Processing of cellular magnesium materials

Y.Yamada, K.Shimojima, Y.Sakaguchi, M.Mabuchi, M.Nakamura, T.Asahina
Materials Processing Department, National Industrial Research Institute of Nagoya, Hirate-cho, Kita-ku, Nagoya 462-8510, Japan
T.Mukai
Mechanical Engineering Department, Osaka Municipal Technical Research Institute, Morinomiya, Joto-ku, Osaka 536-8553, Japan
H.Kanahashi and K.Higashi
College of Engineering, Department of Metallurgy and Materials Science, Osaka Prefecture University, Gakuen-cho, Sakai, Osaka 599-8531, Japan

Abstract

An open-cellular AZ91 was processed by a casting method. The density of the cellular Mg was very low (= 0.05 g/cm^3). The strength of the cellular Mg was in agreement with the value predicted by Gibson and Ashby. Compressive properties of the cellular metals were not affected by the ductility of the solids.

1. Introduction

Cellular materials are super-light materials exhibiting unique properties such as high energy absorption [1]. The applications of cellular materials are in a wide range of impact energy absorbers, silencers, flame arresters, heaters, heat exchangers, constructional materials and so on [2]. Cellular aluminum materials have been extensively developed and investigated [3-9]. Magnesium is a suitable metal for cellular metals because magnesium exhibits a lower density, compared to aluminum. In the present investigation, an open-cellular Mg with a very low density of 0.05 g/cm^3 is fabricated by a casting method and compressive properties of the cellular Mg are investigated.

2. Processing of an open-cellular Mg

An open-cellular AZ91 Mg (Mg-9wt.%Al-1wt.%Zn-0.2wt.%Mn) was fabricated by using a polyurethane foam [10]. A schematic illustration of the production is shown in Fig 1. Plaster was poured into a polyurethane foam, and then the plaster mold was heated to 773 K. Because the polyurethane foam was removed during heating, the plaster mold had a porous structure. Molten magnesium was poured into the porous plaster mold heated to 873 K. In the present investigation, the mold was evacuated because molten magnesium could not flow through narrow routes in the porous plaster mold in gravity casting. After casting, water was sprayed to the plaster mold. The plaster mold was broken down by the water spray and an open-cellular Mg was obtained.

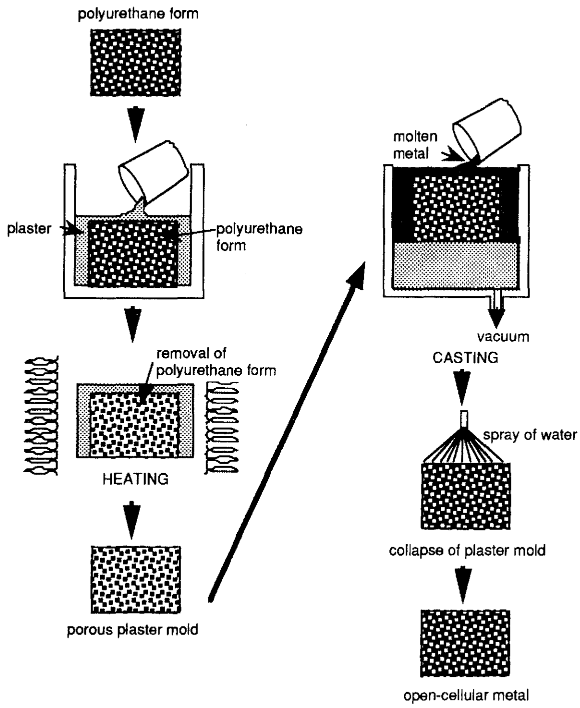

Fig. 1 Schematic illustration of the production of an open-cellular AZ91 Mg.

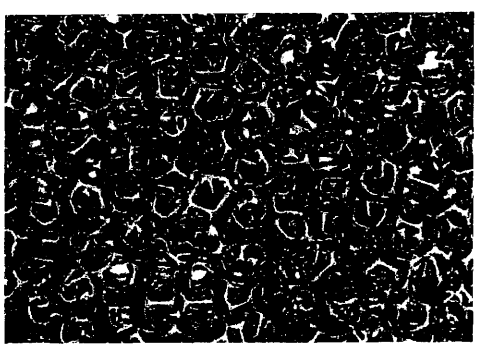

Fig. 2 Optical micrograph of the open-cellular AZ91 Mg.

An optical micrograph of the open-cellular Mg is shown in Fig. 2. There were no areas with closed-cell structure in the cellular Mg. The structure of the cellular Mg was almost the same as that of the polyurethane foam.

A scanning electron micrograph of the cellular Mg is shown in Fig. 3. The average column spacing and thickness were 4.5 and 0.3 mm, respectively. The characteristics of the open-cellular Mg are listed in Table 1. It should be noted that the cellular Mg had a very low density of 0.049 g/cm^3.

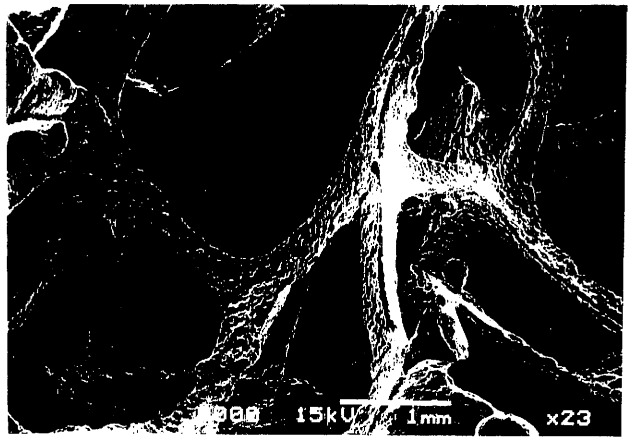

Fig. 3 Scanning electron micrograph of the open-cellular AZ91 Mg.

Table 1 The characteristics of the open-cellular AZ91 Mg.

Column spacing (mm)	Column thickness (mm)	Solid volume fraction (%)	Density (g/cm^3)
4.5 * (3.8 ~ 5.7)	0.3 * (0.2 ~ 0.4)	2.7	0.049

* The average value

3. Compressive properties

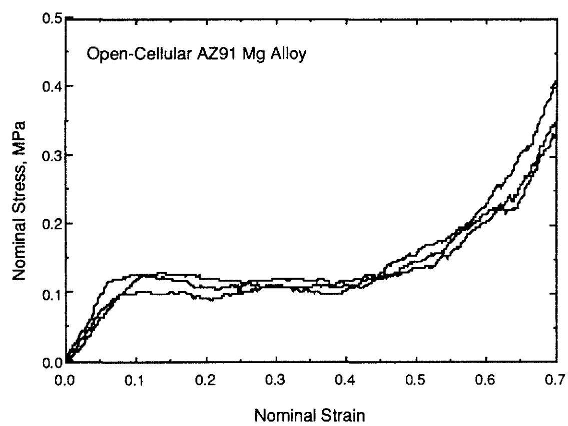

Fig. 4 The compressive stress - compressive strain curves of the open-cellular AZ91 Mg.

Mechanical properties of the open-cellular Mg were investigated in compressive tests [10]. The nominal stress - nominal strain curve of the cellular Mg is shown in Fig. 4. The

Table 2 The density and compressive stress of cellular metals.

Materials	Structure	Density (g/cm^3)	Relative density	Plateau stress (MPa)	Relative stress	References
AZ91 Mg	open-cell	0.049	0.03	0.11	9.2×10^{-4}	
Al	open-cell	0.15~0.39	0.06~0.15	0.3~2.2	6.0×10^{-3}~4.1×10^{-2}	(3)
Al-7Mg	open-cell	0.14~0.54	0.05~0.20	0.9~18.6	3.8×10^{-3}~8.1×10^{-2}	(3)
7075	open-cell	0.25~0.56	0.09~0.21	1.6~13.5	4.6×10^{-3}~3.9×10^{-2}	(3)
Zn	open-cell	0.34~0.54	0.05~0.08	0.1~2.2	5.3×10^{-4}~1.1×10^{-2}	(4)
AA6101	open-cell	0.28	0.1	2.8	3.0×10^{-2}	(5)
Al-5Ca(Ti) (Alporas)	closed-cell	0.22	0.08	1.3	1.0×10^{-2}	(6)
A356/15%SiC	closed-cell	0.27	0.1	---	---	(6)
Al(Si) (Alulight)	closed-cell	0.66~0.85	0.24~0.31	17.1~29.0	6.8×10^{-2}~1.2×10^{-1}	(6)
Al-6Si-4Cu	closed-cell	0.2~0.8	0.07~0.30	5.9~23.7	4.2×10^{-2}~1.7×10^{-1}	(7)
Zn-4Cu	closed-cell	1.0~2.0	0.15~0.27	5.6~22.3	2.7×10^{-2}~1.1×10^{-1}	(7)
Al-Ca(Ti) (Alporas)	closed-cell	0.20	0.07	1.4	8.0×10^{-3}	(8)
Al-7Si-0.3Mg/10%SiC	closed-cell	0.08~0.20	0.03~0.07	0.07~0.29	1.7×10^{-4}~7.5×10^{-4}	(8)
Al/SiC	closed-cell	0.11~0.54	0.04~0.20	0.98~2.62	2.5×10^{-3}~6.7×10^{-3}	(9)

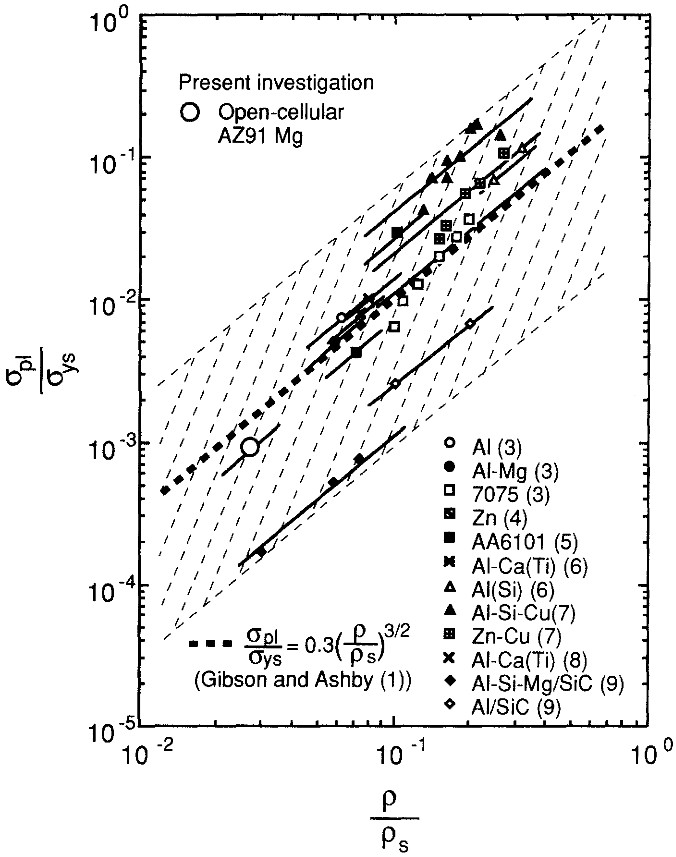

Fig. 5 The relative stress as a function of the relative density in cellular metals.

cellular Mg showed an elastic region at an initial stage, and then a large plateau region with a nearly constant flow stress up to a large strain of 56 %. The flow stress in the plateau region was 0.11 MPa. After the plateau region, the flow stress rapidly increased because of densification. This trend of the cellular Mg is similar to those of other cellular metals [3-9].

The density and compressive stress of cellular metals are summarized in Table 2. It should be noted that the open-cellular Mg exhibited a low density of 0.049 g/cm^3 and a relatively low plateau stress of 0.11 MPa. The flow stress of cellular metals is required to be lower than the threshold which causes damages or injury in order to be able to use cellular metals as energy absorbers. Therefore, it is suggested that the cellular Mg has a high potential as energy absorbers because of the low density and the relatively low plateau stress.

Gibson and Ashby [1] analyzed the relationship between the relative stress, σ_{pl}/σ_{ys}, and the relative density, ρ/ρ_s, assuming that plastic collapse occurs when the moment exerted by the compressive force exceeds the fully plastic moment of the cell edges, where σ_{pl} is the plastic-collapse stress, σ_{ys} is the yield stress of the cell edge material, ρ is the density of the cellular material and ρ_s is the density of the cell edge material, respectively. The relationship between the relative stress and the relative density is given by [1]

$$\sigma_{pl}/\sigma_{ys} = C(\rho/\rho_s)^{3/2} \tag{1}$$

where C is a constant. The relationship between the relative stress and the relative density for cellular metals is shown in Fig. 5. Gibson and Ashby [1] showed that the value of C is 0.3 from data of polyurethane foams and cellular metals. The relationship between the relative stress and the relative density by Eq. (1), assuming that $C = 0.3$, is plotted as a dotted line in Fig. 5. The experimental data of the open-cellular Mg in the present investigation is roughly in agreement with the value predicted in the case of $C = 0.3$. However, there is considerable scatter in the data of other cellular metals. From the results in Fig. 5, a value of C is in a range of 0.03 ~ 2. Curved and corrugated cells affect mechanical properties of cellular metals [6,8,11,12]. Therefore, the scatter in a value of C is probably related to such influences.

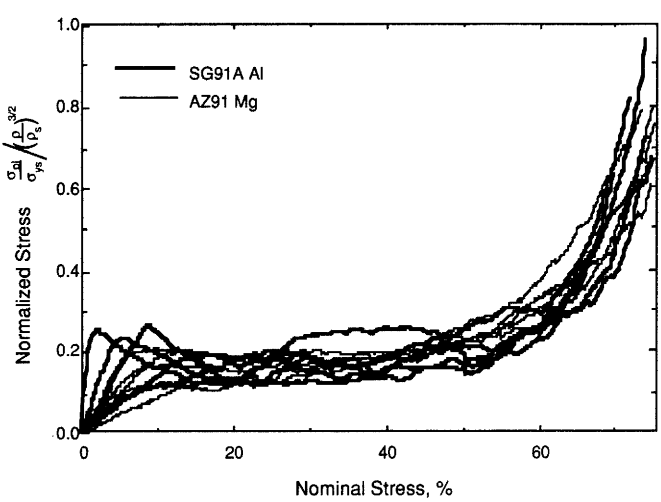

Fig. 6 The normalized stress - nominal strain curves of the cellular SG91A Al and AZ91 Mg.

Recently, it has been shown that the stress - strain relation of the open-cellular AZ91 Mg is in agreement with that of the open-cellular SG91A Al [13]. The normalized stress - nominal strain curves of the cellular SG91A Al and AZ91 Mg are shown in Fig. 6, where the normalized stress is the nominal stress divided by the yield stress of the solid and the three-seconds power of the relative density. The relative density of the cellular Mg (= about 3 %) was almost the same as that of the cellular Al (= about 5 %). It can be seen that the normalized stress - nominal strain curves of the cellular Mg are in good agreement with those of the cellular Al. The stress - strain relation of the AZ91 Mg solid was different from that of the SG91A Al solid, in particular, the AZ91 Mg solid showed much lower ductility than the SG91A Al solid [13]. However, the stress - strain relation of the cellular Mg was the same as that of the cellular Al by compensation with the yield stress of the solid and the relative density. Therefore, it is concluded that the mechanical properties of the cellular metals are not affected by ductility of the solid. This suggests that once the cell edge collapses at the yield point of the solid, the collapsed edge has little ability to bear the load and bends easily by a low stress, as a result, the mechanical properties of the cellular metals are independent of ductility of the solid.

4. Summary

An open-cellular AZ91 was processed by casting. The density of the cellular Mg was very low (= 0.05 g/cm^3). The cellular Mg has a high potential as energy absorbers because of the low density.

The strength of the cellular Mg was in agreement with the value predicted by Gibson and Ashby. By compensation with the yield stress of the solid and the relative density, the stress - strain relation of the cellular Mg was in agreement with that of the cellular Al. The mechanical properties of the cellular metals were not affected by ductility of the solids.

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