Tensile plasticity in monolithic bulk metallic glass with sandwiched structure

Article in Journal of Alloys and Compounds · July 2016
DOI: 10.1016/j.jallcom.2016.07.243

4 authors, including:

Yangyang Cheng
Beihang University (BUAA)
8 PUBLICATIONS 12 CITATIONS

Wentao Wang
Dalian Institute of Chemical Physics
115 PUBLICATIONS 1,539 CITATIONS

All content following this page was uploaded by Yangyang Cheng on 16 August 2016.

The user has requested enhancement of the downloaded file. All in-text references underlined in blue are added to the original document and are linked to publications on ResearchGate, letting you access and read them immediately.
Tensile plasticity in monolithic bulk metallic glass with sandwiched structure

Yangyang Cheng, Shujie Pang**, Chen Chen, Tao Zhang*

Key Laboratory of Aerospace Materials and Performance (Ministry of Education), School of Materials Science and Engineering, Beihang University, Beijing 100191, China

ABSTRACT

Appreciable tensile plasticity is obtained in monolithic Cu-Zr-based BMG with a sandwiched structure introduced by laser surface melting. The sandwiched structure is derived from the evaporation of element Cu in the near-surface zone. It is found that the near-surface and the nether zones are still amorphous structures but possess different elastic moduli and mechanical properties. The tensile results demonstrate that the unique structure can facilitate the formation of multiple shear bands and effectively retard the propagation of shear bands into cracks under tensile loading, thus yielding an appreciable plasticity.

© 2016 Published by Elsevier Ltd.

1. Introduction

Room-temperature plastic deformation of BMGs is dominated by highly localized shear band [1–3]. The shear localization is usually regarded as a consequence of strain softening which is derived from the local evolution of amorphous structure and local heat generation [1,4]. Meanwhile, the stress state has a significant effect on the shear banding behavior [5,6]. Accordingly, under tensile loading, the fracture easily occurs along a single dominant shear band. This induces the catastrophic fracture and nearly zero tensile plasticity. The absence of macroscopic plasticity raises a serious reliability issue for the engineering application of BMGs. In order to mitigate the shortcomings, numerous intrinsic and extrinsic methods have been explored to improve the tensile plasticity of BMGs.

The intrinsic method mainly focuses on carefully tuning the composition of BMGs to alter their inherent amorphous structure [1,7]. For example, under high strain rate (10−3 s−1), the hypoeutectic Zr-based BMG with high Poisson's ratio exhibits tensile plasticity [1]. For La-based BMG, minor addition of element Co and Cu can completely change the beta relaxation behavior, and the ribbon specimens exhibit tensile plasticity [7]. To extrinsically improve the plasticity, considerable research has been devoted to fabricating in-situ/ex-situ BMG matrix composites [8,9]. However, the composite system needs a monolithic BMG with large glass-forming ability, and destroys the overall amorphous structure [10]. Furthermore, BMGs with designed artificial defects (such as pore, notch or cellular structure) or gradient amorphous structure introduced by surface processing are fabricated to obtain tensile plasticity, but the strength is sacrificed and the introduced defects may seriously degrade the fatigue endurance [2,10–15]. On the other hand, the thickness of most testing specimens is less than 1 mm. Considering the size-dependent mechanical behavior of BMGs [16], the tensile plasticity may not be achieved in the bulk specimen with a thickness of several millimeters.

It should be noted that via compositional design BMGs with nano-scale phase separation exhibit large compressive plasticity [17–21]. This is because the interaction between nano-scale soft and hard phases can facilitate the multiplication of shear bands. Nevertheless, under tensile loading the BMGs still fracture catastrophically without plasticity, implying that micro-scale structural heterogeneities should be required to stabilize the shear banding behavior [2]. For example, large tensile plasticity has been obtained in BMG matrix composites where the grain size of the crystalline phase is several tens of micrometers [8,9,22]. Accordingly, if one monolithic BMG with micro-scale phase separation could be designed, the tensile plastic deformability would be improved. In our recent work, we found that when the Cu-containing BMG was treated by laser surface melting (LSM), the composition in the near-surface zone (i.e., laser influenced zone) is slightly different from that of the nether zone (i.e., laser unfluenced zone) due to the loss of element Cu [16]. Consequently, in the present work, Cu-Zr-based BMG with excellent glass-forming ability was selected as the parent material, and in order to enlarge the difference in composition between the near-surface zone and the nether zone, we adjusted the input laser power through changing the laser scanning speed. Meanwhile, minor element Co was added to stabilize the B2 CuZr phase which may be introduced by the LSM. The results demonstrate that under proper laser processing parameters, the evaporation loss of Cu can lead to the formation of a sandwiched structure with amorphous structure, thus yielding an appreciable tensile plasticity.

1.1. Experimental procedures

Alloy ingots with a nominal composition of Cu42.75Zr48.75Al18Co1 (at.%) were produced by arc-melting the mixtures of pure metals with purities above 99.9%, in a Ti-gettered argon atmosphere. Each ingot
was turned over and remelted four times to ensure compositional homogeneity. Rectangular plates with a thickness of 1.2 mm, width of 10 mm and length of 45 mm were fabricated by copper mold casting method and their amorphous structure was identified by X-ray diffraction (XRD) using Bruker AXS D8 X-ray diffractometer with Co Kα radiation. Before subjected to the LSM, the specimen was polished with 2000-grid Si-C papers to reduce the reflectivity and further cleaned with distilled water and acetone. The LSM was carried out along the axial direction on the specimen surface using a 180 W Nd:YAG laser at beam scanning speeds of 65, 100 and 150 mm/min with a focused beam diameter of 1 mm, pulse frequency of 8 Hz, pulse width of 1 ms, laser working voltage of 220 V, and an overlapping of 50%. The structure of the treated specimens was also evaluated by XRD. Electron probe microanalysis was conducted using a JEOL JXA 8100 electron probe microanalyzer in the backscattered electron (BSE) mode linked with energy-dispersive spectroscopy (EDS). Dog-bone shaped tensile specimens with gauge dimensions of 20 mm × 2 mm × 1.2 mm were cut from the laser treated specimens and subsequently grinded and polished. Tensile testing was performed on the as-cast and laser treated specimens at a strain rate of 8 × 10⁻⁴ s⁻¹ on Instron 8801 testing machine at room temperature. Five tensile specimens were tested to ensure the reproducibility of the results. Morphologies of the deformed and fractured specimens were observed by CamScan 3400 scanning electron microscope (SEM). Besides, for the laser treated specimen, in order to characterize the elastic constants and compressive mechanical properties of the laser influenced zone, we prepared the corresponding alloy ingots according to the EDS results, and then fabricated glassy rods with diameter of 2 mm by copper mold casting method. The density was measured by Archimedes' method. The elastic constants were determined by ultrasonic methods. Uniaxial compressive testing was performed at a strain rate of 8 × 10⁻⁴ s⁻¹.

2. Results and discussion

We collected the smoke generated during the process of the LSM and carried out XRD analysis. The crystalline peaks are identified as face-centered cubic copper phase (Fig. 1 (a)). This implies that the evaporation of element Cu occurred in the laser melting region. Fig. 1 (b) shows the XRD patterns of the surfaces of the as-cast and the laser treated specimens. It is evident that the position of the broad diffraction hump of the treated specimen shifts to lower diffraction angle compared with that of the as-cast specimen, suggesting that the evaporation loss of Cu may cause the change in composition of the near-surface zone and alter the amorphous structure. The XRD patterns of the transversal cross-sections are shown in Fig. 1 (c). No distinct crystalline peaks can be observed except for the specimen treated at 65 mm/min where B2 CuZr phase precipitates in the amorphous matrix.

Fig. 2 shows the BSE micrographs of the cross-sections of the specimens treated at different laser scanning speeds. It is notable that for the treated specimens the near-surface zones are brighter than the middle zones, implying that there exists compositional difference. The chemical compositions of the near-surface and the middle zones were determined by EDS and listed in Table 1. The composition of the middle zone is close to the nominal composition of the parent alloy, but the Cu concentration in the near-surface zone is significantly deficient. This further confirms that the LSM leads to the evaporation loss of Cu and generates a sandwiched structure. Besides, the difference in the Cu content between the two zones for the 65 and 100 mm/min treated specimens is larger than that for the 150 mm/min treated specimen. Furthermore, it can be seen that for the 65 mm/min treated specimen numerous spherical B2 CuZr phases are embedded in the near-surface zone, while in the middle zone the B2 phases conglomerate into a crystalline skeleton (Fig. 2 (a)). In the specimens treated at 100 and 150 mm/min there is no precipitation of B2 CuZr phase (Fig. 2 (b) and (c)). Additionally, the depth of the zone where evaporation of Cu occurred also varies with the scanning speed: a slower speed leads to a larger depth.

Fig. 3 shows the tensile stress-strain curves of the specimens before and after the LSM. It can be seen that the as-cast specimen fractures catastrophically without detectable plasticity. In contrast, for the laser treated specimens obvious yielding and plastic strain are observed. The yielding behavior in the 100 mm/min treated specimen is more pronounced than that in the specimens treated at 65 and 150 mm/min. This should be correlated to the structural features generated by the LSM and will be discussed in the following. Moreover, it is notable that the plasticity of the laser treated specimen is comparable to that of the specimens with artificial defects reported in literature [11–15], but its ultimate tensile strength is not degraded.

Since the plastic deformation of BMGs is dominated by shear bands, the fracture feature of the tensile specimen was observed by SEM to further understand the yielding behavior and plasticity. For the as-cast specimen, only limited shear bands appear near the fracture (Fig. 4 (a)). Nevertheless, for the laser treated specimens numerous shear bands are clearly visible (Fig. 4 (b–d)). The shear bands appear not only in the vicinity of the fracture but also in the distance several millimeters away. The insets reveal the deflection and branching of shear bands. Fig. 4 (e) and (f) show the fracture morphologies of the as-cast and the 100 mm/min treated specimens. Both smooth region and radiating vein-like pattern are formed. The smooth region of the 100 mm/min treated specimen (about 25 μm) is significantly wider than that of the as-cast specimen (about 10 μm). The fracture morphologies of 65 mm/min and 150 mm/min treated specimens also consist of smooth region (about 20 μm) and radiating

![Fig. 1. XRD patterns of the smoke generated during the LSM and the as-cast and the laser treated Cu-Zr-based BMG specimens.](image-url)
the above, in – in 0.376 Cu (This and that and al (the dif (cor are is is un 29.3 of mod from Cu with Table 30.6 and shear shear de – zone 1798 as rea – the ra Zone mm/min Con 1 the speed of pos In same face lower process elas that were zone – the more un in – be of glassy the the – of mm/ mod wider the (0.375 com Cu re 80.6 1810 to It plas laser that 100 were re treated un in – is ex mod – 100 [23] 1810 shear re 29.3 at Depth (– show de prop 1719 mod com com scan (g). shear Pois zone. The – 100 produces. Fig. 2. BSE micrographs of the Cu-Zr-based BMG specimens treated at scanning speeds of 85, 100 and 150 mm/min, respectively.

Table 1
Nominal composition of the as-cast specimen and EDS results of the near-surface and middle zones in the specimens treated at different laser scanning speeds. The corresponding Young's modulus (E), shear modulus (G), bulk modulus (B), Poisson's ratio (ν), yielding strength (σy) and compressive strength (σc) were determined by ultrasonic method and compressive testing.

<table>
<thead>
<tr>
<th>Scanning speed</th>
<th>Zone</th>
<th>Composition (at.%)</th>
<th>Depth (μm)</th>
<th>E (GPa)</th>
<th>G (GPa)</th>
<th>B (GPa)</th>
<th>ν</th>
<th>σy (MPa)</th>
<th>σc (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>as-cast</td>
<td>–</td>
<td>Cu45.75Zr54.25Al1.5Co0.7</td>
<td>–</td>
<td>90.0</td>
<td>32.9</td>
<td>115.1</td>
<td>0.369</td>
<td>1792</td>
<td>1870</td>
</tr>
<tr>
<td>65 mm/min</td>
<td>Near-surface</td>
<td>Cu37.5Zr62.5Al1.5Co0.5</td>
<td>170</td>
<td>80.6</td>
<td>29.3</td>
<td>108.9</td>
<td>0.376</td>
<td>1717</td>
<td>1810</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>Cu45.75Zr54.25Al1.5Co0.7</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>100 mm/min</td>
<td>Near-surface</td>
<td>Cu37.5Zr62.5Al1.5Co0.5</td>
<td>128</td>
<td>80.6</td>
<td>29.3</td>
<td>108.9</td>
<td>0.376</td>
<td>1717</td>
<td>1810</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>Cu45.75Zr54.25Al1.5Co0.7</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>150 mm/min</td>
<td>Near-surface</td>
<td>Cu45.75Zr54.25Al1.5Co0.5</td>
<td>105</td>
<td>84.2</td>
<td>30.6</td>
<td>112.0</td>
<td>0.375</td>
<td>1719</td>
<td>1798</td>
</tr>
<tr>
<td></td>
<td>Middle</td>
<td>Cu45.75Zr54.25Al1.5Co0.7</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

Fig. 3. Tensile stress-strain curves of the as-cast and the laser treated Cu-Zr-based BMG specimens.

vein-like pattern (not shown). The smooth region is regarded as the stable shear process prior to fracture, and the width represents the critical shear offset of BMGs [23]. Therefore, the wider smooth region in the laser treated specimen indicates that the treated specimen has undergone more stable plastic shearing process, which is closely related to the constraining effect of the sandwiched structure.

As discussed above, after the LSM the composition and structure in the laser influenced zone are significantly different from those in the uninfluenced zone, showing a sandwiched structure. Accordingly, the unique mechanical behavior of the laser treated specimen should originate from the coupling interaction between the influenced zone and the uninfluenced zone which possess different mechanical properties. In order to elucidate the deformation and fracture mechanisms, we experimentally characterized the elastic moduli and compressive mechanical properties of the glassy alloys with the same composition as that of the laser influenced zone. The details were described in experimental procedure. The properties of the uninfluenced zone refer to those of the as-cast specimen. The results were listed in Table 1. It is found that the influenced zones possess lower elastic moduli compared with the uninfluenced zone, while the variation in strength is slight. Considering the correlation between elastic moduli and plastic flow [3,24], it is reasonable to postulate that the shear banding event preferentially occur in the influenced zone. This is verified by the SEM observation on the side face of the 100 mm/min treated specimen shown in Fig. 4 (g). It is evident that the shear bands in the near-surface zone (indicated by white arrows) are profuse while
scarce in the middle zone (indicated by black arrows). Moreover, a detailed observation (Fig. 4 (h)) reveals that the shear bands in the near-surface zone initiate from the edge and gradually disappeared at the depth of 100–150 μm, i.e., in the vicinity of the interface between the laser influenced and uninfluenced zones. Besides, the shear bands formed in the middle zone also stopped propagating near the interface. Since shear-band dynamic exhibits a compositional dependence [25], the critical stress states for shear band initiation in the laser influenced and the uninfluenced zones should be significantly different. Therefore, the sandwiched structure in the laser treated specimen possesses a constraining effect on the evolution of shear bands into cracks, and can facilitate the formation of multiple shear bands, thus generating an appreciable tensile plasticity.

On the other hand, the present results indicate that, for the laser treated specimens, the yielding behavior is closely related to the structure feature of the laser influenced zone. The slower speed leads to the more loss of Cu, the deeper laser influenced zone and even the precipitation of B2 CuZr phase. The difference in composition and elastic moduli between the influenced and the uninfluenced zones in the 150 mm/min treated specimen is smaller than that in the 100 mm/min treated specimen, and the depth of the laser influenced zone in the former is also less than that in the latter. Accordingly, for the 150 mm/min treated specimen the constraining effect generated by the coupling interaction between the influenced and the uninfluenced zones should be no stronger, and the tensile plasticity is smaller. Furthermore, although the depth of the influenced zone in the 65 mm/min treated specimen is larger than that in the 100 mm/min treated specimen, the precipitation of conglomerating B2 CuZr phase in the middle zone can generate severe stress concentration and significantly deteriorate the coupling interaction to weaken the constraining effect. Consequently, the 100 mm/min treated specimen exhibits the largest tensile plasticity.

3. Conclusions

In summary, for the Cu-Zr-based BMG, the laser surface melting can lead to the evaporation of element Cu in the near-surface zone with micro-scale depth and generate a unique sandwiched structure. The near-surface and the nether zones are still amorphous structures but possess different elastic moduli and mechanical properties, so that the laser treated BMG exhibits appreciable tensile plasticity. SEM observation reveals that the coupling interaction between the laser influenced and the uninfluenced zones can effectively facilitate the formation of multiple shear bands and retard their evolution into cracks. The present work demonstrates that the micro-scale structural heterogeneities in the monolithic BMG can effectively stabilize the shear banding behavior even under tensile loading.

Acknowledgements

This work was supported by the National Natural Science Foundation of China (Grant Nos. 51271008 and 51571005).

References


S.S. Chen, H.R. Zhang, I. Todd, Phase-separation-enhanced plasticity in a Cu47.5Zr46.5Al5.5Nb0.8 bulk metallic glass, Scr. Mater 72–73 (2014) 47.