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# Effect of external disturbances on the strain-rate dependent plastic deformation behavior of a bulk metallic glass

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ABSTRACT

In this work, the effect of external disturbances on the strain-rate dependent plastic deformation behavior of a $Zr_{57}Cu_{20}Al_{10}Ni_{8}Ti_{5}$ bulk metallic glass (BMG) has been examined by tailoring the geometric confinement, stress gradient, and sample size. With the external disturbances, the fracture strains of the BMG specimens become less dependence on the strain rates, and it is found that the confinement of the propagation of shear bands is the dominant deformation mechanism. This is different from previous findings in that multiplication of the shear bands also plays a critical role in accommodating the plastic deformation of BMGs with external disturbances. The present findings not only shed more light on the deformation mechanisms of BMGs under external disturbances, but also suggest that the use of external disturbances can reduce the dependence of the plastic deformation behavior of BMGs on the strain rates.


## 1. Introduction

During past decades, bulk metallic glasses (BMGs), as a new class of structural materials, have attracted great research interest due to their unique properties stemming from non-ordered atomic arrangements, such as superior mechanical properties compared with their crystalline counterparts [1–3]. Without crystalline lattices and defects, the plastic deformation in BMGs is characterized by intermittent bursts of shear events, demonstrating serrations in the stress-strain curves [4–6]. Many studies have shown that the deformation behavior of BMGs is significantly dependent on the strain rate [4,7–11], for example, the fracture behavior [7,12,13] and bursts of shear events [4,14]. With increasing strain rate, the plastic flow in BMGs tends to transit from serrated flow to non-serrated flow [4,14], and the critical strain rate is dependent on the physical nature of the alloys, such as the alloy composition [4,15]. The plastic-flow dynamics of BMGs can also be tuned by the change of strain rates [10]. Simulations of the plastic deformation of metallic glasses show that the yield stress [16–18] and shear transformation zone (STZ) characteristics [19,20] are also dependent on the applied strain rates. For example, Cao et al. [18] have reported the decrease of yield stress at relatively lower strain rates. Understanding the dependence of the plastic deformation behavior of BMGs on the change of strain rates is important before enabling wide applications as structural materials. Recently, Bhattacharyya et al. [11] examined the effect of the internal free volume content on the strain-rate sensitivity of the plastic flow in BMGs, and found that a higher free volume content can reduce the strain-rate sensitivity. However, previous findings have shown that the plastic deformation behavior of BMGs is affected by not only the internal physical properties of the BMGs, such as free volume [21], alloy composition [22–24] and Poisson's ratio [25,26], but also the applied external disturbances, such as geometric confinement [27–29], stress gradient [30–32] and sample size [33,34]. Under external disturbances, such as geometric confinement and the presence of stress gradients, BMGs are able to demonstrate more plastic deformation behavior, resulting from the multiplication of the shear bands and the confinement of their propagations [27,28,30,32,35]. However, how the strain-rate dependent plastic deformation behavior is influenced by the external disturbances has not been documented. In this work, the effect of external disturbances on the strain-rate dependence of the plastic deformation behavior of a BMG is further examined and its deformation mechanism analyzed under different strain rates.

## 2. Experimental

### 2.1. Specimen preparation

As-cast $Zr_{57}Cu_{20}Al_{10}Ni_{8}Ti_{5}$ (at%) BMG specimens were

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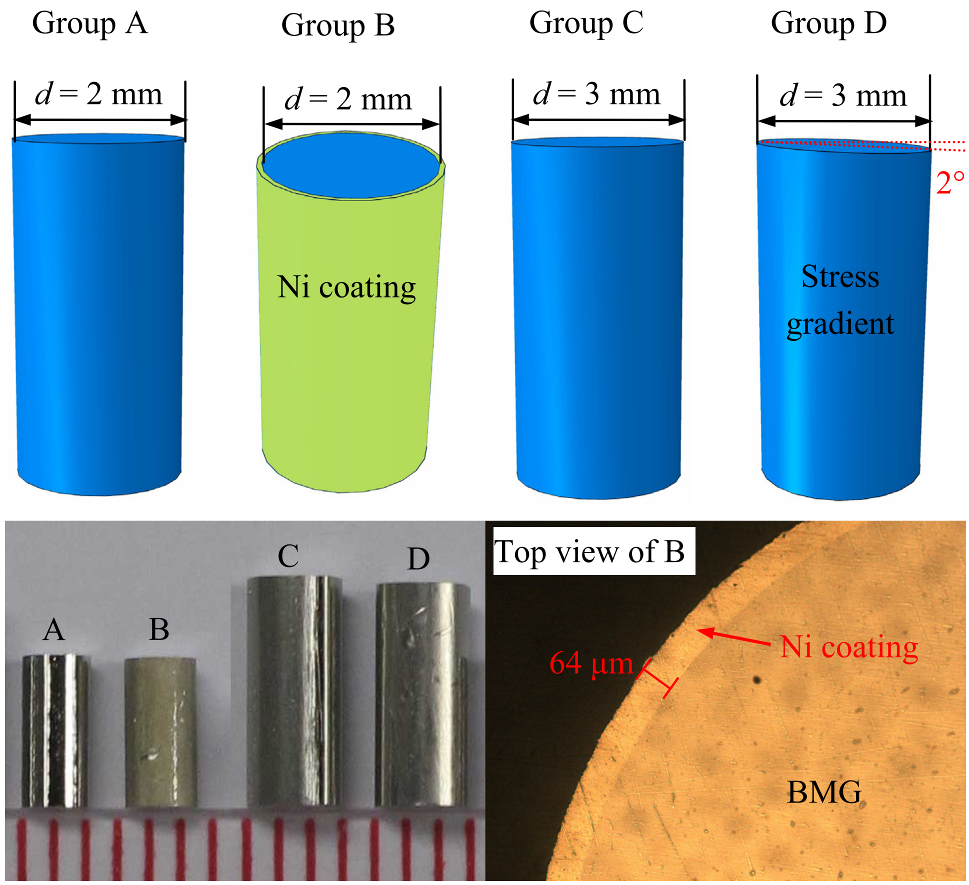


**Fig. 1.** Schematic diagrams of four groups of specimens, where the optical images show the four prepared specimens.

fabricated from the pure elements of Zr (99.8%), Cu (99.999%), Al (99.99%), Ni (99.999%) and Ti (99.995%). Master alloy ingots were firstly produced by arc-melting the pure elements using a WK-II vacuum arc melter under an Ar atmosphere. After remelting the master alloy ingots five times, cylindrical specimens of 3–2 mm diameters were fabricated by suction casting the melted alloy into water-cooled copper molds [32]. The amorphous nature of the as-cast rods was checked using X-ray diffraction (XRD) analysis on a Rigaku SmartLab X-ray diffractometer. To examine the effect of external disturbances on the strain-rate dependent plastic deformation behavior of BMGs, three kinds of external disturbances were introduced in this work: geometric confinement, stress gradient and sample sizes. Four groups of BMG specimens, with aspect ratios of 2, were produced from the cylindrical rods. As shown in the schematic diagram in Fig. 1, Group A and Group C specimens were cut from the cylindrical rods with 2 mm and 3 mm in diameters, respectively. After electro-depositing a Ni layer onto the 2 mm diameter cylindrical rods using an electrolyte and methods described in Ref. [27], Group B specimens with geometric confinement were cut from the coated rods. The Ni thicknesses of Group B specimens were $66 \pm 7$ μm. In Group D, a tilt angle of 2° was tailored on the top surface of the 3 mm diameter specimens, resulting in the presence of stress gradients under subsequent compression tests [30]. The morphology of the prepared specimens was inspected using optical microscopy (OM), and the results are shown in Fig. 1.

### 2.2. Compression tests

Compression tests were conducted on an MTS Qtest/25 materials testing machine at room temperature. The four groups of specimens were tested at strain rates of $5 \times 10^{-3}$, $5 \times 10^{-4}$ and $5 \times 10^{-5}$ s$^{-1}$ respectively, and collected at a rate of 50 data per second. Three specimens for each condition were tested. After compressive testing, the specimens were inspected using scanning electron microscopy (SEM) on a JEOL JSM-6490 scanning electron microscope.

### 2.3. Finite element modelling (FEM) analysis

To characterize the yielding and the evolution of the yielded regions in the Group D specimens, the gradient stress distributions were simulated using FEM analysis based on a commercial ABAQUS package with an ideal elastic-plastic constitutive model [36,37]. Although such constitutive model cannot be used to simulate the nucleation and propagation of shear bands as well as the fracture of BMGs, it is good to characterize the evolution of yielded regions where shear bands are formed [36,37]. The input material parameters for the FEM analysis are 1.635 GPa for the yield stress [36], 82 GPa for Young's modulus [38] and 0.36 for Poisson's ratio [38].

## 3. Results

### 3.1. Effect of external disturbances on the nominal plasticity

The nominal stress-strain curves of four groups of specimens under different strain rates are given in Fig. 2. In Group A, the nominal strain increases significantly as the strain rate decreases (Fig. 2a and e), agreeing well with previous findings [7]. However, when external disturbances were applied to Groups C-D, this trend changed. For the Ni-coated specimens in Group B, they all demonstrated large nominal strains, reaching about 12%. It seems