DYNAMIC YIELD STRENGTH OF A PALLADIUM ALLOY METALLIC GLASS

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Des essais d'impact de Taylor en mode ballistique inverse sont effectués pour déterminer la limite élastique dynamique d'un verre métallique Pd_{77.5}Cu_{6.0}Si_{16.5}. L'interface entre cible et projectile est examinée par microscopie électronique à balayage. Des simulations numériques sont effectuées pour interpréter et confirmer les résultats et les conclusions.

ABSTRACT

Taylor anvil tests in the reverse ballistic mode have been carried out to determine the dynamic yield strength of a Pd_{77.5}Cu_{6.0}Si_{16.5} 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.

1. Background

The G. I. Taylor (Ref. 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 (Ref. 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 (Ref. 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 (see Figure 1).

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. A model system to study is the metallic glass Pd_{77.5} Cu_{6.0} Si_{16.5}.

Figure 1. Results for impacts of cylinders on a rigid boundary, showing that L_f/L_0 scales as $\rho_0 U^2 / 2Y_0$.

Figure 2. Projectile impact end.

Figure 3. Projectile impact surface.

Figure 4. Residue on Al_2O_3 target.

Figure 5. Projectile impact surface.

Figure 6. Projectile impact surface.

2. Experimental procedures and results

Rods of Pd_{77.5} Cu_{6.0} Si_{16.5} were prepared from the melt by quenching evacuated quartz capillaries filled with molten alloy metal into cold brine. 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.

The "reverse ballistic" experimental set up was similar to the one used by Wilkins (Ref. 2) but the palladium glass rod was held in position using a styrofoam fixture and the AD-95 Al₂O₃ projectile fired from our smoothbore gun at 0.0108 cm/ μ s. The Al₂O₃ punch was 2.2 cm in diameter. The initial and final measurements on the rod were L₀ = 0.95 cm, D₀ = 0.199 cm, L_f = 0.86 cm.

The recovered PdCuSi 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 no mushrooming or bulging.

Microscopic pictures were taken of the rod end and the target (see Figures 2-6). The observation of the target and rod was that the rod reached temperatures of the order of the glass transition temperature (T_g = 636° K). Note the melt-like residue on the target and impactor.

The measured initial and final length numbers result in a dynamic yield strength of .0058 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 $\rho_0 = 10.57 \text{ gm/cm}^3$. This number is quite different than the value expected from the microhardness at room temperature. The hardness H is 500 kg/mm², and using the relationship of $H/3 = Y_0$ we expected to obtain 16 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

The specimens recovered from the Taylor anvil tests did not have the customary shape. Figure 7 shows the result of a computer simulation of Taylor anvil with impact velocities of 150 and 350 m/s using HEMP (Ref. 3) and an assumed constant flow stress of 15 kbar. The diametral growth at the impact end is the customary shape from such experiments, although the presence of significant work hardening can affect the detailed diametral profile (Ref. 2). The palladium alloy specimen recovered from our experiments instead showed essentially no diametral growth at the impact end. This observation, together with the metallographic observation of melted material on the recovered anvil led us to consider the effect of adiabatic strength reduction due to the heating from plastic work during a Taylor anvil test.

In Taylor's analysis of the anvil test (Ref. 1) Equations 1-3 are completed by a momentum balance across the plastic front that ignores lateral inertia in the plastic zone, h. (See Figure 8).

$$\frac{dh}{dt} = v \quad (1)$$

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

$$\frac{du}{dt} = - \frac{Y_0}{\rho_0 x} \quad (3)$$

Following Guinan's analysis, (Ref. 4) however, we complete the set by equating the instantaneous loss of kinetic energy from the rigid shank (x) to the plastic work done across

Figure 7. Initial and final state of a PdCuSi rod with constant yield stress (15 kb) impacted at 150 m/s, middle and 350 m/s, bottom. The diametral growth is typical of most metals studied (Ref. 2).

Figure 8. An intermediate state in the solution of Equations (1-3) and (5) for constant yield stress illustrating the variable definitions.

Figure 9. Initial and final state of a PdCuSi rod with initial yield strength 15 kb, $\rho_0 = 10.44$, $\varepsilon_1 = 0.5$, and initial velocities 150 m/s, middle and 350 m/s bottom. Notice the strong localization of plastic strain in the "melt" region.

Figure 10. Initial and final states of PdCuSi rod with initial velocity 350 m/s: From top to bottom they are initial state; final state for constant yield stress $Y_0 = 15$ kb; final state for $\varepsilon_1 = 2$, final state for $\varepsilon_1 = 0.5$.

the plastic front

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

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

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

where the plastic strain ϵ is given by

$$\epsilon = - \ln \frac{v}{u+v} \quad (6)$$

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

$$\frac{L_f}{L_0} = p_0 (1 - \ln p_0) \quad (7)$$

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

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

$$p = \frac{v}{u+v} \quad (9)$$

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

The solution for the final length is in excellent agreement (Ref. 4) with HEMP simulations of Taylor anvil tests of materials with constant flow stress Y_0 , for the range

$$0 \leq \frac{\rho_0 U_0^2}{2Y_0} \leq 2 \quad .$$

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 Ref. 5 for behavior at high strain rates. It utilizes a linear decrease in strength with energy density. (The model in Ref. 5 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,

$$Y = Y_0 \left(1 - \frac{W}{Y_0 \epsilon_1} \right) \quad (10)$$

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

$$\frac{dW}{d\epsilon} = Y_0 \left(1 - \frac{W}{Y_0 \epsilon_1} \right) \quad (11)$$

and solved as

$$W(\epsilon) = Y_0 \epsilon_1 (1 - e^{-\epsilon/\epsilon_1}) \quad (12)$$

which specializes Equation (5) to be

$$\frac{\rho_0 u^2}{2Y_0} = \epsilon_1 \left(1 - p^{\frac{1}{\epsilon_1}} \right) + p - 1 \quad (13)$$

If we consider the right hand side of 13, it has a maximum value of $(\epsilon_1 - 1)$ for $\epsilon_1 > 1$ at $p = 0$. If $\epsilon_1 \leq 1$, then the right hand side is never positive. From this, we infer that if $\epsilon_1 \leq 1$, 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 decelerated 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 ,

$$u_1 = (2Y_0(\varepsilon_1 - 1) / \rho_0)^{1/2}. \quad (14)$$

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 $\varepsilon_1 = 0.5$, Figure 9, $\varepsilon_1 = 2$, and $u_0 \cong 0.5 u_1$, Figure 10. In the HEMP simulations, some localized melting does appear to occur below the critical velocity u_1 , although it does not extend to the lateral boundary.

We now assess the approximate value of ε_1 for the palladium alloy used in the experiments. The measured quasi-static flow stress Y_0 is 15 kb (Ref. 6). 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 $\varepsilon_1 = 1$. Since the glass-temperature of this alloy is 363 °C (Ref. 7), we are assured that for this alloy $\varepsilon_1 < 1$.

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 PdCuSi 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. References

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