X-ray microtomography study of the spallation response in Ta–W

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Abstract. Measurement of the damage field resulting from spallation due to shock induced loading is an important aspect of understanding the mechanisms controlling the dynamic tensile failure process. Furthermore, the ability to observe in three-dimensions, and in a non-invasive manner, the physical damage present in a spalled sample post-impact can provide important data for predictive damage models. In the current study, the influence of peak shock stress and pulse duration on the spallation damage response in the tantalum alloy Ta–2.5% W is presented. Rear surface velocimetry (HetV) measurements from plate impact experiments have been combined with 3-D characterisation and quantification of the resulting damage evolution in the recovered targets using X-ray microtomography. Small differences in spall strength are observed – an increase in the pulse duration results in a decrease in spall strength, while spall strength increases with increase in peak shock stress. The level of damaged induced (void coalescence) is more significant for an increase in pulse duration, with a local damage volume fraction double that of the case for an increase in peak shock stress.

1. Introduction

The response of materials to high strain-rate (impact) loading is of interest to a number of communities. Traditionally, the largest driver has been the military, in its need to understand armour and resistance to ballistic attack. More recently, industries such as aerospace (foreign object damage, bird strike, etc.), automotive (crash-worthiness) and satellite protection (orbital debris) have all appreciated the necessity of such information. It is well established that ductile failure in metals subjected to dynamic tensile loading occurs through a sequential process of nucleation, growth and coalescence of voids and cracks that initiate at the microstructural scale. Spallation refers to the damage and failure process produced by the tensile interaction of release waves associated with shock-induced deformation. Numerous experimental investigations of the spallation process have provided insight concerning the evolution of damage and the influence of microstructure and shock pulse history (peak stress, pulse duration and pulse shape) on the spallation response of various materials [1–5]. Knowledge of the damage field is an important aspect of understanding the mechanisms controlling the failure process and it also serves to both inform and validate models of dynamic failure. Historically, quantification of spallation damage has been determined using stereological analysis of two-dimensional (2-D) metallographic sections, such as in ductile fracture of tantalum [3]. However, 2-D sections cannot fully describe the complex damage features or the spatial relationship between them. While a three-dimensional (3-D) microstructural reconstruction of a spalled tantalum
sample has been created using serial sectioning techniques [6], uncertainties remain related to the destructive nature of collecting successive metallographic sections and the potential for altering the character of the voids by processes such as smearing or re-filling, particularly for ‘soft’ materials. In this respect, as a non-destructive imaging technique X-ray microtomography allows the internal structure of an object to be reconstructed in 3-D, thereby allowing the true damage state to be characterised. We have previously used the technique to investigate the spallation damage response of recovered Ti–6Al–4V targets during plate impact experiments [7]. In the current study, the technique has been used and combined with rear surface heterodyne velocimetry (HetV) measurements during plate impact experiments to investigate the spallation damage response of recovered Ta–2.5% W targets, exploring in particular the effect of varying peak shock stress and pulse duration on said response.

2. Experimental

Impact experiments were undertaken on plates of Ta–2.5 wt. percent tungsten of diameter 65 mm and thickness 3 mm and 6 mm with carbon < 10 ppm, iron 0.249 ppm, molybdenum 2.933 ppm, nickel 0.022 ppm, silicon 0.064 ppm, 2.48 wt. percent tungsten, hydrogen < 5 ppm, nitrogen < 10 ppm, oxygen 24 ppm and the balance tantalum. The original material was cold rolled from ca. 300 mm in a number of stages, with an intermediate annealing treatment of 1100 °C for 1 h between rolling passes. Acoustic properties of the material have been measured using 5MHz quartz transducers with a Panametrics PR5052 pulse generator [8]. The density ($\rho_0$) was measured to be $16.78 \pm 0.01$ g cm$^{-3}$, longitudinal sound speed ($c_L$) $4.12 \pm 0.03$ mm $\mu$s$^{-1}$ and shear sound speed ($c_S$) $2.11 \pm 0.03$ mm $\mu$s$^{-1}$. The Poisson ratio ($\nu$) was 0.322. Shock loading experiments were performed using a 70 mm bore, 3 m long single stage gas gun. Velocity–time wave profiles were recorded from motion on the rear surface of each plate using a HetV system [9]. The mounting of the assembled target on the end of the barrel of the gun was adjusted to provide an alignment of better than 1 mrad. The diagnostic plate was positioned ~ 30 mm away from the target material and was used to support the HetV probe assembly. The probe was mounted in a Gimbal optical mount, which enabled ease of alignment onto the rear surface. Figure 1 shows the typical experimental setup.

Flyer and target plate materials were matched to ensure a symmetrical impact, with the flyer thickness half that of the target to ensure the spall plane was in the centre of the target. Impact velocities of 200 m s$^{-1}$ (shock stress of 6 GPa) onto 3 mm and 6 mm thick targets and 225 m s$^{-1}$ (shock stress of 6.6 GPa) onto a 3 mm thick target were produced. Impact of a 6 mm thick target enabled the effect of longer pulse duration to be investigated for the same impact velocity and shock stress, 1.37 $\mu$s compared to 0.68 $\mu$s for the 3 mm thick target. The impact conditions for the three different targets are summarised in table 1.

![Figure 1. Showing the experimental setup and target assembly for HetV measurements.](image-url)
Table 1. Impact conditions for the three different targets.

| Target No. | Impact Velocity (ms⁻¹) | Impact Stress (GPa) | Pulse Duration (µs) |
|------------|------------------------|---------------------|---------------------|
| 1-1        | 200                    | 6.0                 | 0.68                |
| 1-2        | 200                    | 6.0                 | 1.37                |
| 1-3        | 225                    | 6.6                 | 0.68                |

Following the impact experiments all samples were soft recovered and the resulting damage within the samples was characterized in 3-D by X-ray microtomography. Due to the high X-ray absorption of the Ta–W material, small matchstick samples of cross-section 0.6 × 0.6 mm² were required to ensure adequate transmission of X-rays in the projections. These were cut such that the long axis represented the thickness of the impacted targets. X-ray microtomography measurements were carried out using an Xradia MicroXCT, which was equipped with a 150 keV, sealed tungsten high-energy microfocus X-ray source and a 2048 × 2048 pixel² 16-bit high resolution cooled CCD detector. X-ray energy of 150 keV and current 66 µA gave an X-ray transmission through the sample of ~ 8%. A lead glass filter placed just in front of the X-ray source acted to remove low energy photons from the X-ray beam, thus reducing beam hardening artifacts. 541 projections were collected over a rotation of 180° using a binning factor of 2 (i.e. a frame of the CCD of size 1024 × 1024 pixel²). 20 × magnification, using a compound objective lens, was used to focus the X-ray image captured by the scintillator screen onto the CCD camera, giving a reconstructed voxel size of 1.3 × 1.3 × 1.3 µm³. The exposure time per projection was 60 seconds. The projections were reconstructed into 3-D tomographic volumes using a cone-beam extension of the filtered back projection reconstruction algorithm [10]. 3-D isosurface representations were calculated by segmenting the reconstructed volumes based on grey-level, therefore separating the spall damage (voids) from the sample bulk material. This was performed using image processing techniques in Avizo, a commercial software package from VSG (Visualisation Sciences Group). By selecting a single voxel within a void, all connected voxels to this, within a specified grey-level range, are also automatically selected, ensuring the shape of the void to be defined by the boundary between the void and the metal phase. Applying this for all voids within the scanned region-of-interest (ROI) results in a segmented volume of voids only, which are displayed as a 3-D surface plot. In labeling the segmented voids, each one is defined as an individual object with a unique ID, enabling quantitative measurements of void volume, shape, etc. and their distributions.

3. Results and Discussion

3.1. Free surface velocity profiles

The effect of changes in both shock stress (impact velocity) and pulse duration during shock loading was studied. Free surface velocity traces measured using HetV are presented in figure 2(a), capturing the spallation response under the three different target–impact conditions. A pronounced Hugoniot Elastic Limit (HEL) is observed in each of the three loading profiles at ~ 0.06–0.07 mm µs⁻¹, more easily observed in figure 2(b) showing the initial 1 µs of the histories. Figure 2(c) shows the ‘pull-back’ signal of the free surface velocity histories. The times and velocities are shifted such that the drop from the peak state starts at t=0. The initial unloading is elastic; yield (plastic flow) is dominant when the free surface velocity has fallen by ~ 0.07 mm µs⁻¹ from the peak value, indicated by a slight ‘kink’ in the histories in figure 2(c) at a velocity of around –0.07 mm µs⁻¹. The arrow in figure 2(c) (and figure 2(a)) denotes the magnitude of the pull-back signal, Δµ (illustrated only for target 1-3). While the peak shock stress and pulse duration at peak stress differ between the samples, the pull-back signals are observed to show only small differences. The spall strength, σ_{spall}, can be calculated using the standard straight impedance spall drop relationship [11],

\[ \sigma_{spall} = \frac{\Delta u}{2c_0 \rho_0}, \]
where $c_0$ is the material sound speed, measured independently to be $3.32 \text{ mm} \mu\text{s}^{-1}$ [12]. The spall strengths for the three targets are given in table 2. Small differences in spall strength are observed – while an increase in the pulse duration results in a decrease in the spall strength an increase in the shock stress gives an increase in spall strength.

**Table 2.** Effect of peak shock stress and pulse duration on both spall strength and damage volume fraction in Ta–2.5 W.

| Target No. | Spall Strength, $\sigma_{\text{spall}}$ (GPa) | Damage Volume Fraction (%) |
|------------|---------------------------------------------|----------------------------|
| 1-1        | 4.70                                        | 0.65 (1.69)                |
| 1-2        | 4.47                                        | 1.65 (8.32)                |
| 1-3        | 4.88                                        | 1.60 (4.28)                |

### 3.2. Three-dimensional damage characterisation

The effect of changes in both shock stress (impact velocity) and pulse duration on the extent of spallation damage induced during impact was characterized in 3-D using X-ray microtomography. Figure 3 shows 3-D isosurface representations of the spall region in each of the targets, covering a height (equal to the field-of-view) of 1.2 mm. Damage is illustrated for two different matchstick samples cut from each target (separated left and right), and each of these has two different views of the
damage volume from different angles. In each case, the shock pulse has produced a spall plane nominally at the centre of the target plate. The damage evolution in the three Ta–2.5 W targets is observed to vary as a function of varying peak shock stress and pulse duration while showing small differences in spall strength.

![Figure 3. Reconstructed 3-D isosurfaces comparing damage within the three Ta–2.5 W targets. Separated left and right are two different samples (two views for each sample, with a rotation around the vertical axis). The impact direction is vertical. The arrows indicate the plate mid-plane.](image)

Qualitatively, it is clear from the images that target 1-1 has the least severe damage, with larger isolated voids in a central region and smaller voids above and below this. The effect of increasing the pulse duration (i.e. comparing damage states between targets 1-1 and 1-2) is the coalescence of voids in the central region for 1-2, which are also larger than those observed in target 1-1, to form aggregated damage features. Considering the effect of increasing the peak shock stress (i.e. comparing targets 1-1 and 1-3) the damage state in target 1-3 again shows coalescence of voids but the voids are not as large as those resulting from an increase in pulse duration. Those outside the central coalesced
region are also smaller for the increased peak shock stress state, and similar to target 1-1. The damage states observed in figure 3 for the different loading conditions suggest the primary damage evolution mode to proceed from void nucleation, through void growth to coalescence. A great advantage of X-ray microtomography, over metallography of polished sections for example, is that quantitative analysis can be performed on the segmented 3-D datasets. A measure of the amount of damage induced is given in table 2 by the volume fraction of voids/cracks through the thickness of the impacted targets. Volume fractions shown are calculated relative to the full matchstick sample length (i.e. the target thickness – 3 mm for targets 1-1 and 1-3 and 6 mm for target 1-2). The values in brackets are those calculated relative to the ROI volume of the scan (0.6 × 0.6 × 1.2 mm³) centred on the mid-plane of the target thickness. Target 1-1 clearly contains the least amount of damage of the three shock loading conditions. Of targets 1-2 and 1-3 they contain very similar amounts of damage relative to the respective thickness of material in each case. When only the central 1.2 mm through-thickness dimension is considered for both cases, on the other hand, target 1-2 contains approximately double the amount of damage than target 1-3, suggesting the effect of increasing pulse duration to be more significant, in terms of amount of damage induced, than increasing peak shock stress.

4. Summary and Conclusions
Rear surface HetV measurements have been combined with X-ray microtomography of recovered targets to determine tensile failure mechanisms in Ta–2.5 W during shock loading. The effect of peak shock stress and pulse duration on the spallation damage response has been investigated. Small differences in the ‘pull-back’ spallation signals, and thus spall strength, were observed to result from the three different shock-loading histories. The level of damage induced is observed to increase as a function of varying peak shock stress and pulse duration. Coalescence of voids in the central region of the target thickness results from an increase in each of these. This void coalescence is more significant for the increase in pulse duration, with larger damage features and a local damage volume fraction double that of the case for an increase in peak shock stress.

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