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Dynamic Yield Strength of a Zirconium Base Metallic Glass

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Abstract. Taylor anvil tests in the reverse ballistic mode have been carried out to determine the dynamic yield strength of a Zr 62.6 w/o Cu 13.23, Ti 11.01, Ni 9.77, and Be 3.38 metallic glass. Scanning electron microscopy has been utilized to evaluate the details of the rod and anvil interface after impact. Computer simulations have also been carried out to interpret and confirm the results and conclusions.

Résumé. Le test de TAYLOR par la méthode de balistique inverse a été utilisé pour déterminer la résistance dynamique d'un verre métallique de Zr 62.6%-Cu 13.23%-Ti 11.01%-Ni 9.77% et Be 3.38%. La microscopie électronique á balayage a été utilisée pour examiner l'interface entre la cible et le barreau aprés impact. Des simulations numériques ont été effectuées pour interpréter et confirmer les résultats et les conclusions.

1. BACKGROUND

The G. I. Taylor [1] dynamic compression test consists of firing a cylinder of material at an essentially rigid target and deducing the dynamic yield stress from measurements made on the recovered projectile.

Wilkins and Guinan [2] showed that the simple theory accounted reasonably well for the dependence of the final length of projectiles on impact velocity and flow stress for a variety of real materials.

They [2] demonstrated the validity of the relationship

$$\frac{L_f}{L_0} = \exp\left(-\frac{\rho_0 u_0^2}{2Y_0}\right)$$

over a wide range of velocities where L_f = final length of projectile, L_0 = initial length, ρ_0 = density of the projectile, u_0 = the projectile impact velocity and Y_0 = the dynamic yield strength of the projectile.

The results indicated that a simple test of a penetrator material existed wherein the measurements of initial and final length and the impact velocity on a rigid target allows the experimenter to easily obtain the dynamic yield strength.

One of the authors has long been interested in a class of materials called "metallic glasses" which have theoretical strengths [3]. A model system to study is the metallic glass Zr 62.6 w/o Cu 13.23, Ti 11.01, Ni 9.77, and Be 3.38 which can be prepared in large ingots (see Table 1 for Physical Properties).

2. EXPERIMENTAL PROCEDURES AND RESULTS

Rods of the Zr base metallic glass were prepared from the melt. The rod material was examined by X-ray diffraction and determined to be amorphous. The rod was ground to size and samples cut to length using a diamond saw (see Figures 1,2).

The "reverse ballistic" experimental set up was similar to the one used by Wilkins [2] but the zirconium glass rod was held in position using a styrofoam fixture and the AD-95 Al_2O_3 projectile fired from our smoothbore gun at 0.0274 cm/ms. The Al_2O_3 punch was 2.2 cm in diameter. The initial and final measurements on the rod were L_0 = 1.28 cm, D_0 = 0.306 cm, L_f = 1.03 cm.

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The recovered Zr metallic glass rod was measured by micrometer along its length for changes in diameter near the impact end. It was noted that the rod was straight and we observed very little mushrooming or bulging.

Microscopic pictures were taken of the rod end and the target . The observation of the target and rod was that the rod reached temperatures of the order of the glass transition temperature (Tg = 623° K).

The measured initial and final length numbers result in a dynamic yield strength of .0133 Mb (as a lower limit). The value was calculated using the relationship

$$Y_0 = -\frac{\rho_0 u_0^2}{2 \ln L_f/L_0}$$

where ρ_0 = 6.11 gm/cm^3. This number is quite different than the value expected from the microhardness at room temperature. The hardness H is 598 kg/mm^2, and using the relationship of H/3 = Y_0 we expected to obtain about 20 kb as the strength. This assumes a room temperature strength was dominant as has been observed for polycrystalline metals, but the observations indicate that the impact interface was molten.

3. COMPUTER SIMULATIONS AND ANALYSIS

We developed a material description for performing computer simulations of the Taylor impact test using the HEMP simulation program. The measured elastic properties are density 6.11 g/cm^3, bulk modulus 112 GPa, and shear modulus 37.2 GPa. At an impact velocity of 200 m/s, which was the highest velocity we simulated, we estimate the shock stress to be about 5 GPa, so that the effect of non-linear compressibility will be small. We used the flow stress model described by Steinberg, Cochran and Guinan [4] to incorporate thermal softening. We ignored pressure hardening and work hardening. Since the measured Knoop hardness was 600, we used a yield strength of 2 GPa. The measured glass-transition temperature is 623 K. which we take to be the temperature at which the strength is zero. We used the atomic composition to estimate the specific heat to be 0.33 J/g/K, although the reported Debye temperature of this material, 327 K, suggests that the actual value may be somewhat lower than the ideal value of 3 R that we used.

We performed simulations of the Taylor impact of a rod with 2 mm diameter and 9.6 mm long at velocity of 100, 150, and 200 m/s (see Table II). At the lowest velocity, the rod is stopped before significant melt occurs. As a consequence, the rod exhibits the usual diametrical expansion on the impacted end. At the two higher velocities, severe strain localization and melting occurs at the impact face. At the highest velocity simulated, the rod exhibits both a melt zone and a region of diametrical growth.

In Taylor's analysis of the anvil test [1] Equations 1-3 are completed by a momentum balance across the plastic front that ignores lateral inertia in the plastic zone, h.

$$\frac{dh}{dt} = v \tag{1}$$

$$\frac{dx}{dt} = -(u+v) \tag{2}$$

$$\frac{du}{dt} = -\frac{Y_0}{\rho_0 x} \tag{3}$$

Following Guinan's analysis, [5] however, we complete the set by equating the instantaneous loss of kinetic energy from the rigid shank (x) to the plastic work done across the plastic front

$$\frac{d}{dt}\left(\frac{1}{2}\rho x u^2\right) = W\frac{dx}{dt} \tag{4}$$

where W is the plastic work per unit volume, and is a function of the plastic strain, ε. Eq. (4) can be rearranged using (1-3) to form

$$\frac{\rho_0 u^2}{2Y_0} = \frac{W(\varepsilon)}{Y_0} + \frac{v}{u+v} - 1 \tag{5}$$

where the plastic strain ε is given by

$$\varepsilon = -\ln \frac{v}{u+v} \quad . \tag{6}$$

For the simplest case of constant yield stress Y_0, the Equations (1-3) and (5) can be solved parametrically for the final length L_f

$$\frac{L_f}{L_0} = p_0 \left(1 - \ln p_0\right) \tag{7}$$

$$\frac{\rho_0 U_0^2}{2Y_0} = p_0 - \ln p_0 - 1 \tag{8}$$

in terms of the initial value of the parameter p introduced by Taylor, where

$$p = \frac{v}{u+v} \quad , \tag{9}$$

and p-1 is the instantaneous engineering strain across the plastic front.

The solution for the final length is in excellent agreement [5] with HEMP simulations of Taylor anvil tests of materials with constant flow stress Y_0, for the range

$$0 \le \frac{\rho_0 u_0^2}{2Y_0} \le 2 \quad .$$

Here, we wish to use this method of solution to examine the case where thermal softening plays a significant role. The simplest model for the reduction of the flow stress, Y, due to heating from plastic work was described in [6] for behavior at high strain rates. It utilizes a linear decrease in strength with energy density. (The model in [6] gives the reduction in strength as a linear function of temperature rise, but also assumes a constant specific heat up to the melt temperature). For this case,

$$Y = Y_0\left(1 - \frac{W}{Y_0 \varepsilon_1}\right) \quad . \tag{10}$$

and we define ε_1 to be the ratio of the maximum plastic work to the initial flow stress.

The plastic work, then is defined by

$$\frac{dW}{d\varepsilon} = Y_0\left(1 - \frac{W}{Y_0 \varepsilon_1}\right) \tag{11}$$

and solved as

$$W(\varepsilon) = Y_0 \varepsilon_1 \left(1 - \varepsilon^{-\varepsilon/\varepsilon_1}\right) \quad , \tag{12}$$

which specializes Equation (5) to be

$$\frac{\rho_0 u^2}{2Y_0} = \varepsilon_1\left(1 - p^{\frac{1}{\varepsilon_1}}\right) \; + p - 1 \quad . \tag{13}$$

If we consider the right hand side of 13, it has a maximum value of $(\varepsilon_1\text{-}1)$ for $\varepsilon_1 > 1$ at $p = 0$. If $\varepsilon_1 \le 1$, then the right hand side is never positive. From this, we infer that if $\varepsilon_1 \le 1$, then the material is unable to absorb the kinetic energy of the rod by plastic work at any velocity. The shank of the rod is decellerated by the initial flow stress Y_0, but the heating from plastic work is sufficient to reduce the strength significantly (we will imprecisely refer to this as "melt"), which leaves decelerated projectile shorter, with less mass, and without a flared end from the impact.

If $\varepsilon_1 > 1$, then for this material there is a critical velocity u_1,

$$u_1 = \left(2Y_0\left(\varepsilon_1 - 1\right)/\rho_0\right)^{1/2} \tag{14}$$

Below this velocity, the material behaves normally, although with reduced strength. The rod will have its initial mass and a deformed impact end. With initial velocity above this value, some of the rod will have melted, until the initial yield stress has decelerated the shank to below critical. The remainder of the deceleration will be normal. That is the rod will have lost mass from melting, and will also be deformed at the impact end.

We show the results of HEMP simulations for the case $\varepsilon_l = 0.5$, $\varepsilon_l = 2$, and $u_0 \cong 0.5\ u_l$. In the HEMP simulations, some localized melting does appear to occur below the critical velocity u_l, although it does not extend to the lateral boundary.

We now assess the approximate value of ε_l for the Zr alloy used in the experiments. The measured quasi-static flow stress Y_0 is 20 kb [7]. If we take the room-temperature specific heat to be simple mixture of the atomic composition, .066 cal/g/°C, then a temperature rise of 520° C corresponds to $\varepsilon_l = 1$. Since the glass-temperature of this alloy is 350 °C [8], we are assured that for this alloy $\varepsilon_l < 1$.

4. CONCLUSIONS

The observations made during this study suggest that the Taylor test is not well suited to the evaluation of the dynamic yield strength of metallic glasses, particularly ones with glass transitions as low as the Zr alloy. Furthermore, we suggest caution in using the room temperature hardness or yield strength of metallic glasses as a criteria for a successful material to resist impact loading.

5. ACKNOWLEDGMENTS

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Table 1 **Physical Properties of Zirconium Base Metallic Glass**
Zr 62.6 w/o Cu 13.23, Ti 11.01, Ni 9.77 Be 3.38

Density, ρ	6.10 gm/cm^3
Glass transition temperature (Tg)	623°K
Crystallization temperature (Tc)	693°K*
Debye temperature (from elastic constants)	327°K
C_{11}	162 GPa
C_{44}	37.2 GPa
Bulk modulus	112 GPa
Knoop microhardness @ 200 gm load	598 Kg/mm^2

*At a heating rate of 5° K/minute

Table 2 Computer Calculated Yield Strength Versus Velocity

Velocity km/s	Lf	Lf/L_0	Y_0*
.01	.948	.988	.025
.015	.899	.936	.010
.02	.869	.905	.012

*Y_0 calculated using relationships:

$$Y_0 = -\frac{\rho_0 u_0^{\,2}}{2\ln Lf/L_0}$$

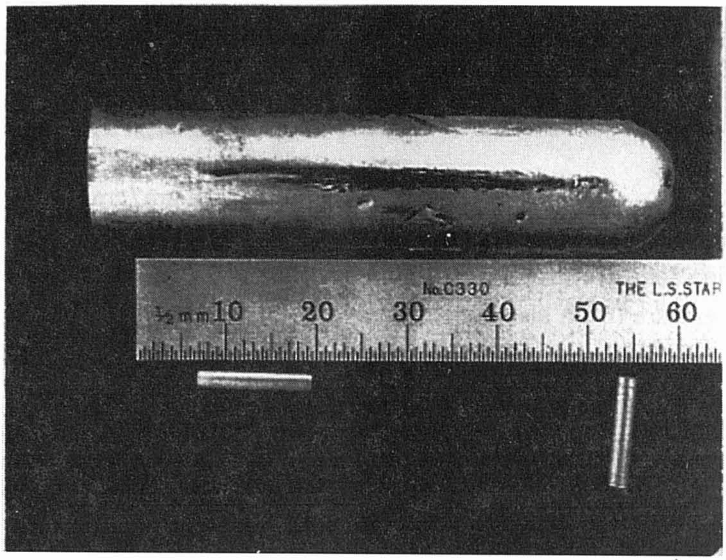

Figure 1. Photo of Zr base metallic glass ingot and projectiles.

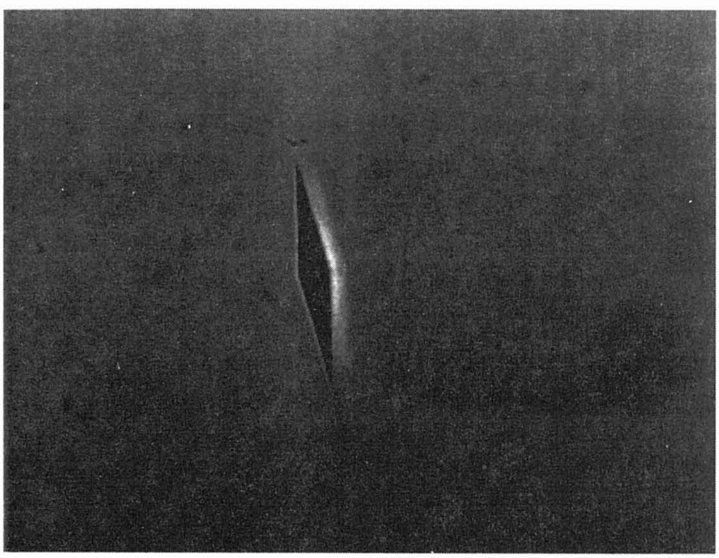

Figure 2. Knoop indentation into Zr metallic glass 200 gm load 500X magnification.