Journal of Alloys and Compounds 504S (2010) S483–S486

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

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

Structure and mechanical properties of Al–Mg alloys produced by copper mold casting

S. Scudino[a,*], M. Sakaliyska[a], K.B. Surreddi[a], F. Ali[a], J. Eckert[a,b]

[a] IFW Dresden, Institut für Komplexe Materialien, Postfach 270116, D-01171 Dresden, Germany
[b] TU Dresden, Institut für Werkstoffwissenschaft, D-01062 Dresden, Germany

ARTICLE INFO

Article history:
Received 3 July 2009
Received in revised form 6 January 2010
Accepted 29 March 2010
Available online 2 April 2010

Keywords:
Metals and alloys
Microstructure
Mechanical properties

ABSTRACT

$Al_{100-x}Mg_x$ bulk samples with $5 \le x \le 80$ have been produced by copper mold casting. Casting has a remarkable effect on phase formation by suppressing the formation of the equilibrium β-Al_3Mg_2 phase for $5 \le x \le 10$ and $x = 50$. In addition, the solid solubility of Mg in Al can be extended from the equilibrium value of about 1 at.% Mg up to values exceeding 10 at.% Mg. Room temperature compression tests reveal interesting mechanical properties. For example, the samples with compositions in the range $5 \le x \le 20$ display high strength ranging from 375 to 650 MPa combined with a fracture strain in the range of 90–10%. These results indicate that copper mold casting is a suitable processing route for the production of Al–Mg alloys with promising mechanical properties.

1. Introduction

Among the advanced engineering materials, nanocrystalline and ultrafine-grained (UFG) Al–Mg alloys are of great interest due to their remarkable mechanical properties consisting of a beneficial combination of high strength, good ductility and low density [1–4], which makes these alloys potential candidates for automotive and aerospace applications. For example, strength exceeding 700 MPa combined with a ductility of about 8% at room temperature have been reported for nanocrystalline Al-5%Mg with grain size of 26 nm [4]. Similarly, UFG Al-7.5%Mg shows strength of about 600 MPa and plastic deformation exceeding 20% [3].

Non-equilibrium processing techniques, such as solid-state processing and rapid solidification, have been extensively used for the production of this type of materials [1–7]. For example, mechanical alloying as well as mechanical milling of Al–Mg leads to the formation of nanocrystalline supersaturated solid solutions [5,6]. By these techniques, the solid solubility at room temperature of Mg in Al can be extended far beyond the equilibrium concentration (1 at.% [8]) up to 40–45 at.% Mg [5,6]. Beside solid-state processing and rapid solidification for the production of metastable materials, copper mold casting has gained increasing interest as versatile non-equilibrium processing techniques for the production of large variety of materials including amorphous alloys, quasicrystalline and nanocrystalline materials, and composites [9–13].

In this work, $Al_{100-x}Mg_x$ bulk samples with compositions in the range $5 \le x \le 80$ have been produced by copper mold casting and the structure and mechanical properties have been investigated. The results reveal that thanks to its relatively high cooling rate (10–100 K/s [14]), copper mold casting permits the production of materials with metastable structures characterized by promising mechanical properties.

2. Experimental

Ingots with nominal composition $Al_{100-x}Mg_x$ (at.%) with $x = 5$, 10, 15, 20, 30, 40, 50, 60, 70 and 80 (purity > 99.9 wt.%) were prepared by induction melting in argon atmosphere. The ingots were remelted several times in order to achieve a homogeneous master alloy. From these ingots, cylindrical bulk samples with 3 mm diameter and 50 mm length were prepared by copper mold casting. The structure of the samples was studied by X-ray diffraction (XRD) using a Philips PW 1050 diffractometer (Co Kα radiation). The cell parameters of the phases were calculated using the PowderCell software package. The density of the samples was evaluated by the Archimedes principle. According to the ASTM standard for compression testing [15], cylinders with a length/diameter ratio of 2.0 (6 mm length and 3 mm diameter) were prepared from the cast samples. The specimens were tested with an INSTRON 8562 testing facility under quasistatic loading (strain rate of $1 \times 10^{-4}\ s^{-1}$) at room temperature. Both ends of the specimens were polished to make them parallel to each other prior to the compression test.

3. Results and discussion

Fig. 1 shows the XRD patterns of the as-cast $Al_{100-x}Mg_x$ rods with compositions in the range $5 \le x \le 80$. The patterns of the samples with $x = 5$ and 10 are characterized by the presence of few broad diffraction peaks, which can be identified as a supersaturated fcc-Al(Mg) solid solution. The diffraction peaks are rather broad, indicating that the solid solution is of nano or ultrafine dimensions.

* Corresponding author. Tel.: +49 351 4659 838; fax: +49 351 4659 452.
E-mail address: s.scudino@ifw-dresden.de (S. Scudino).

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doi:10.1016/j.jallcom.2010.03.208

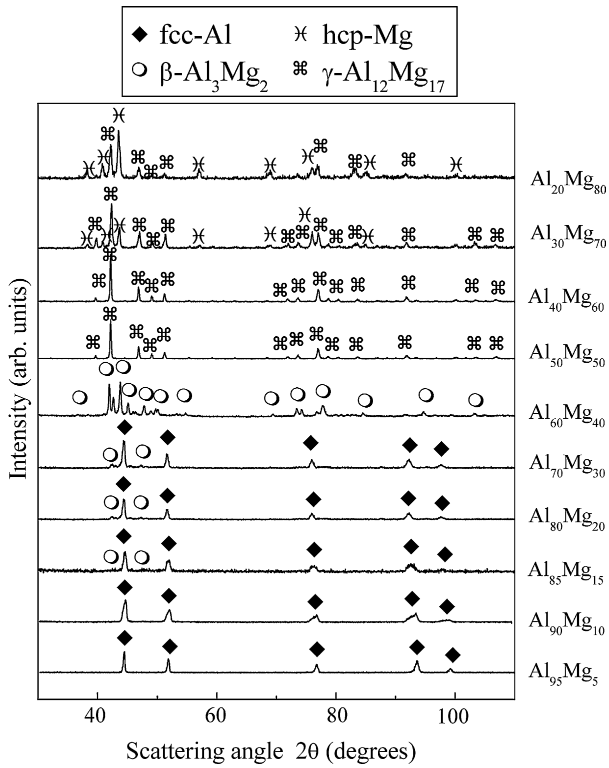

Fig. 1. XRD patterns (Co Kα radiation) for $Al_{100-x}Mg_x$ bulk samples with $5 \leq x \leq 80$ prepared by copper mold casting.

Beside fcc-Al, the patterns of the samples with $x = 15$, 20 and 30 display the presence of an increasing amount of β-Al_3Mg_2 phase, indicating that the formation of the equilibrium phase occurs during solidification. Line broadening increases with increasing Mg content, suggesting the decrease of the grain size with increasing amount of Mg.

The diffraction peaks of the solid solutions in Fig. 1 shift to lower diffraction angles with increasing Mg content. This corresponds to the expansion of the cell parameter of fcc-Al as a consequence of the incorporation of an increasing amount of Mg. The cell parameters of the solid solutions a_0 as a function of the Mg content for the as-cast samples are shown in Fig. 2, together with the data of Luo et al. [7] based on rapidly quenched (RQ) Al–Mg alloys. The values of the cell parameter increase linearly with increasing the

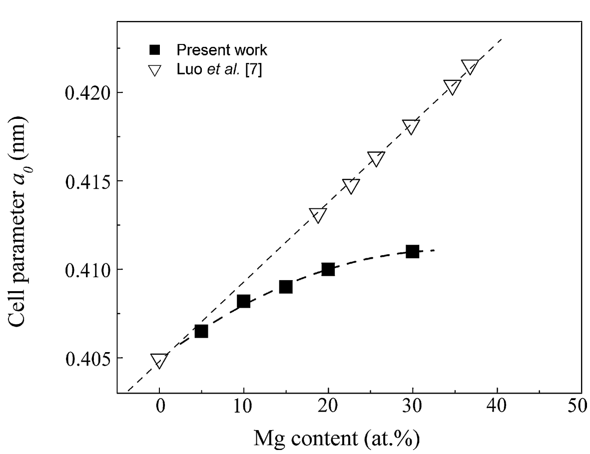

Fig. 2. Lattice parameters a_0 of the fcc-Al(Mg) solid solutions as a function of the Mg content for $Al_{100-x}Mg_x$ cast rods (squares) [present work] and rapidly quenched Al–Mg alloys [7] (triangles).

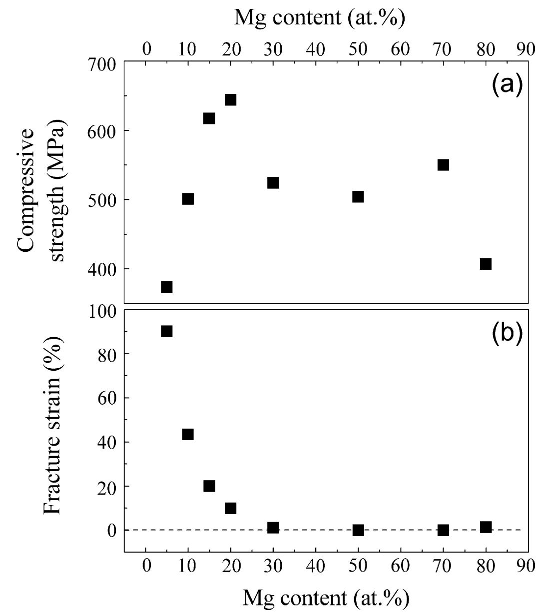

Fig. 3. Compressive strength (a) and fracture strain (b) for the $Al_{100-x}Mg_x$ cast rods evaluated by room temperature compression tests.

Mg content for the RQ Al–Mg alloys (triangles). The cell parameter of the present rods (squares) follows the trend characterizing the RQ Al–Mg alloys for the compositions $x = 5$ and 10, whose structure consists of a single-phase solid solution (Fig. 1), and then it diverges from the data of Luo et al. for larger Mg contents. This is most likely due to the formation of the β-Al_3Mg_2 phase in the cast samples with $x > 10$ (not observed for the RQ alloys [7]), which subtracts an increasing amount of Mg to the solid solution, thus giving a smaller value of the cell parameters than that expected from the linear relationship of Luo et al. [7]. Although the solute content in the solid solutions of the samples with $x > 10$ cannot be evaluated precisely, Fig. 2 suggests that the amount of Mg should exceed 10 at.%.

The pattern of the Al–Mg rod with $x = 40$ shows the formation of the equilibrium β-Al_3Mg_2 phase (Fig. 1). On the other hand, the sample with composition $x = 50$, which should consist of β-Al_3Mg_2 and γ-$Al_{12}Mg_{17}$ phases when prepared at equilibrium conditions [8], displays the formation of single-phase γ-$Al_{12}Mg_{17}$. Single-phase γ-$Al_{12}Mg_{17}$ is also observed for $x = 60$. The cell parameter of the γ-$Al_{12}Mg_{17}$ phase increases from 1.047 to 1.056 nm with increasing the amount of Mg from 50 to 60 at.%. The expansion of the lattice parameter with increasing Mg content is most likely due to the larger atomic diameter of Mg with respect of Al. At equilibrium, the γ-$Al_{12}Mg_{17}$ phase is stable at room temperature only at the composition of about 60 at.% Mg. Therefore, the relatively high cooling rate characterizing copper mold casting [14] suppresses the formation of β-Al_3Mg_2 in the sample with composition $x = 50$. This is in agreement with recent results reporting an extension of the homogeneity range of the γ-$Al_{12}Mg_{17}$ phase to $50 \leq x \leq 70$ by solid-state non-equilibrium processing [16]. Finally, in the range $70 \leq x \leq 80$, casting leads to the formation of two-phase nanostructured materials consisting of the equilibrium γ-$Al_{12}Mg_{17}$ and hcp Mg phases (Fig. 1).

The mechanical properties of the cast rods were evaluated by room temperature uni-axial compression tests and the corresponding mechanical properties are summarized in Fig. 3 as a function of the Mg content. The $Al_{100-x}Mg_x$ samples with compositions in the range $5 \leq x \leq 20$ display high strength combined with remarkable plastic deformation. The compressive strength (the maximum compressive stress which the material is capable of sustaining [17]) sharply increases from 375 MPa for the sample with $x = 5$ to about

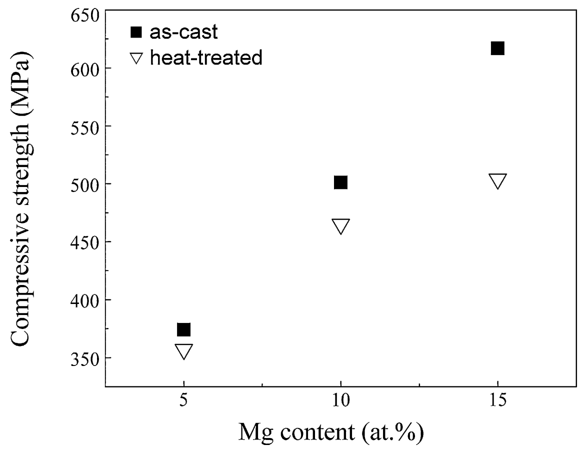

Fig. 4. Compressive strength for the as-cast and heat-treated $Al_{100-x}Mg_x$ rods with $x = 5$, 10 and 15.

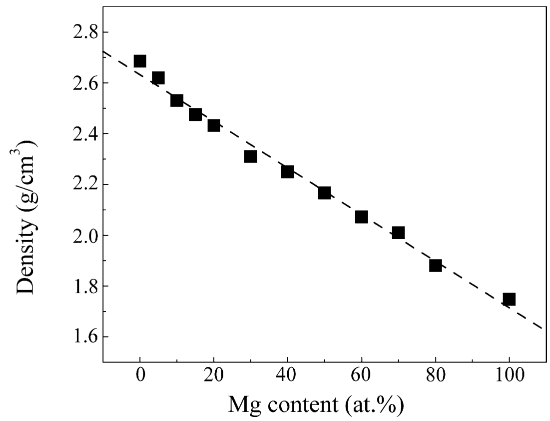

Fig. 5. Density of the Al–Mg cast rods as a function of the Mg content.

650 MPa for the rod with 20 at.% Mg [Fig. 3(a)]. At the same time, the fracture strain [Fig. 3(b)] decreases from 90% to about 10%. With increasing Mg content to 30 at.%, the compressive strength as well the fracture strain are remarkably reduced to 525 MPa and 1.5%, respectively. The sample consisting of the single-phase γ-$Al_{12}Mg_{17}$ ($x = 50$) shows similar characteristics: strength of about 500 MPa and fracture strain not exceeding 1%. Finally, compressive strength of 550 and 410 MPa and values of fracture strain of about 1% and 2% are observed for the samples with $x = 70$ and 80, respectively.

The absence of measurable plastic deformation for the Al–Mg samples with compositions in the range $30 \leq x \leq 80$ is most likely due to the larger amount of intermetallic phases than the samples with lower Mg content. Intermetallic compounds are generally brittle at room temperature. A typical example of RT brittleness of intermetallics is given by the Laves phases [18]. The RT brittleness of the Laves phases is due to their complex close-packed structure and the resistance to dislocation motion [19]. Plastic deformation in Laves phases occurs only at temperatures above two-thirds of the melting point [18] by the "synchroshear" mechanism, which involves the simultaneous motion of atoms on adjacent atomic planes [20,21]. This mechanism is difficult at low temperatures [22], explaining the brittle behavior observed at room temperature. Intermetallics with complex structures, such as β-Al_3Mg_2 and γ-$Al_{12}Mg_{17}$ phases, behave in a similar way. For example, the single-phase β-Al_3Mg_2 does not show plastic deformation at room temperature, while it extensively deforms plastically for temperatures above 500 K [23].

The effect of the high cooling rate (10–100 K/s [14]) and of the corresponding metastable structure formation on the mechanical properties of the cast materials can be appreciated by considering Fig. 4, where the compressive strength of the as-cast rods with $x = 5$, 10 and 15 are plotted together with the strength of the same samples heat-treated at 673 K for one hour in order to obtain the equilibrium microstructure. The difference of compressive strength between metastable and equilibrium structures increases from about 20 MPa for the rod $x = 5$ to more than 100 MPa for the sample with $x = 15$, which indicates that the effectiveness of copper mold casting for improving the mechanical behavior of these materials increases with increasing the amount of Mg.

Fig. 5 shows the density of the cast rods as a function of the Mg content. The density decreases linearly with increasing amount of Mg from about 2.6 g/cm^3 for $x = 5$ to 1.88 g/cm^3 for the sample with $x = 80$. A high specific strength (tensile or compressive strength divided by the density) is one of the most important aspects of lightweight materials. The increase of strength (Fig. 3) together with the simultaneous decrease of density remarkably increases the specific strength of the current samples. For the samples with compositions in the range $5 \leq x \leq 20$, which display high strength combined with remarkable plastic deformation, the specific strength sharply increases from 143 kNm/kg for $x = 5$ to 265 kNm/kg for the sample with $x = 20$. These values of specific strength are higher than those reported for lightweight materials, such as Al-based composites reinforced with ceramic particles [24,25] (about 110 kNm/kg) and with metallic glasses [26] (about 105 kNm/kg), and they are of the same magnitude of high-strength nanostructured Al-based alloys [27] (280 kNm/kg) and Mg-based metallic glasses [28] (290 kNm/kg).

4. Summary

$Al_{100-x}Mg_x$ bulk samples with compositions in the range $5 \leq x \leq 80$ have been produced by copper mold casting and the structure and mechanical properties have been investigated. The relatively high cooling rate characterizing copper mold casting has a remarkable effect on the structure of the rods. Structure investigations shows that the diffraction peaks of the different phases are rather broad, indicating that the phases are of nano or ultrafine-grained dimensions. Casting suppresses the formation of the equilibrium β-Al_3Mg_2 in the samples with $x = 5$, 10 and 50. In addition, the solid solubility of Mg in Al can be extended from the equilibrium value of about 1 at.% Mg up to values exceeding 10 at.% Mg. Room temperature compression tests of the cast rods reveal interesting mechanical properties. The samples with compositions in the range $5 \leq x \leq 20$ show high strength ranging from 375 to 650 MPa combined with a fracture strain in the range 90–10%. The compressive strength of the rods with $x \geq 30$ ranges from 550 to 410 MPa but with negligible plastic deformation. These preliminary results indicate that copper mold casting is a suitable processing route for the production of Al–Mg alloys with promising mechanical properties.

Acknowledgments

The authors thank B. Bartusch, M. Frey, H.-J. Klauß and H. Schulze for technical assistance, and U. Kühn and M. Stoica for stimulating discussions. This work was supported by the EU within the frameworks of the European Network of Excellence on Complex Metallic Alloys, NoE CMA (contract No. NMP3-CT-2005-500140). K. B. Surreddi is grateful for the financial support provided by the DAAD. F. Ali acknowledges the PIEAS for financial support.

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