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SHOCK LOADING AND TAYLOR IMPACT OF Ti-6Al-4V

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Abstract. Lateral stress gauges have been used to measure the variation of shear strength with longitudinal stress in shock loaded Ti-6Al-4V. Results show that lateral stress decreases slightly behind the shock front before reaching a constant level. We believe that this is due to the deformation microstructure not reaching its steady state immediately, but rather evolving over time. We have also observed that the Hugoniot and shear strength of our material is in close agreement to previous work. Recovered Taylor impact specimens show a circular foot print, and x-ray tomography examination shows no evidence of tensile damage immediately under the impact face.

Keywords: Plate impact, Taylor Impact, Ti-6Al-4V, Shear Strength
PACS: 62.50.+p, 62.20.-x, 81.70.Bt, 83.50.-v

INTRODUCTION

The response of the engineering alloy, Ti-6Al-4V to high loading rate situations has been of considerable interest for a number of years. This comes in part from its use in the aerospace industry in the manufacture of fan blades in jet turbine engines. Additionally, it has also received attention due to the possibility of using it in the manufacture of low weight armour systems. The Hugoniot (in stress (σ_X) – particle velocity (u_p) space) was measured by Rosenberg *et al.* [1], also placing the Hugoniot Elastic Limit (HEL) at 2.1 GPa. Gray and Morris [2] determined the equation of state in terms of shock velocity (U_S) and particle velocity, revealing a linear relationship where c_0 and S (the shock parameters) were 5.12 mm μs^{-1} and 1.08 respectively. Dandekar and Speltzer [3] also examined the HEL, showing that it lay in the range 2-3 GPa with little evidence of precursor decay. Razorenov *et al.* [4] demonstrated that oxygen content affected the HEL, increasing by as much as 20% over the composition range 0.105 – 0.24 wt%. Experiments on a low oxygen containing variant by Tyler *et al.* [5] showing an HEL of 2.35 GPa were consistent with the previous authors. Dynamic tensile (spallation experiments) by Dandekar and Speltzer [3] also showed that spall strength increased markedly with pulse duration, as did Tyler *et al.* [5]. In that latter work, microstructural examination led the authors to suggest that the deformation behind the shock front was time dependent, with a corresponding effect upon the spall strength. Lateral stress (σ_y) measurements by Hopkins and Brar [6] showed a slight decrease in lateral stress behind the shock front. From the well known relation,

$$2\tau = \sigma_x - \sigma_y , \qquad (1)$$

where τ is the shear strength, this indicates that the material strengthens behind the shock front, presumably via a dislocation or twinning based mechanism.

EXPERIMENTAL

Plate impact experiments were performed using a 70 mm bore, 3 m long single stage gas gun. Target assemblies were made by sectioning 8 mm thick plates of Ti-6Al-4V in half and introducing a manganin stress gauge (J2M-SS-380SF-025) 4 mm from the front surface. In this way, the gauge would be sensitive to the lateral component of stress. The target was reassembled using a low viscosity epoxy and held in a special jig for a minimum of 12 hours. Voltage data was converted to stress using the methods of Rosenberg *et al.* [7]. The front surface was lapped to a flatness of 5 optical fringes from a monochromatic light source, and then fixed to a 3 mm driver plate of either dural (aluminium alloy 6082-T6) or copper, matched to the material of the flyer plate. In a couple of experiments, an additional stress gauge (LM-SS-025CH-048) was fixed between the two, such that the longitudinal stress and, via impedance matching, the particle velocity could be determined. Gauge calibrations were according to Rosenberg *et al.* [8].

Taylor impact experiments were performed on 7.62 mm diameter rods, with a length/diameter (L/D) ratio of 5. Rods were fired at either a rigid anvil (hardened tool steel) or as symmetrical impacts (rod on rod). The long axis of the rods was parallel to the long axis of the original bar stock. Further details of this experimental setup can be found in Maudlin *et al.* [9]. The recovered cylinders were examined using a high-resolution computerised tomography and digital radiography system (HMXST 225) from X-Tek Systems Ltd, with a microfocus x-ray source (5 μm spot size), with tube potentials up to 225 kV. Recovered cylinders were placed on an object manipulator between the x-ray source and detector (image intensifier and CCD screen), thus providing magnification and rotation for collection of radiographs over a rotation of 360°. Three dimensional tomographic volumes were reconstructed using the methods of Feldkamp *et al.* [10].

MATERIALS

The Ti-6Al-4V in this investigation was obtained as 75 mm bar stock, with samples sectioned from it such that the impact axis was parallel to the long axis of the bar. The material was supplied as hot rolled and annealed. Measured acoustic properties were longitudinal (c_L) sound speed 6.11 mm μs^{-1}, shear (c_S) sound speed 3.13 mm μs^{-1}, and Poisson's ratio (ν) 0.322. The material was shown to possess a $<10\bar{1}0>$ rod axial fibre texture of moderate strength (*ca.* x 4). The microstructure consists of primary alpha particles in a transformed beta matrix.

RESULTS AND DISCUSSION

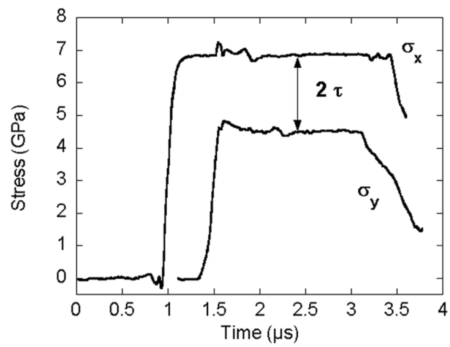

Figure 1. Stress gauge traces for a 5 mm copper flyer at 454 m s^{-1} using a Ti-6Al-4V target assembly.

In Fig. 1, we show the results of combined longitudinal and lateral stress gauge measurements, from the impact of a 5 mm copper flyer plate at an impact velocity of 454 m s^{-1}. As the longitudinal gauge was between the driver plate and the Ti-6Al-4V target, it can only be used to determine the Hugoniot stress for these particular impact conditions, and from impedance matching, the particle velocity, u_p. The lateral stress trace shows a slight but noticeable relaxation for a period of approximately 0.5 μs after the arrival of the shock, before reaching a near constant level. This suggests (from equation 1) that the shear strength increases over this period. Similar behaviour has been observed in face centred cubic materials such as nickel alloys and has been equated with increases in dislocation density behind the shock front [11].

In Fig. 2 we present the Hugoniot of Ti-6Al-4V, as determined in stress – particle velocity space by Rosenberg *et al.* [1]. We have included our own Hugoniot measurements (made using the same techniques), showing that our own results are in close agreement. We have also used the shock velocity (U_S) particle velocity data of Gray and Morris [2] to calculate the hydrodynamic pressure, P_{HD}, through,

$$P_{HD} = \rho_0 U_S u_p \quad (2),$$

again showing close agreement between our own data, that of Rosenberg *et al.* [1] and Gray and Morris [2].

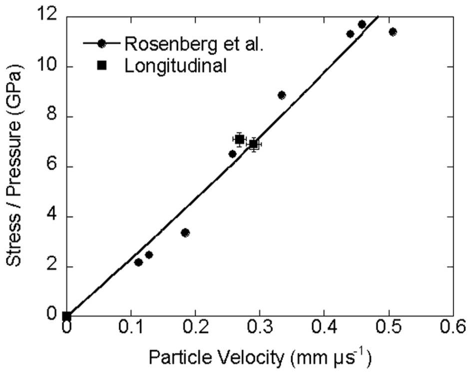

Figure 2. Hugoniot of Ti-6Al-4V determined in stress – particle velocity space.

These results indicate that the Hugoniot of Ti-6Al-4V is not overly sensitive to the microstructural state, or variations between batches.

In Fig. 3, we present the variation of shear strength with applied shock stress for Ti-6Al-4V. The straight line fit is the calculated elastic response according to,

$$2\tau = \frac{1-2\nu}{1-\nu}\sigma_x . \quad (3)$$

We have included the results of Hopkins and Brar [6], and it can be seen that there is clear agreement between the two sets of data. Although they did not specify the condition of their material, it suggests that shear strength is not overly sensitive to material state. The data is also observed to deviate below the calculated elastic response at a stress of *ca.* 2 GPa, indicating that the Hugoniot Elastic Limit – HEL lies somewhere around this point. This is consistent with the work of others [3, 5] who place the HEL in the range 2-3 GPa.

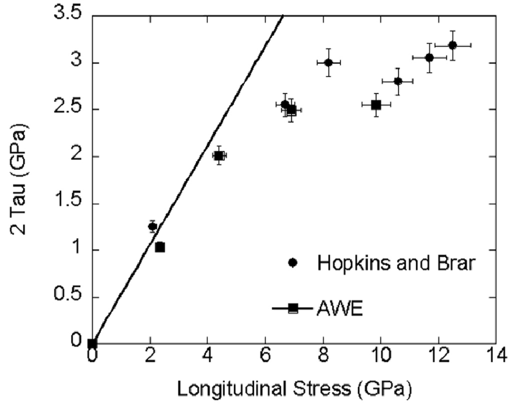

Figure 3. Variation of shear strength with applied shock stress for Ti-6Al-4V.

In Fig. 4 we present a photograph of a recovered Taylor cylinder, impacted onto a rigid anvil at 353 m s^{-1}.

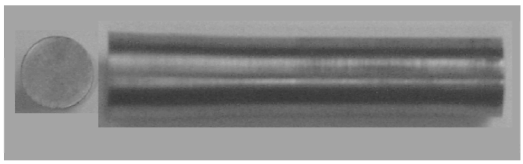

Figure 4. Recovered Taylor cylinder of longitudinally orientated Ti-6Al-4V. Impact was symmetrical (rod on rod) at a velocity of 353 m s^{-1}. The rod shown was the impactor, travelling from right to left. The rod footprint is shown to the left.

In this and all other samples, deformation was limited to a slight increase in diameter behind the impact face. The footprint was observed to be circular, suggesting that anisotropy in the radial plane is minimal, as would be expected from the fibre texture in this material.

Finally, in Fig. 5, we present an x-ray tomography in a sample impacted at velocity of 238 m s^{-1}. In particular, we were interested to observe the possibility of damage along the central axis, immediately behind the impact face, induced by the interactions of releases causing a region of net tension. As the results show, no such failure occurred, as might be expected from a material with a high tensile (spall) strength.

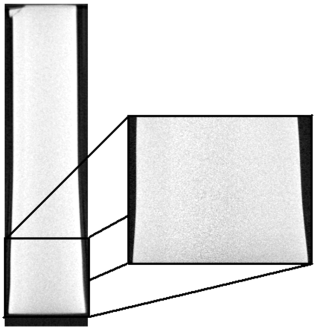

Figure 5. Hugoniot XRT section of Ti-6Al-4V rod, impacted onto a rigid anvil at 238 m s^{-1}. No damage is evident.

CONCLUSIONS

The shock response of Ti-6Al-4V has been determined as a function of its variation of shear strength with applied shock stress. Measured lateral stress traces show a decrease behind the shock front before levelling out after *ca.* 0.75 μs. It has been proposed that this be due to the generation of dislocation and twin deformation structures that take time to fully develop, thus resulting in an evolving shear strength. Measurements of the Hugoniot and shear strength show agreement with previous workers, suggesting that in these parameters, Ti-6Al-4V is not especially sensitive to the initial state.

Analysis of recovered Taylor impact specimens show that when impacted along the long axis of the original bar, a circular foot print is obtained. This suggests that the properties of Ti-6Al-4V are not variable in the radial plane, and is consistent with quasi-static data. Deformation around the impact face is limited, indicating that much of the deformation is accommodated elastically, as might be expected from a material with a high yield strength. Finally, x-ray tomography has shown no evidence of tensile damage under the impact face, again as might be expected from a material with a high tensile (or spall) strength.

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