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Elevated temperature flow behaviour of a Mg-based bulk metallic glass

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Abstract

The flow behaviour in the supercooled liquid region of a low-pressure die-cast $Mg_{65}Cu_{25}Y_{10}$ (at.%) bulk metallic glass over a range of temperatures (150–170 °C) and strain rates (10^{-3} to 10^{-1} s^{-1}) was investigated by tensile testing. In most cases, the maximum elongation obtained was 1300% without failure due to the limitations of the maximum traveling distance of the tensile testing machine. The flow behaviour was analysed in terms of the free volume model with the results used in conjunction with experimental data to construct deformation maps in terms of peak stress, strain rate and temperature for identifying the homogeneous and inhomogeneous deformation zones under various testing conditions.

Keywords: Bulk metallic glass; Crystallization; Deformation; Supercooled liquid; Mg alloy; Plasticity

1. Introduction

Bulk metallic glasses (BMGs) have the potential for use as structural materials due to their outstanding properties such as high specific strength, wear and corrosion resistance [1–3]. They are easily produced in bulk form due to their high glass forming ability with most alloys exhibiting a large supercooled liquid (SCL) region defined by the temperature interval between the glass transition temperature (T_g) and the primary crystallization temperature (T_x) [1–3]. The large SCL region of BMGs is useful since there is a significant decrease in viscosity with increasing deformation temperature that allows these materials to be plastically deformed to very large strains [4]. The early work on the high temperature flow behaviour of metallic glasses was limited because it was only possible to produce thin ribbons of material exhibiting a small SCL region [1–3]. However, BMGs can easily be produced with diameters well in excess of 1 mm and have a SCL region greater than 40 °C; this has resulted in detailed investigations of the high deformation behaviour of many types of BMG over the past few years [4–18].

Due to the impressive formability of BMGs in the SCL region, it is important, from an engineering viewpoint, to generate a better understanding of the high temperature flow behaviour of these materials. Despite extensive investigations on the mechanical properties of BMGs since 1990s, most studies have been carried out by compressive testing [15,16] although a limited number of studies have been reported on tensile deformation with off-standard specimens (see, e.g. [4,7,15]). In the ternary Mg–Cu–Y system, the hot deformation studies to date have been carried out in compression [10,19]. In the present work, standardized tensile test specimens of $Mg_{65}Cu_{25}Y_{10}$ (numbers indicate at.%) BMG, in compliance with ASTM E8-04, were produced using an in-house grinding method for investigating the formability of this material in the SCL region.

2. Experimental procedure

The $Mg_{65}Cu_{25}Y_{10}$ BMG was prepared in stages using high purity Mg (99.8 wt.%), Cu (99.99 wt.%) and Y (99.999 wt.%). As a first step, $Cu_{71.5}Y_{28.5}$ master alloy was prepared by arc-melting the mixture of constituent elements in an argon atmosphere. Stoichiometric amounts of master alloy and magnesium were prepared and die-cast in the form of rods. The final stage involved injection casting into a copper mould to form amorphous bars with dimensions of 3 mm × 7 mm × 113 mm. A more detailed description of the casting process is given elsewhere [20]. The degree of crystallization of both the as-cast and deformed samples was determined by X-ray diffraction (XRD) using a Philips MRD diffractometer using Cu Kα radiation and transmission electron microscopy (TEM) using a Philips CM200 field emission gun TEM. The thermal properties of the alloy were

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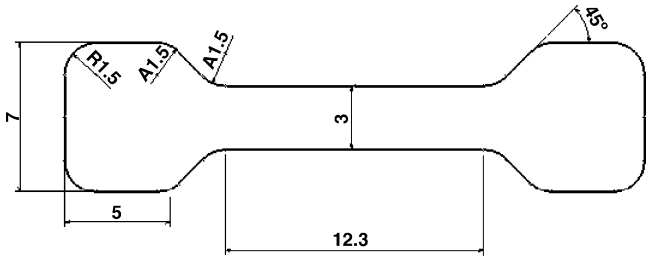

Fig. 1. Schematic diagram showing the dimensions of the cylindrical tensile test samples (mm).

determined using a TA 2010 differential scanning calorimeter (DSC) at a heating rate of 2–20 K/min. For this range of heating rates, the error of determining T_g and T_x is less than 0.5 K using indium as a calibration standard. Isothermal DSC measurements have recently been carried out on the same material at various test temperatures to determine the onset of crystallization and the kinetics of crystallization [21].

Due to the brittle nature of the alloy at room temperature [10], high-quality tensile test samples in accordance with ASTM E8-04 were produced from the injection-cast rods using an in-house grinding technique involving the simultaneous rotation and grinding of the rectangular-shaped sample to generate 3 mm diameter samples of gauge length 12.3 mm (Fig. 1). Tensile testing was carried out at temperatures of 150–170 °C in increments of 5 K and strain rates ranging from 10^{-3} to 10^{-1} s^{-1}. The tensile samples were subsequently deformed in air using an MTS 810 hydraulic testing machine equipped with a 1 kN load cell and an MTS 651 Environmental Chamber for high-temperature testing. Due to the amorphous nature of the alloy, there were no major problems with oxidation of the samples, with each sample retaining a high luster, after tensile testing [22]. A built-in Eurotherm 2024 temperature controller was employed to maintain constant temperature within ±1 K. Since the built-in thermocouple was at the inside corner of the furnace chamber, an additional type-K thermocouple was positioned close to the specimen to monitor the temperature at the specimen surface. The chamber was preheated to each preset temperature prior to mounting the specimens. Due to the fact that T_g is not a unique physical property of the glass but, rather, a rate dependent kinetic quantity [1–3], the heating rate of the specimen was kept constant at 5 K/min after reaching T_g. Tensile testing commenced after the sample was stabilized for 10 min at a given temperature. The data are given as stress and strain which equates to true stress and true strain at low strains, i.e. where the material deforms by uniform extension to a characteristic peak stress, as illustrated in Fig. 4. Since deformation becomes less uniform beyond the peak stress, true values of stress and strain rate are more difficult to calculate.

3. Results and discussion

3.1. Differential scanning calorimetry

In order to determine the characteristic temperatures T_g and T_{x1}, DSC scans were performed using a range of heating rates. The results of isochronal measurements are given in Fig. 2 that

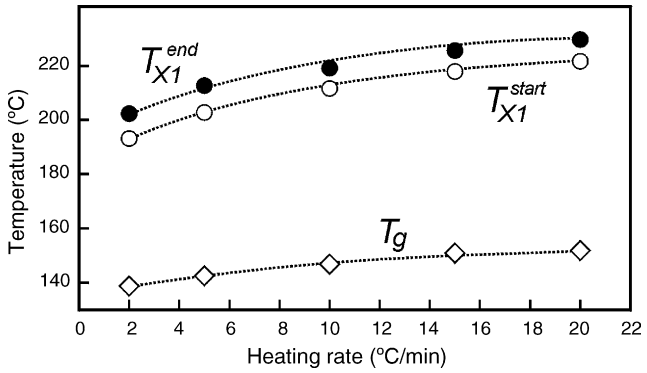

Fig. 2. Effect of heating rate on the characteristic temperatures T_g and T_x (the start and end temperatures for crystallization are given). The error associated with each DSC measurement is ±3 K.

shows that both T_g and T_{x1} increases with increasing heating rate. Like other amorphous materials, the glass transition (endothermic phenomenon) does not occur at a certain temperature, but over a range of ~12 K. At a heating rate of 5 K/min, the SCL region ($\Delta T_x = T_{x1} - T_g$) was found to be 59 K. Isothermal annealing at temperatures ranging from 160 to 210 °C was also carried out to determine the allowable timeframe for tensile testing before the onset of crystallization [21]. Using the isothermal DSC results shown in Fig. 3, the maximum test temperature was 170 °C since higher temperatures resulted in rapid crystallization [21,22].

3.2. Tensile flow behaviour

In the SCL region, the tensile flow behaviour was found to be highly strain rate and temperature dependent with Fig. 4a showing typical stress–strain curves generated at a strain rate of 1×10^{-2} s^{-1} for various temperatures and Fig. 4b showing stress–strain curves at 170 °C for true strain rates in the

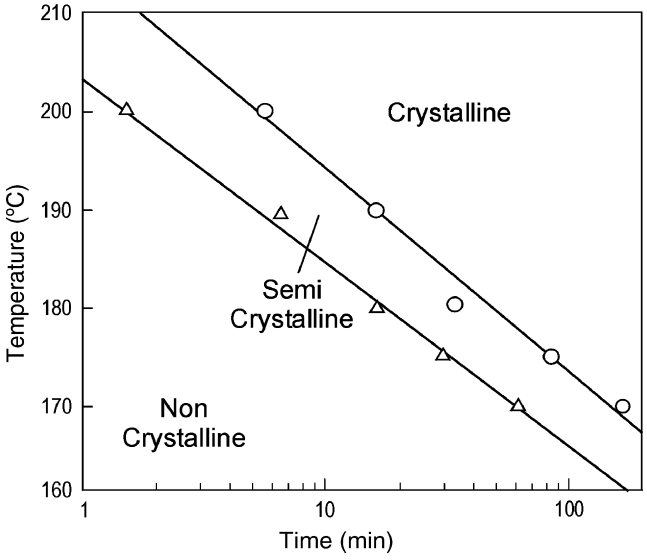

Fig. 3. Effect of annealing temperature on the rate of isothermal crystallization of the alloy (boundaries between fully crystalline, partly crystalline and non-crystalline regions are estimated by the filled lines).