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Mechanical properties of Mg–Li–Cu–Y metallic glass composites

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ABSTRACT

The mechanical behaviour of $Mg_{65-x}Li_xCu_{25}Y_{10}$ ($x = 9$, 14 and 19) metallic glass composites has been studied. For 9 and 14 at.% Li the alloys exhibit a brittle behaviour. The microstructure of the alloy containing 9 at.% Li consists of a bcc Mg-Li solid solution phase embedded in an amorphous phase. Higher concentrations of Li promote the formation of the bcc phase, Mg_2Cu and also a small volume fraction of Y-containing intermetallic. The alloy with the highest Li content, i.e. 19 at.%, exhibits a compressive engineering strain of 25%. The hierarchical microstructure design with multiphase components allows for the operation and interaction of different deformation behaviour to provide for useful levels of plastic deformation.

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1. Introduction

Monolithic Mg-based bulk metallic glasses (BMGs) are interesting because they have high specific strength. However, they are among the most brittle BMGs, which is a severe limitation for their use in engineering applications. Since Inoue et al. [1] reported in 1988 the production by melt-spinning of Mg–Ce–Ni amorphous ribbons different monolithic Mg-based BMGs have been fabricated such those corresponding to the Mg–Cu–Y system [2].

In order to improve their ductilily it is necessary to avoid the formation of highly localized shear bands that can lead to catastrophic failure. For this reason, to improve the ductility it is favorable to limit the propagation of shear bands and to distribute the plastic strain over a number of shear bands. This objective can be achieved fabricating metallic glass composites [3] by adding particles from outside (ex situ composite) or adding an element having a positive heat of mixing with at least one of the elements of the alloy so that it tends to be segregated during solidification (in situ composite). For example, it was reported [4] that the addition of large enough amounts of Li to the Mg–Cu–Y system can lead to the formation of a bcc phase in 1 mm thick as-cast strips. However, while this microstructure has the potential to exhibit ductility, the mechanical behaviour has not been previously studied.

2. Experimental procedure

Elements with purity higher than 99.9 wt.% were used as starting materials. Master alloys of Cu–Y were prepared by arc melting in a Ti-gettered high purity argon atmosphere. They were re-melted at least three times to obtain good chemical homogeneity. Stoichiometric amounts of master alloys were then melted with Mg and Li in an induction furnace under a high purity argon atmosphere to obtain the required alloys. Rod samples with a diameter of 2 mm were obtained by remelting the alloy in a quartz tube and subsequent injection into a copper mold in a purified inert atmosphere. The cross-sections of the as-cast rods were analyzed by X-ray diffraction (XRD) in a Rigaku D/max 2400 diffractometer with monochromated Cu Kα radiation. The volume fraction of different constituent phases was calculated using the linear intercept method. In this approach, a test pattern of lines of known length is randomly laid over a plane section, and the individual intercept lengths across features of interest are measured.

Uniaxial compression tests of samples 2 mm in diameter and 4 mm length were performed at room temperature at a strain rate of $5 \times 10^{-4}\ s^{-1}$. The Vickers hardness was obtained from 10 measurements using a Mitutoyo macroindenter HM-211. The microstructure and morphology of the fracture surface were observed using a scanning electron microscope (SEM). The formation of glassy structure was confirmed by transmission electron microscopy (TEM) using nano-beam electron diffraction (NBED).

3. Results and discussion

Fig. 1 shows the XRD patterns taken from the cross-section of the 2 mm diameter $Mg_{65-x}Li_xCu_{25}Y_{10}$ ($x = 9$, 14, 19) rods. For the alloy with 9 at.% Li only one low intensity peak associated with the bcc phase superimposed on a broad peak is detected. However, for Li contents of 14 and 19 at.% two additional weak peaks associated with the bcc phase, high intensity peaks corresponding to a Mg_2Cu phase and very weak peaks associated with Y-containing intermetallic ($Mg_{24}Y_5$ or Mg_2Y) were detected. While the high intensity XRD peaks detected in the 2 mm diameter as-cast rods with 14 and 19 at.% Li content would suggest that the alloys are fully crystalline,

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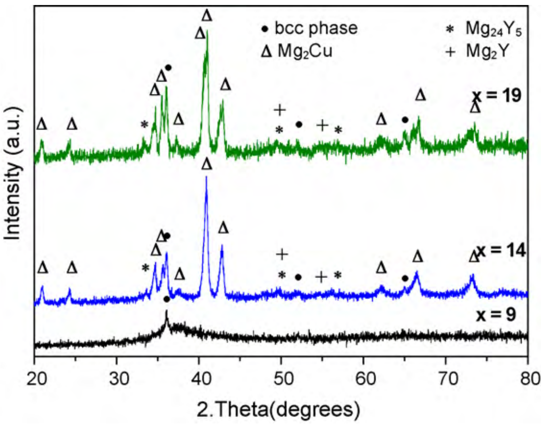

Fig. 1. XRD patterns of the 2 mm diameter $Mg_{65-x}Li_xCu_{25}Y_{10}$ (x = 9, 14, 19) as-cast rods.

the HRTEM of Fig. 2a shows that amorphous regions are observed even for 19 at.% Li. For this alloy, the presence of the bcc phase has been confirmed by nano-beam electron diffraction (NBED) in TEM (Fig. 2b).

Fig. 3a shows the compressive engineering stress–strain curves of the 2 mm diameter $Mg_{65-x}Li_xCu_{25}Y_{10}$ (x = 9, 14, 19) as-cast rods tested at room temperature. The alloys with 9 and 14 at.% Li are brittle probably because the volume fraction of ductile bcc Mg–Li solid solution phase is too low to arrest the shear bands: 11–18 vol.% (for 9 at.% Li), 17–19 vol.% (for 14 at.% Li) and 16–25 vol.% (for 19 at.% Li). It is suggested that there is a critical concentration of about 20 vol.% bcc solid solution phase above which the alloy exhibits compressive plasticity. When the Li content increases from 9 to 14 at.% the compressive strength and hardness decreases from 615 to 590 MPa and from 213 to 166 HV, respectively. However, the compressive plasticity of the alloy with the highest Li content, i.e. 19 at.%, increases dramatically to 25% and exhibits an ultimate compressive strength of 585 MPa. The lower density of Li than that of Mg is responsible for the relatively small density of the 19 at.% Li-containing alloy which has a specific strength of 1.95×10^5 N m kg^{-1}. This value is slightly higher than the specific strength of $M_{65}Cu_{7.5}Ni_{7.5}Zn_5Ag_5Y_{10}$ [5] and similar to the specific strength of $Mg_{65}Cu_{25}Tb_{10}$ [6,7], though its compressive plasticity is larger.

The SEM fracture surface (Fig. 3b) of the 2 mm diameter $Mg_{56}Li_9Cu_{25}Y_{10}$ rod shows a very smooth and featureless surface along with a river pattern associated with cleavage fracture of brittle materials. This fracture morphology is consistent with the brittle

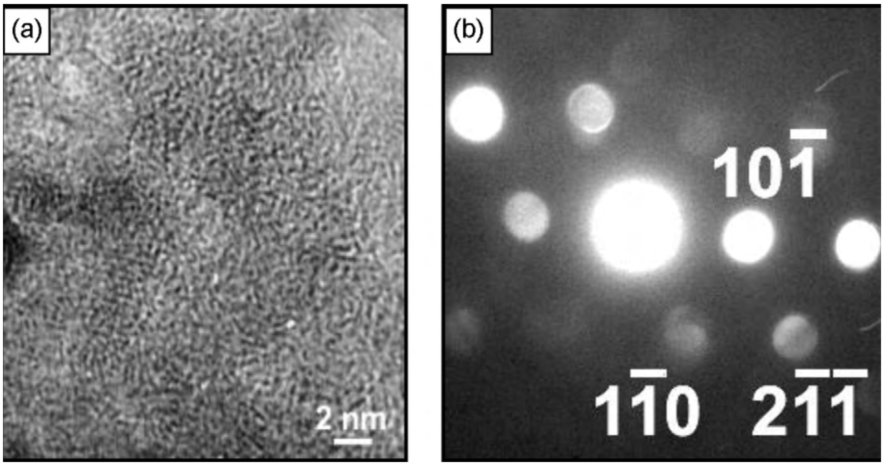

Fig. 2. (a) HRTEM micrograph of the amorphous phase and (b) NBED pattern of the bcc phase for the 2 mm diameter as-cast $Mg_{46}Li_{19}Cu_{25}Y_{10}$ rod.

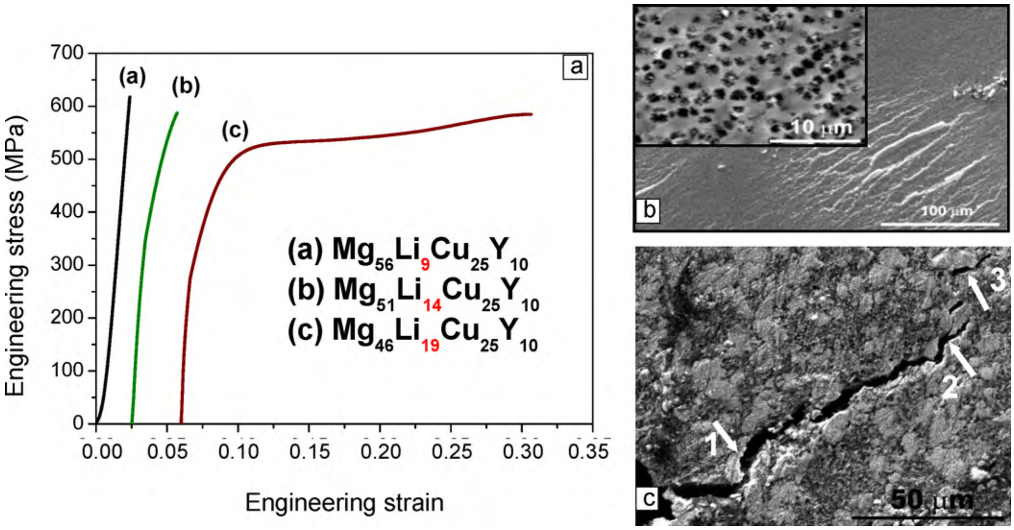

Fig. 3. (a) Compression engineering stress–strain curves for the 2 mm diameter as-cast rods. (b) SEM micrograph of the fracture surface of the 2 mm diameter as-cast $Mg_{56}Li_9Cu_{25}Y_{10}$ rod. (c) SEM micrograph of the crack tip propagating in the 2 mm diameter as-cast $Mg_{46}Li_{19}Cu_{25}Y_{10}$ rod. The crack can propagate through the Mg_2Cu phase (1), and it can be diverged (2) or deflected (3) by the Mg_2Cu phase.

behaviour in compression that can be explained by a localized shear mechanism. The inset shows a magnified image of the fracture surface with a high volume fraction of 1–3 μm size particles. From the XRD results it can be deduced that these particles correspond to the bcc Mg–Li solid solution phase embedded in an amorphous phase. However, the microstructure of the alloy is different for higher Li contents. As was previously reported by us [8], the presence of a large volume fraction of soft bcc Mg–Li phase that can be easily deformed in combination with the Mg_2Cu phase that can interact with cracks accounts for the compressive plasticity of the 19 at.% Li containing alloy. The composite containing 9 at.% Li deforms by shear banding. The composite containing 19 at.% Li deforms differently depending on the plastic strain [8], for low loads the bcc phase work-hardens by dislocation slip and the large Mg_2Cu phase fractures. For larger plastic strain the microcrack propagation can be hindered by the ductile bcc phase and interacts with the Mg_2Cu phase (intergranular or transgranular). In this work the focus is on the interaction of cracks with the Mg_2Cu phase which has a large influence on the malleability of the 19 at.% Li-containing alloy as it can limit the propagation of cracks.

The SEM micrograph of Fig. 3c shows the propagation of a crack through the microstructure of a 2 mm diameter as-cast $Mg_{46}Li_{19}Cu_{25}Y_{10}$ rod tested in compression. According to the energy dispersive X-ray analysis (EDX) in SEM, the bright phase corresponds to Mg_2Cu (13–27 vol.%) and the small dark regions to the bcc phase (16–25 vol.%). When the macrocrack tip starts to propagate, the stored strain energy is initially high enough to propagate through the Mg_2Cu phase (transgranular fracture marked by arrow 1 in Fig. 3c). However, as the crack grows, the energy is partially released so that the energy at the crack tip is sufficiently low to diverge (arrow 2) or deflect (arrow 3) when it reaches a large Mg_2Cu phase.

4. Conclusions

The $Mg_{65-x}Li_xCu_{25}Y_{10}$ alloys with 9 and 14 at.% Li are brittle, but for 19 at.% Li, the alloy has a compressive plasticity of 25% and an ultimate compressive strength of 585 MPa. The large volume fraction of soft bcc Mg–Li phase that can be easily deformed and the interaction of the cracks with the Mg_2Cu phase accounts for the remarkable ductility.

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