Effect of Loading Rate on Dynamic Fracture Morphology of a Zr-Based Bulk Metallic Glass

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Low-velocity plate impact experiments using a single-stage gas-gun are performed on Zr58.5Cu15.6Ni12.8Al10.3Nb2.8. Compressive fracture surfaces of the samples subjected to varying impact velocities and stress amplitudes are evaluated in order to study their loading rate dependence. Samples impacted at increasing loading rates, from increasing velocities of impact, show a larger extent of localized melting while those subjected to increasing stress show a transition from ductile to brittle fracture. These observations suggest that the mechanisms and morphology of fracture are strain-rate dependent.

1. Introduction

Bulk metallic glasses (BMG) are a novel class of materials with mechanical properties that are superior compared to their crystalline counterparts. Their high strength, hardness, corrosion and wear resistance make them attractive for a wide range of applications from athletic equipment to kinetic energy penetrators. As such, there is a need to characterize their mechanical response over a broad range of loading rates. In general, three types of testing regimes, each requiring experimental techniques unique to that regime, are needed in order to achieve loading rates between $10^{-5}$–$10^{3}$ s$^{-1}$; in order of increasing loading rates those include: quasi-static (servo-hydraulic machines), dynamic (Taylor anvil tests, Hopkinson bar) and shock-loading tests (normal plate impact, pulsed laser, explosives). To date, most studies on the mechanical response of BMG have been performed in the $10^{-5}$–$10^{3}$ s$^{-1}$ range of loading rates by using either quasi-static tension/compression tests or dynamic tests using the Split Hopkinson Pressure Bar (SHPB). Additionally, shock loading experiments using the plate impact technique have been performed in the range of $10^{2}$–$10^{6}$ s$^{-1}$. However, findings on the strain rate dependence of the strength and fracture morphologies of BMG have been conflicting and to the best of our knowledge no such study has been performed in the intermediate range of $10^{2}$–$10^{5}$ s$^{-1}$ loading rate using the plate impact configuration.

While several authors reported that the effect of strain rate on the strength of BMG under dynamic loading conditions is negligible, some observed positive strain rate sensitivity and others reported negative strain rate sensitivity of BMG. Among those who reported a lack of strain rate sensitivity, some observed that the fracture surfaces of BMG specimens damaged at increasing strain rates exhibited similar fracture features, while others observed varying fracture morphologies indicating that different damage mechanisms dominate the fracture process at different strain rates, suggesting the dependence of fracture morphology on strain rate. It has also been suggested that the strain rate dependence of deformation behavior in BMG varies with material composition, specimen shape and loading procedure.

In this work, Zr-based BMG samples with nominal composition Zr58.5Cu15.6Ni12.8Al10.3Nb2.8, also known as Vitreloy 106a, were subjected to plate impact experiments to determine the effect of varying loading rate and stress on observed fracture features. In order to elucidate on the dynamic behavior at an intermediate range of loading rates, the impact velocities from the single-stage gas-gun tests ranged from 60 to 150 m/s which are equivalent to loading rates of the order $10^{3}$–$10^{5}$ s$^{-1}$. Specifically, these tests are performed in a regime not previously explored using the plate impact experimental technique.

2. Experimental Method

The Vitreloy 106a sample was prepared by vacuum arc melting a mixture of high-purity metals in an argon atmosphere and then casting into copper molds to make a rectangular slab of the BMG. Cylindrical samples, 18.75 mm in diameter, and 3 mm in thickness were cut using electric discharge machining. Samples were polished using 400-grit SiC paper in order to remove a thin crystalline surface layer formed due to interaction with the mold. X-ray diffraction of as-received sample confirmed its amorphous nature. The samples, which were backed by a 3 mm thick tungsten base plate, were then impacted by projectile-comprising of a tungsten flyer 22 mm in diameter, 13 mm in thickness embedded in a Delrin sabot 50 mm in diameter, 25 mm in thickness-launched from a single stage gas gun. A schematic of the experimental set-up is shown in Fig. 1. Velocity of the projectile is measured by two receivers

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A total of six cylindrical samples were impacted in two sets of experiments: the first in which three samples were impacted with flyers of different materials at the same impact velocity to determine the effect of varying stress amplitude, and the second in which three additional samples were impacted using a tungsten flyer with increasing velocities to ascertain the effect of varying impact velocity, and therefore loading rate. For all the experiments performed, the initial impact stress in the BMG sample was calculated using the impedance matching technique, which has been derived elsewhere. Using the second Rankine-Hugoniot jump impedance matching technique, which has been derived elsewhere, the initial impact stress is calculated in this manner and is equal to each other, and by solving a quadratic equation in the subscripts F and S denote flyer and sample respectively. At the moment of impact, traction and velocity continuity require that the stress at the flyer-sample interface at impact is obtained. The initial impact stress is calculated in this manner and is summarized in Table 1.

### Results and Discussion

The impacted samples and their fragments were recovered from the target chamber following impact, and their fracture surfaces were examined using JEOL JSM-7001 SEM. For all the samples impacted, bright flashes of visible light were seen upon fracture. This was also observed by others and was noted as being suggestive of local melting on fracture of the BMG.

The micrographs in Fig. 2 show the fracture surfaces from samples subjected to varying amplitudes of loading stress from being impacted by flyer plates of different materials—aluminum 2024, stainless steel 304 and tungsten—at impact velocities 60.67 ± 0.26 m/s. For the sample impacted with aluminum, as seen in Fig. 2(a), the fracture surface shows dimpled pattern typical of ductile fracture. The sample impacted by stainless steel shows a similar fracture surface; however, there also seems to be a dense accumulation of melted droplets and numerous cracks. As seen in Fig. 2(c), the sample impacted by tungsten, however, seems to have a fracture surface that looks very different from the previous two i.e. no dimple patterns. Instead there is an evenly distributed pattern of rivers, as well as some cusps and smooth areas typical of brittle, BMG failure. This is indicative of the nature of deformation turning brittle from ductile as the impact stress is increased.

Fracture surfaces of samples impacted by tungsten flyers at varying loading rates show a combination of different fracture patterns (rivers, veins, smooth areas, droplets etc), as is apparent from Fig. 2(c), since final fracture likely occurs due to different modes at different locations. This occurrence of various fracture patterns for a given impact condition is also apparent in Fig. 3. However, at each loading rate, one dominant fracture pattern which covered most of the
fracture surface was observed, while other features were distributed over smaller areas. The dominant fracture pattern corresponding to each loading rate was studied further at higher magnification and is discussed in the following paragraph.

The micrographs in Fig. 4 depict fracture surfaces from samples subjected at varying loading rates from being impacted by a tungsten flyer at velocities of 62 m/s, 92 m/s, 110 m/s and 150 m/s. For the sample impacted at 62 m/s, as seen in Fig. 4(a), river-like patterns cover most of the fracture surface. This is typical of fracture surfaces of BMG.11,12,22) It is observed that rivers are also interspersed with occasional smooth regions i.e. areas of fast catastrophic failure, and cell-like veins or cusps. River patterns arise out of the flow of low viscosity BMG from localized adiabatic heating. When the low-viscosity material separates in the shear slip bands as the BMG deforms, pores are opened up, resulting in the formation of cell-like vein morphology.4,33)

The fracture surface of the sample impacted at 92 m/s showed belts of melted BMG, river-like veins and arrays of cusps along with resolidified melted droplet particles amidst them. Cusps, as seen in Fig. 4(b), form in the direction of shear force and are evidence of plastic flow in the direction of shear. The sample impacted at 110 m/s depicts arrays of cusps, in Fig. 4(c), with the overall fracture surface being more inhomogeneous than previous ones. The cusps are lined by coarser cell walls and contain resolidified droplets. Regions of cusps bordered by melted bands indicate areas of crack growth and propagation. BMG impacted at 150 m/s shows patterns of rivers and cusps that are flanked by large melted belts, as seen in Fig. 4(d). The observed morphology from these samples damaged at four different loading rates shows varied fracture features indicating that damage mechanisms are strain rate dependent. Increasing amounts of melted droplets and zones on fracture surfaces of samples impacted at higher velocities is evidence of higher temperatures being reached at high strain rates.24) The X-ray diffraction patterns of the as-received and fractured samples, as seen in the inset in Fig. 4, confirm the amorphous structure of the as-received sample as well as that of the impacted sample fragments.

Micrographs of samples impacted with tungsten at increasing velocities, and therefore increasing loading rates, show that the deformation becomes increasingly inhomogeneous, suggesting a dependence of fracture mechanisms and morphology on strain rate. There also seems to be an increased level of melting, suggesting that there is a greater release of fracture energy resulting in higher temperatures, with each subsequent velocity, as seen from increasing...
amounts of resolidified particles and viscous, melted belts. Fracture morphologies of samples impacted at the lower loading rates (corresponding to the lower impact velocities of 62 m/s and 92 m/s), show evidence of shear fracture being the dominant mode of failure through the presence of cleavage “river” and veins, which are formed from the pulling apart of low viscosity material. As the loading rate is increased (corresponding to increased impact velocities of 110 m/s and 150 m/s), there is not enough time for heat generated from friction effects during the shear fracture process to be sufficiently conducted through the material. Therefore, there is a large agglomeration of melted droplets and bands. At the higher loading rates, temperature and melting effects are more pronounced in the failure process than at low loading rates where shear fracture is the main mode. Micrographs of samples impacted at 60.67 ± 0.26 m/s with different flyer materials, resulting in varying shock amplitudes, show that with increasing amplitude, the nature of damage from compression changes from ductile to brittle.

4. Conclusions

The presented results, obtained under low-velocity impact loading conditions using the plate impact technique at previously unexplored intermediate levels of strain rate (10³–10⁴ s⁻¹), show a dependence on the applied loading rate resulting from the occurrence of different fracture mechanisms at varying levels of loading rate. This work indicates that there is a strain rate sensitivity in Vitreloy 106 at intermediate loading rates, in agreement with some of the previous observations at lower and higher strain rates.5,12,13,19,20,24 Therefore, the strain rate sensitivity in this particular BMG appears to be independent of loading procedure. Further investigations of other BMGs over a wide range of loading rates and stresses will allow the study of possible transitions regions for the mechanical deformation, thus opening the possibility for new applications.

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