Materials Science & Engineering A 582 (2013) 155–161

Contents lists available at SciVerse ScienceDirect

Materials Science & Engineering A

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

# In situ observation of bending stress–deflection response of metallic glass

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ARTICLE INFO

*Article history:*
Received 14 February 2013
Received in revised form
15 April 2013
Accepted 9 May 2013
Available online 29 June 2013

*Keywords:*
Metallic glass
Shear band
Bending Test
In situ observation

ABSTRACT

Understanding the shear banding mechanism is of significance not only for improving the mechanical performance of metallic glassy components but also for designing new metallic glassy materials with better combinations of strength and toughness. In this study, through an in situ bending experiment under a scanning electron microscope, the shear banding behavior and the bending stress-deflection response were investigated. We found that the flexural strength was higher than either the tensile strength or the compressive strength of the identical metallic glass. The initial appearance of shear bands was observed at a stress lower than the flexural yield strength. As shear band propagating stably, the flexural stress increases with increasing the deflection, which is similar to but analytically found different with the traditional "work-hardening" behavior of metallic crystalline materials. At the peak stress, a shear banding instability with an abrupt increment of plastic deformation localization and shear cracking was found. Some shear band zones were observed and the size of the zone in tension side of the bending sample was found larger than that in compression side.

## 1. Introduction

With the great superiority of extremely high strength, high elasticity and plastic-like processing, bulk metallic glasses (BMGs) have been expected to be used as structural materials since they were developed [1,2]. At room temperature, the plastic deformation of most BMGs always favors to localize into shear bands. The shear banding behavior not only directly influences the room temperature deformation and fracture behaviors, but also affects some mechanical properties such as plasticity and toughness of BMGs [3–5]. For example, many ductile BMGs exhibit multiple shear banding behaviors [5–8], while only few or even no shear bands can be observed in brittle BMGs even under confined loading [9–11]. By tuning the size and distribution of second phases to induce more shear bands to initiate and to stabilize shear bands from instable propagation, some BMG composites with considerable tensile plasticity have been developed recently [12,13]. Consequently, in order to design new BMGs or engineering structural components with already developed BMGs for better mechanical performance [14], it is of significance to understand the underlying mechanism of shear banding.

Although abundant research interests have been attracted and significant progress have been made, up to now several issues on shear banding mechanism have still not confirmed conclusions yet [3]. For example, the critical stress conditions for shear band initiation remains inconclusive. Traditionally, the yielding of a material means the onset of plastic deformation [15]. However, for BMGs, the yield stress may not be the critical stress for shear band initiation. Some investigators [16,17] carefully observed the load-displacement curves of tension or compression and found pop-ins with the corresponding stresses below the yield stress. They concluded that the activity of shear bands may start at a stress smaller than the yield stress read from the stress–strain curves, while direct observation of shear band initiation still lacks. After yielding, the stress–strain curves of some monolithic BMGs show a "work-hardening"-like behavior [8,18], while the shearing induced dilatation and temperature rise are considered to cause shear band softening, leading to the lack of plasticity under tension [14,19–22]. This makes one wondering whether the nature of shear banding is softening or hardening.

Owing to the relatively confined loading mode, bending test is widely used as an effective method to characterize the mechanical performance of brittle or quasi-brittle materials such as ceramics or BMGs [15,23–26]. When a BMG sample subjected to bending, the inherent stress gradient facilitates the formation of multiple shear bands, which arouses researches on BMGs through bending mainly focusing on the assessment of plastic deformation ability or size effect [26–30], whereas the bending stress–deflection response has rarely been studied. In the present study, by conducting an in situ bending experiment under a scanning electron microscope (SEM), we tried to establish a corresponding relationship between the microscopic shear banding evolution and macroscopic bending

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http://dx.doi.org/10.1016/j.msea.2013.05.091

stress–deflection response. The flexural strength, the “work-hardening” phenomenon as well as the shear band zones (SB zones) in the bending BMG sample will be also discussed.

## 2. Experimental

Because of the excellent glass formation ability as well as high strength [31], $Ti_{40}Zr_{25}Ni_3Cu_{12}Be_{20}$ (at%) (Ti-BMG) was chosen and confirmed to be fully amorphous using X-ray diffraction and high resolution transmission electron microscopy (HRTEM). The transmission electron microscopy (TEM) observations of the as-cast Ti-BMG were conducted on FEI Tecnai F20. The TEM samples were prepared by a series of thinning processes, i.e., mechanical polishing, dimpling and ion-milling. To reduce the possible effect of ion-milling on the structure of the samples, a low voltage of 4.5 kV was used. As shown in Fig. 1, Neither appreciable nano-scale crystals nor microstructural inhomogeneities can be observed from the HRTEM image and the corresponding selected area electron diffraction (SAED) pattern, showing the fully amorphous structure of the as-cast Ti-BMG, which agrees with the XRD results. The mechanical properties of the fabricated Ti-BMG were tested by uniaxial compression and tension at room temperature and quasi-static strain rate ($10^{-4}\ s^{-1}$) with an Instron 5982 testing machine. The measured compressive strength and tensile strength are 1.84 GPa and 1.68 GPa, respectively, showing a strength asymmetry, in accordance with many other BMGs [3,32,33]. The as-cast material was then cut into bending specimens with a plate shape by an electric spark cutting machine. After carefully grinded and polished by 1.5 μm diamond paste, the final dimensions of the specimens are 0.85 mm (thickness, $t$) × 3.13 mm (width, $b$) × 10 mm (length, $s$). Three-point bending experiments were carried out using a Gatan MTEST2000ES Tensile Tester under a Leo Supra 35 SEM. A special jig was used to convert the tensile loading mode into bending mode. The displacement rate of the bending test was controlled as a constant of 0.55 μm/s. The span length of the three-point bending test is $l=6$ mm. The deformation features were observed in situ with the Leo Supra 35 SEM, but some more detailed observations were done with the test paused.

## 3. Results

### 3.1. Flexural stress–deflection curve

Fig. 2 shows the flexural stress–deflection curve of Ti-BMG under in situ three-point bending. Only the high stress portion of the complete curve was presented in order to show the yielding behavior more clearly but without loss of useful information. The flexural stress is defined as the tensile normal stress at the middle point of the outer surface, which can be written as [34,35]

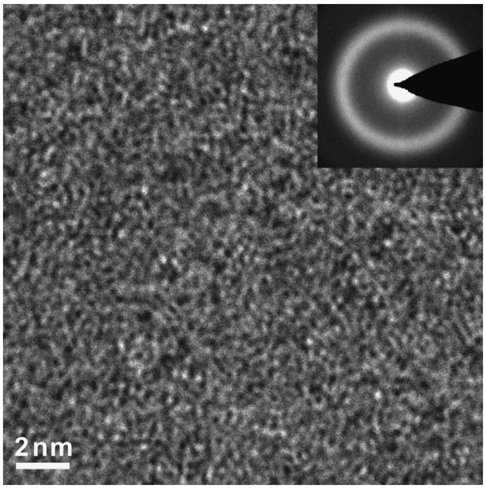

**Fig. 1.** HRTEM image and the corresponding SEAD pattern of the as-cast $Ti_{40}Zr_{25}Ni_3Cu_{12}Be_{20}$ BMG.

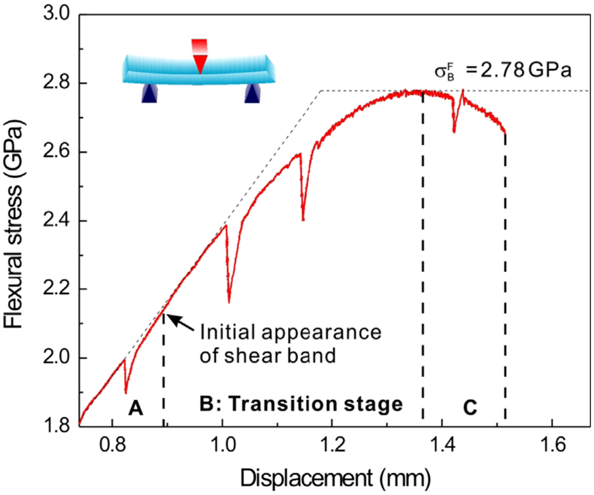

**Fig. 2.** Flexural stress–deflection curve of $Ti_{40}Zr_{25}Ni_3Cu_{12}Be_{20}$ BMG under in situ three-point bending. Only the high stress portion of the complete curve is presented.

$$\sigma=\frac{3Fl}{2bt^2}, \tag{1}$$

where $F$ is the applied load; $l$, $b$ and $t$ are the span length, width and thickness of the sample, respectively. It should be noted that the obvious stress drops on the curve are not true responses of the materials to the applied load but were formed due to stress relaxation of the testing system as test paused for the detailed SEM observations [36]. According to the stress–strain behavior and the results about shear band initiation (see Section 3.2), we can divide the flexural stress–deflection curve into three different stages termed as A: elastic stage; B: transition stage; and C: plastic stage, as shown in Fig. 2. In the transition stage, as shear plastic deformation increases, the flexural stress increases, exhibiting a “work-hardening”-like phenomenon, while a “work-softening”-like behavior can be seen in the stage C. The “work-hardening”-like phenomenon can also be seen in the bending curves of BMGs investigated by other authors [23,26,29], implying that this should be one characteristic of bending stress–defection response. More discussions on the mechanisms of the hardening and softening phenomenon will be presented in Section 4.

Considering the flexural strength $\sigma_B^F$ (i.e., the peak stress at the flexural stress–deflection curve), it is interesting to found that for the present Ti-BMG $\sigma_B^F=2.78$ GPa, which is ~1.51 times as high as the compressive strength (1.84 GPa) and ~1.65 times as high as the tensile strength (1.68 GPa) of the same material. Through a survey of literatures [24,26,29,30,37,38], we found that the higher flexural strength than the strengths measured under uniaxial loading is not a unique observation for the studied Ti-BMG. The flexural strengths and compressive strengths of some BMG compositions were listed in Table 1. Obviously, the higher flexural strength than compressive one should be another characteristic of bending stress–deflection response of BMGs.

For ceramics, the flexural strengths are often ~50% higher than the tensile strength, which was attributed to the effect of defects in samples [35]. In bending sample, the maximum tensile stress only distributes in a very thin layer near the outer surface, the amount of defects in which should be much less than that in a tensile specimen due to the very smaller volume for the thin layer. Thus a higher stress is required to break specimen under bending