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# Failure of $Zr_{61}Ti_2Cu_{25}Al_{12}$ bulk metallic glass under torsional loading

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ABSTRACT

The torsional properties of the $Zr_{61}Ti_2Cu_{25}Al_{12}$ BMG have been tested using cylinder samples, including the shear yield strength, shear elastic strain limit and shear modulus. Under torsional loading, the BMG fails via a major shear band, without obvious macroscopic plasticity on the specimen surface. The shear band maintained stable propagation by a distance of ~300 μm (~20% of cylinder radius) before final catastrophic failure, owing to the constraint of stress gradient along the radial direction. The combined tensile, compressive and torsional properties of the $Zr_{61}Ti_2Cu_{25}Al_{12}$ BMG suggest that recent ellipse criterion and eccentric ellipse criterion are more appropriate than other well-known ones in describing the yield behavior of this BMG. The cooperative shear model underestimates the shear elastic strain limit, because of its default assumption that the yielding behavior follows the Tresca yield criterion.


## 1. Introduction

Over the past two decades, bulk metallic glasses (BMGs) have received considerable attention because of their exceptional mechanical properties, including their high yield strength and elastic strain limit [1–4]. As is well understood, the plastic flow of BMGs under confinement-free loading condition, such as uniaxial tension and compression, is dominated by highly localized shear bands due to severe strain localization [5,6]. Most monolithic BMGs therefore lack macroscopic ductility and have been categorized as quasi-brittle materials. Nonetheless, several BMGs such as $Pd_{79}Ag_{3.5}P_6Si_{9.5}Ge_2$ [7] and $Zr_{61}Ti_2Cu_{25}Al_{12}$ [8] have been found to be damage-tolerant, exhibiting crack-resistance (*R*-curve) behavior and a fracture toughness higher than 150 MPa$\sqrt{m}$. Meanwhile, these BMGs also show respectable fatigue damage resistance [9,10], owing to elevated barrier for cracking.

For a candidate material for structural applications, its failure behavior under torsional loading is also of interest, apart from routine tensile and compressive properties. However, to our knowledge, very few studies have been carried out on the torsional behavior of BMGs. This is probably due to the rarely available combination of high toughness and robust glass-forming ability for specimen fabrication. In a torsional experiment on Vitreloy 1, Bruck et al. [11] showed that only a small plastic strain (~0.2%) was visible before catastrophic fracture set in. The case of $Pd_{40}Cu_{30}Ni_{10}P_{20}$ BMG was very similar [12]. With $Zr_{44}Ti_{11}Cu_{10}Ni_{10}Be_{25}$ BMG (LM-1B), in contrast, Kovács et al. [13] claimed that the surface plastic strain was as large as 36% in torsion. Based on acoustic emission (AE) measurement conducted together with surface observation, such large torsional plasticity was ascribed to the activation of multiple shear bands, which was facilitated by an internal stress gradient along the radial direction on specimen cross section [14]. As such, the failure mechanism of BMGs under torsional loading remains unsettled, particularly for the shear-banding events including their initiation and instability.

Furthermore, it has been a long-standing debate as to which yield criterion of isotropic solids should be applied to BMGs [11,15–17]. BMGs have the following three typical features. First, the yield strength, $\sigma_y$, of BMGs in uniaxial compression is generally greater than that in uniaxial tension. Second, both the compressive fracture angle ($\theta_C$) and tensile fracture angle ($\theta_T$) under quasi-static loading conditions deviate from the theoretical maximum shear stress plane at 45° with respect to the loading direction, with $40° < \theta_C < 45°$ and $50° < \theta_T < 65°$, respectively. In addition, it was noticed that the tension fracture angle can sometimes exceed 65° under certain loading conditions, such as cryogenic temperatures and dynamic loading, and even reach approximately 90° [18–21]. Third, the extent of deviation from 45° is markedly asymmetrical. These findings indicate that the normal stress on shear plane plays a role, even though the shear stress is predominantly responsible

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for the incipient flow and the shear banding process of BMGs. Therefore, compared with the Tresca and von-Mises yield criteria, the Mohr-Coulomb yield criterion, which considers the effects of both shear and normal stresses, may be more appropriate to describe the yield behavior of BMGs [16,22–25]. However, it is noteworthy that the deviation of failure angle from 45°, according to the prediction by the Mohr-Coulomb criterion, would be symmetric under compressive and tensile loadings; this contradicts the observations in experiments, as mentioned above. Recently, two new criteria were proposed by Zhang et al. [26–28] and Dai et al. [29], to better explain these three features mentioned above. Note that when a cylindrical specimen is under torsional loading, a monotonic shear stress is imposed on the outer surface of the specimen. The additional data of torsional properties contribute important information to examine the validity of the yield criteria, and should therefore be used in combination with the tensile and compressive data [16,30].

In the present work, a high-toughness $Zr_{61}Ti_2Cu_{25}Al_{12}$ BMG (in atomic percentage, known as ZT1 [31]) is selected to investigate the torsional failure behavior. The purpose of this study is threefold. First, the failure mode will be revealed based on torsional properties and fractography, particularly observations of shear-banding events under monotonic shearing stress. Second, the applicability of the yield criteria will be examined with the torsional properties attained. The third aspect is a comparison of the observed shear elastic strain limit at room temperature, $\gamma_C$, with the value predicted by a master equation based on the cooperative shear model (CSM) by Johnson and Samwer [6].

## 2. Experimental

### 2.1. Sample preparation

The fabrication and mechanical properties of as-cast ZT1 BMG rods have been described elsewhere [32]. Four samples with a diameter of 7 mm were used for the torsional tests, with overall length $L = 50$ mm and gauge length $l = 15$ mm. The specimen diameter of the gauge section and the grip section was machined and polished to 3 mm and 6.8 mm, respectively, conjoined by a fillet with a radius of $R = 3$ mm, as displayed in Fig. 1. In order to catch the global plastic deformation, a fine ink line parallel to the torsional axis was marked on the sample outermost surface.

### 2.2. Torsional tests and calculation methods

The engineering shear stress, $\tau$, and shear strain, $\gamma$, on the surface of cylinder samples under torsional loading was determined, based on the relation of $\tau = 2T/(\pi a^3)$ and $\gamma = a\theta_{gauge}/l$, respectively, where $T$ is the torque, $a$ is the radius of the gauge section, $\theta_{gauge}$ is the rotation angles of the gauge section, and $l$ is the gauge length [33].

We note that the overall rotation angle, $\theta$, recorded by the testing machine consists of two contributions, one from the fillet section, $\theta_{fillet}$, and the other from the gauge section, $\theta_{gauge}$. The actual $\theta_{gauge}$ is $\theta_{gauge} = \theta - 2\cdot\theta_{fillet}$, where $\theta_{fillet}$ was calculated from Ref. [34]:

$$\theta_{fillet} = \frac{2T}{\pi G}\int_0^{\varphi_0} R\cdot\cos\varphi\cdot(R + a - R\cdot\cos\varphi)^{-4}d\varphi \quad (1)$$

where $G$ is the shear modulus of the material, $R$ is the fillet radius and $\varphi_0$ is the angle of the fillet measured in the counter-clockwise direction, as shown in Fig. 1.

Torsional tests of the samples were performed on the Instron 8874 testing machine with a rotation rate of 0.057°/s, which corresponded to a surface shear strain rate of $10^{-4}$/s. In order to ensure the axial force to be controlled as zero during loading, upper gripping head of testing machine was set to move free in the axial direction.

### 2.3. Fracture surface observation

Observation of the side and fracture surfaces of fractured samples was conducted in Quanta 600 and Zeiss Supra 55 scanning electron microscope (SEM). The 3-dimensional X-ray computed tomography of fracture surface of the samples was characterized with VersaXRM-500 3D X-ray microscope and LEXT OLS4000 laser optical microscope (LOM).

## 3. Results

### 3.1. Torsional properties and shear deformation

Fig. 2 illustrates a typical engineering shear stress-strain curve of the ZT1 BMG. As indicated, the shear stress increases linearly with strain in the elastic regime, followed by a small apparent plastic strain of only ~0.2% prior to final catastrophic fracture. The shear yield strength, $\tau_y$, was defined as the point that significantly deviated from linearity [35], as marked by an arrow in the inset. Then, the shear yield strength and shear elastic strain limit were determined to be $\tau_y = 950 \pm 16$ MPa and $\gamma_C = 3.02 \pm 0.04\%$, respectively. By fitting the slope of the linear section in the curve, the shear modulus $G$ was estimated to be 31.5 ± 0.1 GPa, which is comparable to the value measured with resonant ultrasound spectroscopy, $G = 30.2$ GPa [31]. In terms of the area under the linear part of the curve, the elastic strain energy density was found to be $1.4 \times 10^4$ kJ/m$^3$, which is very close to the value of $1.6 \times 10^4$ kJ/m$^3$ determined from the tensile stress-strain curve [36]. This finding satisfies with the Beltrami-Haigh strain energy theory very well [37], which predicts failure or inelastic action of the material at a point when the strain energy per unit volume exceeds a specified limit.

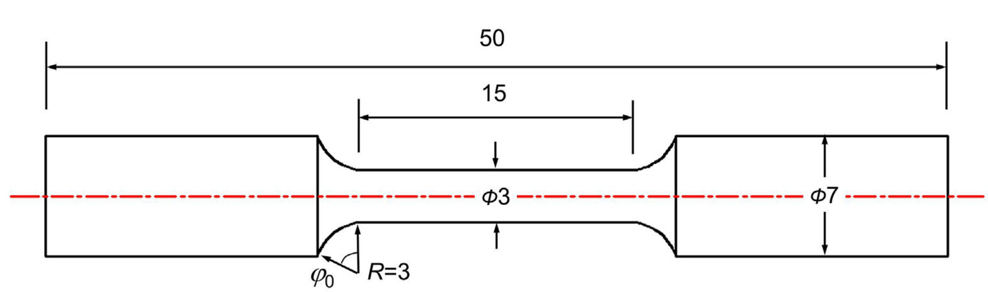


**Fig. 1.** Schematic diagram of cylinder specimen dimensions for torsional tests.