Normal stress effect on plastic yielding of notched metallic glass: a finite element simulation study

Wen Zhong, Yanan Ren, Jing Hu and Huiyu Xiang
School of Material and Mechanical Engineering, Beijing Technology and Business University, Beijing 100048, People’s Republic of China

E-mail: hujing@th.btbu.edu.cn

Abstract
The pressure or normal stress effect on the plastic yielding of metallic glasses (MGs) is still poorly understood due to their complex nature of deformation process. A knowledge on the internal stress distribution and evolution around the plastic shearing plane holds the key for understanding the above issue. In this study, we studied the plastic deformation process of a notched bulk metallic glass by finite element simulation using the von-Mises yielding criterion and Mohr-Coulomb yield criterion, respectively. The internal shear stress distribution and evolution on the notched shear plane was analyzed, and the yielding strength is extracted by averaging the shear stress on the shear plane. It was found that the plastic flow of MGs is greatly influenced by the pressure/normal stress effect as captured by Mohr-Coulomb yielding criterion, and the strength extracted with the criterion agrees well with that obtained from experiments. The effect of pressure/normal stress on the plastic flow of MGs are also discussed from the mechanistic viewpoint. Our results may help for understanding the underlying origin for the pressure/normal stress effect on the plastic flow of MGs.

1. Introduction
As a new type of amorphous materials, metallic glasses (MGs) have many unique performance such as superb strength and hardness, excellent corrosion resistance and high wear resistance, thus has wide potential applications in engineering field (Schuh et al 2007, Yavari et al 2007). However, compared to conventional crystalline alloys, MGs display completely different deformation and fracture mechanisms which are still poorly understood (Qiao et al 2016, Liu et al 2018). Generally, when a MG was deformed at room temperature, almost all plastic strain is concentrated within the nanoscale shear band regions with a thickness of only about 10–20 nm. Due to pronounced strain softening effect, the shear band is susceptible to become unstable and runaway during the deformation process, which will result in catastrophic fracture of MGs ultimately. Although physical origin for the strain softening, i.e. shear-induced structural disordering versus temperature rise, is still debated, shear localization and work softening in MGs have become the main obstacle for their widespread applications (Spaepen 1977, Flores and Dauskardt 2001, Lu et al 2003, Ding et al 2014). Therefore, the understanding on plastic deformation behavior of amorphous alloy and its mechanical response mechanism, especially on the shear band formation and propagation mechanism, is of vital importance for the practical application of amorphous alloys (Wright et al 2001, Bian et al 2002, Widmer-Cooper et al 2008 Dong et al 2019).

Over past decades, many theoretical models related to local shear deformation and fracture behavior of amorphous alloys have been proposed (Wang et al 2018), such as the well-known free-volume model (Argon 1979, Wright et al 2003) and shear transformation zone (STZ) theory (Leamy et al 1972, Liu et al 1998). To a certain extent, these models could explain the shear localization process, i.e. shear band formation, as well as the relationship between the shear band and the material’s macroscopic properties. Yet, the plastic deformation and fracture mechanism of amorphous alloy is still not fully understood, especially on the pressure effects on the plastic flow process. As earlier as 1975, Davis and Kevesh (Davis and Kavesh 1975) studied the effects of hydrostatic pressure on the yield behavior and fracture characteristics of Pd$_{77.5}$Cu$_6$Si$_{16.5}$ metallic glass.
They found that the compressive behavior of the amorphous alloy showed a dependence on the normal stress, and the yielding of the amorphous alloy was consistent with the Mohr-Coulomb criterion. However, after an examination on the tensile, compressive and twisted combination experiments of Pd78Cu6Si16 metal glass and theoretical calculation, Kimura concluded that the yield behavior of Pd78Cu6Si16 metal glass follows the Von-Mises criterion. Recent years, accumulating experimental evidences showed that the plastic flow and fracture behaviors of MGs under compression and tension were asymmetric, such as yielding strength, fracture angles et al (Zhang et al 2003a, Pan et al 2015, Wang et al 2015). These differences clearly indicate the effects of shear/normal stress on the plastic flow of MGs. Despite of these studies, the detailed mechanism underlying the stress-dependent plastic flow behavior is still poorly understood. Addressing the issue relies on in-depth examination on the evolution of shear stress and normal stress on the shear plane during the deformation process of MGs.

Notched metallic glass have abstracted many interest because the global plasticity of metallic glass specimens could definitely improve, including normal and nano scale sample (Sha et al 2015, Yang et al 2017, Dutta et al 2018), and several methods, such as slipline field theory, finite element analysis (FE) and Neuber’s stress analysis, etc, have also been applied to reveal the effects of notch (Qu et al 2014). However there are more attention paid on the effects of notches shape and sharpness, little care on the slope of the notch (Henann and Anand 2009, Sha et al 2015, Chen et al 2016, Gu et al 2017), but with different slope, there may exhibit different deformation and stress-strain state. And also when we want to check different yield criterion, such as Mises and Mohr-Coulomb criterion, the notch without slope may restrict the progress of shear bands, and the model may look like to afford Mises Criterion. In order to avoid this kind of false appearance, the sloped notch models were usually selected.

In this study, in order to study the shear/normal effect on the plastic yielding and flow of MGs, the plastic deformation process of a notched bulk metallic glass with von-Mises yielding criterion and Mohr-Coulomb yield criterion were simulated by using FE analysis respectively, which may supplement the shortage of internal stress and strain changes of material cannot be real-time observed by experiments (Ruan et al 2011). The internal shear stress distribution and evolution on the notched shear plane is analyzed. Based on shear stress analysis at the yielding point, the shear strength of the MG under two different criterions is calculated and compared to that obtained from compression experiments. Our results clearly suggested that the plastic flow of MGs is greatly influenced by the shear/normal stress effect as captured by Mohr-Coulomb yielding criterion, and the extent of the stress affect the shear flow of MGs is extracted.

2. FE simulation and experiments

2.1. Numerical FE simulation procedure

Experimentally, bulk MG samples with notches in different inclined degrees were often used to precisely control the shear band formation along specified inclined degrees. In uniaxial compression experiments, the angle of the primary shear plane of MGs is about 42°. Therefore, to make sure that there is only a single shear band formed during deformation, the MG samples with two parallel notches with inclined angle of 42° were manufactured, as shown in figure 1(a). The overall size of the MG sample is 2.5 mm × 1 mm × 1 mm, and the notch has a width of 0.3 mm and a depth of 0.3 mm.

The deformation process of the sample is numerically simulated in commercial software Abaqus. The mesh and boundary conditions of the model are shown in figure 1(b). In order to simulate the quasi-static process and observe the sawtooth rheology of the amorphous alloy during compression, the sample was compressed with a constant strain rate of \(5 \times 10^{-4} \text{ s}^{-1}\). The load was imposed on the upper surface of the sample, and the lower


To compare the results between simulation and experiments, a typical bulk MG with the composition Zr_{52.5}Ti_{5}Cu_{17.9}Ni_{14.6}Al_{10} (Vit105) was used. The alloy ingots with the nominal composition were produced by arc-melting mixture of pure metals (purity >99.5% in mass) in a Ti-gettered argon atmosphere. To ensure the homogeneity of composition, each ingot was re-melted at least three times. Plate samples with width of 10 mm and thickness of 2.5 mm were obtained by suction casting into a copper mold. The amorphous nature of as cast-samples was examined by x-ray diffraction (XRD) and differential scanning calorimetry (DSC) methods. Cubic samples with a size of 2.5 mm × 1 mm × 1 mm were cut from MG plate by a diamond saw with water cooling and then carefully ground the two ends. The notches were induced by electric sparking method. The uniaxial compression tests were performed on Instron electromechanical 5869 test system equipped with constant strain rate of 5 × 10^{-4} s^{-1} at room temperature. The strain was measured by a laser extensometer (Fiedler) equipped on the testing machine. After deformation, the morphologies of shear bands and fracture surfaces were investigated by a high-resolution scanning electron microscopy (SEM, Gemini 1530).

### 3. FE simulation and experimental results

#### 3.1. Displacement—load curve in FE simulation

The compression deformation of MGs was simulated with the Von-Mises and Mohr–Coulomb yield criterion, respectively. The material parameters was shown in table 1 (Lund and Schuh 2004, Baricco et al 2009, Vargonen et al 2012). Here, the cohesion angle θ is 10° (tan(θ) = 0.176), corresponding with the 42° shear fracture angle. The simulated load–displacement curves under two yield criteria were shown in figure 2. As can be seen, almost the same elastic deformation were exhibited for the two yield criteria. After the linear elastic deformation, both samples enter into the plastic deformation stages. In the plastic deformation region, the increase of the load with the displacement was not affected by the work-hardening behavior of MGs, but related to the stress concentration around the notches during the deformation. For each curve, the yield points (labeled as IIV and ILM for Von–Mises yield criterion and Mohr–Coulomb yield criterion, respectively) were selected. The values of load and displacement for IIV and IIM were shown in table 2. It can be see that the model using Mohr–Coulomb criterion yield earlier, corresponding to the time t = 20 s, while the yield time of the sample using Von–Mises criterion is t = 22.178 s. This phenomenon implied that the nominal yielding stress required for the Von–Mises criterion is greater than that for the Mohr–Coulomb criterion.

#### 3.2. The stress evolution on the notched shear plane

In general, the plastic flow of MGs is highly localized within a thin shear band, which is often along a primary shear plane. The formation of a shear band is regarded as the occurrence of macroscopic yielding of MGs (Zhang et al 2003b, Fornell et al 2009). To understand the shear/normal stress effect on the plastic yielding and flow behavior of MGs, we investigated the evolution of internal stress (shear stress and normal stress) along the primary shear plane at different deformation stages. The results of shear stress and normal stress were extracted by the second development using the software of MATLAB. The fracture location and fracture section are shown in figures 3(a) and (b), it can be seen that the amorphous model under both yield criteria fractured along the notched grooves. Due to the stress concentration, the main shear band and shear plane precisely formed along

| Yield criterion | Mohr-coulomb | Cohesion yield stress (MPa) | Friction angle (θ) | Cohesion angle (θ) | Density (g cm⁻³) | Young’s modulus (GPa) | Possion’s ratio |
|----------------|--------------|----------------------------|-------------------|-------------------|------------------|---------------------|-----------------|
|                | 800          | 6°                         | 10°               |                   | 6.0              | 89                  | 0.37            |
the fracture section too (Yu et al 2007, Caris and Lewandowski 2010). Thus, the distribution of shear stress and normal stress on the fracture section were analyzed.

The contours of shear stress evolution at the fracture section using the two yield criterion were shown in figure 4. Three typical points I.V, I.M, II.V, II.M, III.V, III.M were selected from figure 1, which were corresponding to a time of elastic stage $t = 10$ s, the time of yielding points $t = 20$ s (for Mohr-Coulomb yield criterion)/22.178 s (for Von-Mises yield criterion) and a time of plastic flow stage $t = 35$ s respectively.

During the elastic stage (the time node of this stage is $t = 10$ s), the trends of shear stress according to the two yield criteria are the same, and the stress values are almost the same. The larger shear stress of the fracture section distributed on both sides of the section, and as closer to the groove area, the greater the stress value is. The

---

**Table 2.** Various stress and strain values of experimental and simulation results.

|                           | Von-Mises yield criterion | Mohr-Coulomb yield criterion | Experiment |
|---------------------------|---------------------------|------------------------------|------------|
| Maximum shear stress (MPa)| 711                       | 621.5                        | —          |
| Minimum shear stress (MPa)| 471                       | 514.5                        | —          |
| $\tau_{\text{max}} - \tau_{\text{min}}$ (MPa) | 240                       | 107                          | —          |
| Yield stress (MPa)        | 1176.36                   | 1118.05                      | 1129.50    |
| Yield strain              | 0.0097                    | 0.0098                       | 0.010      |
| Average shear stress value on 42° oblique section (MPa) | 655.0965 | 592.0172 | 578.0726 |

---

**Figure 2.** Displacement-load curves obtained from FE simulation with Von-Mises criterion and Mohr-Coulomb criterion.

**Figure 3.** Compression fracture contours of the amorphous model. (a) The schematic diagram of the fracture location of the amorphous model. (b) The schematic diagram of the fracture section of the amorphous model.
maximum shear stress of the amorphous model with Von-Mises yield criterion reaches 505 MPa, and the amorphous model with Mohr-Coulomb yield criterion is 504 MPa. The smaller shear stress is uniformly distributed inside the section, and the minimum stress values under both yielding criteria are both 235 MPa. This implies that the stress concentration phenomenon exists in the notched grooves, which cause the stress gradient changing drastically in the outer region initially, and the stress value increasing rapidly. Then the shear stress inside the plane away from the stress concentration area changed uniformly and continued to increase.

With the proceeding of compression, both model samples show yield phenomena at compression time of \( t = 20 \) s (for Mohr-Coulomb yield criterion) / 22.178 s (for Von-Mises yield criterion), respectively. According to the map of contours, the trends of shear stresses under the two yield criteria are basically the same as that in the elastic stage, the larger shear stress is distributed outside the plane and the smaller shear stress is distributed inside the plane. However, there are differences between the stress distributions and the stress values at the yield point. Based on the value axes, the shear stress distribution on the section with the Mohr-Coulomb yield criterion is more uniform at the yield point, and the maximum shear stress value in the outer region of the plane differs from the minimum shear stress value inside the plane by only 107 MPa. For the model sample with Von-Mises yield criterion, the change of stress gradient from inside to outside of the plane is more obvious, and the difference between the maximum shear stress and the minimum shear stress is 240 MPa. The relatively uniform shear stress distribution with the Mohr-Coulomb criterion clearly suggests the effect of pressure/normal stress effect on the plastic flow of MGs.

After yielding, both model samples enter into the plastic flow stage. According to the contours at the time of \( t = 35 \) s, the shear stress on the section is almost uniform for the amorphous model using the Von-Mises yield criterion, and the magnitude of shear stress varies between 678.7 MPa and 699.7 MPa, the stress gradient change gently. The maximum shear stress value at this stage drops about 11.3 MPa as compared to that at yield point. In contrast, the distribution of shear stress on the plane id relatively inhomogeneous for the model sample using the Mohr-Coulomb yield criterion. The cross-sectional stress varies between 542.4 MPa and 586.2 MPa, and the stress fluctuation range is larger than that for the Von-Mises yield criterion. The maximum shear stress at this stage is also lower than that at the yield point.

The normal stress of the shear plane was also extracted at the same time points, and the evolution contours during the compression were shown in figure 5. It can be seen that there are large differences between the normal stress distribution and the shear stress distribution of the shear plane at different stages, yet the evolution trends of the normal stress distribution are similar for the two yield criteria. In the elastic stage, the magnitude and distribution of the normal stress are almost the same for the two criteria: the larger stress appears at notched groove regions and the lower edge of the shear plane, while the normal stress is relatively low and uniform inside the plane. At the yield point, the distribution of normal stress is similar for both criteria, which is inhomogeneous with the largest stress appearing at the lower edge region and the smallest stress distributing at the center region. The stress magnitude of the Mohr-Coulomb criterion is overall lower than that of Von-Mises criterion. In the plastic flow stage, the distribution of normal stress is still inhomogeneous and the stress
magnitude is slightly increased as compared to that at the yield point. This is different from the case of shear stress which is uniformly distributed across the whole plane in the plastic flow stage.

3.3. Experimental results
To further understand the FE simulated results above, we performed the uniaxial compression tests on the notched MG samples with the same size and shape as that in FE simulation. The typical displacement-load curve obtained from the experiments is shown in figure 6. As can be seen, the experimental curve resembles the curves obtained from FE simulation, where the elastic, yielding and plastic flow stage can be clearly observed. After yielding, the stress-strain curve exhibits an obvious superimposed oscillations phenomenon, which is closely related to the stick-slip motion of the primary shear band. When the compression test is carried out at room temperature, the macroscopic plastic deformation of the amorphous alloy is prone to localized shear bands, which appear as non-uniform flow of the material at the microscopic level, while the formation and expansion of the shear bands produce a sawtooth rheology on the load curve (Lu and Ravichandran 2003, Ott et al 2006). From SEM observations (the inset in figure 6), a shear step due to the shear band sliding can be clearly seen on the side surface of the MG sample. The band is formed on the 42° shear plane along two grooves, which is in

Figure 5. The normal stress contours of the amorphous model at the fracture section at different compression stages. (a) $t = 10$ s using the Von-Mises yield criterion; (b) $t = 22.1781$ s using the Von-Mises yield criterion; (c) $t = 33$ s using the Von-Mises yield criterion; (d) $t = 10$ s using the Mohr-Coulomb yield criterion; (e) $t = 20$ s using the Mohr-Coulomb yield criterion; (f) $t = 35$ s using the Mohr-Coulomb yield criterion.

Figure 6. Displacement—load curve and SEM image of fracture shear band obtained from experiment.
agreement with simulation results. The yield load defined as the reflection point of the deformation curve is 642 N. While the yield loads obtained from FE simulation are 727 N and 657 N for the Von-Mises yield criterion and Mohr-Coulomb yield criterion, respectively. It is obvious that the simulation sample with the Mohr-Coulomb yield criterion is much closer to the experimental results.

Since the stress distribution are not uniform for the notched samples, we calculated the nominal stress-strain curves (the load was divided by the cross-section area without considering the notch area). The experimental and simulated stress-strain curves are shown in figure 7. As can be seen, the trend of the three curves are basically the same. There are a linear elastic phase, an inflection point characteristics of the yield transition and a slightly rising plastic flow stage. Since there is no stick-slip sliding in the simulation, so the simulated curves are smooth in compared to the experimental curves. The values for the stress and strain at the yield point extracted from the three curves are shown in table 2. From the figure and table, one can see clearly that the stress-strain curve obtained using the Mohr-Coulomb yield criterion is closer to the experimental results. At the yield point, the difference between stress value getting from Mohr-Coulomb criterion and the experimental value is 11.45 MPa, and the difference between the stress values getting from the Von-Mises criterion and the experimental is 46.86 MPa. The strain results from the two yield criteria differs by 0.0001, and the model using Mohr-Coulomb yield criterion is closer to the experimental results.

4. Discussion

From both experimental and simulated results, one can see that a shear band is formed on the plane 42° inclined to the loading axis, which is consistent with those reported in previous studies (Zhang et al 2004, Sergueeva et al 2005). However, due to the existence of the notched grooves, the stress distribution on the shear plane is not uniform. Therefore, we attempt to calculate the average shear stress across the whole shear plane in FE simulation based on which the real shear strength of the MG can be Firstly, the principal stress of each element node on the plane was extracted from FE simulation. Then the shear stress values in the 42° direction of each node, \( \tau_n \), were calculated by the following equation (Gere 1984):

\[
\begin{align*}
\sigma_n &= \sigma_1 l^2 + \sigma_2 m^2 + \sigma_3 n^2 \\
\tau_n &= \sqrt{\sigma_1^2 l^2 + \sigma_2^2 m^2 + \sigma_3^2 n^2 - \sigma_n^2} \\
l^2 + m^2 + n^2 &= 1
\end{align*}
\]

Where \( \sigma_1, \sigma_2, \sigma_3 \) are the principal stress of the node; \( l, m \) and \( n \) are components of the unit vector for the 42° plane. Once \( \tau_n \) for all nodes were obtained, the average shear stress across the shear plane could be calculated by equation (1). The summary of the average shear stress getting from simulations and experiments was shown in table 2. The average shear stress obtained from Von-Mises yield criterion model is 655.0965 MPa, which differs by 77.0239 MPa from experimental result. The average shear stress obtained by applying the Mohr-Coulomb yield criterion is 592.0172 MPa, which differs by 13.9446 MPa compared with the experimental value. Again, the FE simulation with Mohr-Coulomb yield criterion is closer to the experimental results under the compressive load.

---

**Figure 7.** The comparison of stress—strain curves obtained from FE simulation and experiment.
obtained. Although the MGs is well known to follow the Mohr-Coulomb criterion. Yet the details underlying that how the criterion affects the stress distribution and evolution from the elastic regime to the plastic regime is poorly understood. We found that with the Mohr-Coulomb criterion, the stress distribution around the shear plane become significantly different as compared to the Von-Mises criterion from the yield point, which could thus induce structural inhomogeneity, and ultimately affect the shear band formation direction.

From the results above, we can see that the Mohr-Coulomb yield criterion is more suitable for describing the plastic yielding and flow of MGs. This criterion takes into account the effect of normal stress on the plastic shear of materials, which are widely used in shear-dilation materials such as the granular materials(Schuh and Lund 2003). In general, the Mohr-Coulomb yield criterion is written as(Lund and Schuh 2004):

\[
\tau_y = k_y - a_n \sigma_n
\]

where \(\tau_y\) is the effective yield stress for shear on the shearing plane, \(k_y\) is the shear resistance of the glass in pure shear, \(a_n = \tan \theta\) is the friction coefficient with \(\theta\) is the friction angle. \(\sigma_n\) is the normal stress on the shear plane. For the uniaxial compression, the shear stress \(\tau\) and the normal stress \(\sigma_n\) on a shearing plane have the relations:

\[
\sigma_n = \frac{\tau}{\cos \theta},\quad \tau = \sigma_n \sin \theta\cos \phi_n\]

where \(\sigma_n\) is the compressive yield strength of the glass, \(\theta\) is the shear angle of the plane. For the occurrence of plastic yielding with the Mohr-Coulomb criterion, the friction coefficient \(a_n\) fulfill the relation: \(a_n = \cot(2\theta)\). Therefore, we have \(\theta = 90^\circ - 2\theta\). Since the primary shear or the fracture often occurs along a plane with \(\theta \approx 42^\circ\), the corresponding friction angle \(\theta \approx 6^\circ\). That’s the reason why we choose the friction angle \(\theta \approx 6^\circ\) in the FE simulation. In addition, we also use a sample with two notched groove along the shear plane of 42°. In this case, the sample will be precisely yield along the shearing plane of 42°, no matter the plastic flow of the glass follows the Von-Mises criterion or the Mohr-Coulomb criterion. So the simulation results for the two criterions can be directly compared.

As compared to previous experimental studies on the pressure/normal stress effect on the plastic flow of MGs, our simulation could not only obtain the overall stress-strain response, but also could track the stress/strain distribution and their evolution with the deformation strain. As can be seen, in the elastic deformation stage, both the magnitude and distribution of the stress are the same for the two yield criterion. Once the sample yields, the stress distribution begin to become different due to the effect of normal stress on the plastic flow of MGs. For the compressive normal stress, the plastic yielding become much easier for the Mohr-Coulomb criterion. As can be found in the shear stress contour, the maximum difference of the shear stress for the two criterions can be directly compared. Indeed, once yielding, the normal stress will begin to come into effect. The normal stress will interfere with the shear flow process and aggravate the shear stress inhomogeneity, especially at the yielding point. As can be seen, the maximum shear stress appears at the lower edge part vertical to the notched grooves, indicating that the plastic yielding will first occur at this site. This is contrast to the common view that the shear stress distribution will be symmetrically distributed due to the symmetrical notches. In fact, for each element involving in the plastic deformation, there is a shear stress and normal stress. There should be different for the elements at different positions. There are complex stress interactions between these elements, especially around the notch. When there is a normal stress effect on the plastic flow, the interactions between the elements will become more complex than the case without normal stress effect. So the stress interaction between the elements will finally result in asymmetric distribution of stress, ultimately the overall plastic yielding behavior of MGs. While in the steady plastic stage, shear stress gradually becomes uniform. These findings will provide new insights on the mechanism of plastic yielding and flow of MGs. Indeed the Von Mises and Mohr-Coulomb models are both macroscopic model for describing the overall response of MGs. However, the yielding criteria also have a microscopic physic origin. There are many previous studies on this topic. For example, Schuh et al studied the atomistic origin for the plastic yielding criterion of MGs from the element deformation model and comparation with atomic simulation and experimental data (Schuh and Lund 2003). They provide an atomic-level explanation for pressure-dependent yield in MGs. The parameters in the plastic yielding criterion have physical meaning corresponding to the atomic disordered structure. However, this has beyond the scope of our current paper and will be studied in a further study.

5. Conclusions

In summary, we studied the plastic deformation process of a notched bulk metallic glass by finite element simulation using the von-Mises yielding criterion and Mohr-Coulomb yield criterion, respectively. The internal shear stress and normal stress distribution and their evolution on the notched shear plane with the plastic deformation were analyzed. It was found that the normal stress not only affects the magnitude of the shear stress,
but also their distribution as the plastic yielding occurs. The interplay between the normal stress and the shear stress on the shear plane lead to inhomogeneous and complex stress distribution even for a symmetrical notched shape. The yielding strength of MG is also extracted by averaging the shear stress on the shear plane for two criterions. By comparing to the experimental results, it is clear that the Mohr-Coulomb yielding criterion is more suitable for describing the plastic flow of MGs. Our results show that the effect of normal stress on the plastic flow of MGs are much more complex than that commonly regarded.

Acknowledgments

The work is supported by the National Natural Science Foundation of China (NSFC) (No. 51601002, 51671121, 51520105001, 51761135125) and the Fundamental Research Funds for the Central Universities of China (Grant No. 30917015107).

ORCID iDs

Jing Hu https://orcid.org/0000-0001-5137-4019

References

Argon A 1979 Plastic deformation in metallic glasses Acta Metall. 27 47–58
Baricco M, Basier T A, Das J and Eckert J 2009 Correlation between Poisson ratio and Mohr-Coulomb coefficient in metallic glasses J. Alloys Compd. 483 125–31
Bian Z, He G and Chen G L 2002 Investigation of shear bands under compressive testing for Zr-base bulk metallic glasses containing nanocrystals Scr. Mater. 46 407–12
Caris J and Lewandowski J J 2010 Pressure effects on metallic glasses Acta Mater. 58 1026–36
Chen S H, Chan K C, Wang G, Wu F F, Xia L, Ren J L, Li J, Dahmen K A and Liaw P K 2016 Loading-rate-independent delay of catastrophic avalanches in a bulk metallic glass Sci. Rep. 6 21967
Davis L A and Kavesh S 1975 Deformation and fracture of an amorphous metallic alloy at high pressure J. Mater. Sci. 10 453–9
Ding J, Patinet S, Falk M L, Cheng Y and Ma E 2014 Soft spots and their structural signature in a metallic glass Proc. Natl Acad. Sci. 111 14052–6
Dong F, He M, Zhang Y, Wang B B, Luo L S, Su Y Q, Yang H W and Yuan X G 2019 Investigation of shear transformation zone and ductility of Zr-based bulk metallic glass after plasma-assisted hydrogenation Materials Science and Engineering: A 759 105–11
Dutta T, Chaurasia A, Singh I, Narasimhan R, Thamburaja P and Ramamurty U 2018 Plastic deformation and failure mechanisms in nano-scale notched metallic glass specimens under tensile loading J. Mech. Phys. Solids 111 393–413
Flores K M and Dauskardt R H 2001 Mean stress effects on flow localization and failure in a bulk metallic glass Acta Mater. 49 2527–37
Fornell J, Surinach S, Baro M D and Sort J 2009 Unconventional elastic properties, deformation behavior and fracture characteristics of newly developed rare earth bulk metallic glasses Intermetallics 17 1090–7
E. J. Hearn 1985 Mech. Mater. 2nd SI edn (New York: Van Nostrand Reinhold) T S P https://doi.org/10.1016/C2013-0-01257-1
Gostin P F, Eigel D and Grell D 2015 Comparing the pitting corrosion behavior of prominent Zr-based bulk metallic glasses Journal of Materials Research 30 233–43
Gu J, Zhang T W, Jiao Z M, Wang Z Y, Wang Z H, Ma W and Qiao J W 2017 Improvement of dynamic notch toughness for the Zr56 Co28 Al16 bulk metallic glass by local pre-deformation J. Non-Cryst. Solids 473 96–101
Henann D L and Anand L 2009 Fracture of metallic glasses at notches: Effects of notch-root radius and the ratio of the elastic shear modulus to the bulk modulus on toughness Acta Mater. 57 6057–74
Leamy H J, Wang T T and Chen H S 1972 Plastic flow and fracture of metallic glass Metallurgical and Materials Transactions B 3 699
Liu C T, Heatherly L, Horton J A, Easton D S, Carmichael C A, Wright J L, Schneibel J H, You M H, Chen C H and Inoue A 1998 Test environments and mechanical properties of Zr-base bulk amorphous alloys Metallurgical and Materials Transactions A 29 1811–20
Lu J and Ravichandran G 2003 Pressure-dependent flow behavior of Zr41.2Ti13.8Cu12.5Ni10Be22.5 bulk metallic glass J. Mater. Res. 18 2039–49
Lu J, Ravichandran G and Johnson W 2003 Deformation Behavior of the Zr41.2Ti13.8Cu12.5Ni10Be22.5 Bulk Metallic Glass Over a Wide Range of Strain-Rates and Temperatures Acta Materialia 51 3429–43
Lund A C and Schuh C A 2004 The Mohr–Coulomb criterion from unit shear processes in metallic glass Intermetallics 12 1159–65
Ott R T, Sansoz F, Jiao T, Warner D, Molinari I F, Ramesh K T, Hufnagel T C and Fan C 2006 Yield criteria and strain-rate behavior of Zr27Cu49Ni14 metallic-glass-matrix composites Metallurgical and Materials Transactions A 37 3251–8
Pan J, Zhou H F, Wang Z T, Li Y and Gao H J 2015 Origin of anomalous inverse notch effect in bulk metallic glasses J. Mech. Phys. Solids 84 85–94
Qu R, Zhang P and Zhang Z 2014 Notch effect of materials: strengthening or weakening? Journal of Materials Science & Technology 30 599–608
Ruan H H, Zhang L C and Lu J 2011 A new constitutive model for shear banding instability in metallic glass Int. J. Solids Struct. 48 3112–27
Schuh C A, Hufnagel T C and Ramamurty U 2007 Mechanical behavior of amorphous alloys Acta Mater. 55 1087–109
Schuh C A and Lund A C 2003 Atomistic basis for the plastic yield criterion of metallic glass Nat. Mater. 2 449–52
Sergueeva A V, Mara N A, Kuntz J D, Lavernia E J and Mukherjee A K 2005 Shear band formation and ductility in bulk metallic glass Philos. Mag. 85 2671–87
Sha Z D, Pei Q X, Liu Z S, Zhang Y W and Wang T J 2015 Necking and notch strengthening in metallic glass with symmetric sharp-and-deep notches Sci. Rep. 5 10797
Spen F 1977 A microscopic mechanism for steady state inhomogeneous flow in metallic glasses Acta Metall. 25 407–15
Vargonen M, Huang L and Shi Y 2012 Evaluating Mohr–Coulomb yield criterion for plastic flow in model metallic glasses J. Non-Cryst. Solids 358 3488–94
Wang Z, Qiao J W, Yang H J, Liaw P K, Huang C J and Li L F 2015 Serration dynamics in a Zr-based bulk metallic glass Metallurgical and Materials Transactions a-Physical Metallurgy and Materials Science 46A 2404–14
Wright W J, Schwarz R B and Nix W D 2001 Localized heating during serrated plastic flow in bulk metallic glasses Materials Science and Engineering; A 319–321 229–32
Wright W J, Hufnagel T C and Nix W D 2003 Free volume coalescence and void formation in shear bands in metallic glass J. Appl. Phys. 93 1432–7
Widmer-Cooper A, Perry H, Harrowell P and Reichman D R 2008 Irreversible reorganization in a supercooled liquid originates from localized soft modes Nat. Phys. 4 711–5
Wang B B, Luo L S, Guo E Y, Su Y Q, Wang M Y, Ritchie R O, Dong F Y, Wang L, Guo J J and Fu H Z 2018 Nanometer-scale gradient atomic packing structure surrounding soft spots in metallic glasses npj Computational Materials 4 41
Yang G N, Sun B A, Chen S Q, Shao Y and Yao K F 2017 The multiple shear bands and plasticity in metallic glasses: a possible origin from stress redistribution J. Alloys Compd. 695 3457–66
Yavari A R, Lewandowski J J and Eckert J 2007 Mechanical properties of bulk metallic glasses MRS Bull. 32 635–8
Qiao J W, Jia H J and Liaw P K 2016 Metallic glass matrix composites Materials Science and Engineering R 100 1–69
Liu Y Y, Liu P A, Li J J, Liaw P K, Spieckermann F, Kiener D, Qiao J W and Eckert J 2018 Universally scaling Hall-Petch-like relationship in metallic glass matrix composites Int. J. Plast. 105 225–38
Yu P, Bai H Y, Zhao J G, Jin C Q and Wang W H 2007 Pressure effects on mechanical properties of bulk metallic glass Appl. Phys. Lett. 90 051906
Zhang Z F, Eckert J and Schultz L 2003a Difference in compressive and tensile fracture mechanisms of Zr59Cu20Al10Ni8Ti3 bulk metallic glass Acta Mater. 51 1167–79
Zhang Z F, He G, Eckert J and Schultz L 2003b Fracture mechanisms in bulk metallic glassy materials Phys. Rev. Lett. 91 045505
Zhang Z F, Eckert J and Schultz L 2004 Fatigue and fracture behavior of bulk metallic glass Metallurgical and Materials Transactions a -Physical Metallurgy and Materials Science 35A 3489–98