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Deformation behavior of commercial Mg-Al-Zn-Mn type alloys under a hydrostatic extrusion process at elevated temperatures[†]

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Abstract

This paper presents the deformation behavior of commercial Mg-Al-Zn-Mn type alloys during hydrostatic extrusion process at elevated temperatures. In the current study commercial Mg-Al-Zn-Mn type alloys with different Al contents were subjected to hydrostatic extrusion process at a range of temperatures and at ram speeds of 4.5, 10 and 17 mm/sec. Under the hydrostatic condition at 518K, the alloy with Al contents of 2.9 wt% was successfully extruded at all applied speeds. The alloys with Al content of 5.89 and 7.86 wt% were successful up to 10mm/sec, and finally extrusion of alloy with Al content 8.46wt% was successful only at 4.5 mm/sec. These results show that the deformation limit in the Mg alloys in terms of extrusion speed greatly extended to higher value in the proximity of lower Al content. It is presumed that deformation becomes harder as Al content increases because of strengthening mechanism by solute drag to increase of supersaturated Mg_{17} Al_{12} precipitates. Also, microstructures of cast and extruded Mg alloys were compared. Defect-wide microstructure of cast alloy completely evolved into dense and homogeneous microstructure with equiaxed grains.

Keywords: Mg alloys; Hydrostatic; Extrusion; Formability; Deformation

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1. Introduction

Much attention has been paid to magnesium alloy for the last decade because of its strong potential use as lightweight as well as energy-saving material in structural applications [1]. Nonetheless, industrial utilization is still low due to its poor formability at relatively low temperature even though it has higher specific strength than aluminum. Various processes have been employed to promote its mechanical properties in terms of strength and ductility, which include rolling [2], hot forging [3] and conventional extrusion [4, 5] and hydrostatic extrusion [6, 7] etc. Among them hydrostatic extrusion is a novel process very suitable for forming hardly-deformed materials like magnesium due to hydrostatic state applied during the process, helping them be smoothly shaped at relatively low temperature. It, therefore, would be very useful to evaluate the degree of deformation with respect to forming speeds and forming temperatures when hydrostatic deformation process applies. In the meantime, unfortunately, to date, formability information on AZ series (Mg-Al-Zn-Mn) magnesium alloys by mutual comparison at the same deformation conditions seems to be insufficient although independent studies on each material are easily accessible. In the current study, in this respect, deformation limits of AZ type magnesium alloys (AZ31, AZ61, AZ80 and AZ91) are studied by subjecting them to hydrostatic extrusion at different extrusion speeds and at different elevated temperatures, which will give insights to utilizing hydrostatic extrusion for hardly-deformed materials in terms of deformation limits.

2. Experimental procedures

A series of AZ type Magnesium alloys, AZ31, AZ61, AZ80 and AZ91, were cast and homogenized for 10 hours at 673K. Each alloy has increasing content of Al component with increasing alloy number, as shown in Table 1.

Following heat treatment, alloys were cut into cylindrical billet with the dimension of Φ80 x 250mm. For extrusion a hydrostatic extruder developed in KITECH was used, which has maximum load capacity of 600 tons. Extrusion chamber is

Table 1. Chemical composition of AZ type alloys in wt%.

	Al	Zn	Mn	Mg
AZ31	2.90	0.69	0.32	Bal.
AZ61	5.89	0.73	0.30	Bal
AZ80	7.86	0.41	0.20	Bal
AZ91	8.46	0.51	0.13	Bal

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Table 2. Processing parameters.

ExtrusionTemp. (K)	573, 518, 393, 353
Ram Speed(mm/s)	4.5, 10, 17
Extrusion Ratio (ER)	10, 16, 25

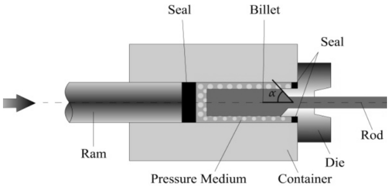


Fig. 1. Schematic illustration of hydrostatic extrusion.

90mm in diameter. At first each billet was inserted into the extrusion chamber just before extrusion die with 45° half angle, which was filled with pressure medium called LLDPE polyethylene epoxy. The chamber was preheated for homogeneous temperature distribution inside. The billets were subjected to hydrostatic extrusion, depicted in Fig. 1 for schematic illustration, at temperatures of 573, 518, 393 and 293K and at ram speeds of 4.5, 10 and 17 mm/sec.

The experiments were conducted in the sequence of lowering extrusion temperature. Initial billets were reduced to Φ25, Φ20 and Φ16 corresponding to extrusion ratio (ER), 10, 16, 25, respectively. The processing parameters are summarized in Table 2.

The extruded billets were cut into cylindrical specimens with a gauge length of 62mm and followed by being pulled with tension at room temperature with a speed of 2mm/min using a 10 ton capacity MTS tester. Simultaneously, the specimens were carefully polished and microstructures were observed by optical microscope and were compared with cast specimens.

3. Results and discussion

3.1 Deformation limits

A series of magnesium alloys, first, subject to hydrostatic extrusion at different ram speeds at 573 and 518K with extrusion ratio of 25 were carefully inspected over the surfaces of the billets with cracks being developed and the results are shown in Fig. 2. As shown, (a) under the hydrostatic extrusion conditions at 573K AZ31 alloys were successfully extruded at all applied speeds. AZ61, AZ80 and AZ91 were successful at 4.5mm/s, and at higher speeds cracks immediately appeared on the surfaces of billets. In Fig. 2(b) similar behaviors on crack development with respect to ram speed or deformation rate are observed for the case of extrusion at 518K. It is, in particular, noted that billets that had undergone hydrostatic extrusion at lower temperature seemed to have even better surfaces with less crack generation, which was not clearly manifested yet here. It is, however, noted in both cases that at each ram speed extruded billets happened to have more severe cracks on their surfaces with increasing Al content.

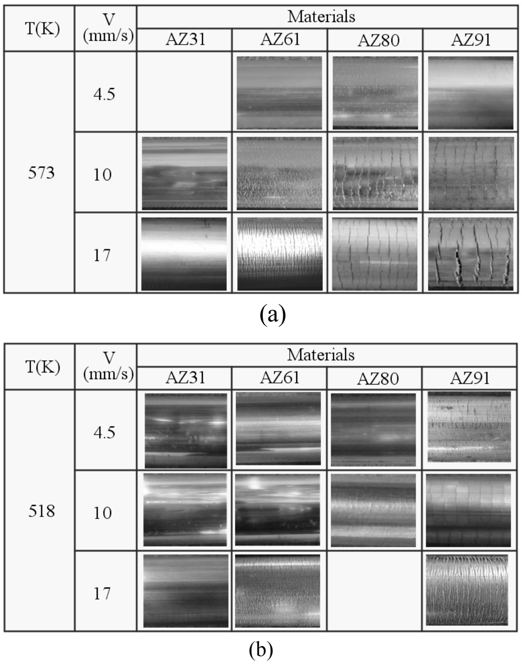


Fig. 2. Surface cracks created after hydrostatic extrusion at (a) 573K and (b) 518K.

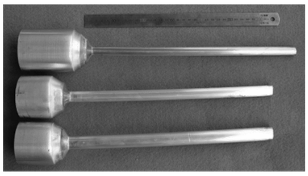
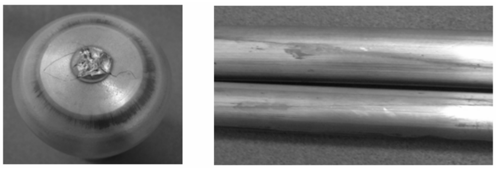


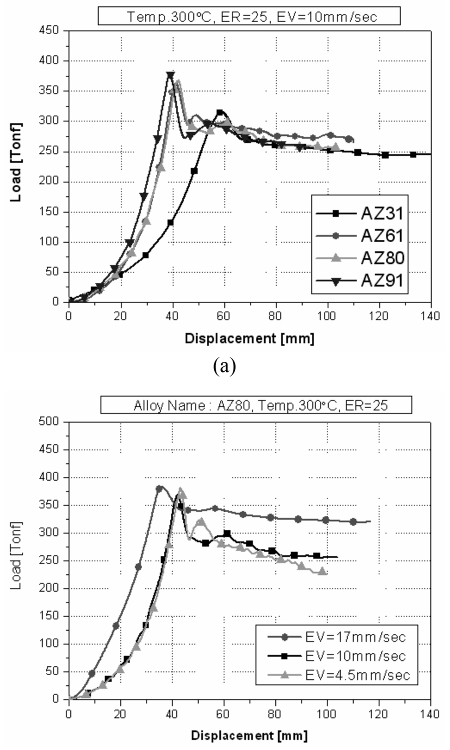
Fig. 3. The appearances of the AZ31 billet extruded at 393K with ER of10, 16 and 25.



(a) (b)

Fig. 4. The appearances of the AZ31 billet extruded at 353K with ER = (a) 25 and (b) 16.

Since AZ31 was deformed without any difficulty under the less deformable conditions such as lower extrusion temperature and higher ramp speed at 573 and 518K, at even lower temperature of 393K was it subjected to the hydrostatic extrusion at most severe forming speed of 17mm/s with ER of 25, 16 and 10. Fig. 3 shows the billets that had undergone extrusion with different ER. It is recognized that there is no evidence of producing cracks on the surfaces after subjection showing smooth and nice-looking surfaces. At even further lower temperature of 353K hydrostatic extrusion made the AZ31 billet to be broken down completely into two parts, long extruded heads and short tails for ER 25, and the billet at ER 16 had left severe cracks behind all over the surfaces, as shown in Fig. 4.



(a)

(b)

Fig. 5. Extrusion loads in terms of (a) Al content and (b) ram speed for AZ80 alloy.

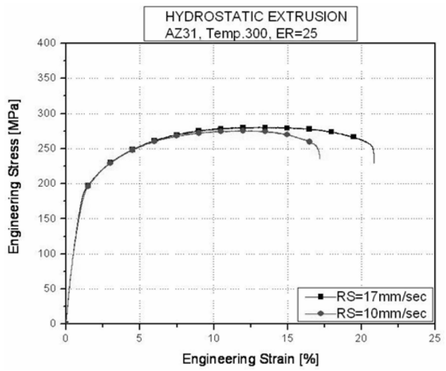
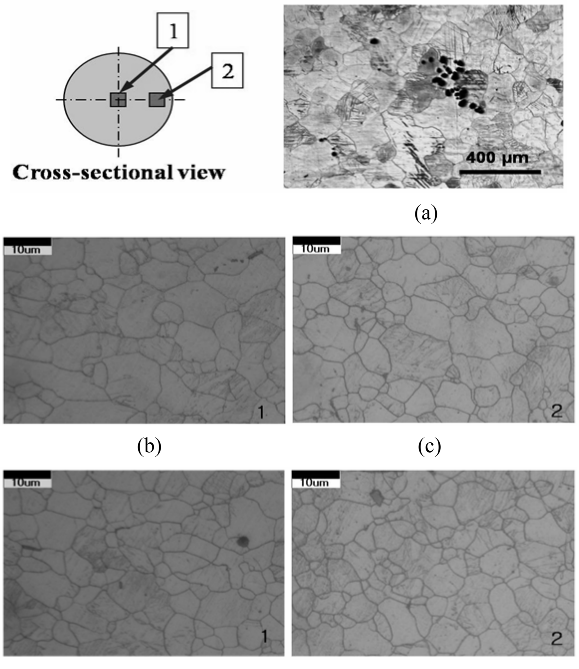


Fig. 6 Room temperature tensile behavior of AZ31 alloy subjected to hydrostatic extrusion at speeds of 10 and 17mm/s at 573K.

3.2 Extrusion loads

Extrusion loads were recorded during experiments in terms of displacements for each alloy with different Al content. As shown in Fig. 5(a), AZ31, the one with lowest Al content, increases slowly up to roughly 320 tonf at a peak load and extrusion starts from this point, decreasing in load slowly to 250 tonf till the end of the process. Detailed inspection shows that the higher Al content Mg alloys had, the larger peak loads they came to reach and the loads decayed and stabilized in similar manner with insignificant variation. In terms of ram speed, however, for AZ80 alloy undergoing hydrostatic extrusion, immediately after the peak loads, steady state loads had clear difference such as higher values at faster speeds.



(a)

(b) (c)

(d) (e)

Fig. 7. Optical micrographs of AZ 31 specimens (a) before and (b) after extrusion in position 1 and (c) in position 2, and of AZ61 specimens (d) after extrusion in position 1 and (e) in position 2.

3.3 Tensile behaviors

Tensile behavior was investigated at room temperature for AZ31 specimens extruded at 573K with ER=25 at two different ram speeds of 10 and 17mm/s, shown in Fig. 6. Two engineering strain-stress curves are fairly coincident with each other without significant difference, showing the yield strength approximately at 160MPa and the ultimate tensile strength peaked at 273MPa or nearby except for the fact that the specimen with extrusion speed at 10mm/s ended up with a little earlier fracture than the one at 17mm/s in elongation to failure.

It seems that extrusion speeds did not affect the tensile properties of this alloy, which can be associated with the results in Fig. 2 in that AZ31 alloy has excellent formability in the examined range of the speeds, making a hardly perceived distinction between them. According to the crack inspections, as seen in Fig. 2(a) and (b), particularly for the case of AZ31 alloy, the extruded surface, in practice, was smooth and well-defined without any trace amount of cracks developed at all examined ram speeds and at a temperature as low as 393K in this investigation.

3.4 Microstructures

Microstructures by optical microscope were observed in the specimens of AZ31 and AZ61 alloys extruded at 573K with ER=25, compared with cast alloys before the processes.

As shown in Fig. 7(a), a cast AZ31 alloy possesses ill-defined microstructure in which various defects exist inside and/or at grain boundaries. Even near the center of micrograph is collective area of micropores observed, indicating typical microstructures of cast metals.

It is noted in Fig. 7(b) and (c) that defect-wide microstructure of cast alloy completely evolved into dense and well-defined microstructure from the center to nearby edge on its cross-section where grain shapes are almost equiaxed. Fig. 7 (d) and (e) shows that AZ61 that undergone through extrusion has fairly similar microstructures with the case for AZ31 in (b) and (c), seemingly, only differing in grain size a bit smaller in the microstructure. Under this condition AZ61 left a significant number of cracks on the surface through the billet. To reveal substructure generating persistent cracks, more detailed study on microstructure would be recommended using TEM or other tools.

4. Discussion

As can be seen in Fig. 2, firstly, with increasing Al content, deformation by extrusion tended to be much harder. It has been noted that Al content in magnesium alloy has the most favorable effect on strength and ductility among various additional elements. In alloying Mg with more than 2 wt% Al by casting, the equilibrium phase $Mg_{17}Al_{12}$ precipitates from supersaturated solid solution upon aging, which enhances the alloy strength. In practice, $Mg_{17}Al_{12}$ forms a network around grain boundaries as Al content increases [8]. In this regard the strength becomes larger and lowers the ductility. The ductility decreases rapidly over 8% correspondingly in the current study, AZ91. F. Zarandi et al.[9] investigated rolling and deformation behavior of AZ series Mg alloy in terms of addition of both Al and Mn. It was found that increasing Al content to 6 wt% resulted in edge cracking during hot rolling.

More severe cracks happened to occur at faster ram speeds because of increasing external stress exerted on billets in a shorter period common to the deformation of other metals. As shown in Fig. 8, however, the deformation limit of hydrostatic extrusion has been extended to higher values in terms of forming speed at all alloys regardless of the amount of Al content when compared to other processes.

Especially, expansion is more noticeable at the lower content and the gaps on deformation limit between hydrostatic extrusion and the other process are gradually reduced with increasing Al content. It is also noted that for AZ31 alloy extrusion was completely successful at a temperature down to 393K, probably being the first report on such a low deformation in magnesium alloys. Consequently, the formability of magnesium alloy has been extended to extremely lower temperature, probably due to the hydrostatic state equally distributing external stresses over a billet and helping it to become easily deformed at even lower temperature.

5. Conclusions

Under hydrostatic extrusion AZ type magnesium alloys extended their formability compared to other extrusion processes. The formability tended to extend with decreasing Al content as well as at slower ram speed. It is also noted that hydrostatic extrusion seemed to have made it possible to deform AZ31 alloy at lowest possible temperature of 393K among reported data, which might be attributed to the characteristic of the hydrostatic extrusion process. Especially for AZ31 alloy, tensile behaviors are well coincident with extrusion data in such a way that AZ31 alloy well deformed at any ram speed. Microstructure also shows typical evolution from cast structure to the structure observed in wrought alloys.

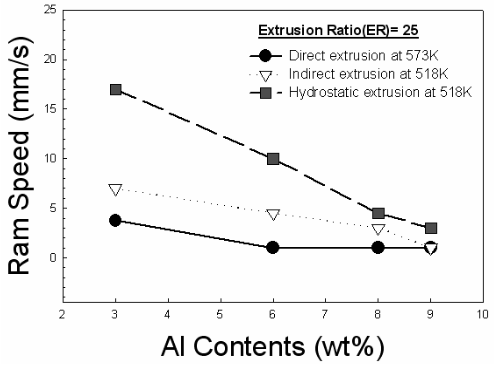


Fig. 8. Deformation Limit bounded by maximum ram speeds in terms of Al contents for AZ magnesium alloys.

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