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AUTHOR(S): G. T. Gray III and C. E. Morris

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INFLUENCE OF PEAK PRESSURE ON THE SUBSTRUCTURE EVOLUTION AND SHOCK WAVE PROFILES OF Ti-6Al-4V

G.T. Gray III and C.E. Morris
Los Alamos National Laboratory
Los Alamos, New Mexico USA

INTRODUCTION

Although the response of titanium alloys to dynamic loading is beginning to be understood, little experimental data exists concerning the structure/property relationships of titanium alloys subjected to shock loading. These studies are complicated by the fact that pure alpha titanium undergoes a polymorphic phase transition from hexagonal to a more open hexagonal omega phase at high pressure. The omega phase transformation in alpha Ti under shock or hydrostatic loading treatment conditions exhibits a large hysteresis that is responsible for retention of the high-pressure omega phase to atmospheric pressure /1,2/. The omega phase induced in pure Ti is observed to be morphologically similar to omega phase formed in as-quenched beta-phase alloys based on Zr, Ti, and Hf /3/. Crystallographically the phase transformation is believed to be a diffusionless displacive transition /2,3/. The influence of alloying alpha titanium on the details of the substructure evolution and occurrence of the omega phase transition has not defined a consistent pattern. Measurements of Hugoniot of Ti-6Al-4V (hereafter Ti-6-4), using manganin gauges, by Rosenberg et. al./4/ shows a break in the pressure-particle velocity curve at approximately 10 GPa which was attributed to a dynamic phase transformation, probably omega. Conversely, shock recovery experiments by Petrov et. al. /5/ on a two phase alloy Ti-6.5Al-3.5Mo-.25Si, using transmission electron microscopy (TEM) analysis, found no evidence of omega phase after shock loading. In summary, quantitative experimental data on omega volume fraction, in pure Ti and Ti-alloys, versus peak pressure and an understanding of the nature of the discontinuity observed in the pure Ti Hugoniot, the pressure at which omega transformation occurs in pure Ti and Ti-alloys remains unknown/1/.

The object of the present study was to investigate the influence of peak pressure on the residual structure/property relationships and the wave profile behavior of shock-loaded Ti-6-4. A further aim of the present work was to determine if the alpha - omega phase transformation occurred in Ti-6-4 using "real-time" VISAR and post-mortem shock recovery techniques.

EXPERIMENTAL

This investigation was performed on as-received Ti-6-4 supplied in the form of forged 120-mm-diameter-bar stock of composition in (wt. %) : 6.33 Al, 4.23 V, 0.02 Fe, 0.02 C, 0.18 O, and bal. Ti. The texture of the forged bar stock displayed four-fold symmetrical transverse texture, typical of forged bar product, with the c-axis approximately 35 to 45 degrees off the bar axis. Samples for shock recovery and wave profile experiments were sectioned from the starting bar stock such that the shock direction was parallel to the bar axis. The starting microstructure possessed a duplex morphology, sometimes called a nodal microstructure, comprised of lamellar areas of alpha and beta and uniaxial alpha grains of nominally 3 microns. The compressive yield strength of

As-received starting material was measured to be 1014 MPa. Ultrasonic shear wave and longitudinal wave measurements of the starting Ti-6-4 in the three orthogonal cube directions revealed the material to be very isotropic in nature with an average sound speed of 4.95 km/sec.

Shock recovery and wave profile experiments were performed using a 40-mm angle-stage gas/powder gun. The shock recovery sample assembly consisted of a 76 mm thick, 12 mm diameter sample fitting tightly into a similarly sized red recess in the inner momentum trapping ring / spall plate (25.4 mm diameter). This central cylinder was in turn surrounded by two concentric momentum trapping rings with outside diameters of 31.7 and 44.5 mm. The sample surface was protected from impact and the entire sample from spallation by a close-fitting cover plate (2.54 mm) and spall plate (12 mm), respectively. All assembly components were made of Ti-6-4 to ensure impedance matching during shock loading. The sample assembly was placed in a steel impact cylinder that allowed passage of the sample / inner momentum ring through a central hole but stopped the projectile. Samples were "soft" recovered and simultaneously cooled by decelerating the sample / inner momentum trapping ring in a water catch chamber positioned immediately behind the impact area. This procedure allowed successful recovery of shock loaded samples possessing residual strains of less than 2%. Samples were shock loaded to 5, 10, and 13 GPa for 1 microsecond pulse duration through the impact of properly accelerated Ti-6-4 flyer-plates backed to a projectile filled with low-impedance glass microballoons. These shock pressures are equivalent to transient strains during the shock compression (defined as $\frac{2}{3} \ln(V/V_0)$) of 0.025 for 5 GPa, 0.05 for 10 GPa, and 0.065 for 13 GPa.

Wave profile measurements were made utilizing stepped cylindrical Ti-6-4 targets to measure absolute elastic wave velocities. Four diametrically opposite PTZ crystal pins were placed on each level to measure the shock velocity through the target and the tilt of the projectile at impact. Precision of the wave velocity measurements is believed to be better than 1%. The wave profiles were measured with a VISAR built at Los Alamos using the design developed by Willard Hemsing /6/. The specially designed photomultiplier circuits used had a risetime of 1-ns. For the VISAR wave profile measurements two types of windows were used. On most of the shots LiF windows were utilized, however sapphire windows were used in a few cases to alter the nature of the elastic wave interaction at the target-window interface. LiF has a shock impedance less than Ti-6-4 whereas sapphire has a shock impedance greater than Ti-6-4. Symmetric impacts were performed in all VISAR shots. Laser alignment of the shock recovery assemblies and the VISAR wave profile experiments provided tilts at impact of the order of 1 mrad for gas shots and 3 mrad for powder shots.

Compression specimens were electro-discharge machined (EDM) from the recovered shock-loaded sample and the "post-mortem" mechanical behavior studied by loading the samples at a strain rate of 0.0015 s^{-1} . Samples for TEM examination were sectioned from the shock-loaded discs which remained after the 4 samples were removed. TEM foils were prepared in a solution of 84% ethanol, 10% butanol, and 6% perchloric acid at -40°C with 9 volts using a Rueter's Electropolisher. The foils were examined using a JEOL 200EX operating at 200 kV equipped with a double-tilt stage.

RESULTS

The substructure and reload compression yield strength of Ti-6-4 following shock loading was found to depend on the peak pressure. The reload compressive yield strength of Ti-6-4 was observed to increase with increasing peak pressure from 1040 MPa at 5 GPa, 1095 MPa at 10 GPa, and 1165 MPa at 13 GPa. These values indicate that only a small amount of shock-induced hardening occurred over these shock pressures. The reload compression stress-strain curves exhibited continuing work-hardening showing that the observed low yield strength increases were not due to structure saturation. Electron microscopic examination of the shock-loaded Ti-6-4 revealed that the dislocation substructure is dependent on the shock peak pressure at a constant shock pulse duration. Figures 1 through 3 present TEM micrographs characteristic of the deformation substructure of shock-loaded Ti-6-4 as a function of peak pressure. Increasing the peak pressure from 5 to 13 GPa is observed to increase the overall dislocation density; the 5 GPa Ti-6-4 sample exhibiting a low overall dislocation density for a shock loaded sample. The substructure of the 5 GPa shock sample is characterized by planar slip bands within the alpha grains on prism, basal, and pyramidal planes (Figure 1). Increasing the shock pressure to 10 GPa is observed to result in deformation twinning in addition to planar slip; the twins most often observed in grains whose mean size was larger than average. At 13 GPa the number of grains containing deformation twins is seen to increase



Figure 1: TEM micrograph of Ti-6-4 shocked to 5 GPa showing planar slip bands.

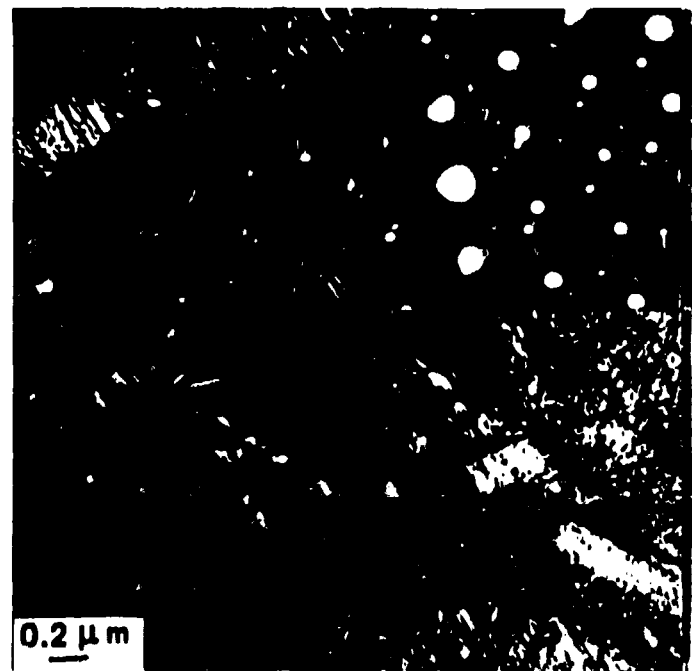


Figure 2: TEM micrograph and SAD of (1121) twins in Ti-6-4 shocked to 10 GPa.

substantially. Selected area diffraction analysis of the deformation twins in the 10 and 13 GPa samples shows that the twins were all (1121) type "tension" twins, i.e. they cause extension along the hexagonal unit cell c-axis. The

ervation of only a single twinning type, while not statistically conclusive, represents SAD analysis of 10 twinned grains in at least 4 TEM foils of both the 8 and 13 GPa samples. This observation is interesting considering that the twinning shear of $\{1121\}$ twins is high (0.638) compared to $\{1012\}$ twinning shear. There are also tensile twins and have a twinning shear of (0.167). The $\{1121\}$ twins were seen to be fine and needle-like in morphology, with only a single variant typically observed. No evidence of the retention of omega phase was found using either bulk X-ray diffraction or SAD-TEM analysis of the shock recovered samples.

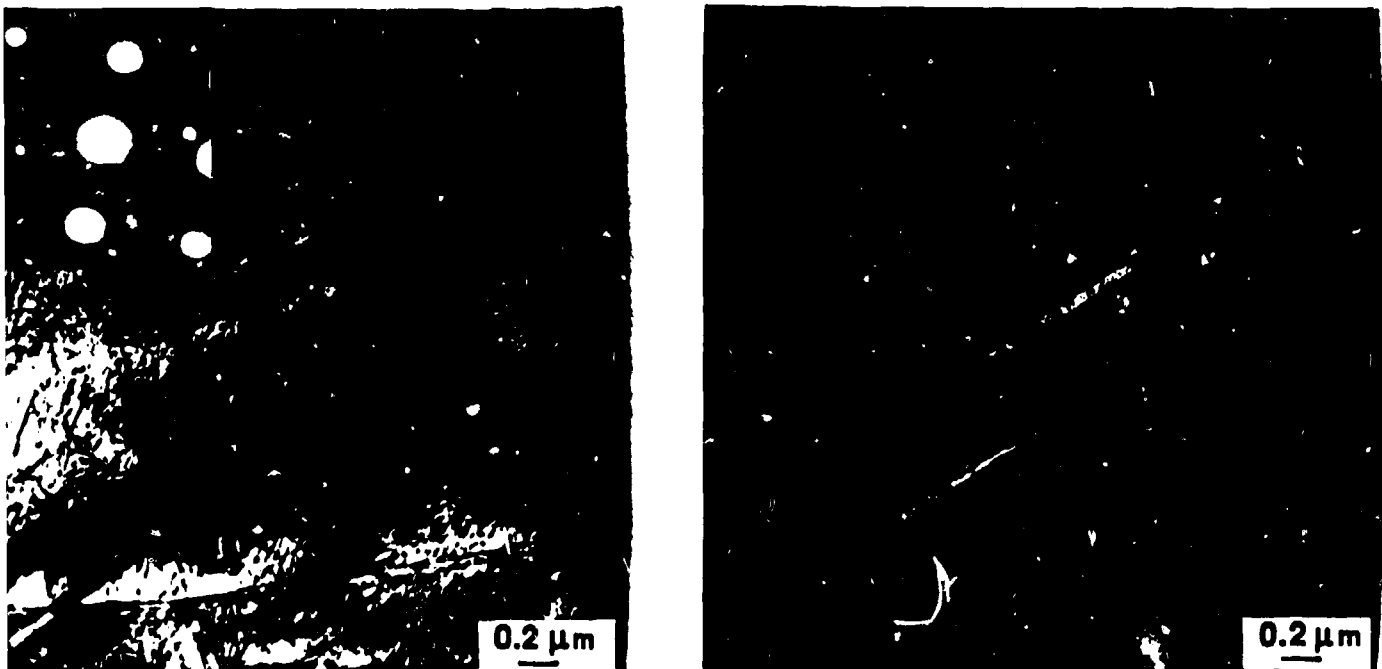


Figure 3: TEM a) brightfield and b) darkfield micrographs with SAD pattern of 1) deformation twins in a $[1213]$ alpha zone ; Ti-6-4 shocked to 13 GPa.

Wave profiles of Ti-6-4 in the two-wave region, termed the shadow region, exhibited a large elastic wave, with an average value of 2.8 GPa, followed by a shock wave. A characteristic wave profile for a 12.7 mm thick Ti-6-4 jet shock loaded to 8-GPa is shown in Figure 4. Measurements of the wave profiles showed that the elastic wave in Ti-6-4 has a risetime of 5-ns. It is clear from the wave-profile records that the elastic wave has coalesced into a shock. The bump in the profile record, denoted by the arrow in Figure 4, was thought to be possible evidence of a phase transition wave. In actuality the bump is due to the elastic wave reflecting off the target-window interface subsequently interacting with the approaching bulk shock wave. The bump in the wave-profile was found to disappear if the LiF window was replaced with a sapphire window which results in a reflected bulk compression wave rather than an elastic wave reflected off the interface. In the sapphire window case, there is only a single elastic wave and a single bulk shock wave.

Hugoniot data for Ti-6-4 are summarized in Figure 5. The elastic wave velocity at ambient conditions is seen to be 6.15 km/s and increases to 6.30 km/s at the Hugoniot Elastic Limit (HEL) where $U_p = 0.101$ km/s. For U_p values less than 6.3 km/s a two-wave structure was seen to exist. For U_p values greater than 6.3 km/s only a single shock is present. A linear least squares fit for the low pressure region ($U_p < 1.4$ km/s) gives $U_s = 5.123$ km/s + $1.083 U_p$. For the high pressure region the fit is $U_s = 5.03$ km/s + $1.056 U_p$.

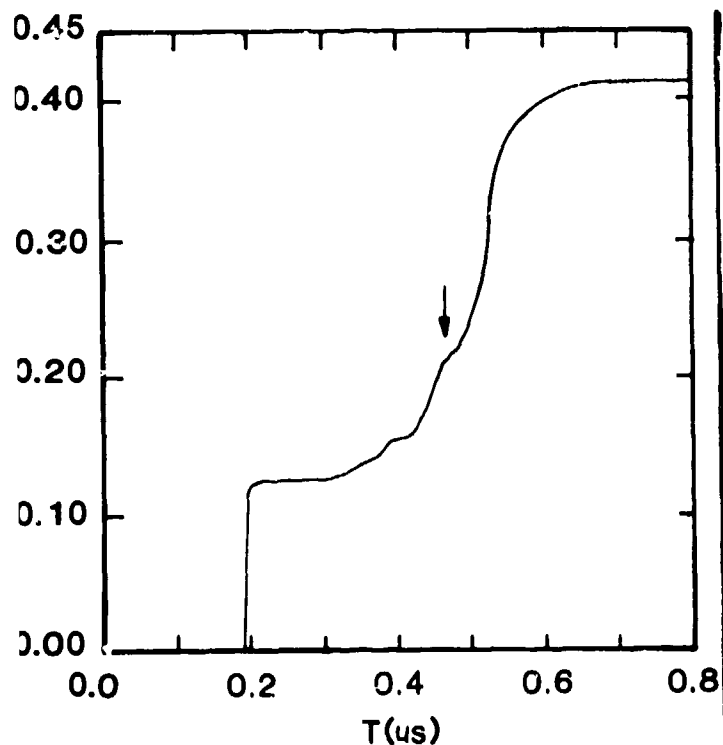


Figure 4: 8 GPa VISAR wave profile of a 12.7 mm-thick Ti-6-4 target.

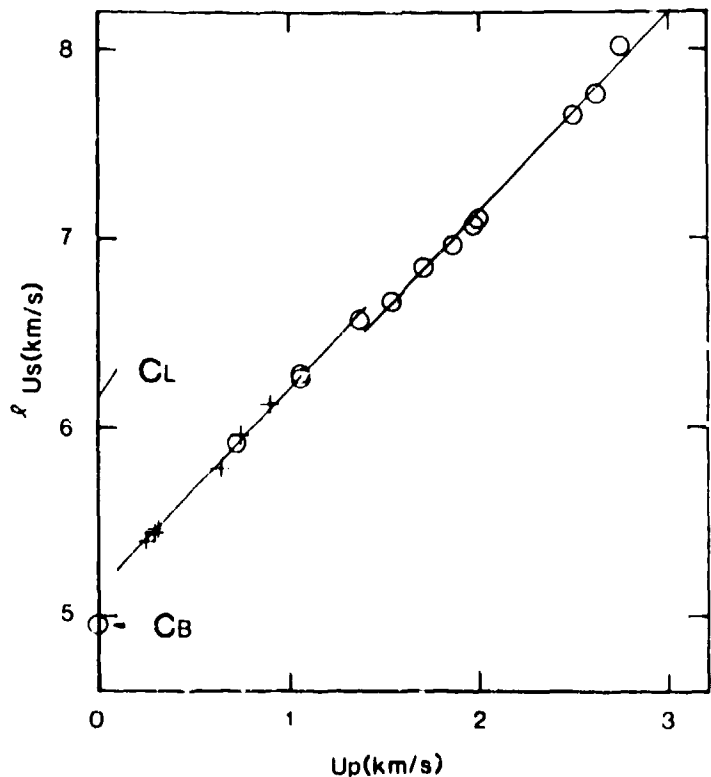


Figure 5: Ti-6-4 Hugoniot. The crosses denote VISAR data and the circles denote previous flash gap experiments.

DISCUSSION

The results of the present shock-recovery and wave-profile experiments indicate that Ti-6-4 remains in its alpha-beta phases and does not transform to the gamma phase in the pressure range studied. The wave profiles of Ti-6-4 measured display classic elastic-plastic behavior with the elastic wave followed by a shock wave. The Hugoniot of Ti-6-4 shows a linear $U_s - U_p$ relationship with no evidence of a phase transformation to 24 GPa from the VISAR data and to 10 GPa with the previous flash-gap data. While it is theoretically possible that a second-order phase transition or a very small volume change first-order phase transition in Ti-6-4 may be unresolvable utilizing VISAR techniques, our present measurements on pure alpha-Ti readily shows the omega transition at approximately 10 GPa. In addition, bulk X-ray diffraction and TEM observations revealed no evidence of the omega transition in Ti-6-4.

The most likely explanation for the absence of the alpha to omega transition in Ti-6-4 is believed to be related to either: 1) the effect of alloying conditions on the electronic structure of the alpha and/or 2) the influence of alloying on the elastic interactions of the alloying elements in the hexagonal lattice on the alpha lattice spacing and movement of linear defects. In the first case it is hypothesized that aluminum alloying or interstitial oxygen, which both act as electron donors and raise the electron:atom ratio of alpha-Ti, make the phase transition energetically unfavorable. This may occur through influencing the phonon transfer which has been suggested as a mechanism for the alpha - omega transition/7/. Alternately, the alloying of the alpha in Ti-6-4 may suppress the omega transition due to the influence of aluminum and/or oxygen on the dilatational fields associated with the linear defects involved in the displacement and shuffles in the atomistic ordering as modeled to explain omega formation in Ti/3/. The suppression of omega phase in Ti-6-4 through alloying is consistent with alloying results on beta-phase Ti-Mo-Hf where increasing hydrogen content enhances omega formation by increasing the temperature at which the athermal beta-omega reaction begins/8/. In view of the small interstitial size of hydrogen ions, it was postulated that this effect is most probably explained on an electronic basis/8/.

The substructure evolution in Ti-6-4 as a function of peak pressure is observed to reflect the high HEL and texture of the starting material. Firstly, the 5 GPa sample exhibits planar slip similar to that seen in Ti-6-4 strained at conventional strain rates to small strains with no evidence of deformation twins. A symmetrical Ti-6-4 shock to the HEL of 2.8 GPa is equivalent to a shock compression strain of nominally 1.1 %, calculated using the Ti-6-4 uniaxial measured values at the HEL. Since the 5 GPa shock compression strain is only 1.4 % larger than the HEL value, the low overall dislocation density and lack of twinning is consistent with the fact that a sizable portion of this shock was elastic. With increasing shock pressure the substructure of Ti-6-4 is observed to deform via {1121} type deformation twins which is thought to reflect the influence of the starting material texture and strain rate on twinning in Ti-6-4. Studies on the tensile deformation of polycrystalline Zr by McD-Hill/9/ showed that while {1121} type twins occur infrequently at room temperature and slow strain rates, increasing the strain rate by a factor of 10 greatly increases the number of observed {1121} twins. In addition during rapid deformation at 77K, the resolved shear stress for all twinning mechanisms appeared to approach the same value, implied by the fact that twins occurred on planes with the highest orientation factor, irrespective of the mode of twinning. Applied stress orientation studies on Zr /9/ further showed that {1121} twinning is favored in the orientation range where the stress axis makes an angle between 20 and 60 degrees with the basal pole where coincidentally the orientation factors for prism slip and {1012} twinning are low. In the present shock study of Ti-6-4 the transverse texture of the starting material coupled with the high strain rates experienced during shock loading appear to activate {1121} twinning in a similar manner to that seen under high rate loading of Zr.

CONCLUSIONS

Based upon a study of the effect of peak pressure on the substructure evolution and shock wave profiles of Ti-6-4 the following conclusions can be drawn: 1) In the velocity range investigated no evidence of an alpha to omega phase transition was observed in Ti-6-4 with either VISAR wave profiles or shock

very experiments. 2) Increasing peak pressure results in an increased dislocation density and yield strength in shock-loaded Ti-6-4; deformation twins, of the {1121} type, are observed in the 10 and 13 GPa shocked samples. Ti-6-4 exhibits a large elastic wave, on the average of 2.8 GPa. 4) The low pressure Hugoniot for Ti-6-4 is given by $U_s = 5.123 \text{ km/s} + 1.083 U_p$ for $U_p < 1 \text{ km/s}$; the high pressure relation is given by $U_s = 5.030 + 1.056 U_p$.

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