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Characterization and modelling of *in-situ* La-based bulk metallic glass composites under static and dynamic loading

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ABSTRACT

Samples of La-based bulk metallic glass composites (BMGC) were tested under both static and dynamic compression, and their deformation mechanism analysed. The strain rates imposed ranged from $6 \times 10^{-5}/s$ to $1.6 \times 10^{3}/s$. Quasi-static compression was performed using an Instron universal testing machine, while dynamic compression was applied by means of a Split-Hopkinson Pressure Bar (SHPB), which was used to study the rate sensitivity of this type of material. La-based BMGC samples with different degrees of crystallinity were also fabricated to examine the influence of crystalline volume fraction on the composite. A high speed infrared (IR) camera was employed to measure the temperature increase during deformation. This study focused on: (1) characterization of the deformation mechanism and strain rate sensitivity of BMGC; (2) the influence of crystalline volume fraction on BMGC material and (3) establishment of a large-deformation rate-independent thermomechanical constitutive model, suitable for incorporation a finite element analysis (FEA) code.

1. Introduction

Bulk metallic glass (BMG) has been widely studied in recent decades because of its high strength and relatively large elastic strain. However, because of an absence of a work hardening mechanism in monolithic BMG, the material generally fails upon yielding and shows little plasticity at room temperature, which limits its the application in structural components. Many attempts have been made to enhance the toughness of BMG. Generally, plasticity in BMG is attributed to the creation and interaction of multiple shear bands. Many BMGs have been found to exhibit finite global plasticity in compression, while no plasticity in tension at room temperature [1–3]. This is because when plastic deformation occurs, propagation of some micro shear bands may be constrained by hydrostatic press in compression; this prohibits the creation of major shear band or even fracture. Consequently, more micro shear bands will be initiated in order to accommodate continued deformation. This mechanism accounts for the ductility. Inspired by this, it has been found that adding a second reinforcement phase into monolithic BMG material can also inhibit shear band propagation, and hence enhance ductility. Research groups from Caltech first proposed the possibility of synthesizing BMG composites (BMGC) [4] and found that introducing tungsten and 1080 steel wires into $Zr_{41.25}Ti_{13.75}Cu_{12.5}Ni_{10}Be_{22.5}$ matrix could greatly enhance the toughness of the amorphous alloy [5]. Subsequently, another class of BMGCs was also synthesized by incorporating a crystalline phase formed *in-situ* [6]; this precipitated second phase is able to constrain the propagation of shear bands, and accommodate a large increase in global plastic strain and impact resistance.

Depending on how the second crystalline phase is introduced into the BMGC alloy, the material synthesis procedure can be either *in-situ* or *ex-situ*. For *in-situ* composites, the second phase precipitates out of the metallic glass either during casting or post-processing of the amorphous alloy. For *ex-situ* methods, a reinforcement phase is added during casting of the alloy. Hence, the interface between the glassy matrix and the crystalline phase is much stronger for *in-situ* composites [7]. Experiments also show that *in-situ* BMGCs are better able to limit the propagation of shear bands and promote generation of multiple shear bands; this facilitates an increase in plasticity, compared to *ex-situ* composites.

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Considerable work has been done to identify the deformation mechanisms in BMGCs, and it is well recognized that retarding shear band initiation and propagation, as well as the promotion of multiple shear band creation influence their toughness [7,8]. However, most of these studies have focused only on Zr-based BMGCs, and little experimental data is available for other types of such composites. Whether the plastic deformation mechanism is similar for all BMGCs is debatable. Furthermore, previous experimental work on the mechanical behaviour of BMGCs at dynamic strain rates is very limited [9–11]; the effect of strain rate of this type of material is still not fully understood. Therefore, further experimental investigation on a variety of BMGC materials is required for a better understanding of their deformation mechanisms, as well as their mechanical response at different strain rates.

Recently, Li and his co-workers conducted systematic studies on synthesizing La-based BMGCs with different volume fractions of the crystalline phase (denoted by v_f) [12]; their mechanical behaviour was examined [13]. However, their study focused primarily on static deformation, with only some qualitative descriptions of dynamic tests using a Charpy device. Liu and Shim [14] have conducted some strain rate sensitivity studies on monolithic La-based BMG, but have not provided any information on composites. Lee et al. [13] concluded that the yield strength in compression and tension obey a rule of mixtures relationship, but this assertion is not always valid. Schuh et al. [8] examined the results of numerous experimental studies and highlighted that the rule of mixtures is only valid for low volume fractions ($v_f < 0.3$) of the crystalline phase for dendritic *in-situ* composites. Therefore, further experiments are needed to investigate the effect of the degree of crystallinity.

Constitutive models are used to describe the mechanical behaviour of materials and there has been extensive work on constitutive modelling of BMG. There are some recent examples of continuum-based theories capable of modelling the response of metallic glass deformation [15–21]. These models treat free volume as a state variable, and apply various flow rules for evolution of plastic deformation. However, most of these studies focused on BMG modelling at high temperatures. The model developed by Anand and Su [16] is suitable for room temperature, but they focused on only monolithic BMG material.

Recently, Marandi and Shim [22] proposed a constitutive model for bulk metallic glass composites based on the work of [19]. In their model, a rule-of-mixtures relationship for the Cauchy stress and an affine deformation assumption were adopted, i.e.

$$\mathbf{F} = \mathbf{F}_{(1)} = \mathbf{F}_{(2)} \tag{1}$$

where $\mathbf{F}_{(1)}$ and $\mathbf{F}_{(2)}$ are the deformation gradients for the crystalline and amorphous phases. However, this assumption is only valid for small elastic deformation. For large plastic strain and large crystallinity volume fractions, it is generally believed that this assumption is not satisfied [8]. Therefore, further investigation is required to develop a large-deformation constitutive model.

Consequently, in this study, the La-based BMGC developed by Lee et al. [13]. is examined in relation to various experimental tests. The following Section (Section 2) introduces the BMGC fabrication and testing methodology. In Section 3, experimental results obtained are analysed and discussed in detail, including a study of the deformation micro-mechanism and rate-dependence, as well as the influence of degree of crystallinity. A high speed infra-red (IR) camera is also utilised to capture the temperature rise during deformation. In Section 4, a large-deformation thermo-mechanical constitutive model is established, and conclusions are presented in Section 5.

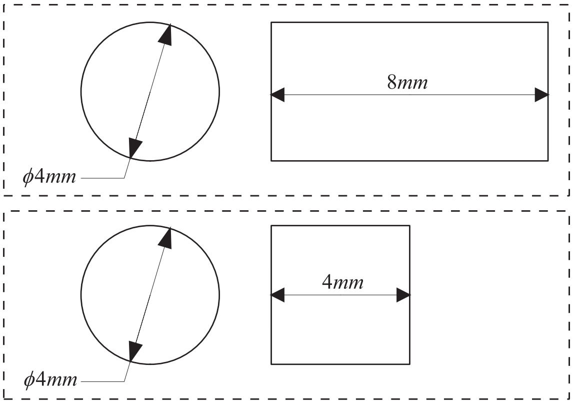

Fig. 1. Orientations of test samples with different aspect ratios.

2. Material fabrication and testing

In this study, $La_{74}Al_{14}Cu_6Ni_6$ BMGC alloy with a 50% volume fraction[1] crystalline dendrite phase was prepared by arc-melting a mixture of La (99.9%), Al (99.9%), Ni (99.98%) and Cu (99.9999%) in an argon atmosphere, according to the work of Lee et al. [13]. The molten alloy was then injected into a copper mold to produce ingots. The as-cast ingots were machined into small cylindrical specimens, 4 mm in diameter. Samples with two aspect ratios, 2:1 and 1:1 were fabricated for static and dynamic compression tests, respectively, as shown in Fig. 1. The specimen surfaces which came into contact with the testing machines were ground and made parallel to each other. Polishing was effected using super fine 1200 grit silicon carbide paper. At least three tests were performed for each testing condition to ensure that experimental scatter was acceptable.

The microstructure of the composites was examined by optical microscopy, as shown in Fig. 2, where the black areas represent the crystalline α-La phase and the white areas are the monolithic amorphous phase [13]. The volume fraction of the crystalline phase is around 50%, which is measured from the micrograph, using image analysis. An X-ray Diffraction (XRD) pattern for this composite is given in Fig. 3, and shows intense peaks corresponding to a crystalline HCP lanthanum phase in the form of dendrites. These peaks do not appear in XRD spectrum for monolithic BMG because of its intrinsic amorphous structure.

Compression tests at quasi-static strain rates were performed using an Instron 8874 universal testing machine. The specimen contact surfaces were ground and lubricated by molybdenum disulphide (MoS_2) to reduce friction. Constant strain rates between $6 \times 10^{-5}/s$~$1 \times 10^{-2}/s$ were applied; these were measured directly from a strain gauge attached to the specimen. Dynamic compression tests were conducted using a Split-Hopkinson Pressure Bar (SHPB) device. Annealed copper disks were employed as pulse shapers, and inserted between the striker and the input bar to promote stress equilibrium and constant strain rate during plastic deformation. In these tests, the strain rates ranged from $200/s$ to $1600/s$. Fracture surfaces and specimen microstructure were observed using field emission scanning electron microscopy (FE-SEM).

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[1] For simplicity, the crystalline phase volume fraction is denoted by v_f.