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SHOCK RESPONSE OF Ti-6Al-4V

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Abstract. The shock behavior of a new Ti-6Al-4V alloy has been characterized up to stress levels of 13 GPa. Examination of velocity profiles obtained from five transmission experiments indicate elastic-plastic behavior in the material. Magnitude of the HEL lies between 2 - 3 GPa and appears to be dependent on material thickness. Spall strength tends to vary with changes in pulse width, ranging from 3.3 - 4.2 GPa.

INTRODUCTION

Ti-6Al-4V alloy has been used extensively in aircraft and aerospace applications. However, to successfully transition it to widespread use in the combat theater as armor for ground vehicles, the production and fabrication costs of this alloy must be reduced. Efforts to meet this goal have resulted in a new Ti-6Al-4V alloy. The material used in the present work was produced from a mix of 32% titanium sponge and 62% Ti-6Al-4V turnings, with the balance made up of aluminum shot and V-Al Master alloy. The primary cost savings come from the use of titanium sponge and Ti-6Al-4V turnings. The ingot was electron beam melted in a cold, water-cooled copper, hearth furnace. The motivation for the present work was to compare the shock response of this material (low cost alloy) with the alloy of the same composition used in aircraft/aerospace applications. Shock experiments were performed to obtain information on the shock, release, and tensile behavior of this alloy.

MATERIAL

The nominal composition of the alloy (in weight percentage) is: Al (6.28), V (4.16), O (0.176), Fe (0.151), C (0.025), and N (0.008). The remainder is titanium. The 6.35 cm thick plate used in this work was annealed at 1213K for two hours, roller leveled, and annealed at 1033K for one hour. The micro-structure consists of equiaxed alpha phase with intergranular beta phase. The static mechanical properties; yield strength, tensile strength, and ductility measured by elongation and reduction in area under tension indicated that the material is isotropic[1]. Wells et.al. [1] reported the values of yield and tensile strength as 896 ± 13 and 958 ± 7 MPa, respectively. The values of elongation and reduction in area are 13 and 24.5 percent, respectively. The measured value of density is 4.42 ± 0.01 Mg/m^3, while the values of ultrasonic longitudinal and shear wave velocities are 6.12 ± 0.07 and 3.17 ± 0.13 km/s, respectively. The values reported here for density and wave velocities are the averages of measurements carried out on twenty specimens, and are essentially the same as those of the traditional alloy.

EXPERIMENT

Experiments were performed using a 100 mm diameter light gas gun. Measured projectile velocities ranged from 398 - 662 m/s, with an uncertainty of less than 0.5%. These values were obtained by shorting out four sets of charged pins, which were separated by predetermined distances.

Particle velocity profiles were acquired using a Push-Pull VISAR, and recorded on high speed digital oscilloscopes. A fiber optic probe was placed 30 mm behind the target (Fig. 1). When impact occurred, the probe transmitted a velocity history of the target's rear surface to the VISAR. The precision of the VISAR measurements was 1%.

Ti-6Al-4V specimens used in the experiments were 40 mm in diameter, with thicknesses of 2 - 8 mm. Specimens were flat and parallel within 10 μm. The rear surfaces of the targets were polished to produce a diffuse reflective surface for use with the VISAR probe. Z-cut sapphire and tungsten carbide discs were also used as impactors. These discs were flat within 10 μm and required no surface preparation. Design of the experiments ensured that data obtained on the shock, release, and tensile behavior of the alloy was captured during a state of uniaxial strain. Experimental configurations are listed in Table 1.

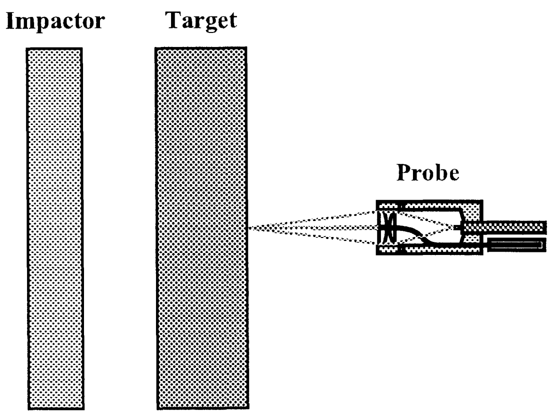

Figure 1. Transmission Experiment Configuration.

RESULTS

Five transmission experiments were performed to generate stress levels between 5 and 13 GPa. These experiments provide information about the magnitude of the Hugoniot Elastic Limit (HEL) and its dependence on specimen thickness, the nature of the inelastic response, and the spall threshold. The results of these experiments are summarized in Table 1. Figure 2 shows the recorded free surface velocity profiles in these experiments. This figure shows that the shock compressed state in the titanium alloy is attained through the propagation of an elastic wave of amplitude between 2 and 3 GPa with the final state attained through the propagation of a slower shock wave. The amplitude decay of the elastic precursor with propagation distance is clearly evident from the profiles obtained in experiments 836 and 907. Specimens used in these experiments were 8 and 1.8 mm thick, respectively. The slower shock wave has the signature of plastic wave propagation. The results of these experiments are discussed under the sub-headings of Elastic Compression, Plastic Compression, and Spall Threshold.

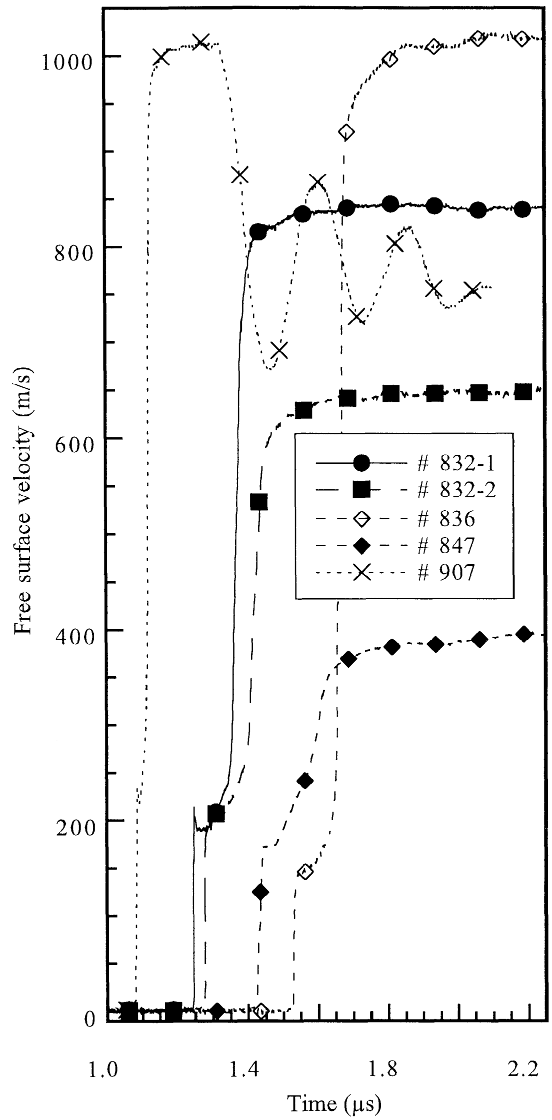

Figure 2. Wave Profiles in Ti-6Al-4V.

Elastic Compression

The value of the HEL varied between 2.02 and 2.95 GPa. The uncertainty of these values is 1.2%. Experiments 836 and 907 were performed to generate peak stresses of 13 GPa. Specimens used in these experiments were 8 and 1.8 mm thick respectively, with corresponding HEL's of 2.02 and 2.95 GPa. This suggests that the value of the HEL is dependent upon specimen thickness. Since the wave profiles do not show significant post-yield hardening, assuming that strain rate effects do not

Table 1. Summary of Transmission Experiments in Ti-6Al-4V.

	Experiments [a]				
	832-1(S)	832-2	836(WC)	847	907(WC)
Thickness(mm)					
Impactor	6.024	3.954	4.011	4.028	0.947
Target	5.980	5.993	7.999	6.003	1.858
Impact Velocity (km/s)	0.653	0.653	0.662	0.398	0.657
Elastic Compression					
Particle velocity (km/s)	0.094	0.096	0.0745	0.0855	0.109
HEL (GPa)	2.57	2.61	2.02	2.30	2.95
Density (Mg/m3)	4.483	4.488	4.472	4.481	4.498
Inelastic Compression					
Shock velocity (km/s)	5.45	5.36	5.51	5.18	5.43
Peak stress (GPa)	10.47	8.10	13.10	4.91	13.00
Particle velocity (km/s)	0.418	0.326	0.524	0.199	0.521
Density (Mg/m3)	4.770	4.688	4.866	4.579	4.867
Release					
Free surface velocity (km/s)					
Measured	0.839	0.650	1.025	0.397	1.009
Calculated	0.826	0.641	1.042	0.383	1.029

[a] S and WC denote that the impactors were Z-cut sapphire and tungsten carbide, respectively.

Table 2. Summary of Spall Data on Ti-6Al-4V

	Experiment				
	832-1	832-2	836	847	907
Impact stress (GPa)	8.10	10.47	13.1	4.91	13.00
Pulse width (μs)	1.285	1.078	1.163	1.325	0.274
Pull-back velocity (km/s)	0.302	0.272	0.298	0.314	0.342
Spall strength (GPa)	3.63	3.32	3.67	3.65	4.18

influence the magnitude of the HEL (σ_{HEL}) when an 8 mm thick specimen is used, the value of dynamic yield stress (Y_d) can be calculated using

$$Y_d = 2\, C^2_s / C^2_L\, \sigma_{HEL} \qquad (1)$$

where C^2_s and C^2_L are the shear and longitudinal wave velocities, respectively.

The calculated value of Y_d for the titanium alloy is 1.09 GPa which is close to yield stress value of 1.15 GPa determined by Weerasooriya[2] under compression at strain rates of 1300-3000 s^{-1}.

Plastic Compression

The shock velocity following the elastic precursor depends on the final stress attained in the alloy. It varies from 5.18 to 5.51 km/s (Table 1). This is the effective shock velocity relative to the particle velocity of the elastically deformed alloy i.e., the particle velocity associated with the HEL. The magnitude of the shock velocity is similar to the alloy's bulk sound speed. Hence, the alloy deforms plastically above the HEL. This inference is reinforced by calculating the values of the free surface velocities on the assumption that the alloy follows elastic-perfectly plastic behavior, and comparing them to the observed free surface velocities. The difference in free surface velocity is less than 2%, except in experiment 847 where the difference is 3.6%. The values of release impedance calculated from the data in Table 1 vary from 24.9 to 26.6 Gg/m^2s. The shear stress sustained by this alloy varies from 0.5 GPa at the HEL (2.0 GPa) to 0.88 GPa at 13 GPa. These values were obtained from the offset between the hydrodynamic compression curve and the Hugoniot. The hydrodynamic compression curve was calculated from the data given by Morris et al.[3].

Spall Threshold

The experiments were designed to provide information on the alloy's spall threshold. The pulse widths of the first four experiments varied from 1.1 to 1.3 μs, while that of #907 was 0.274 μs. The magnitude of pull-back particle velocity ranged from 0.272 to 0.342 km/s. Considering the precision of these values, the differences in the pull-back velocities suggest that spall strength is dependent upon pulse width. This observation needs to be verified during experiments in the future. The spall thresholds, calculated from the product of plastic impedance and half the magnitude of the pull-back velocity, vary from 3.3 and 4.2 GPa (Table 2). Secondary spall resistance, as described by Johnson et al.[4], was observed in the velocity traces and verified through inspection of the recovered targets.

COMPARISON

The shock response of Ti-6Al-4V has been studied by numerous investigators[3,5-10]. We assume that the materials used in the previous works were for aircraft/aerospace applications. The results of these efforts are compiled in Table 3.

Table 3. Summary of Shock Properties of Ti-6Al-4V.

	HEL (GPa)	Pulse width (μs)	Spall Strength (Impact stress) (GPa)
Morris et al.[3]	2.8		
Kanel and Petrova[5]	2.0		3.4
Me-Bar et al.[6]		1.2	4.1-5.0 (10.5)
Froeschner et al.[7]		0.15	4.7-4.9
Chhabildas et al.[8]	2.3	1.0	5.1 (13.6)
Andriot et al.[9]	2.8	1.0	3.6-4.2 (52-64)
Brar and Hopkins[10]	2.7		

The HEL of this alloy was found to vary from 2 to 2.8 GPa. No mention of elastic precursor decay was found. Shock compression beyond the HEL was attained through plastic deformation.

Brar and Hopkins[10] report that shear strength increases in their material from 0.9 GPa at the HEL to 1.6 GPa at 12.5 GPa. These values were taken from simultaneous measurements of longitudinal and lateral stresses. The present work shows that shear strength of the low-cost alloy increases from 0.5-0.7 GPa at 2.0-2.6 GPa to 0.9 GPa at 13 GPa.

The values of spall strength reported in this work are similar to those reported by Kanel and Petrova[5], and Andriot et al.[9] but less than those reported by Chhabildas et al.[8] and Me-Bar et al.[6]. Me-Bar et al. [6] reported that the initial microstructure of the alloy did not influence the spall threshold. Additionally, the variation in the pulse width (Table 3) does not appear to explain the differences in the spall strength values of Ti-6Al-4V reported earlier[3,5-9]. However, the present work indicates that spall strength of the low cost alloy is pulse width dependent.

To sum up, the shock response of the low-cost alloy and the aircraft quality alloy under shock compression and release are essentially the same, but vary with respect to their spall strengths.

REFERENCES

1. Wells, M. G. H., Burkins, M, Roopchand, B, and Fanning, J. The mechanical and ballistic properties of an electron beam single melt of Ti-6Al-4V plate. To be published in *9th World Conference on Titanium*, Saint Petersburg, Russia, 7-11 June 1999.
2. Weerasooriya, T, Unpublished.
3. Morris, C. E., Winkler, M. A., and Mitchell, A. C., "Ti-6Al-4V Alloy Wave Profile Measurements In The Shadow Region" in *Shock Waves in Condensed Matter 1987*, edited by S. C. Schmidt and N. C. Holms, Elsevier Publishers B. V., Amsterdam, 1988, pp. 265-268.
4. Johnson, J. N., Hixson, R. S., Tonks, D. L., and Zurek, A. K., "Rate Dependent Spallation Properties of Tantalum" in *Shock Compression of Condensed Matter - 1995*, edited by S. C. Schmidt and W. C. Tao, AIP Conference Proceedings 370, New York 1996, pp. 523-526.
5. Kanel, G. I., and Petrova, E. N., "The Strength of Titanium BT6 at Shock-Wave Loading" in II Workshop on Detonation (USSR), Chernogolovka, 1981, pp. 136-142.
6. Me-Bar, Y., Boas, M., and, Z., Mat. Sci. Eng. 85,77-84 (1987).
7. Froeshner, K. E., Maiden, D. E., and Chau, H. H., J. Appl. Phys. 65, 2964-2973 (1989).
8. Chhabildas, L. C., Barker, L. M., Asay, J. R., and Trucano, T. G., "Spall Strength Measurements On Shock-Loaded Refractory Metals" in *Shock Waves in Condensed Matter 1989*, edited by S. C. Schmidt et.al. Elsevier Publishers B. V.,Amsterdam, 1990, pp. 429-432.
9. Andriot, P. Lalle, P., and Dejean, J. P., "Quasi-Elastic Behavior Of Pure Titanium And TA6V4 Titanium Alloy At High Pressure" in *High Pressure Science and Technology-1993*, edited by S. C. Schmidt et.al. AIP Conference Proceedings 309, New York, 1994, pp. 1009-1012.
10. Brar, N. S. and Hopkins, A, "Shock Hugoniot and Shear Strength of Ti-6-4", In *the proceedings of this Conference 1999*, Snowbird, Utah.