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Ductile-brittle transition behavior of tungsten under shock loading

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Resumé: La transition ductile-fragile du tungstène formé à chaud a été examinée sous des conditions de chargement de choc au cours d'expériences de choc/récupération douce à 22° C et 400° C. Les résultats de l'expérience à 22° C indiquent que des tensions résultant de chocs (19 GPa) apparaissent sous forme de processus de fractures, c'est à dire qu'il n'y avait aucune indication de déformation plastique résultant du choc et l'échantillon a été réduit en morceaux. À 400° C l'échantillon a été récupéré intact et la plasticité entraînée par le choc a entraîné la formation de bandes de déformation et une augmentation de la densité de dislocation du matériau. Les résultats de cette expérience montrent le principe de la transition ductile-fragile du tungstène dans des conditions de chargement de choc uni-axial et indiquent qu'une déformation explosive du tungstène résultera en une pulvérisation due au chargement de choc.

Abstract: The ductile-brittle transition behavior of warm-forged tungsten under shock loading conditions was examined by performing shock/soft-recovery experiments at 22° C and 400° C. The results of a recovery experiment at 22° C indicate that shock (19 GPa)-induced strains were accommodated by fracture processes, i.e. there were no indications of shock-induced plastic deformation, and the test sample was reduced to rubble. At 400° C the test sample was recovered intact and the shock-induced plasticity caused deformation banding and an increase in the dislocation density of the material. The results of these experiments demonstrate the principle of a ductile-brittle transition behavior of tungsten under uniaxial shock loading conditions and indicate that explosively-driven deformation of the material studied will likely result in pulverization due to shock loading.

1. INTRODUCTION

The mechanical behavior of tungsten, like many body center cubic (BCC) metals, is characterized by a ductile-brittle transition temperature (DBTT) below which little or no macroscopic plastic deformation occurs prior to fracture (1,2). The DBTT of tungsten has been studied extensively and has been found to be highly dependent on the nature of the material. For example, alloying additions (3,4), interstitial impurities (4,5), grain size with accompanying changes in impurity segregation (6,7), and thermomechanical processing (8,9) have all been

reported to have profound effects on the DBTT. The DBTT has also been found to be dependent on the rate of loading (10,11). In general, the ductile-brittle transition behavior occurs at higher temperatures with increasing strain rate.

Shock loading, via planar flier plate impact, subjects solids to unique strain, pressure and temperature histories (12). This deformation history is characterized by compressive uniaxial strain and high hydrostatic confining pressure. In this work we present results of two shock/soft-

recovery experiments performed at temperatures of 22° C and 400° C. Analysis of the results indicates that, as in the case of other types of mechanical loading, there is a DBTT associated with shock loading.

Table 1. Shock recovery experiments and results.

Temperature	Peak shock pressure	Shock duration	Transient strain	Result
22° C	19 GPa	1 μ s	7.2%	Sample was rubblized
400° C	15 GPa	1 μ s	5.8%	Sample recovered intact

2. SHOCK/SOFT-RECOVERY EXPERIMENTS

The test material was prepared by warm forging of a pressed and sintered powder metallurgy billet. Forging was performed at a temperature below the recrystallization temperature. Optical light metallography indicated an elongated grain structure and the average grain size was estimated to be about 30 μ m. Bulk chemical analyses were performed and the levels of impurities were found to be as follows (by weight %): O = 0.002, C = 0.002, N < 0.001, C < 0.002, all others less than 0.02.

Shock-recovery experiments were performed using an 80-mm single stage gas gun (12). The specimen assembly, as shown in Figure 1, consisted of a 5.08-mm-thick, 38-mm-diameter sample, sandwiched behind a 38-mm-diameter, 2.54-mm-thick cover plate. Both components were tightly fitted into a bored recess of a 7°- tapered, 12.7-mm-thick, central momentum disk. The sample was protected from spallation by backing the central momentum disk with a 3.8-mm-thick spall plate. The central disk and spall plate were further surrounded by two concentric momentum trapping rings with outside diameters of 69.8 mm and 82.5 mm.

Two assemblies were shock loaded in vacuum, one at a temperature of 22° C and the other at a temperature of 400° C (summaries of these experiments are given in Table 1). An insulated nichrome heating wire wrapped around the circumference of the shock assembly was used to heat the shock assembly. Peak shock pressures of 19 GPa (22° C experiment) and 15 GPa (400° C experiment) were achieved by impacting

the specimen assembly with a tungsten flyer plate at velocities of 459 m/s and 367 m/s respectively. The thickness of the flyer plate (2.2 mm) resulted in shock durations of 1 μ s. Soft recovery and simultaneous cooling are achieved by decelerating the central momentum disk in a water catch chamber positioned immediately behind the impact area.

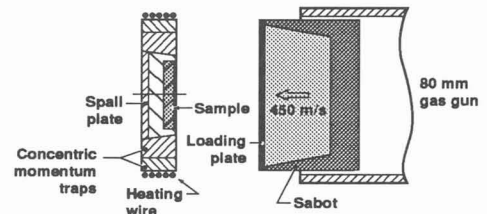


Figure 1. Sectional view of sample assembly and sabot/flyer-plate.

The shock/soft-recovery assembly (and sample) shock loaded at 22° C were reduced to rubble. The catch tank was searched for remnants of the sample (which were identified by the thickness of the recovered pieces) and approximately 20% of the rubblized sample was recovered. Most of the recovered pieces measured on the order of 3 mm by 3 mm. The experiment performed at 400° C resulted in the recovery of the sample intact. The final thickness of this intact shocked disk was measured and the residual strain was calculated to be approximately 1%. In addition to the residual strain through the thickness, the shock recovered disk was found to be slightly dished (approximately 1 mm out of flat at the center).

3. MICROSTRUCTURAL ANALYSES

3.1 Optical light metallography

Metallographic examination of the shocked material indicated that shock loading at 22° C resulted in massive amounts of internal cracking (in addition to the obvious participation) as shown in Figure 2-a. The internal cracking appeared to occur predominately along the vestiges of grain boundaries that were initially formed in the powder billets during sintering. The microstructure of the material shock loaded at 400° C was found to have no internal cracking and significant amounts of deformation banding, as shown in Figure 2-b. The deformation banding could be due to extensive slip and/or deformation twins, although no evidence of deformation twinning was found using

transmission electron microscopy (TEM). There were no indications of banding of this nature observed in the material shocked at 22° C, which suggests that the shock-induced deformation which occurred at this temperature was accommodated primarily by internal cracking (in addition to elastic deformation).

3.2 Transmission Electron Microscopy

The substructures of the tungsten in the starting condition and following shock pre-straining at 22° C and 400° C were examined using TEM. The tungsten was sectioned parallel to the loading direction using a low-speed diamond saw and the slices were mechanically thinned resulting in 100- μm -thick foils. The foils were mechanically dimpled using 3-micron-diamond paste to a center thickness of nominally 25 microns. TEM foils were ion-milled at approximately -150° C using a 6 kV ion source at a grazing angle of 10 to 15 degrees. Characterization of the test materials was performed using a JEOL 2000EX equipped with a double-tilt stage at an accelerating voltage of 200 kV.

The substructure of the tungsten following the shock/soft-recovery at 22° C exhibited a low overall dislocation density, similar to the starting material. This substructure suggests that the strains induced during the shock prestraining at 22° C were, by and large, not accommodated by generation and movement of dislocations (plastic deformation). Such a response would be similar to a truly brittle material which has insufficient slip systems to accommodate the deformation imposed by the shock process, e.g. a ceramic material.

The substructure of the starting material, shown in Figure 3-a, consists of subgrains with low angle boundaries (nominally 3 microns in diameter) containing a relatively low density of dislocations. The dislocations observed were found to be long-straight screw type dislocations. This observation is consistent with the substructures previously seen in a number of refractory metals. Due to the disparity in the forces needed to move and cross-slip screw vs. edge dislocations, edge dislocations can more readily accumulate or annihilate into the subgrain walls. The screw segments are more difficult to move because of the kinking process necessary for them to propagate.

The substructure of the tungsten after shock prestraining at 400° C has a significantly higher

dislocation density in the subgrain interiors, as shown in Figure 3-b. The substructure within the subgrains consists of random dislocation tangles in most subgrains and some reorganization of these tangles into dislocation cells in some of the larger subgrains. Reduction in the local strain energy will drive this reorganization to form a cellular configuration.

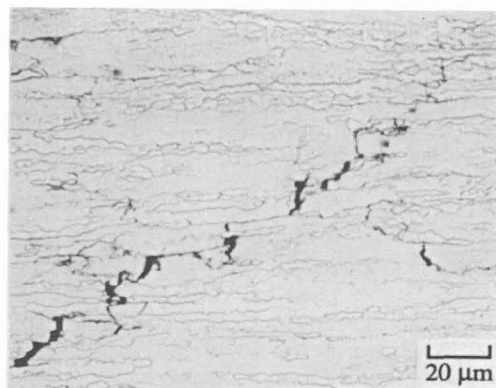


Figure 2-a. Optical light micrograph of a section of a recovered fragment of tungsten which was shocked at 22° C. Extensive amounts of cracking occurred as a result of the shock loading. There are no indications of plastic loading, i.e. deformation banding, due to the shock loading. This suggests that the shock induced deformation was accommodated by fracture processes.

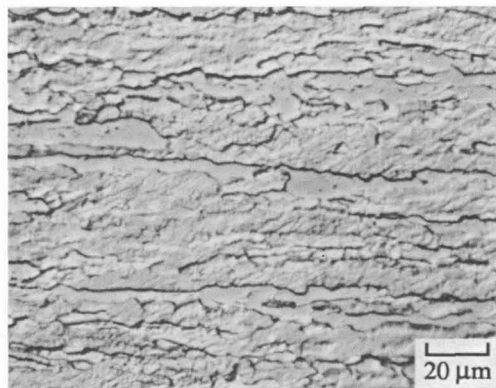


Figure 2-b. Optical light micrograph of the test material after shock loading at 400° C. Banding of deformation is indicated diagonally across the microstructure. This banding is not observed in the test material in the starting condition, leading to the conclusion that the deformation banding is due to plastic deformation which occurred during shock loading.

These TEM observations clearly indicate that the strains introduced into the test material during shock loading at 400° C were accommodated by dislocation generation and movement.

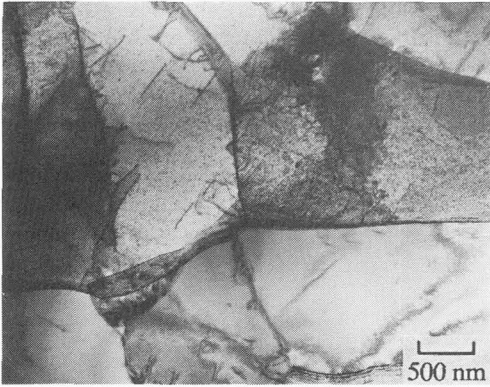


Figure 3-a. TEM micrograph of the test material in the as-warm-forged condition. Note the extensive network of low angle grain boundaries which form subgrains on the order of 3 μm .

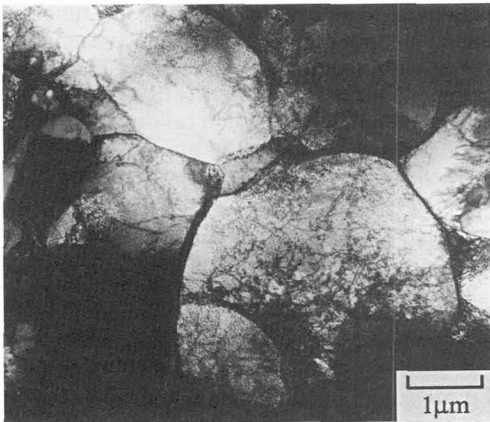


Figure 3-b. TEM micrograph of the material shock loaded at 400° C. The shock loading produced a substantial increase in the dislocation density. There are some indications of dislocation substructure with cell sizes on the order of 300 nm in diameter.

3.3 Scanning Electron Microscopy

Fracture surface features of the tungsten sample that was shocked at 22° C were examined using scanning electron microscopy (SEM). A distinct difference in the morphologies of the fractures was observed in the planes normal and parallel to the forging (and shock propagation) direction. Cracking that occurred in the plane normal to the

forging direction, as shown in Figure 4-a, was found to be predominately intergranular in nature, with polygonal features corresponding to the size and shape of subgrains identified using TEM. Significant amounts of secondary intergranular cracks are also present on these surfaces. Cracking that occurred in planes parallel to the forging direction, as shown in Figure 4-b, was found to be of mixed character with relatively equal amounts of intergranular and transgranular features. It is clear from these SEM observations that the shock loading at 22° C caused massive amounts of internal damage with crack dimensions ranging from submicron to millimeters.

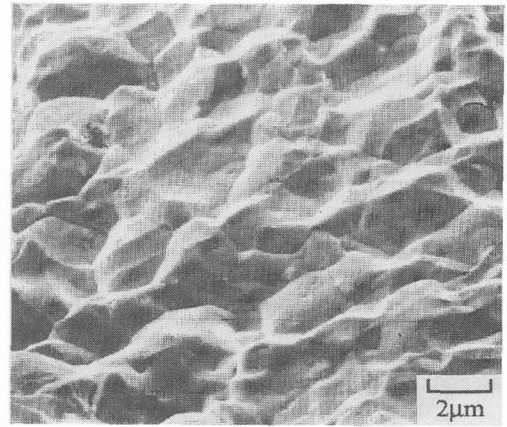


Figure 4-a. SEM micrograph of a fracture plane normal to the shock propagation. This fracture surface has polygonal features on the order of 3 μm in diameter that are intergranular in nature.

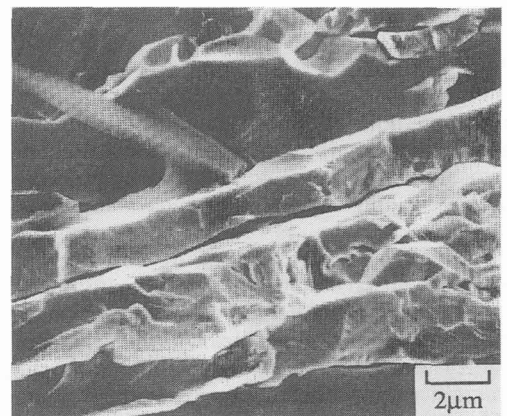


Figure 4-b. SEM micrograph showing the predominately transgranular fracture paths of cracks which propagated parallel to the propagation of the shock wave.

4. DUCTILE - BRITTLE TRANSITION BEHAVIOR UNDER SHOCK LOADING

Planar shock waves impose a unique combination of uniaxial-strain-deformation, temperature and pressure histories on solids, as shown schematically in Figure 5. The strain rates during the shock-rise and release are generally on the order of 10^6 to 10^7 s^{-1} and, in general, the temperature and pressure increase during the shock-rise and decrease during the release.

Increase in temperature during the shock-rise occurs due to conversion of mechanical work into thermal energy and because the material is adiabatically compressed (note that the former is a function of the constitutive behavior of the material and hence is affected by the microstructure, impurity levels, etc.). Decrease in temperature generally occurs upon shock-release because adiabatic decompression generally results in a larger decrease in temperature than the continuing increase in temperature due to mechanical work. A shock pressure of 19 GPa is estimated to result in a temperature increase of approximately 37° C and a residual temperature after shock release of 10° C (13). These changes in material temperature are relatively small and we may ignore them, i.e., we may assume our experiments are isothermal. However, higher shock pressures typically produced by high explosives produce temperatures rises on the order of hundreds of degrees Celsius and can not be ignored.

The amount of strain that occurs during the shock-rise and release is primarily a function of some of the physical properties of the solid and not strongly dependent on the microstructure or mechanical behavior of the material. Because of this, we can use established shock Hugoniot data for tungsten and the following expression to calculate the transient equivalent-strain, ϵ_{st} , produced by the shock loading (shock-rise and release),

$$\epsilon_{st} = \frac{4}{3} \ln \left(\frac{V_s}{V_o} \right), \quad (1)$$

where V_o is the initial specific volume and V_s is the specific volume at the peak shock pressure determined from the Hugoniot for tungsten. The transient shock strains calculated for the experiments performed in this work are given in Table 1.

Metals can accommodate imposed strain fields by any of several well documented mechanisms depending on the deformation conditions (temperature, pressure, strain-rate, etc.). In the case of tungsten under the conditions of shock loading, shock induced strain is first accommodated by elastic deformation. Further straining can be accommodated by dislocation generation and movement, and/or deformation twinning, and/or a microcracking related mechanism. Note that microcracking during shock loading would have to be associated with shear loading (Mode II and/or Mode III cracking) because of the absence of tensile stresses during shock-rise and release. It may be argued that the deformation mechanism(s) which accommodated the imposed strain will be essentially the one(s) which contribute the least to increase in internal energy.

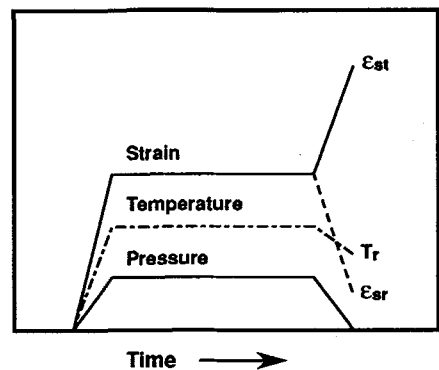


Figure 5. Schematic of the strain, temperature and pressure histories associated with shock loading. The state of strain is uniaxial (all components of the strain tensor are zero except the strain parallel to the shock propagation direction.) Transient strain, residual strain and residual temperature (ϵ_{st} , ϵ_{sr} and T_r , respectively) are, to a large extent, a function of the constitutive response of the test material.

The process of determining (and quantifying) a ductile-brittle transition behavior under uniaxial-strain shock loading is difficult because of the complex deformation history associated with planar shock as described above. The work presented here provides some insight into the topic of DBT behavior under the unique deformation conditions associated with shock loading. If the microcracking of the test sample shocked to 19 GPa at 22° C occurred during the

shock-rise, which appears to be the case, then we can conclude that shock loading at pressures greater than 19 GPa will also result in microcracking of the test material. If the microcracking occurred during shock release we can not make this statement because of the significant effects of temperature and pressure on the mechanical behavior of tungsten. For example, the higher temperatures associated with higher shock pressures would favor a dislocation deformation mechanism resulting in an effective decrease in the DBTT relative to the initial test temperature. Although we note that the higher strain-rates associated with higher shock pressures would favor brittle behavior.

Because of the very complex nature of the DBT under shock loading, better understanding will most likely come from the computer code simulations of the experiment using physically based models for damage and an accurate constitutive model for strength.

5. SUMMARY

Shock/soft-recovery experiments on warm forged tungsten have been performed at 22° C and 400° C. The major findings of this work are as follows:

1. Based on microstructural analyses, at 22° C the shock (19 GPa)-induced strains appear to be accommodated by fracture processes, i.e. indications of shock induced plastic deformation were not observed. The shock-induced damage (internal cracks) resulted in the reduction of the test sample to rubble.
2. A sample of material shock-loaded at 400° C was successfully recovered intact. Microstructural analyses indicated that the shock-induced plasticity caused deformation banding and an increase in the dislocation density of the material.
3. The results of these experiments demonstrate the principle of a ductile-brittle transition behavior under uniaxial shock loading conditions. Based on microstructural analyses it is hypothesized that shock loading at 22° C to pressures greater than or equal to 19 GPa will result in extensive microcracking of the forged tungsten used in this study.

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