Journal of Alloys and Compounds 504S (2010) S496–S499

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: www.elsevier.com/locate/jallcom

Effect of rapid cooling and extrusion ratio on the mechanical property of Mg alloys

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ARTICLE INFO

Article history:
Received 3 July 2009
Received in revised form 5 April 2010
Accepted 8 April 2010
Available online 14 May 2010

Keywords:
Mg alloys
Powder metallurgy
Extrusion
High strength
Grain size

ABSTRACT

$Mg_{95}Zn_{4.3}Y_{0.7}$ (at.%) alloy powders were prepared using an inert gas atomizer, followed by warm extrusion. The powders were almost spherical in shape, and the grain size, compared with the cast product, was fine being less than 5 μm. The microstructure of bars extruded was examined as a function of the extrusion ratio using scanning electron microscope (SEM), energy dispersive X-ray spectroscope (EDS) and X-ray diffractometer (XRD). As the extrusion ratio increased from 10:1 to 20:1, the powders fully deformed with refining the grain size. Both the ultimate strength and elongation also showed a dependence on the extrusion ratio.

1. Introduction

Alloys fabricated via powder metallurgy (PM) combined by rapid solidification (RS) generally showed an elevation in the mechanic properties, compared with those prepared by the conventional ingot metallurgy [1–3]. It was mainly according to the microstructural refinement and structural homogeneity. The contribution of RS-PM to the mechanical properties was found elsewhere [4–6]. The extension of RS-PM to Mg alloy, which recognized as a strong candidate for replacing the existent light weight structural materials, has been little progressed due to the danger in making and processing. The possible approach was by ball milling [7]. In the early 2000s, some of reports on the investigation of RS-PM Mg alloys suggested that it showed a remarkably high strength near 600 MPa [8–10], although it has conducted using the closed system of high vacuum atomization and extrusion. Thus, it has required proposing much more economic way of production than the one by mentioned above.

In the present investigation, the powders of $Mg_{95}Zn_{4.3}Y_{0.7}$ (at.%) alloy were prepared using an industrial atomizer excluding the concept of vacuum and closed system, followed by the extrusion. It is a typical composition bearing the ultra high tensile strength, low friction coefficient and wear resistance in both the ambient and elevated temperatures, corresponding to the distribution of metastable icosahedral phases ($Zn_{60}Mg_{30}Y_{10}$ in at.%) in the Mg matrix. The effects of extrusion ratio and temperature were investigated on the materials properties to identify the possibility of industrial application using the atomization.

2. Experimental

$Mg_{95}Zn_{4.3}Y_{0.7}$ (at.%) alloy powders were fabricated using a gas atomization, in which the master alloy was remelted at 200 K above the liquidus temperature. The atomization conducted using an industrially scaled high-pressure gas atomizer equipped with a boron nitride melt delivery nozzle of 3 mm in diameter and a hole type Ar gas nozzle operating at a pressure of 5 MPa. The melt flow rate, as estimated from operating time and weight of atomized melt, was about 0.8 kg/min. The size distribution of the atomized powders was measured by a conventional sieving method, and the powders ranging 63–89 μm was selected and used for the extrusion. The powders as atomized were degassed at 500 K for 20 min and extruded at 653 K under the applied pressure of 200 MPa, with the area reduction ration of 10:1, 15:1 and 20:1.

The structure of powders as atomized and bulks consolidated was characterized using a X-ray diffractometry (XRD) with monochromatic Cu Kα radiation over 2θ range of 20–80° at power of 5 kW in a Philips 1729 X-ray diffractometer. The microstructure was examined by optical microscopy (OM; Simatzu) and scanning electron microscopy (SEM; JSM 5410). Tensile strength of extruded bar was measured at the room temperature using Instron type machine. Fracture patterns of the tested samples were observed using scanning electron microscopy (SEM).

3. Results and discussion

Fig. 1(a) shows a microstructure of atomized $Mg_{95}Zn_{4.3}Y_{0.7}$ alloy powders within the size of 63–89 μm. It consisted of cellular type grains with an average size of about 4 μm. The microstructure showed the solidification rate dependence that the grain size was found to coarsen linearly from 1.5 μm to 4.6 μm as the initial powder size increased from 32 μm to 90–150 μm, respectively. It was

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doi:10.1016/j.jallcom.2010.04.036

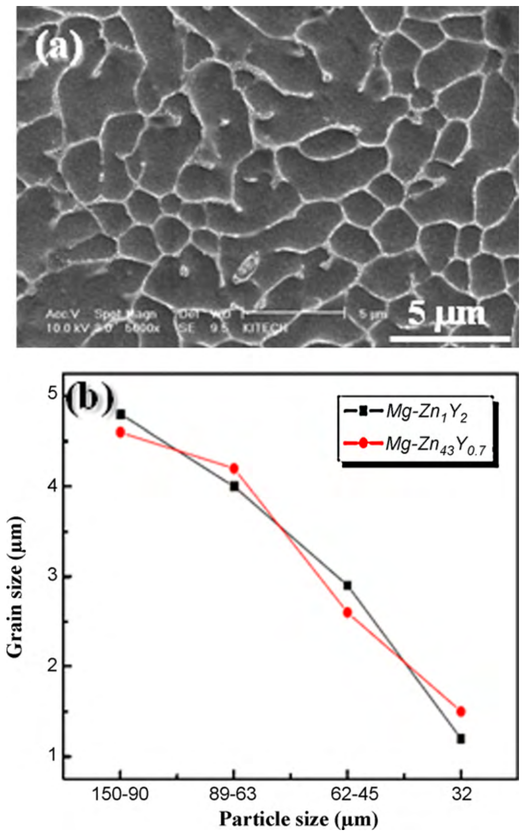

Fig. 1. Microstructure of Mg–Zn4.3–Y0.7 alloy powders (63–89 μm) as atomized (a), and the grain size variation with the initial powder size (b).

generally known for the atomization that the solidification rate increased as the powder size decreased [4]. Nevertheless, the atomized powders showed to form as approximately 10 times finer grains as the cast products [11].

The extrusion behavior of the Mg alloy powders gas atomized was as shown in Fig. 2, in which the microstructure was arrayed along the extrusion direction. The alloy bar extruded with the ratio of 10:1 contained the many powder shape particles which seemed to be unreformed as marked by dashed circles in Fig. 2(a). Also, the plastic flow pattern was not uniform, especially, around the powders unreformed (described by white arrows). It suggested that the extrusion ratio of 10:1 was not enough to deform the strong Mg–Zn–Y alloy powders. The powders might become a source of inhomogeneous plastic flow. However, both the flow patterns became disappeared with increasing the ratio to 15:1 as seen in Fig. 2(b). Further increase to 20:1 resulted in forming the fully and uniformly deformed microstructure (c). The sizes of powders unreformed with the extrusion ratio was listed in Table 1, in which the initial size of 72 μm turned into 40 μm and 32 μm with the ratio of 10:1 and 15:1, respectively. The reason that the smaller powders remained with little deformation as the extrusion ratio increased was due to the strength difference with the powders as solidified. It

Table 1
Size changes of undeformed powders and grains contained in the extruded bars as a function of area reduction ratio.

	Atomized powder	Extrusion ratio		
		10:1	15:1	20:1
Undeformed powder size (μm)	76	42	32	Not found
Grain size (μm)	3.5	3.0	2.1	1.5

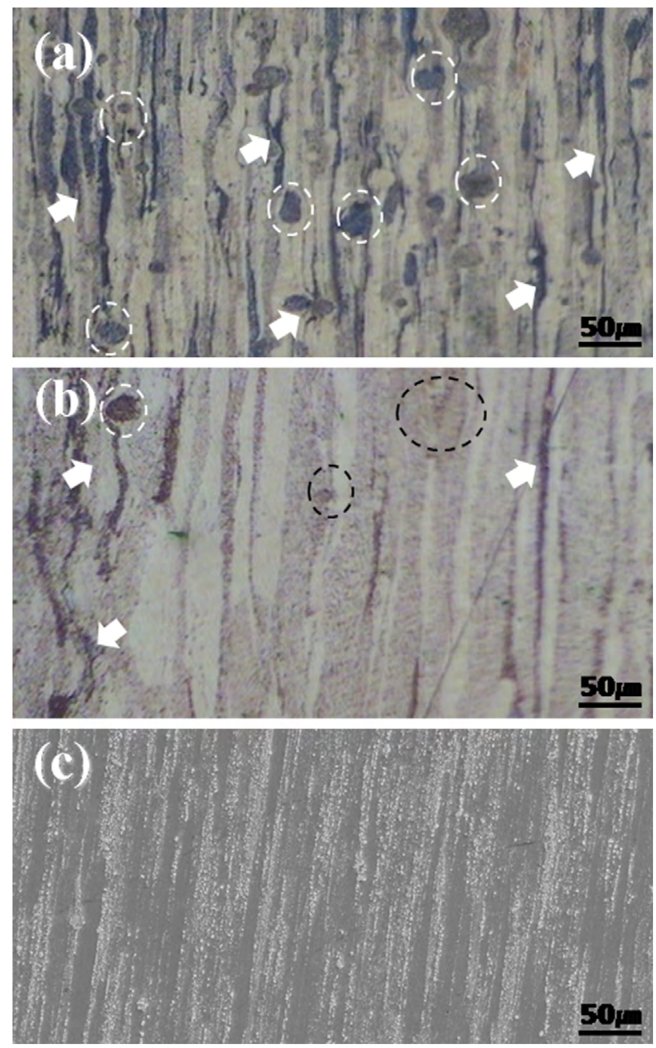

Fig. 2. Microstructure of extruded bar taken at the parallel to the extrusion direction with the extrusion ratio: (a) 10:1, (b) 15:1, (c) 20:1.

is generally understood that the finer the atomized powder size, the stronger the strength due to the fine and uniform microstructure. This relationship the resultant grain size with the atomized powders was given in Fig. 1. To sum up, the plastic flow pattern shown in Fig. 2 indicated that the extrusion ratio became an important factor for obtaining the uniform microstructure, especially for the hardly deformable alloy powder like Mg which is of HCC structure. This could be supported from Table 1, which listed the variation of sizes of undeformed powder and grains as a function of extrusion ratio.

Considering the extrusion ratio of 10:1, 15:1 and 20:1, the solidified powders had to deform into the size of approximately 9.5, 7.8 and 6.7 μm, respectively. It corresponds to the fact that the extrusion ratio defined the area reduction ratio between the billet and the extruded bar. The mismatch between the real (40 μm, 32 μm and 'not found' in Table 1) and estimated sizes (9.5 μm, 7.8 μm and 6.7 μm) calculated using the extrusion ratio indicated that the Mg–Zn–Y alloy powders are strong enough to deform at least 20:1. Hong et al. suggested that the kind of mismatch often occurred during the powder extrusion [12]. TEM investigation, though not shown here, indicated the atomized and extruded Mg–Zn–Y alloy consisted of fine I phases (approximately 100 nm in diameter) in the Mg matrix, which was quite finer than those formed in the cast sample (coarser than 1 μm).

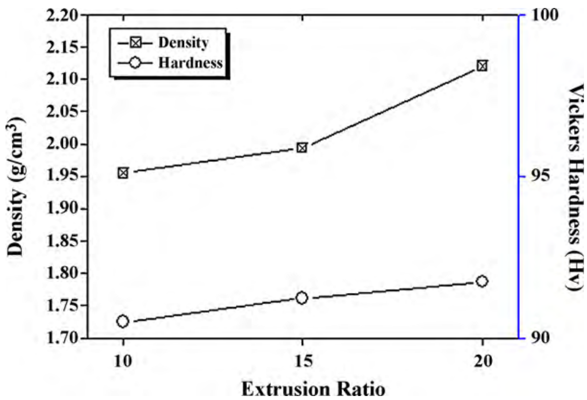

Fig. 3. Variation of density and hardness presents as a function of the extrusion ratio.

Effect of the extrusion ratio on the density and hardness is as shown in Fig. 3. As the ratio increased from 10:1 to 15:1 and 20:1, the density was increased from 1.61 to 1.97 and 2.15 g/cm^3 (nearly 99% of theoretical value), while the hardness from 90 to 91 and 92 Hv, respectively. The similar pattern was also appeared in the tensile properties such as the stress and elongation, which was increased as the extrusion ratio increased. At the extrusion ratio of 10:1, 15:1 and 20:1, ultimate tensile strength (UTS) measured to be about 270, 300 and 330 MPa, respectively, as shown in Fig. 4. The elongation was also, respectively, elevated from 3.5% to 12.5% and 17.5%. The improvement in both the stress and strain could be explained by the microstructural homogeneity (Fig. 2) and the density increase (Fig. 3a) as the extrusion ratio. It is general that the strength and elongation behaved reversely, that if the former increased, the latter became down. However, in the investigation, both of them were improved simultaneously. So that that the RS-PM Mg alloys processed not in the closed system had a potential of further increase in the properties, possibly by modifying the powder surface structure during atomization and by improving the microstructural uniformability during the extrusion.

Fig. 5 shows the fracture pattern of the alloy bars after the tensile test. The undeformed powders were found to exist at the lowest extrusion ratio of 10:1, and the size was also larger than those in the bar of 15:1. However, no trace of incomplete deformation was examined in the extrusion ratio of 20:1, indicating the full deformation. It was well agrees with the micrograph (Fig. 2).

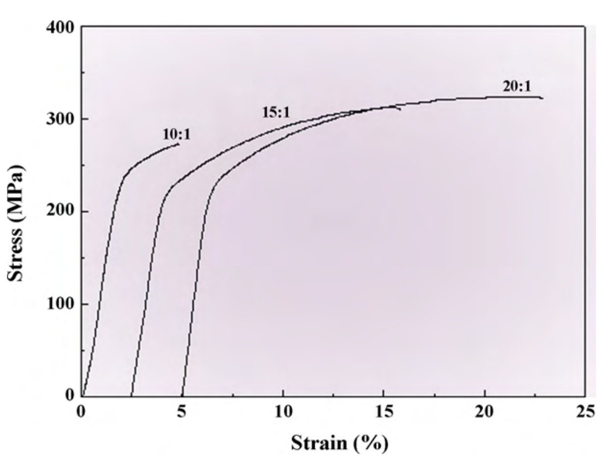

Fig. 4. Stress–strain curves of extruded bars with the extrusion ratio.

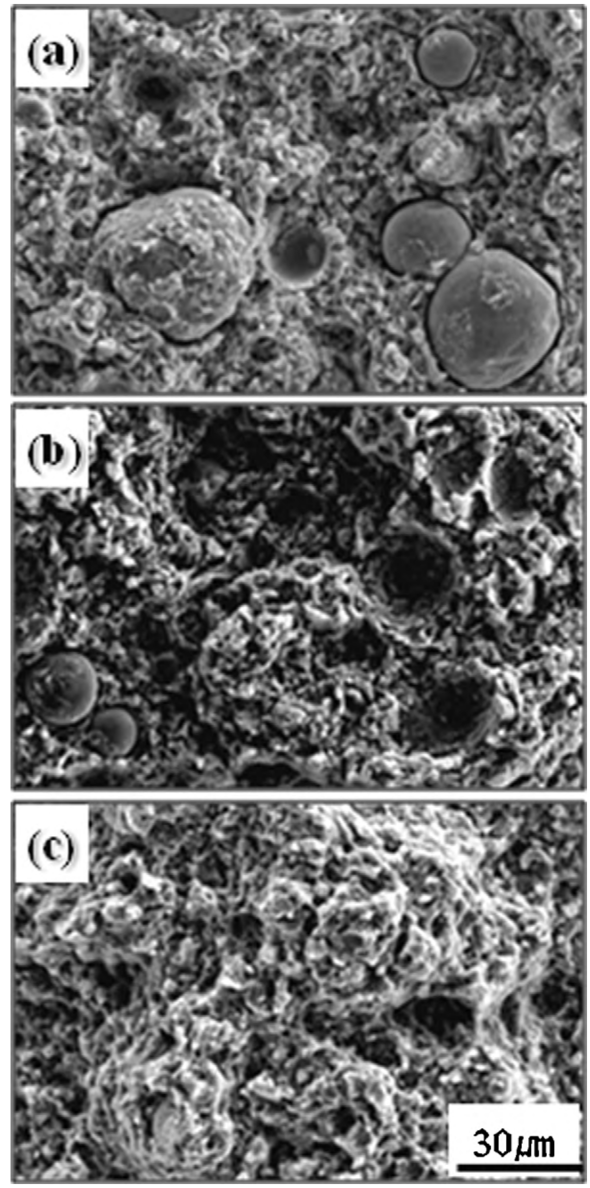

Fig. 5. SEM fracture pattern of alloy bars tensile tested: (a) 10:1, (b) 15:1 and (c) 20:1.

4. Conclusion

$Mg_{95}Zn_{4.3}Y_{0.7}$ alloy powders atomized under an Ar atmosphere were almost spherical in morphology. The grain size of about 1.5–4.6 μm, though its dependence on the initial powder size, became fine after the extrusion as about 2–3 μm. The powders as solidified consisted of icosahedral (I-) phases embedded in the α-Mg matrix. As the extrusion ratio increased from 10:1 to 15:1 and 20:1, the tensile strength increased from 270 MPa to 300 and 330 MPa, respectively. The elongation was also increased from 3.5% to 12.5% and 17.5%, respectively. Both the simultaneous increases were attributed to the increase in the degree of deformation of powders as the extrusion ratio increased.

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