

# Development of extrusion-torsion simultaneous processing for grain refinement in Magnesium alloys

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**Abstract.** We have proposed a new extrusion process combined with torsion. Extrusion-torsion simultaneous processing is a very attractive technique for fabricating a rod-shape material with high strength and excellent workability. The grain size of AZ91D magnesium alloy was gradually decreased with increasing the torsion speed in as extrusion-twisted conditions. Grain refinement under 2 $\mu$ m was achieved by the optimized extrusion-torsion condition. Hardness was increased by the addition of torsion speed comparing with as solution-treated and as extruded samples. Hardness change was dependent on the extrusion-torsion temperature.

## 1. Introduction

Magnesium alloys have the characteristics of low density, high specific strength, high dimensional stability, and is recyclable [1,2]. They are the reason for the significant demand of magnesium alloys in the automotive industries. Weight reduction improves the fuel efficiency and thus the exhaust emission is considerably reduced in automobiles [3]. However, magnesium alloys exhibit poor formability and possess only moderate strength making them impossible for wider applications in electronics, automotive and aerospace industries [4]. Recent researches have shown that the ductility and strength of magnesium alloys at room temperature can be significantly enhanced by texture control and microstructure refinement. It is well-known that grain refinement has the great potential to improve both strength and ductility of magnesium alloys.

Nowadays, most magnesium alloy products are manufactured by industrial die casting or semi-solid forming, while the plastic work processing is seldom employed because of the limited ductility in the hexagonal close-packed structure [5]. At room temperature, magnesium and its alloys deform essentially by basal slip and twinning, which limit their formability. Mizushima et al. reported that texture randomizing and grain refinement in extruded AZ31B magnesium alloy was achieved by the use of torsion working and subsequently annealing [6]. Through this process, the room temperature workability of magnesium alloys drastically improved. Aida et al. proposed a new extrusion process functionally combined with torsion for fabricating a rod-shape material with high strength and excellent workability [7].

The present work aims to optimize the processing conditions for extrusion-torsion simultaneous processing, refine the grain size and increase the hardness, using AZ91D magnesium alloy. Deformation angle measurement, microstructure observation and hardness testing was performed using extrusion-twisted samples processed under various working temperatures and torsion speeds.

## 2. Experimental

The commercial AZ91D magnesium alloy billet with a dimension of 50 mm diameter was used. The solution treatment was performed at 683 K for 345.6 ks in an argon gas atmosphere. It was extrusion-twisted with a 100 t vertical oil pressure press machine. Figure 1 shows the extrusion-torsion simultaneous working apparatus used. The extrusion ratio is 50 and the ram speed is 0.1 mm/s. The extruded material appearing from the die was fixed



by chucks, and was twisted immediately under the various conditions. The working temperature during extrusion-torsion simultaneous processing is varied from 648 K to 678 K. The temperature of 678 K corresponds to  $\alpha$ -Mg single phase, 648 K, 658 K and 668 K is  $\alpha$ -Mg and  $\beta$ -Mg<sub>17</sub>Al<sub>12</sub> duplex phase in equilibrium phase diagram of Mg-9%Al-1%Zn alloy. The torsion speed is varied from 0 rpm to 25 rpm. The ram load and twisting torque during extrusion-torsion simultaneous processing was monitored by electromotive force sensor. The extrusion-twisted sample with the dimensions of 7.1 mm diameter and about 300 mm length was removed from the container and water-cooled. The shear strain on the sample surface was decided from the torsion angle between the extrusion direction and die line using the stereo-microscope. The obtained sample was applied to microstructure observation. The sample surface was mechanically polished by a SiC impregnated emery paper from #500 to #2500 using water as the lubricant. The ground sample was then polished using the diamond paste with a diameter of 1  $\mu$ m dipping on a buff. Following the polishing operation, the etching was done using picric acid-ethanol solution. The microstructure was observed using an optical microscope. Vickers hardness was measured by a micro hardness test machine under an indentation load of 0.98 N and the time of 20 s.

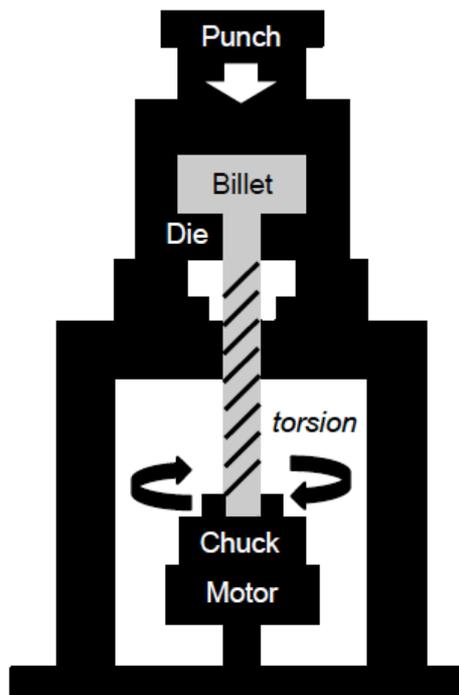


Fig. 1 Extrusion-torsion simultaneous working apparatus.

### 3. Results and discussion

Figure 2 shows the relation between ram load and time from the load addition to billet. The sample edge was squeezed out from the extrusion die taking for 90 s and was fixed by rotation chuck about 10 mm length. The extrusion was restarted with increasing the ram load. The torsion was added at the ram load reaching to 60 ton. The extrusion-torsion operation was performed under the constant load of 80 ton.

Variation of deformation angle in sample surface with the difference between torsion speed is shown in figure 3. According to figure 2, the deformation angle showed irregular change, however, there was the stable area in the sample length over 180 mm.

Table 1 shows the comparison between calculated and experimental deformation angle. The calculated deformation angle was theoretically decided from the extrusion speed and torsion speed. The calculated deformation angles were generally consistent to the experimental one. It was determined that the actual torsion was carried out exactly to the theoretical.

Figure 4 shows the optical micrographs of as received, as solution-treated, as extruded and as extrusion-twisted AZ91D magnesium alloy bar in the sectional outer parts. The solution treatment was performed at 683 K for 345.6 ks prior to extrusion and extrusion-torsion. The second phase such as precipitated  $\beta$ -Mg<sub>17</sub>Al<sub>12</sub> was fully diffused and solutionized in the  $\alpha$  matrix by the solution treatment. The grain size of as solution-treated was 36  $\mu$ m. The grain size was decreased in as extruded sample. The dynamic recrystallization seemed to occur during extrusion at 678 K. The microstructure was gradually decreased with increasing the torsion speed in as extrusion-twisted conditions. Grain refinement of 6  $\mu$ m was achieved in the case of extrusion-twisting at 25 rpm. Furui et al. reported that the crystal texture of AZ91D magnesium alloy was changed from basal to pyramidal dominations with the addition of torsion during extrusion. The randomizing of crystal orientation was accelerated by the torsion [8].

Hardness distribution with torsion speed in AZ91D magnesium alloy extruded and extrusion-twisted at 678K is shown in figure 5. Hardness was increased by the addition of torsion speed comparing with as solution-treated and as extruded samples. High hardness was obtained in the sectional outer part with increasing the distance from the center part. This hardness distributions is constrained by the fundamental formula for shear strain  $\gamma$  on a twisted round bar;  $\gamma = r \cdot \theta / L$  [9], where  $r$  is the radius in a cross section perpendicular to the torsion axis,  $\theta$  is torsion angle in the point of radius  $r$  and  $L$  is the gauge length between torsion edges.

Hardness distribution with extrusion-torsion temperature in AZ91D magnesium alloy extrusion-twisted at 5rpm is shown in figure 6. The low hardness was obtained at the extrusion-torsion temperature of 678 K corresponds to  $\alpha$ -Mg single phase. On the other hand, hardness was increased with decreasing the extrusion-torsion temperature from 648 K to 668 K corresponds to  $\alpha$ -Mg and  $\beta$ -Mg<sub>17</sub>Al<sub>12</sub> duplex phase. The volume fraction of precipitated  $\beta$ -Mg<sub>17</sub>Al<sub>12</sub> phase was significantly increased with decreasing the extrusion-torsion temperature.

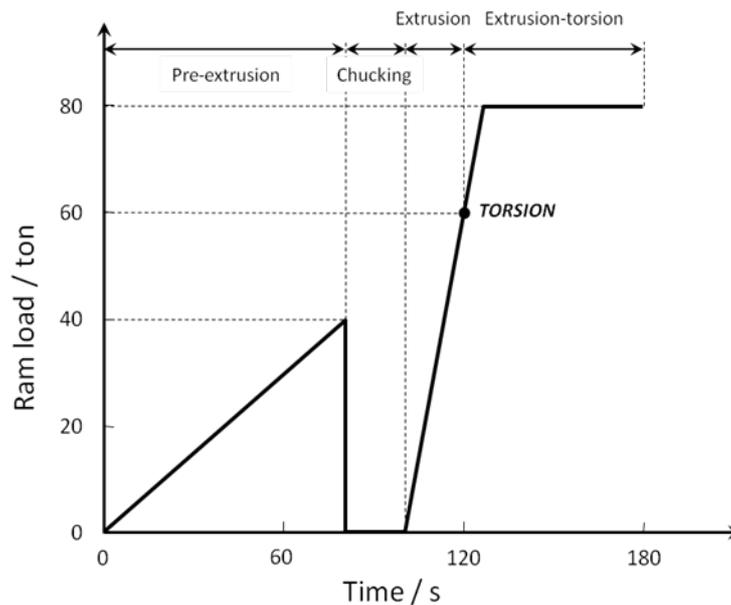


Fig.2 Relation between ram load and time from the load addition to billet during extrusion-torsion simultaneous processing.

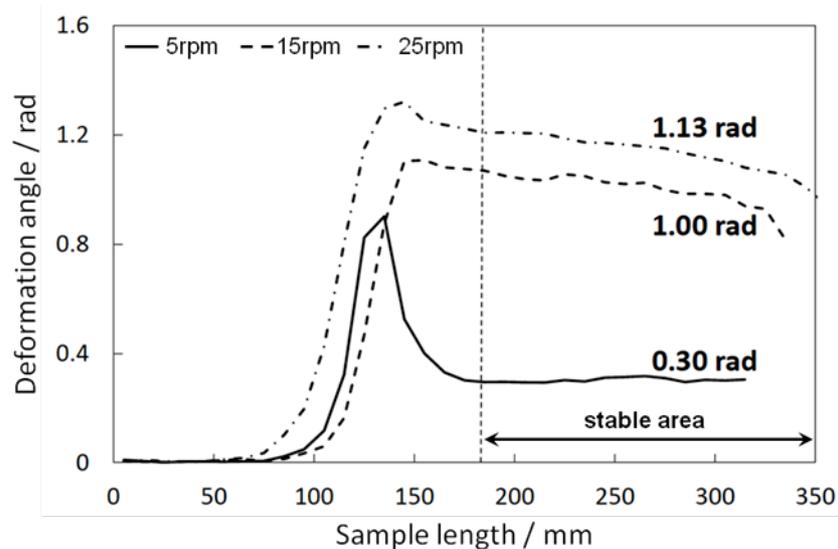


Fig.3 Variation of deformation angle in AZ91D magnesium alloy sample surface with the difference between torsion speed.

Table 1 Comparison between calculated and experimental deformation angle in radian.

	calculated	experimental
5rpm	0.36	0.30
15rpm	0.84	1.00
25rpm	1.08	1.13

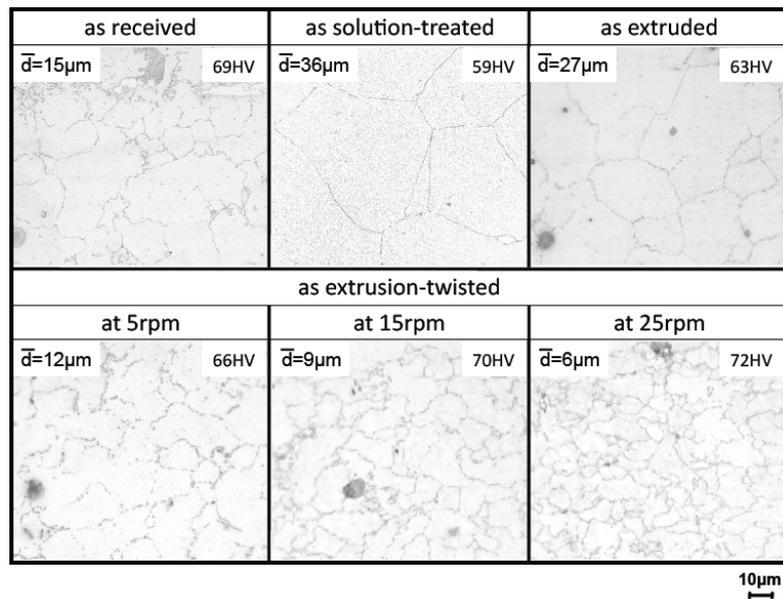


Fig.4 Optical micrographs of as received, as solution-treated, as extruded and as extrusion-twisted AZ91D magnesium alloy bar in the sectional outer parts.

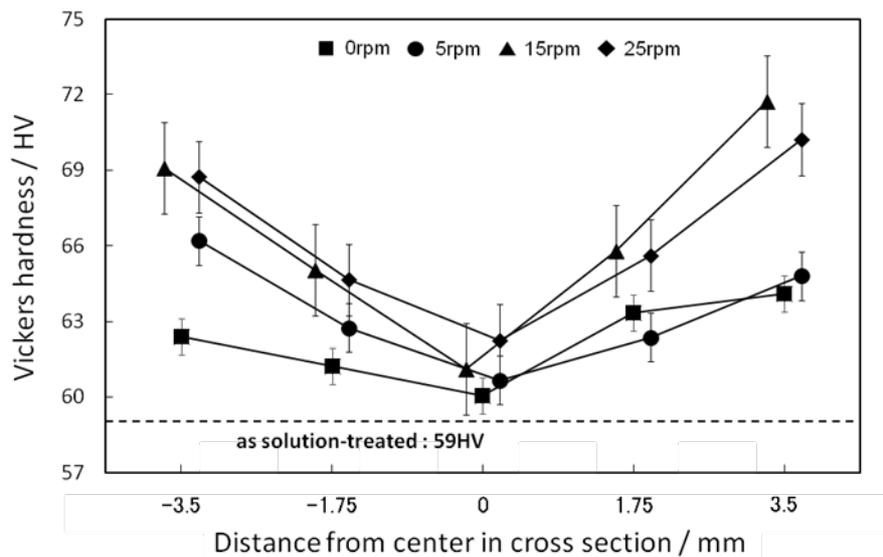


Fig.5 Hardness distribution with torsion speed in AZ91D magnesium alloy extruded and extrusion-twisted at 678K.

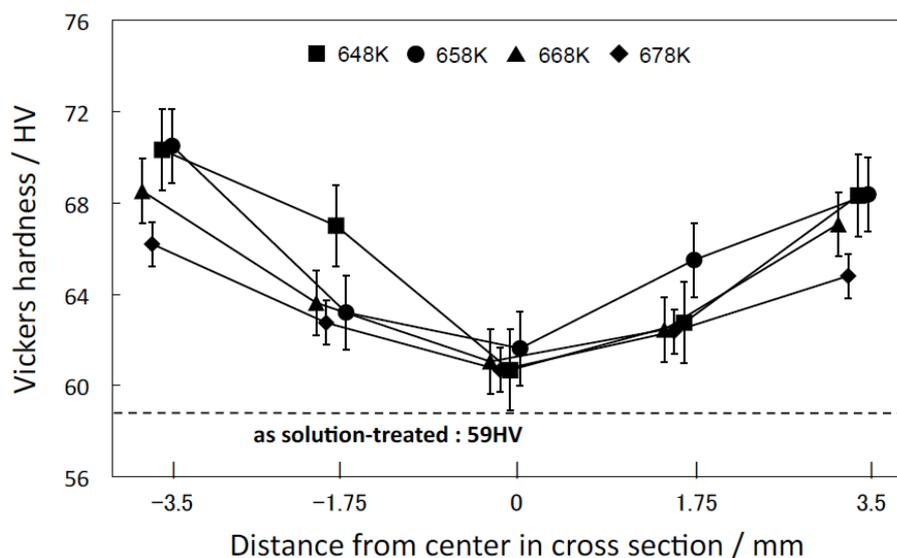


Fig.6 Hardness distribution with extrusion-torsion temperature in AZ91D magnesium alloy torsion-twisted at 5rpm.

#### 4. Conclusions

The extrusion-torsion simultaneous processing was developed for grain refinement in AZ91D magnesium alloy. From the results of the investigations, the following conclusions were obtained.

- (1) The grain size of AZ91D magnesium alloy was gradually decreased with increasing the torsion speed in as extrusion-twisted conditions. Grain refinement under 2 $\mu$ m was achieved by the optimized extrusion-torsion condition.
- (2) Hardness was increased by the addition of torsion speed comparing with as solution-treated and as extruded samples, and was dependent on the extrusion-torsion temperature.

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