Journal of Alloys and Compounds 648 (2015) 18–21

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

journal homepage: http://www.elsevier.com/locate/jalcom

# The effect of cooling rate on the plasticity of amorphous metal

Z.J. Ma [a, *], Y.C. Guo [a], Lugee T. Li Yeung [b], P.H. Gao [a, c], Z. Yang [a], X.R. Zeng [d]

[a] School of Materials and Chemical Engineering, Xi'an Technological University, Xi'an 710032, PR China
[b] Eontec Company Limited, DongGuan 523000, PR China
[c] State Key Laboratory for Mechanical Behavior of Materials, School of Materials Science and Engineering, Xi'an Jiaotong University, Xi'an 710049, PR China
[d] Shenzhen Key Laboratory of Special Functional Materials, Shenzhen Laboratory of Ceramic Technology and Engineering, College of Materials Science and Engineering, Shenzhen University, Shenzhen 518060, PR China

ARTICLE INFO

*Article history:*
Received 4 May 2015
Received in revised form
24 June 2015
Accepted 26 June 2015
Available online 2 July 2015

*Keywords:*
Amorphous
Cooling rate
Plasticity
High vacuum die-casting

ABSTRACT

The deficient plasticity is one of the largest barriers for the application of amorphous metal as structural materials. In this article, how to improve the plasticity of amorphous metal by means of adjusting the cooling rate was discussed in detail. The experimental samples were prepared by high vacuum die-casting with $Zr_{53.2}Ti_{13.8}Cu_{8.9}Ni_{5.6}Be_{13.5}Nb_5$ (at. %) and $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}$ $Be_{22.5}$ (at. %). And then the plastic samples were compared with the common amorphous samples from perspective of preparation parameters and microstructure. The relationship among mechanical properties, cooling rate and microstructure was discussed so as to discover the essential microstructural mechanism of plasticity of amorphous metal. As for $Zr_{53.2}Ti_{13.8}Cu_{8.9}Ni_{5.6}Be_{13.5}Nb_5$ alloy whose critical cooling rate is higher, the morphology of crystalline phases can be adjusted by changing the cooling rate to improve its plasticity. As for $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}$ $Be_{22.5}$ alloy whose critical cooling rate is lower, phase separation which can be obtained by controlling the cooling rate would be an effective method to get amorphous metal with high plasticity. In other words, appropriate cooling rate is a key important parameter to make the brittle amorphous metal into ductile materials.



## 1. Introduction

The excellent mechanical properties of amorphous metal have received more and more attention in the advanced materials field because of its special atomic arrangement inherited directly from the liquid state [1–5]. In recent years, the increments of amorphous system and critical dimension have also laid foundation for the practical application of its commercialization [6–8].

Because slip plane and dislocation mechanism don't exist in amorphous metals which are different from common polycrystalline metal, its ability of plastic deformation is very poor. Usually the compression plastic strain is not more than 2% and tensile plastic strain at room temperature is almost zero. That has seriously restricted the application of amorphous metals as structural materials in engineering [9]. In 2007, W.H. Wang's research group prepared amorphous metal with high strength (>1.7 GPa) and high compression plasticity (>150%) at room temperature. Since then, the plasticity of amorphous metal became the research focus of material scientists again as one of the core scientific questions in amorphous physics and material field [10].

There have been several approaches to improve the ductility of amorphous metal, which can be generally classified into two categories. The first method is the adjustment of component or preparation process which can bring into the microstructural heterogeneities in amorphous metal [11,12]. The other one is to add the dispersive inclusions (second phases) which adopt the principle of composite materials [13–17]. In addition, surface modification was one of the most important ways to improve the plasticity of amorphous metal [18–21]. In conclusion, the aim of all these methods is to multiply the shear bands and induce a more homogeneous distribution of plastic deformation. And the control of process parameters plays a crucial role during ductile amorphous metal preparation.

Among these process parameters, the cooling rate was undoubtedly the most important influencing factor [22–27] and the concept of critical cooling rate appeared with the birth of amorphous metal. However, there is little research about the effect of cooling rate on the plasticity of amorphous metal. In this paper, the critical cooling rate would not be our focus. Above or below the critical cooling rate, the effect of different cooling rate on the plasticity of amorphous metal will be discussed respectively.

* Corresponding author.
*E-mail addresses:* 9216053@qq.com, zhijun_ma@hotmail.com (Z.J. Ma).

http://dx.doi.org/10.1016/j.jallcom.2015.06.212
0925-8388/

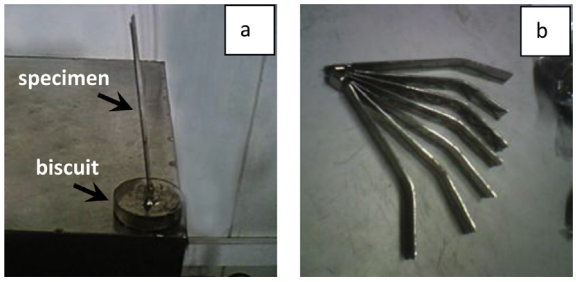


**Fig. 1.** (a) As-cast plate sample with biscuit and (b) some plastic samples after three-point bending test.

## 2. Experimental materials and methods

Two kinds of amorphous metals, $Zr_{53.2}Ti_{13.8}Cu_{8.9}Ni_{5.6}Be_{13.5}Nb_5$ (at.%) and $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10}Be_{22.5}$ (at.%), were involved in this paper and referred to as A and B respectively. Alloy B with high glass-forming ability (GFA) is the first commercial amorphous metal produced by Liquidmetal Technologies in 1992 [28] and also named as vit1. One of the key differences between alloy A and B is the addition of element Nb which leads to the decrease of GFA in alloy A.

The master alloy ingots with a nominal composition were prepared by arc-melting mixtures of Cu(99.99%), Zr(99.99%), Ti(99.99%), Ni(99.9%), Nb(99.99%) and Be (impurity < 0.01%) under Ti-gettered high-purity argon atmosphere. The ingots were up-side down and remelted three times in order to ensure chemical homogeneity. And then the ingots were remelted and vacuum die-cast into different mold to obtain the plate specimens (Fig. 1a) with dimensions of 100 mm × 10 mm × 0.8 mm. During sample preparation of alloy A, there were three kinds of mold with different cooling rate, which were made of steel, copper and water-cooled copper respectively. And the corresponding sample identifications were A1, A2 and A3. Likewise, sample B1 and B2 were prepared by steel and copper mold respectively as for alloy B.

After cutting the biscuit from the as-cast plate samples, three-point bending tests were carried out using Sans ETM503C testing device at a constant strain rate 0.001 $s^{-1}$. Some tested samples were shown in Fig. 1b. The morphology of crystalline phase was observed by optical microscopy (OM; Leica DM2500P). The structural characterization was examined by X-ray diffraction (XRD; SHIMADZU, LabX XRD-6000) with Cu Kα radiation. The detailed microstructures were investigated by high-resolution transmission electron microscopy (HRTEM; JEOL, JEM-2010F) combined with energy dispersive X-ray spectrometry (EDX; Oxford instrument INCA system). Thin foils for HRTEM investigation were prepared using Precision Ion Polishing System (GatanModel 691) with a liquid-nitrogen cooling system at beam energy of 2.5 KeV.

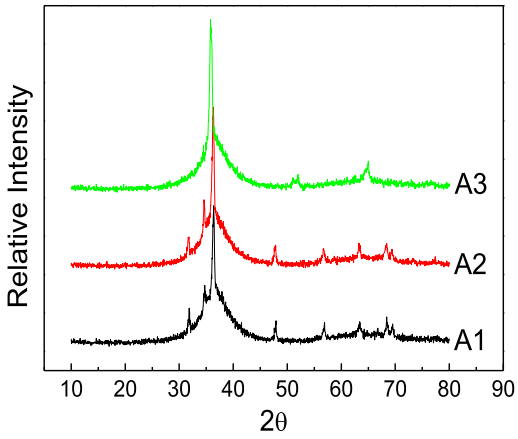


**Fig. 3.** The XRD spectra of sample A1, A2 and A3.

## 3. Results and discussion

### 3.1. The effect of cooling rate on the properties of alloy A

Fig. 2a presents the typical stress–strain curve of three types of samples, A1, A2 and A3. Obviously, the three-point bending strength of A2 and A3 is almost same. Moreover, A2 possesses the best plasticity among these three types of samples. Both the

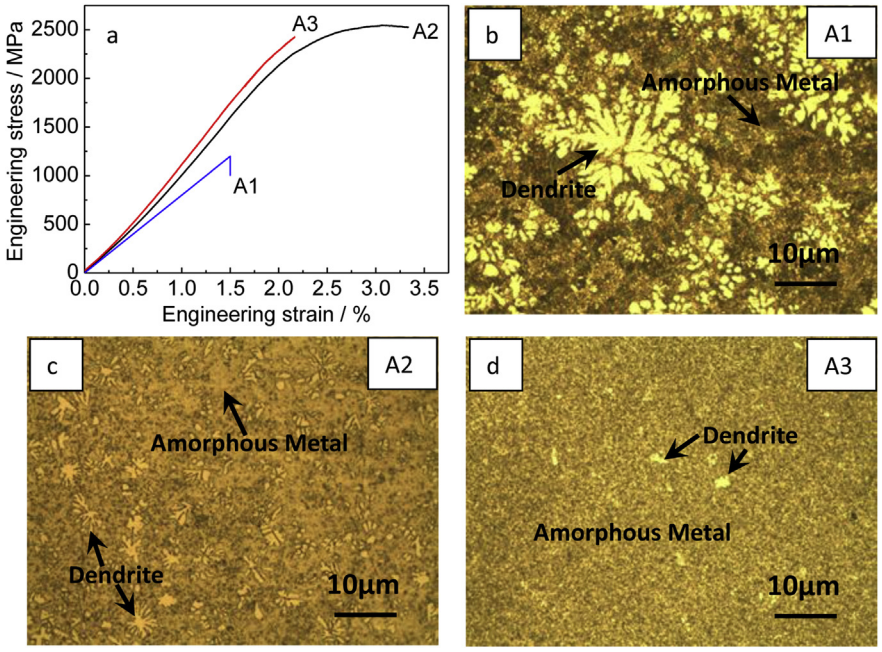


**Fig. 2.** (a) Typical three-point bending stress–strain curve of three kinds of samples A and the corresponding OM micrographs of the (b) A1, (c) A2 and (d) A3.