High tensile strength reliability in a bulk metallic glass

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We report high strength reliability under tension of a bulk metallic glass (BMG), demonstrated by its high uniformity in strength found over a statistically significant number of specimens, despite the fact that the samples all showed no macroscopic plasticity. Weibull statistical analysis showed that the Weibull modulus of the material is 36.5, which is much higher than the values of more typical brittle materials, further confirming BMGs’ high reliability [Appl. Mech. Rev. 5, 449 (1952)].

Bulk metallic glasses (BMGs) have been drawing increasing attention over recent years. Previous investigations have shown that although BMG materials usually exhibit substantial high strength and hardness, they usually fail by one dominant shear band with highly localized strain deformation. They also generally show a very limited macroscopic uniform plastic deformation, leading to catastrophic failure without any warning. This kind of fracture behavior is generally believed to be a sign that BMGs are mechanically less reliable, with essentially no macroscopic plastic strain. So far, the study of mechanical properties of BMGs has been predominantly carried out in compression, where generally very limited uniform plastic strain is reported, except for a few recent cases. Few tensile tests for BMG have ever been reported in the literature, despite the fact that tensile testing is undoubtedly more critical for evaluating a material in its industrial application. Furthermore, any defects introduced during the sample preparation will have a significant affect on its tensile behavior. Consequently, a systematic investigation of the mechanical behavior of BMG, for example, strength and ductility, by means of tensile tests would not only provide conclusive evidence of mechanical response but also provide a valuable insight into their intrinsic deformation mechanism. In this paper, we report a BMG possessing a striking uniformity in tensile strength, thus demonstrating an unusually high predictability; despite the fact that stress-strain curves of this glass under tensile conditions had shown typical behavior similar to that of ceramic materials.

Amorphous plates with the composition of \( \text{Zr}_{48}\text{Cu}_{45}\text{Al}_{7} \) were produced in thickness of 4 mm. The amorphous state of the plates was investigated by x-ray diffraction (XRD) using a Rigaku D/max 2400 diffractometer with monochromated Cu K\( \alpha \) radiation (\( \lambda = 0.1542 \) nm). The glass transition and crystallization behavior of the samples were analyzed in a Netzsch 404C differential scanning calorimeter (DSC) under flowing purified argon at a heating rate of 20 K min\(^{-1} \). Young’s modulus, shear modulus, and Poisson’s ratio of the samples at room temperature were evaluated by the impulse excitation technique (IET). The apparatus excited the test specimen by a light mechanical impact (impulse excitation). The vibration signal captured by a laser vibrometer was analyzed with the resonance frequency and damping analyzer. Young’s modulus was calculated to be 90.9 GPa from the resonant frequency according to ASTM E 1259-94. The shear modulus \( G \) and Poisson’s ratio were determined to be 33.0 GPa and 0.377, respectively. Multiple flat, dog-bone shaped tensile specimens with a gauge dimension of \( 4 \times 1 \times 0.7 \) mm\(^3 \) were prepared by electrodischarge machining from \( \text{Zr}_{48}\text{Cu}_{45}\text{Al}_{7} \) plates. The two surfaces in the thickness direction and the two surfaces in the width direction of each sample gauge were carefully polished to be parallel to each other. The exact final width and thickness of each sample, after mechanical polishing, were measured by a scanning electron microscope (SEM) and found to be from 900–950 \( \mu \)m and from 300–350 \( \mu \)m, respectively. Uniaxial tensile tests were performed on a Tytron 250 Microforce Test System at a strain rate of \( 6 \times 10^{-3} \) s\(^{-1} \). A specially designed apparatus was used to ensure that the axis of the sample and the loading direction were aligned. A contactless laser extensometer was used to calibrate and measure the strain of the samples during loading.

\( \text{Zr}_{48}\text{Cu}_{45}\text{Al}_{7} \) was reported to form full glass with 8 mm in diameter. Figure 1 shows the XRD pattern of the sample,

![FIG. 1. XRD pattern with DSC curve inset of a 4 mm \text{Zr}_{48}\text{Cu}_{45}\text{Al}_{7} \) plate.](https://apl.aip.org/apl/figure?DOI=10.1063/1.2838715)
indicating that it is fully amorphous. The inset DSC curve shows that it has the typical thermal behavior of a BMG, i.e., a distinct glass transition with a large supercooled liquid region ($\Delta H$=3.71 K). The total heat of crystallization is $\Delta H_{cr}$=56 J/g, being similar to that of fully glassy ribbons and further confirming the fully amorphous nature of these as-cast samples.

Figure 2 displays 22 tensile stress-strain curves of the amorphous samples. Not surprisingly, no significant plastic strains were observed from the tensile strain-stress curves, indicating that the deformation of BMG is fairly localized. However, the statistic result from the tensile strength shows a narrow distribution ranging from a minimum value of 1630 MPa and a maximum value of 1790 MPa, with a mean value of 1705 MPa. This remarkably narrow strength distribution is attractive in BMG, especially under tension. In contrast with the minimum and maximum values of strength 1790 and 1890 MPa obtained for the same alloy under compression, the tensile fracture strength is slightly lower and its dispersion is slightly higher. Such a similarity in tensile and compressive strengths along with, importantly, narrow distribution in the strength indicate that the fracture mode of BMGs is evidently very different from common brittle materials, where their tensile strength can be about a factor of 10 less than that in compression and is usually highly scattered. The elastic modulus evaluated directly from the tensile stress-strain curve is $\sim$89 GPa, similar to the 90.9 GPa determined by IET; both are comparable to the 88.7 GPa of a similar BMG Zr$_{48}$Cu$_{48}$Al$_4$.

Figure 3 displays SEM micrographs of a typical tensile fracture surface of BMG Zr$_{48}$Cu$_{48}$Al$_4$. It is evident that the shear behavior of the BMG under tension is consistent with what has been reported before, where the shear displacement started by a dominant shear band. It is only in the middle of the shear displacement, a crack formed and the failure took the mode of crack propagations. The fracture angle between the stress axis and the shear plane of the samples is about 54°. The morphology of the fracture surface is also consistent with the above observation. There are two regions on the surface. Region I shown in Figs. 3(a) and 3(b) is dominated by the vein-like structures. The dimple structure of region II indicates that this part underwent tearing after the formation of the crack at the later stage of the failure. The tearing fracture is probably caused by the offset between the tensile loading axis and the axis of the sample after partial displacement of the sample. This mode of failure process has been observed in all of the specimens tested.

Weibull statistics is a well established characterization tool in the field of fracture strength of brittle materials where failure occurs by crack growth from a single, critical flaw. The Weibull model has historically been applied to ceramics and brittle metals to describe the scatter in strengths as well as in the fracture probabilities.
as strength variations due to specimen size.\textsuperscript{14} Nevertheless, very limited literature data are available on the Weibull statistic distribution of strength for bulk metallic glasses; those available were all conducted on glassy ribbons.\textsuperscript{15–17} The characteristic failure mode of BMGs satisfies the weakest link assumption in analogy to conventional brittle materials in which the dominant shear band should be triggered by one weakest element in the sample. This offers a means to explore the mechanical behavior of BMGs through Weibull statistic analysis.

Weibull related the cumulative failure probability $P_f$ of a volume $V$ of material under a uniaxial tensile stress $\sigma$ by the following relationship:\textsuperscript{18}

$$P_f = 1 - \exp\left(-V \left(\frac{\sigma - \sigma_0}{\sigma_0}\right)^m\right),$$

(1)

where $\sigma_0$ is a scaling parameter and $m$ is the Weibull modulus. $\sigma_0$ is the location parameter, at which there is a zero failure probability, and it is usually taken as zero for the safest assumption.\textsuperscript{19}

For $N$ nominally identical specimens ranked from weakest ($i=1$) to strongest ($i=N$), the failure probability $P_{f,i}$ of the $i$th one has been set by Weibull to be

$$P_{f,i} = \frac{i}{N+1},$$

(2)

where $i$ is for the $i$th sample and $N$ is the total number of sample tested. The parameters of Weibull distribution can be obtained by linearizing Eq. (1), thus we have

$$\ln\left(\frac{1}{1-P_f}\right) = \ln V + m \ln \sigma - m \ln \sigma_0.$$  

(3)

By fitting a straight line to $\ln(\ln(1/(1-P_f)))$ as a function of $\ln \sigma$, the Weibull modulus $m$ is simply the slope and the scaling parameter $\sigma_0$ can be determined from the intercept.

Figure 3(d) shows the Weibull plot of the tensile strength of amorphous Zr$_{48}$Cu$_{45}$Al$_7$ alloy. It is interesting to find that a Weibull modulus of 36.5 was simulated from the narrow dispersion in strength [the error in $m$ is estimated to be within 10% (Ref. 20)]. This value is smaller than that of 73.5 for the same alloy under compression tests, but much higher than the common $m$ values for ceramics of 5–10.\textsuperscript{6,12} Reasonably good agreement between high Weibull moduli from tension and compression tests along with their high values is found indicating that the deformation mechanisms of BMGs and typical ceramics are essentially different, although both of them lack macroscopic plastic strain in their stress-strain curves. Weibull analysis based on the statistical dispersion in strength represents that BMGs are predictable which is basically different from brittle materials, despite their plasticity-free behavior.

The tensile strength of a brittle solid such as a ceramic is very sensitive to interior flaws and cracks. In a tensile test, the largest suitably oriented flaw propagates unstably when the critical stress intensity for it is attained. In contrast, our current casting BMGs, containing much fewer cracks and flaws, possibly possess a large fracture toughness\textsuperscript{21} preventing the propagation of crack and flaws. The SEM observations also point out that the failure of our specimen started by shear band displacement, further explaining why our samples have such a high uniformity as our samples are highly homogeneous due to its amorphous nature. The flaws in ceramic materials are generally cracks and voids which are micron sized. Although this study shows that our specimens are free of these defects, we cannot definitely rule out their possible existence introduced during casting, which are responsible for the sample failure. Considering the nature of the amorphous structure, we also speculate that another type of flaw would be in the subnanoscale. Regardless the flaw size, the narrow distribution in the measured strengths is a result of narrow distribution in the flaw size, large or small.\textsuperscript{22}

What these flaws are and how they influence the nucleation of shear band critically leading to the uniformity in tensile strength will need further study. Figure 3(d) also indicates the possibility of bimodal population of flaws, although we only analyzed the data as a single set as no significant difference in fracture mode was observed. It is also noticed that our sample has a very high Poisson’s ratio of 0.377. It has been reported that a high Poisson’s ratio leads to high plastic deformation. Whether such a high tensile strength uniformity is associated with high Poisson’s ratio remains to be studied.

In conclusion, our present results on tensile test of BMGs suggested that these lack uniform plastic strain at least under our present testing condition. However, the Weibull analysis indicated that it has a much high reliability with a Weibull modulus of 36.5, which is much higher than those of ceramic and other brittle materials. High predictability in the tensile strength of BMGs is capable to avoid the catastrophic fracture during service, promoting their potential engineering application. This apparent high reliability is of significant interest in consideration of the applications of BMGs.

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\textsuperscript{2}W. L. Johnson, MRS Bull. \textbf{24}, 42 (1999).


