Effect of shock wave duration on dynamic failure of tungsten heavy alloy

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Abstract. It has been well established that dynamic fracture or spall is a complex process strongly influenced by both microstructure and the loading profile imparted to the specimen. Having previously considered ductile materials with damage and deformation kinetics that are volume additive and therefore relative slow, here we consider a brittle material with damage and deformation kinetics that are fast. The present study elucidates the effect of loading profile on the fundamental mechanisms of brittle fracture in brittle tungsten heavy alloy (WHA) specimens. Spall experiments are performed with two significantly distinct shock pulse durations and accompanying unloading rates. For both profiles, it is observed that the failure in WHA is by brittle trans-particle crack growth with additional energy dissipation through crack branching in the more brittle tungsten particles. We also observe that for the 15.4 GPa peak shock stress, the wave profile does not influence the spall strength significantly. This is believed to be directly linked to the relative insensitivity of WHA to time dependent processes.

1. Introduction

The influence of shock-wave-loading profile on the failure processes in a brittle material has been investigated. Tungsten heavy alloy (WHA) specimens have been subjected to two shock-wave loading profiles with a similar peak stress of 15.4 GPa but different pulse durations. Contrary to the strong dependence of spall strength on wave profile observed in ductile metals, for WHA, specimens subjected to different loading profiles exhibited similar spall strength and damage evolution morphology. Post-mortem examination of recovered samples revealed that dynamic failure for both loading profiles is dominated by brittle cleavage fracture, with additional energy dissipation through crack branching in the more brittle tungsten particles. Overall, in this brittle material all relevant damage kinetics and the spall strength are shown to be dominated by the shock peak stress, independent of pulse duration. Escobedo et al. [1] have recently presented an extensive discussion of the material pedigree on the material presented in the current work.

2. Material

All target materials were prepared from a tungsten heavy alloy (WHA) plate with a composition of ~92.5% W and the remainder of Ni and Fe. The alloy possesses a composite microstructure of tungsten particles in an austenitic matrix comprised of tungsten, nickel and iron. The volume fraction of W particles of 0.859 ± 0.003 and a particle size of ~50 ± 19 µm.
3. Plate impact experiments
Plate impact experiments were conducted using an 80 mm bore gas launcher previously presented by Gray [2]. Two identical WHA targets, 20mm in diameter and 4mm-thick, were prepared with press fit momentum trapping rings to mitigate perturbations from edge release waves. The experimental parameters are listed in table 1 and the schematics for the two experiments are shown in figure 1. A loading profile with a long-pulse (L) duration was achieved by using a 2 mm-thick W monolithic impactor. The relative thickness of the target and impactor was chosen to locate the spall plane at the midline of the target (figure 1a). Furthermore, this geometry causes a relatively slow interaction of release waves that generates a wide tensile pulse within the WHA. Alternatively, a profile with a significantly shorter pulse (S) duration was achieved with a layered impactor consisting of a 0.5 mm thick W backed with a low-density microballoon composite (\( r = \sim 400 \text{ kg/m}^3 \), almost 50 times lower density than WHA). For this geometry, the release waves interact relatively faster than the previous case, which results in a narrower tensile pulse (figure 1b). Impact velocity was measured to an accuracy of 1% using a sequential pressure transducer method and sample tilt was fixed to \( \sim 1 \text{ mrad} \) by means of an adjustable specimen mount. Both experiments were executed to achieve a peak compressive stress of \( \sim 15.4 \text{ GPa} \), which is significantly higher than the reported range for the spall strength of WHA. The free surface velocity (FSV) profiles were measured using Photon Doppler Velocimetry (PDV) single-point probes.

| Exp. ID | Impactor | Peak free surface velocity (mm/\( \mu \text{s} \)) | Pulse duration (\( \mu \text{s} \)) | Compressive stress (GPa) |
|--------|----------|---------------------------------|------------------|-------------------|
| L (Long Pulse) | W | 2.0 | 0.383 | 0.375 | 0.5 | 15.37 |
| S (Short Pulse) | W/ldm | 0.5/5 | 0.391 | 0.377 | 0.05 | 15.46 |

Notes: (a) ldm = low density material, microballoons

4. Free surface velocity profiles
The free surface velocity (FSV) profiles for the experiments reported herein are shown in figure 2a. These measurements were performed at the sample back free surface. Key parameters and calculated values are listed in table 1. The peak free surface velocities are 0.375 and 0.377 mm/\( \mu \text{s} \), corresponding to peak compressive stresses of \( \sim 15.4 \text{ GPa} \) (calculated using the Hugoniot parameters for tungsten: \( C_0 = 4.022 \text{ mm/\( \mu \text{s} \)} \) and \( s = 1.26 \)). Both loading profiles exhibit a slight inflection in the shock front at \( \sim 0.1 \text{ mm/\( \mu \text{s} \)} \), potentially indicative of the Hugoniot elastic limit (HEL). Although the long pulse profile exhibits some rounding and increases slightly with time, the stress pulse remains within 95% of the peak stress for \( \sim 0.5 \mu \text{s} \), before starting to release. In contrast, the short pulse profile exhibits a sharp transition at peak stress and remains within 95% of the peak stress for less than 0.05 \( \mu \text{s} \). Upon release both profiles exhibit a classic pull-back signal and ringing, generally indicative of spall or dynamic fracture occurring within the sample [3].

A more detailed view of the pull-back regions is shown in figure 2b. The drops in the free surface velocity (DFSV) from the peak states to the minima are 0.056 and 0.067 mm/\( \mu \text{s} \) for the long and short pulse profiles respectively. From these results, the spall strengths (\( \sigma_{spall} \)) for the two experiments can be determined using the corrected relationship proposed by Kanel [4]:

\[
\sigma_{spall} = \frac{1}{2} \rho_0 c_B (\Delta FSV + \delta),
\]

where \( \rho_0 \) is the ambient density (19.26 g/cm\(^3\)), \( c_B \) is the bulk sound speed (4.022 mm/\( \mu \text{s} \)), and \( \Delta FSV \) is the observed pull-back signal (as shown in figure 2b.). The accuracy of the spall strength is improved by correcting for the \( \Delta FSV \) in equation (1) [4].
\[ \delta = h \left( \frac{1}{C_B} - \frac{1}{C_L} \right) \left( |\dot{u}_l| + |\dot{u}_r| \right), \]  

where \( h \) is the thickness of the spalled region (measured in optical micrographs as \( \sim 1.75 \) mm for profile L and 0.4 mm for profile S), \( C_L \) is the longitudinal sound speed (5.22 mm/\( \mu \)s), \( \dot{u}_l \) and \( \dot{u}_r \) are the unloading and re-compression rates calculated as

\[ |\dot{u}_l| = \frac{1}{2} \frac{dFSV}{dt}, \quad \text{and} \quad |\dot{u}_r| = \frac{1}{2} \frac{dFSV}{dt}, \]  

where \( dFSV/dt \) is measured from the pull-back signal and listed in table 2. The unloading rates \( \dot{u}_l \) are normally interpreted as indicators of the kinetics of the tensile pulse imposed on the target [5]. As such, these values indicate that the sample subjected to the shorter pulse profile experienced a faster tensile stress rate as compared with the sample subjected to the longer pulse profile.

![Figure 1. Schematics showing the x-t diagrams of the trajectory and interaction of compressive (C, colored as red) and release (R, colored as blue) waves, as well as the development of compressive and tensile pulses for: (a) the monolithic WHA impactor imposing a loading profile with long pulse duration in compression and wide tensile pulse; and the (b) the layered impactor imposing a loading profile with shorter pulse duration in compression and a narrow tensile pulse.](image)

**Table 2.** Calculated and measured parameters from FSV data

| Exp. ID. | Pull-back characteristics | | | | | |
|---|---|---|---|---|---|---|
| | \( \Delta \text{FSV} \) (mm/\( \mu \)s) | \( \dot{u}_l \) (mm/\( \mu \)s\(^2\)) | \( \dot{u}_r \) (mm/\( \mu \)s\(^2\)) | \( \delta \) (mm/\( \mu \)s) | Spall strength (GPa) | Corrected Spall strength (GPa) |
| L | 0.056 | 0.144 | 0.036 | 0.0029 | 2.16 | 2.28 |
| S | 0.067 | 0.295 | 0.114 | 0.0020 | 2.59 | 2.66 |
Figure 2. (a) Traces of the free surface velocity showing shock loading with long (L) and short (S) pulse durations. The curves are plotted such that the drop from the peak state starts at similar times for both experiments. (b) Region of the free surface velocity highlighting the back reaction signal, indicative of spall plane formation.

The corrected spall strength values calculated using equations (1) to (3) are listed in Table 2; they differ by only ~14 %, being slightly higher in profile S as compared to the profile L. These spall strength values are consistent with those reported in the literature [6-8]. It is worth noting that the difference between the two specimens is less than the sample-to-sample scatter generally reported for WHA and is consistent with the statistical variation within a given sample reported by Vogler and Clayton [8], therefore being statistically insignificant for this brittle material. Moreover, this difference is an order of magnitude less than reported for the spall strength dependence on wave profile observed in ductile metals [9,10]. For these two reasons the difference between the two samples reported in this article can be considered negligible.

Figure 3. Optical micrographs of the spalled samples loaded with the longer pulse (a-b); and (c-d) profile S. The shock direction is from bottom to top. The spall plane is significantly rougher for the longer pulse, while it is more localized with less bifurcation of cracks for the shorter pulse.
5. Damage examination

Several differences are observed in the optical micrographs, figure 3, of the cross sections of the recovered samples. The location of the spall plane within the thickness of the target is as expected, centered for the profile L but near the rear of the target for the shorter pulse profile. This results from the difference in timing for the interaction of the release waves off the back of the impactor and target because of the different impactor designs. Of greater interest is that the spall plane in both samples is very localized in the form of cracks consistent with brittle fracture in contrast to the diffuse damage zones seen in ductile metals failing via void nucleation and growth [10]. Minimal plastic deformation is observed in the microstructure adjacent to the spall plane and no voids are seen to occur, as is associated with incipient spall in ductile materials. In neither case are the cracks perfectly flat, but rather follow a path with fracture roughness and crack-path tortuosity consistent with the length-scale of the tungsten particles.

Electron backscatter diffraction (EBSD) images in figure 4a further highlight secondary cracks formed underneath the primary crack (i.e. spall plane). There is a set of cracks that have linked up across multiple particles and significant fracturing of individual W particles is seen where the crack does not appear to propagate into the matrix or surrounding particles. This type of sub-surface damage of the brittle phase is often observed when mechanical toughening is achieved through a multi-phase composite microstructure. The WHA has also been characterized by Dynamic-Tensile-Extrusion (Dyn-Ten-Ext), which is a novel test method for the investigation of material response under extreme tensile conditions, comprising the combined conditions of large tensile strains ($\varepsilon > 1$) and high strain rates ($\dot{\varepsilon} > 10^4 \text{ s}^{-1}$), effectively serving as a tensile analog to the Taylor cylinder impact test [11,12], illustrated in figure 5. Interestingly, when the same WHA is loaded under Dyn-Ten-Ext where very large tensile strains and strain rates are achieved, this more constrained loading allows for substantial plasticity within tungsten particles, figure 4b. Almost no cracking is observed. Rather the tungsten particles rotate to align with the extrusion direction and undergo substantial deformation, a behavior characteristic of ductile materials [14]. The temperature excursion taken by the Dyn-Ten-Ext specimens is expected to differ significantly from that taken but the plate impact specimens, which might lead to enhanced plastic processes.

Figure 4. EBSD orientation maps near the spall plane of the spalled specimens loaded with the long pulse on the left. The shock direction is from bottom to top and the color indicates the particle’s crystalline orientation with respect to the shock direction according to the color key. EBSD orientation maps of a WHA Dynamic Tensile Extrusion sample on the right. The Dyn-Ten-Ext sample has been extruded from left to right.
Figure 5. (a) Schematic of Taylor rod impact and (b) Dyn-Ten-Ext, with representative maximum principal strain. Dark blue denotes unstrained material, while red regions exhibit a strain of approximately 100%. (c) Taylor gun facility at Los Alamos National Laboratory [13].

6. Conclusions
Although the imposed wave profiles do not significantly affect the value of the spall strength of WHA, the difference in waveform does significantly change the area of the sample put into tension. The acceleration rates appear to be indicative of the ability to form a complete spall plane. In this regard, the higher rate measured with the shorter pulse correlates with a single, flatter, less tortuous, spall plane observed in the spalled sample.

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