International Journal of Impact Engineering 106 (2017) 110–119

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

Compressive behaviour of tungsten fibre reinforced Zr-based metallic glass at different strain rates and temperatures

Gang Chen[a], Yifei Hao[b,*], Xiaowei Chen[c,d], Hong Hao[e]

[a] *Shock and Vibration of Engineering Materials and Structures Key Laboratory of Sichuan Province, Institute of Systems Engineering, China Academy of Engineering Physics, Mianyang, Sichuan 621999, China*
[b] *Key Laboratory of Coast Civil Structure Safety of Ministry of Education, Tianjin University, Tianjin 300072, China*
[c] *Advanced Research Institute for Multidisciplinary Science, Beijing Institute of Technology, Beijing 100081, China*
[d] *The State Key Lab of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, China*
[e] *Tianjin University and Curtin University Joint Research Center of Structural Monitoring and Protection, Centre for Infrastructural Monitoring and Protection, School of Civil and Mechanical Engineering, Curtin University, Bentley, WA 6152, Australia*

ARTICLE INFO

Article History:
Received 6 June 2016
Revised 15 January 2017
Accepted 21 March 2017
Available online 22 March 2017

Keywords:
Bulk metallic glass
Tungsten fibre
Mechanical properties
Split Hopkinson pressure bar
Dynamic compression
High temperature

ABSTRACT

Because of the excellent mechanical, physical and chemical properties, bulk metallic glass (BMG) materials have shown profound potential in a wide range of engineering applications. To prevent catastrophic failure of monolithic BMG at very small strains, metal fibres or ceramic particles are normally used to reinforce the material and improve the ductility. Mechanical properties of Zr-based BMG reinforced with 80% Tungsten fibres by volume were experimentally investigated in the present study at room temperature and elevated temperature up to 873 K. The quasi-static and dynamic compressive deformation and fracture behaviour were investigated by means of INSTRON, MTS testing machines and split Hopkinson pressure bar (SHPB), respectively. The failure patterns and mechanical properties of cylindrical specimens with different aspect (length to diameter) ratios under quasi-static compression were studied. It was found that the failure of BMG composite material was resulted from the combination of BMG shear failure, fibres' axial splitting and fibre-matrix debonding. Results of quasi-static tests at different temperatures revealed that the yield strength decreased with temperature, and the strain hardening behaviour was replaced with strain softening after the yield stress when the temperature was elevated. Results from SHPB tests at room temperature showed approximately 30% higher strengths compared to the quasi-static counterpart, but the specimens were found partially losing the deformability and fail at smaller strains. The dynamic strengths were also found to decrease with the increase of temperature. An empirical relation to describe the change of yield strength due to temperature elevation was proposed based on the test data. The mechanism of self-sharpening behaviour of penetrator made of BMG composites was explained based on the material behaviour at high strain rate and high temperature.

1. Introduction

Bulk metallic glass (BMG), known as amorphous alloy, is normally produced by extremely rapid cooling from the liquid state, which hinders the crystallisation kinetics [1]. The microstructure of amorphous alloys is disordered, with atoms of significantly different sizes occupying random positions, and does not have any of the defects that limit the strength of their crystalline counterparts. This gives BMG materials promising mechanical, physical and chemical properties such as high strength, high stiffness, high elastic strain limit, high fracture toughness, high resistance to wear and corrosion, soft magnetism, low magnetisation loss, and superconductivity etc. [2–5]. Because of these advantages amorphous alloys have received significant scientific and technological attention [6–8]. However, monolithic BMG materials lack of plastic deformation and exhibit catastrophic failure due to highly localised shear bands [9–12]. This defect markedly impedes possible applications of this novel material in engineering practices, and has motivated explorations and efforts to improve the ductility of these monolithic BMG materials by adding a second phase of material as reinforcement to hinder the propagation of single shear band and initiate multiple shear bands in BMG material, which results in the development of BMG based composites [13–16].

Choi-Yim et al. investigated the quasi-static and dynamic deformation behaviour of $Zr_{57}Nb_5Al_{10}Cu_{15.4}Ni_{12.6}$ BMG reinforced with 80% tungsten fibres, 50% volume fraction (V_f) of tungsten particles, or 50% V_f of mixed tungsten/rhenium particles and reported that the BMG composites exhibited higher plastic elongation than their monolithic counterpart [12]. The mechanical properties of

* Corresponding author.
E-mail address: hao.yifei@tju.edu.cn (Y. Hao).

http://dx.doi.org/10.1016/j.ijimpeng.2017.03.017

$(Zr_{55}Al_{10}Ni_5Cu_{30})_{98.5}Si_{1.5}$ BMG reinforced with tungsten fibres up to 70% V_f were studied by Qiu et al. [17]. Besides the observation of apparent improvement in plastic deformability due to multiple shear band formation, the authors found that the compressive failure mode of the composites changed from shear banding to localised fibre buckling and tilting as the V_f of tungsten fibre increased. Zhang et al. [18] studied the effects of tungsten fibre with varying V_f between 10% to 60% on the quasi-static failure mode of $Zr_{41.25}Ti_{13.75}Ni_{10}Cu_{12.5}Be_{22.5}$ BMG composites at room and high temperature. It was found that at room temperature composite with a higher V_f of tungsten reinforcement exhibited an improved fracture strength and plasticity while composites at high temperature tended to fail in bending due to reduced viscosity of the metallic glass matrix [18]. Compared to the monolithic $Zr_{38}Ti_{17}Cu_{10.5}Co_{12}Be_{22.5}$ BMG, the better plastic deformability of BMG composite reinforced with 80% V_f of tungsten fibre was also confirmed in [19].

From the review of literature, tungsten fibres have been proven to be able to effectively reinforce BMG materials and markedly improve their ductility/plasticity. However, previous research studies mainly focused on quasi-static and dynamic properties at room temperature (e.g. [20]) or quasi-static properties at high temperature (e.g. [18]) of tungsten fibre reinforced Zr-based BMG composites. It was found that both the temperature and strain rate have significant effects on the mechanical behaviour of most materials. Mechanical properties and behaviour of BMG composites at high strain rate and high temperature have not been studied yet. The present paper reports experimental study on quasi-static and dynamic compressive behaviour of $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10.0}Be_{22.5}$ BMG composite reinforced with 80% V_f of tungsten fibres at room and elevated temperatures. The behaviour and properties of the composite were investigated and discussed. It was found that the dynamic yield stresses were apparently higher than the static counterpart, but had insignificant difference within the strain rate range between 450 s^{-1} and 2000 s^{-1}. At elevated temperature, the quasi-static yield strength decreased and no strain hardening could be found, different from the quasi-static tests at room temperature. The material under dynamic loadings was found to degrade with temperature. Similar to the static properties at high temperature, strain softening was found rather than strain hardening in the post-yielding range. Scanning electron microscope (SEM) analysis was conducted to more comprehensively understand the failure mechanism of BMG composites under different loading conditions. Based on the observation from the series of tests and analyses, a new insight to explain the ‘self-sharpening’ behaviour of BMG composite was proposed.

2. Experimental programme

Ingots of $Zr_{41.2}Ti_{13.8}Cu_{12.5}Ni_{10.0}Be_{22.5}$ alloy were cast by melting a mixture of the constitutive elements with purity ≥ 99.4%. Tungsten fibres with nominal diameter of 250 μm were straightened and cut into 150 mm in length. The composite specimens were fabricated in a resistive furnace by heating and melting the ingots in an evacuated tube made of quartz with tungsten fibre reinforcement occupying 80% volume, applying pressure infiltration, followed by quenching in a supersaturated brine solution. Cylindrical specimens were machined from Ø8.5–150 mm BMG composite ingots, with axis parallel to the fibre direction. The density of the composite is 17.5 g/cm^3. The specimens were mechanically polished prior to being tested. Image of the cross section from SEM is given in Fig. 1. Totally thirty specimens were prepared and tested.

Quasi-static compressive tests at room temperature of 293 K were conducted by using INSTRON 1196 universal testing machine while tests at elevated temperature were carried out on a computer-controlled, servo-hydraulic MTS 810 testing machine with a temperature controlled air furnace. The loading speed in quasi-static tests was controlled at 0.5 mm/min.

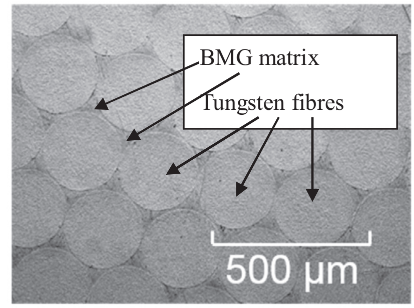

Fig. 1. Microscopic image of specimen cross section.

Split Hopkinson pressure bar (SHPB) testing system was used to study the dynamic compressive behaviour of the Zr-based BMG with tungsten fibre reinforcements at high strain rate. The schematic diagram of typical SHPB apparatus is given in Fig. 2. Basically it consists of a pressure vessel, striker bar, incident and transmitted pressure bars with specimen sandwiched in between, an absorption bar and buffer. The compressed gas is stored in the vessel. Once released, the striker bar in the vessel is accelerated and impinges the incident pressure bar, generating an elastic compressive stress wave that propagates towards the specimen. Upon reaching the specimen-bar interface, part of the stress wave is transmitted into the specimen while the rest is reflected. After a few reflections between the two ends/interfaces of the specimen, the stress along the specimen approximately reaches uniformity. The compressive stress wave leaves the specimen and propagates forward along the transmitted bar, and is absorbed by the absorption bar and buffer. Strain gauges are normally attached at the midpoints of the pressure bars so that the time dependent elastic strains, which directly relate to stresses, of each test can be obtained to analyse the dynamic properties of tested specimens.

Based on the theory of one-dimensional stress wave propagation, when the specimen deforms uniformly, the strain rate of the specimen is proportional to the reflected wave while the stress within the specimen is proportional to the transmitted wave. The integration of strain rate over time gives the strain histories of the specimens. Therefore the stress, strain and strain rate in the specimen can be calculated based on the strain data recorded by gauges on the incident and transmitted pressure bars as follows [21].

$$\sigma(t) = E\left(\frac{A}{A_s}\right)\varepsilon_T(t) \tag{1}$$

$$\varepsilon(t) = -\frac{2C_0}{L}\int_0^T \varepsilon_R(t)dt \tag{2}$$

$$\dot{\varepsilon}(t) = -\frac{2C_0}{L}\varepsilon_R(t) \tag{3}$$

where E, A and C_0 are respectively the modulus of elasticity, area of cross section and speed of elastic wave of pressure bars; A_s and L denote the area of cross section and length of specimens; and ε_T and ε_R represent the transmitted and reflected strain, respectively.

In the SHPB apparatus adopted in the present study, the diameter of bars is 25 mm. The lengths of striker bar, incident bar and transmitted bar are 300, 2000 and 2000 mm, respectively. Pressure bars are made of high-strength steel with yield stress of 2.5 GPa, modulus of elasticity of 200 GPa and speed of elastic wave of 5064 m/s. Strain gauges were glued at midpoints of pressure bars. Blocks made of cemented carbide YG20C with strength more than 3 GPa were used as load adaptors in both quasi-static and SHPB tests. Strain gauges were connected to high-frequency strainmeter with bandwidth of