 95 HV, respectively.

Fig. 7 Optical micrographs of typical cross-sections of as-cast and extruded $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ specimens after forging at $T_s = 723$ K (arrowheads: twin deformation in α -Mg phase, arrows: kink deformation in LPSO phase).

4. Microstructure

Figure 7 shows optical micrographs of typical cross-sections of the $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ specimens forged at $T_s = 723$ K. The forged alloys consisted of two phases, the α -Mg matrix and the LPSO phase, and no phase transformation or formation occurred during forging. However, it has been shown that feature deformation occurred in each phase during forging. In the comparatively coarse α -Mg matrix grains of the as-cast and 623 K-extruded specimens after forging, profuse twins were observed. However, in the LPSO phase region, twinning was not found and some kink-deformation bands were observed. Arrowheads and arrows in Fig. 7 indicate representative twin deformation in the α -Mg phase and kink deformation in the LPSO phase, respectively. In the recrystallized α -Mg grains of the 723 K-extruded specimen after forging, a small number of twins was observed, while kink-deformation bands were frequently observed around the LPSO phase region.

As mentioned above, the microstructures of forged $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ alloy were characterized by twin deformation in the α -Mg matrix coarse grain region and kink-deformation in the LPSO phase region. Twin deformation in Mg-Zn-Y alloy was considered to be a supplementary deformation mechanism of a strong anisotropic dislocation slip,¹⁸⁾ and cannot bring about a sufficiently uniform deformation during forging. In order to avoid macroscopic strain localization

during forging, it is necessary to utilize the grain boundary slip in the recrystallized fine grains region. As shown in Fig. 4, forgeability of the $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ alloy was sensitively affected by the extrusion temperature of the alloy before forging. The extruded $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ alloys had three regions, the dynamically recrystallized α -Mg grains region, the hot-worked α -Mg grains region and the kink-deformed LPSO phase region. Higher temperature extrusion increased the area fraction of dynamically recrystallized α -Mg fine-grains and decreased that of the hot-worked α -Mg region in the $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ alloys (Fig. 1), resulting in enhancement of forgeability. Furthermore, as shown in Fig. 5, the flow stress curves in forging showed a tendency towards work hardening, although apparent softening by temperature rise during forging was observed in a few forged specimens. Formation of a kink-deformation band in the LPSO phase and α -Mg phase region may strengthen the Mg alloys,¹³⁾ because macro kink deformation bands that were formed perpendicular to the primary slip direction¹⁹⁾ became an obstruction to basal slipping.

5. Finite Element Simulation to Determine Isothermal Flow Stress Curve

5.1 Isothermal flow stress curve

It is difficult to compress the billet isothermally at a practical forging speed, because the billet temperature is changed during upsetting by heat generation in the billet and heat transfer from the billet surface. The influence of the temperature change on the flow stress must be considered to accurately obtain the flow stress curve. In this study, the flow stress curve, including the temperature change obtained in Fig. 5, is called a natural flow stress curve. To estimate the isothermal flow stress without the influence of the temperature change from the natural flow stress curves, a calculation method for the isothermal flow stress proposed by Kada *et al.*¹⁴⁾ was applied in this study. In this method, the isothermal flow stress was calculated by combining experimental results from the upsettability test with finite element analysis.

5.2 FE simulation conditions

The rigid-plastic finite element method, RIPLS-Forge²⁰⁾ was employed to calculate the load during the upsettability test, and the temperature distribution was calculated by the finite element simulation for heat conduction. In the simulation, the rigid-plastic and the heat conduction finite element calculations were carried out alternately. Table 1 shows the computational conditions used for the simulation of the upsettability test. The dimensions, geometries and temperatures of the billet and tools used for the simulation were set to be the same as the experimental conditions. Specific heat and thermal conductivity used in this simulation were quoted from previous report.²¹⁾ Heat transfer coefficients of billet-tool contact and free surface were determined by the experimental heating test of the specimen, and the frictional condition of the billet-tool interface was assumed to be sticking (no sliding) because a concentrically grooved dies were used in the experiment. The natural flow stresses obtained from experiment at different forging temperatures

Table 1 Computational conditions used for the simulation of upsettability test.

Initial temperature of billet, T_s/K	473–773
Tool temperature/K	473–523
Air temperature/K	293
Tool speed/ $\text{mm}\cdot\text{s}^{-1}$	8.3
Coefficient of friction	Sticking (no sliding)
Density of billet/ $\text{kg}\cdot\text{m}^{-3}$	1853
Specific heat of billet/ $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$	893 ²¹⁾
Thermal conductivity of billet/ $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$	65 ²¹⁾
Heat transfer coefficient of billet-tool contact/ $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$	5000
Heat transfer coefficient of free surface/ $\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$	16

Fig. 8 Isothermal flow stress curves of as-cast and extruded $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ alloys calculated by FEM incorporating experimental results.

(Fig. 5) were employed in the first step of estimating the isothermal flow stresses.

5.3 Calculated isothermal flow stress curves

The isothermal flow stress curves of $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ alloys calculated from the natural flow stress curves at various forging temperatures are shown in Fig. 8. The isothermal flow stress curves showed a tendency towards work hardening. The values of the isothermal flow stress were higher than the natural ones. This indicates the billet temperature was raised by heat generation during upsetting.

To verify the validity of the calculated isothermal flow stress curve, the histories of the upsetting load and stroke in experiment and finite element simulation of extruded $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ alloy were compared as shown in Fig. 9. The load-stroke curves were calculated by using the isothermal

Fig. 9 Load-stroke curves of 723 K-extruded $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ alloy during upsetting in experiment and FEM ($T_s = 673$ K).

(Fig. 8(b)) and the natural flow stress curves (Fig. 5(c)) in the finite element simulation. It can be seen that the load history calculated by using the isothermal flow stress curves agrees fairly well with the experimental one.

For the purpose of highly accurate FE analysis for plastic deformation, it is vital to obtain an accurate flow stress curve. From the above results, it is expected that FE analysis for the plastic deformation of the $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ alloys can be carried out by inputting the calculated isothermal flow stress curves as material properties.

6. Conclusions

To develop a forging process for high strength Mg-Zn-Y alloys with LPSO structure, the forging properties of $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ alloy were examined with the upsettability test. The following results were obtained.

- (1) As-cast and 623 K-extruded $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ specimens were separated by shear type fracture at low reductions in height. In upsetting of 723 K-extruded specimens, the fracture mode changed from shear type to ductile type at upsetting temperature around 673 K.
- (2) The isothermal flow stress curves of $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ alloy, which was obtained by removing the influence of the temperature change during upsetting, was accurately estimated by incorporating experimental results in a finite element simulation.

- (3) The isothermal flow stress curves of $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ alloy under high strain rate compression at 473–773 K indicated a tendency towards work hardening.
- (4) An increase in the recrystallized α -Mg matrix grain region in the extruded $\text{Mg}_{97}\text{Zn}_1\text{Y}_2$ alloys improved forgeability of the alloys.

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