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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

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

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

EXPERIMENTAL

.s investigation was performed on as-received Ti-6-4 supplied in the form of ged 120-mm-diameter-bar stock of composition in (wt. %) : 6.33 Al, 4.23 V, Fe, 0.02 C, 0.18 O, and bal. Ti. The texture of the forged bar stock played four-fold symmetrical transverse texture, typical of forged bar duct, with the c-axis approximately 35 to 45 degrees off the bar axis. ples for shock recovery and wave profile experiments were sectioned from the rting bar stock such that the shock direction was parallel to the bar axis. starting microstructure possessed a duplex morphology , sometimes called a odal microstructure, comprised of lamellar areas of alpha and beta and iaxed alpha grains of nominally 3 microns. The compressive yield strength of e as-recieved starting material was measured to be 1014 MPa. Ultrasonic shear ve and longitudinal wave measurements of the starting Ti-6-4 in the three thogonal cube directions revealed the material to be very isotropic in nature th an average sound speed of 4.95 km/sec.

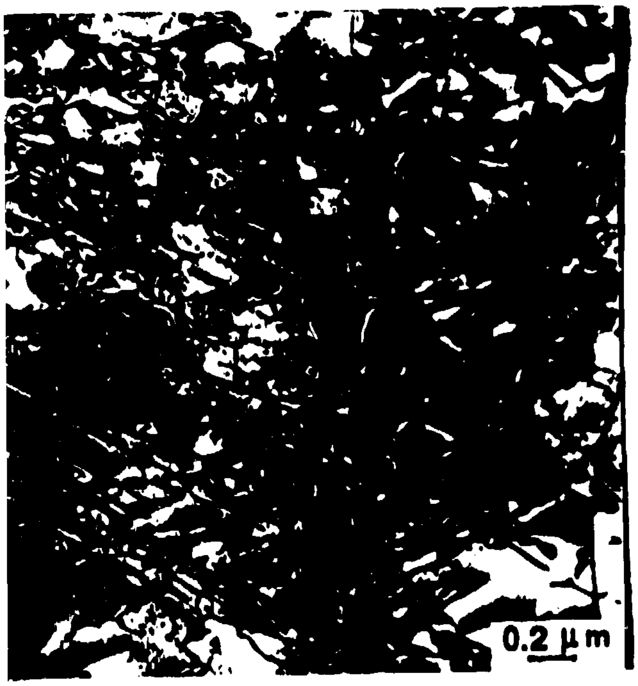
ock recovery and wave profile experiments were performed using a 40-mm ngle-stage gas/powder gun. The shock recovery sample assembly consisted of a 76 mm thick, 12 mm diameter sample fitting tightly into a similarly sized red recess in the inner momentum trapping ring / spall plate (25.4 mm ameter). This central cyclinder was in turn surrounded by two concentric mentum trapping rings with outside diameters of 31.7 and 44.5 mm. The sample rface was protected from impact and the entire sample from spallation by a ose-fitting cover plate (2.54 mm) and spall plate (12 mm), respectively. All sembly components were made of Ti-6-4 to ensure impedance matching during ock loading. The sample assembly was placed in a steel impact cyclinder that lowed passage of the sample / inner momentum ring through a central hole but opped the projectile. Samples were "soft" recovered and simultaneously cooled decelerating the sample / inner momentum trapping ring in a water catch amber positioned immediately behind the impact area. This procedure allowed ccessful recovery of shock loaded samples possessing residual strains of less an 2 %. Samples were shock loaded to 5, 10, and 13 GPa for 1 microsecond lse duration through the impact of properly accelerated Ti-6-4 flyer-plates xed to a projectile filled with low-impedance glass microballoons. These ock pressures are equivalent to transient strains during the shock mpression (defined as $2/3 \ln(V/V_0)$) of 0.025 for 5 GPa, 0.05 for 10 GPa, and 065 for 13 GPa.

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

mpression specimens were electro-discharge machined (EDM) from the recovered ock-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 amination were sectioned from the shock-loaded discs which remained after the M samples were removed. TEM foils were prepared in a solution of 84% thanol, 10% butanol, and 6% perchloric acid at -40 °C with 9 volts using a ruer's Electropolisher. The foils were examined using a JEOL 2000EX operating 200 kV equipped with a double-tilt stage.

RESULTS

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



ɪure 1: TEM micrograph of Ti-6-4 ıcked to 5 GPa showing planar .p bands.

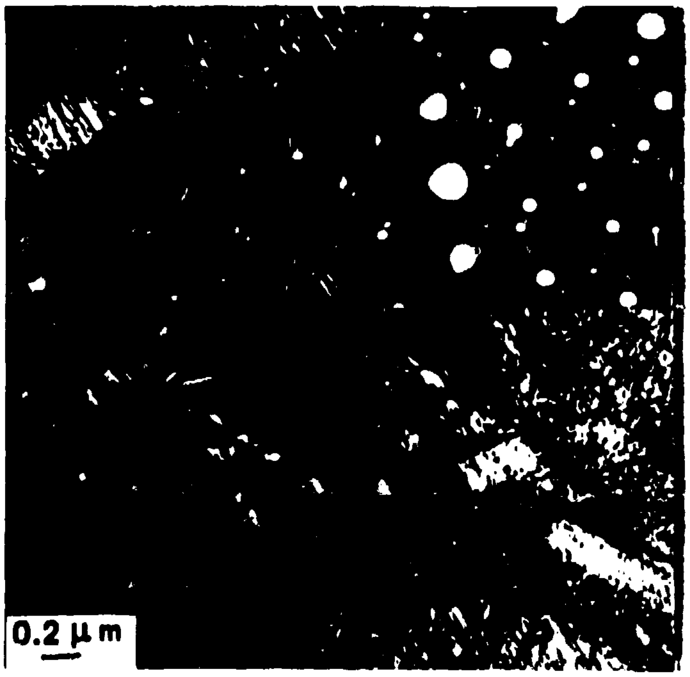
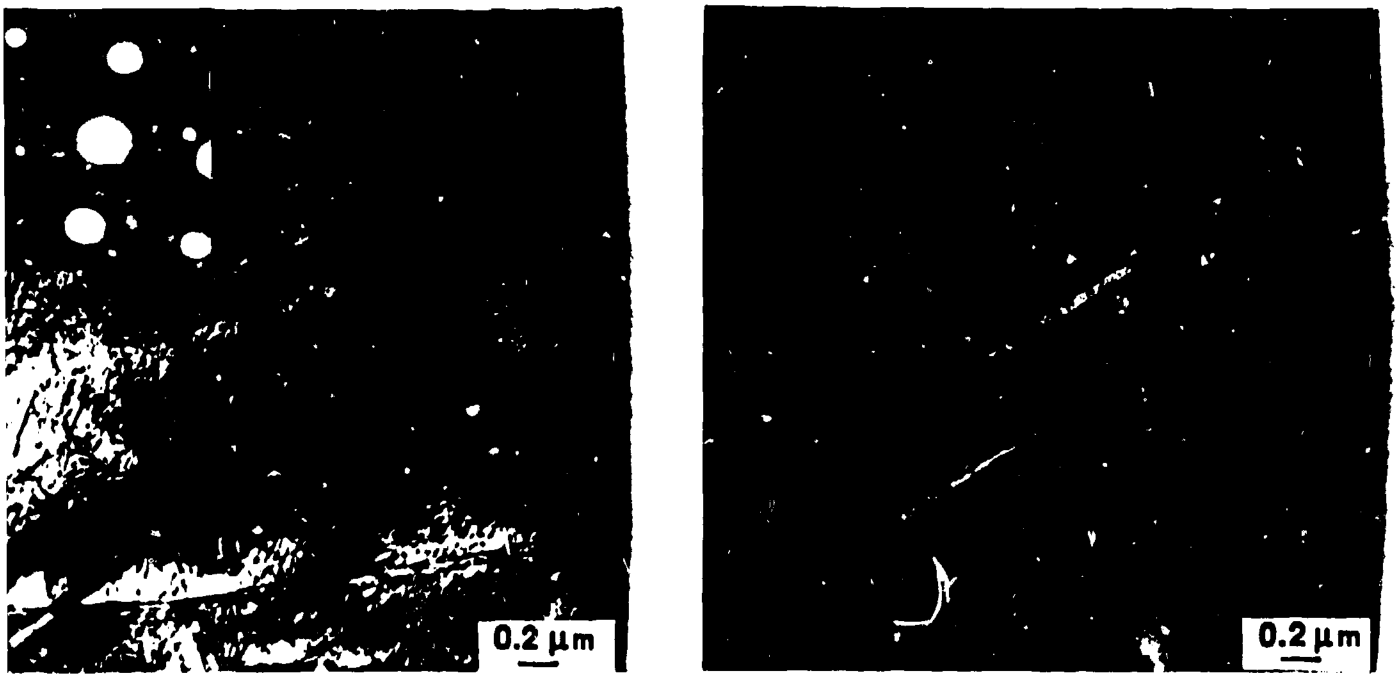


Figure 2: TEM micrograph and SAD of (1121) twins in Ti-6-4 shocked 10 GPa.

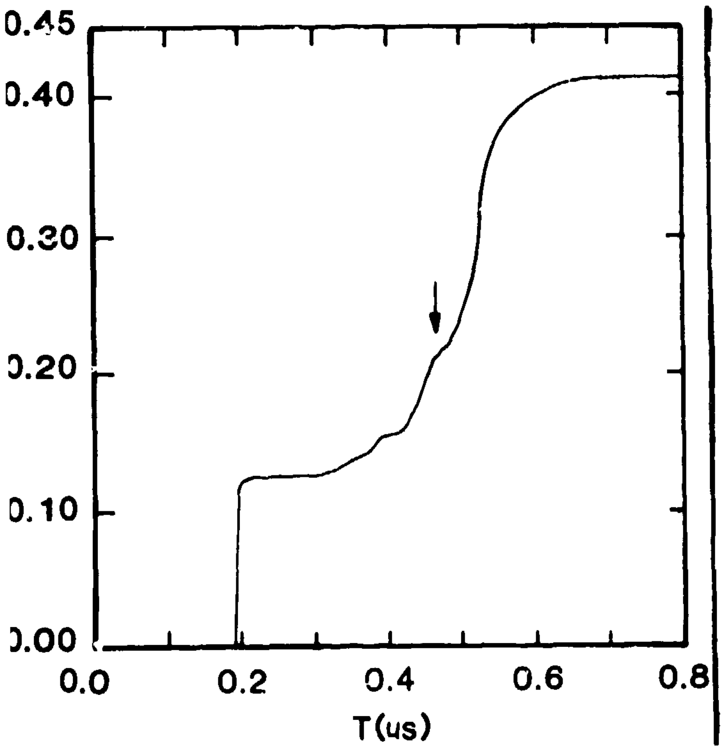
ıstantially. Selected area diffraction analysis of the deformation twins in ı 10 and 13 GPa samples shows that the twins were all (1121) type "tension" .ns, i.e. they cause extension along the hexagonal unit cell c-axis. The ervation of only a single twinning type, while not statistically conclusive, resents SAD analysis of 10 twinned grains in atleast 4 TEM foils of both the and 13 GPa samples. This observation is interesting considering that the ning shear of {1121} twins is high (0.638) compared to {1012} twinning h are also tensile twins and have a twinning shear of (0.167). The {1121} s were seen to be fine and needle-like in morphology, with only a single iant typically observed. No evidence of the retention of omega phase was d using either bulk X-ray diffraction or SAD-TEM analysis of the shock overed samples.



re 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, bited 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 et shock loaded to 8-GPa is shown in Figure 4. Measurements of the -profiles showed that the elastic wave in Ti-6-4 has a risetime of 5-ns. It ars from the wave-profile records that the elastic wave has coalesced into ock. The bump in the profile record, denoted by the arrow in Figure 4, was t thought to be possible evidence of a phase transition wave. In actuality bump is due to the elastic wave reflecting off the target-window interface subsequently interacting with the approaching bulk shock wave. The bump in wave-profile was found to disappear if the LiF window was replaced with a hire window which results in a reflected bulk compression wave rather than lastic wave reflected off the interface. In the sapphire window case, there nly a single elastic wave and a single bulk shock wave.

Hugoniot data for Ti-6-4 are summarized in Figure 5. The elastic wave ocity at ambient conditions is seen to be 6.15 km/s and increases to 6.30 s at the Hugoniot Elastic Limit (HEL) where $U_{p1} = 0.101$ km/s. For U_s values s than 6.3 km/s a two-wave structure was seen to exist. For U_s values ater than 6.3 km/s only a single shock is present. A linear least squares for the low pressure region ($U_p < 1.4$ km/s) gives $U_s = 5.123$ km/s + 1.083 For the high pressure region the fit is $U_s = 5.03$ km/s + 1.056 U_p.



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

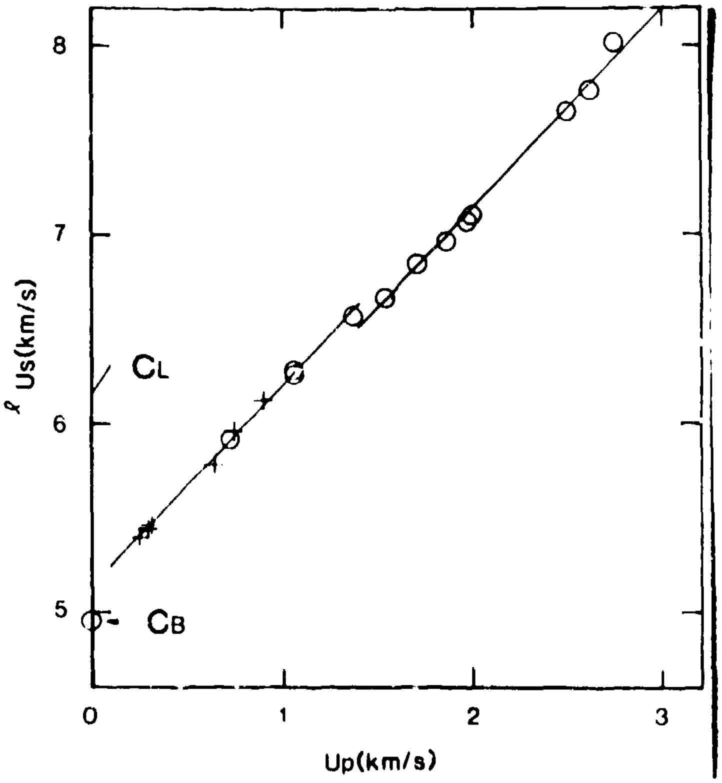


Figure 5: Ti-6-4 Hugoniot. The crosses denote VISAR data and the circles denote previous flash gap experiments.

DISCUSSION

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

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

ı substructure evolution in Ti-6-4 as a function of peak pressure is observed reflect the high HEL and texture of the starting material. Firstly, the 5 ı sample exhibits planar slip similar to that seen in Ti-6-4 strained at ıventional strain rates to small strains with no evidence of deformation .ns. A symmetrical Ti-6-4 shock to the HEL of 2.8 GPa is equivalent to a ıck compression strain of nominally 1.1 %, calculated using the Ti-6-4 ıoniot measured values at the HEL. Since the 5 GPa shock compression strain only 1.4 % larger than the HEL value, the low overall dislocation density , lack of twinning is consistent with the fact that a sizable portion of this ıck was elastic. With increasing shock pressure the substructure of Ti-6-4 is ıerved to deform via {1121} type deformation twins which is thought to 'lect the influence of the starting material texture and strain rate on .nning in Ti-6-4. Studies on the tensile deformation of polycrystalline Zr by ıd-Hill/9/ showed that while {1121} type twins occur infrequently at room ıperature and slow strain rates, increasing the strain rate by a factor of '0 greatly increases the number of observed {1121} twins. In addition during ıid deformation at 77K, the resolved shear stress for all twinning mechanisms ıoared to approach the same value, implied by the fact that twins occurred on .nes with the highest orientation factor, irrespective of the mode of .nning. Applied stress orientation studies on Zr /9/ further showed that 21} twinning is favored in the orientation range where the stress axis makes angle between 20 and 60 degrees with the basal pole where coincidently the entation factors for prism slip and {1012} twinning are low. In the present ıck study of Ti-6-4 the transverse texture of the starting material coupled .h the high strain rates experienced during shock loading appear to activate 21} twinning in a similar manner to that seen under high rate loading of Zr.

CONCLUSIONS

ed upon a study of the effect of peak pressure on the substructure evolution shock wave profiles of Ti-6-4 the following conclusions can be drawn: 1) r the velocity range investigated no evidence of an alpha to omega phase nsition was observed in Ti-6-4 with either VISAR wave profiles or shock very experiments. 2) Increasing peak pressure results in an increased ocation density and yield strength in shock-loaded Ti-6-4; deformation s, of the {1121} type, are observed in the 10 and 13 GPa shocked samples. i-6-4 exhibits a large elastic wave, on the average of 2.8 GPa. 4) The low sure Hugoniot for Ti-6-4 is given by U_s = 5.123 km/s + 1.083 U_p for U_p < km/s; the high pressure relation is given by U_s = 5.030 + 1.056 U_p.

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