Yield Criteria and Strain-Rate Behavior of $Zr_{57.4}Cu_{16.4}Ni_{8.2}Ta_8Al_{10}$ Metallic-Glass-Matrix Composites

R.T. OTT, F. SANSOZ, T. JIAO, D. WARNER, C. FAN, J.F. MOLINARI,
K.T. RAMESH, and T.C. HUFNAGEL

We have examined the yielding and fracture behavior of $Zr_{57.4}Cu_{16.4}Ni_{8.2}Ta_8Al_{10}$ metallic-glass-matrix composites with a small volume fraction (~4 pct) of ductile crystalline particles under quasi-static uniaxial tension and compression and dynamic uniaxial compression. The yield stress of the composite is the same for quasi-static tension and compression, consistent with a von Mises yield criterion. The measured average angle between the shear bands and the loading axis in quasi-static compression is 47 ± 2 deg, significantly larger than the value of ~42 deg typically reported for single-phase metallic glasses. Finite element modeling (FEM) shows that the measured value is consistent with both the von Mises criterion (48 ± 4 deg) and the Mohr–Coulomb criterion (46 ± 5 deg). The fracture surface angles, however, are 41 ± 1 deg (compression) and 54 ± 2 deg (tension), in good agreement with observations of single-phase metallic glasses. At low strain rates ($<10^{-1}$ s^{-1}), the yield stress is independent of strain rate, while at higher strain rates ($>10^0$ s^{-1}), the failure stress decreases with increasing strain rate, which again is similar to the behavior of single-phase glasses. These results indicate that while the presence of the particles has a significant effect on the yield behavior of the composites, the fracture behavior is largely governed by the properties and behavior of the amorphous matrix.

I. INTRODUCTION

YIELD criteria are important for predicting the behavior of ductile engineering materials under multiaxial loading conditions and can also provide insight into underlying mechanisms of deformation. The question of which yield criterion is most appropriate for metallic glasses has received considerable attention in the literature. Two popular choices have been the von Mises criterion:

$$k = \frac{\sqrt{6}}{6}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2\right]^{1/2} \quad [1]$$

where k is the yield stress in pure shear and $\sigma_1 \geq \sigma_2 \geq \sigma_3$ are the principal stresses and the Mohr–Coulomb criterion:

$$k = \tau + \alpha\sigma_n \quad [2]$$

where τ and σ_n are the shear stress and the normal stress on the slip plane, respectively, and α is a constant. Some of the early work on Pd-based glasses[1] suggested that the von Mises criterion was most appropriate, while other researchers favored the Mohr–Coulomb criterion.[2]

The development of new Zr-based alloys with outstanding glass-forming ability in the early 1990s created new interest in the properties of metallic glasses and facilitated studies of mechanical behavior by providing bulk specimens for testing. The most obvious difference between the von Mises and Mohr–Coulomb criteria is that the former predicts that the yield stress will be the same in uniaxial tension and compression, while the latter predicts that they will be different. Reports in the literature differ on this point. Zhang and co-workers, for instance, report that the yield stress is significantly lower in tension than in compression,[3] while Lewandowski and co-workers report no significant difference.[4] Complicating matters is the fact that what is usually reported is a *fracture* stress, not a yield stress. Because metallic glasses do not strain harden, they are susceptible to shear localization and premature fracture initiating at defects. Thus, it is not clear that any tension/compression asymmetry reported solely on the basis of fracture stresses actually represents the fundamental yielding behavior of the material.

Other studies, however, also favor the Mohr–Coulomb criterion. For instance, indentation studies and FEM on metallic glasses show that the load-displacement curves appear to show pressure- or normal-stress dependence.[5,6] Furthermore, Schuh and Lund[7,8,9] have used atomistic simulations to model yielding in metallic glasses; they also report that the yield stresses exhibited by metallic glasses can be described in the framework of the Mohr–Coulomb criterion. The predicted value of α = 0.123 for their simulations was found to compare well with the experimentally determined values of 0.11 to 0.13.[2,5]

Several authors have also used fracture surface angles to infer the underlying yield behavior of metallic glasses. Again, the assumption (sometimes implicit) is that the fracture occurs on the same planes as slip. Under the von Mises

R.T. OTT, Postdoctoral Fellow, is with the Materials and Engineering Physics Program, Ames Laboratory (USDOE), Ames, IA 50011. Contact e-mail: rtott@ameslab.gov F. SANSOZ, Assistant Professor, is with the School of Engineering, University of Vermont, Burlington, VT 05405. T. JIAO, formerly Postdoctoral Fellow, Department of Mechanical Engineering, Johns Hopkins University, Baltimore, MD 21218, is Postdoctoral Research Associate, Division of Engineering, Brown University, Providence, RI 02912. D. WARNER, Graduate Student, and J.F. MOLINARI and K.T. RAMESH, Professors, Department of Mechanical Engineering, and T.C. HUFNAGEL, Professor, Department of Materials Science and Engineering, are with Johns Hopkins University. C. FAN, formerly Postdoctoral Fellow, Department of Materials Science and Engineering, Johns Hopkins University, is Research Assistant Professor, Department of Materials Science and Engineering, University of Tennessee, Knoxville, TN 37996.

Manuscript submitted March 6, 2006.