High-Strain-Rate Deformation of Ti-6Al-4V through Compression Kolsky Bar at High Temperatures

S. Gangireddy, S.P. Mates

Materials Science and Engineering Division, MML, NIST, Gaithersburg, MD, USA

ABSTRACT
In this paper, we present our first results from the study of the constitutive response of a popular Titanium alloy, Ti-6Al-4V, using a variation of the compression Kolsky Bar technique that employs electrical pulses to achieve high temperatures. Experiments are conducted at temperatures ranging from room temperature to 1000 °C at a strain rate of about 2200 s^{-1} and a heating rate of about 1500 °C/s. The dynamic stress-strain results demonstrate significant thermal softening in the alloy that could be described by Johnson-Cook equation with m = 0.8 up to 650 °C. Above 650 °C the rate of change in the flow stresses was faster, which is attributed to allotropic transformation that results in a change in the phase fractions of the hcp and bcc phases present in the alloy. Evidence of transformation is observed in the microstructure of post-compression specimens, which showed an acicular morphology formed from the high temperature bcc phase on quenching.

KEY WORDS: Kolsky Bar, Ti-6Al-4V, High-Temperature, Dynamic-Response, Thermal-Softening

INTRODUCTION
Methods for mechanical testing under rapidly applied loading are well established, such as the Split-Hopkinson Pressure Bar (SHPB) or Kolsky Bar technique. Variations of Kolsky Bar with additional components for achieving high temperatures exist as well. Typically miniature furnaces, induction coils, or radiation heating are used [1, 2, 3]. Heating times associated with these methods are typically on the order of minutes. At NIST, a new variation of Kolsky Bar system has been developed [4, 5] where electrical current is pulsed directly through the sample while it sits fixed between the incident and transmission bars. This technique gives us a unique advantage of rapid heating rates, up to 6000 K/s, where the heating time can be less than one second. Such rapid heating combined with rapid loading conditions creates a closer simulation to extreme physical processes such as high speed machining, explosive impact and other highly dynamic thermo-mechanical events. These results can give valuable insights that may lead to improved cutting processes or development of better blast-resistant structures.

Ti-6Al-4V is a widely used titanium alloy with aerospace applications owing to its excellent combination of high specific strength and corrosion resistance [6]. Pure titanium is allotropic and undergoes transformation from hcp (α) to bcc (β) crystal structure at elevated temperatures. The alloy Ti-6Al-4V contains both alpha stabilizing Aluminum (6 wt %) and beta stabilizing Vanadium (4 wt %) and consists of a mixture of α + β phases at room temperature [7]. At higher temperatures, the phase fraction of β increases, and above a temperature of about 995 °C the alloy is 100 % β [8]. This is known as the β-transus temperature. The mechanical response of this material can therefore be expected to be strongly dependent on temperature. The temperature sensitivity of the dynamic mechanical response of a commercial Ti-6Al-4V alloy was investigated using NIST's electrical pulse-heated Kolsky Bar system in the temperature range of 23 °C to 1008 °C under a strain rate of about 2200 s^{-1}.

EXPERIMENTAL PROCEDURE
A commercial Ti-6Al-4V alloy of composition, 6.65 % Al, 4 % V, 0.02 % C, 0.23 % Fe, 0.007 % N, 0.197 % O, 0.003 % H, is studied in this investigation. The as-received material's microstructure consisted of globular α phase grains in a β matrix. The alloy, purchased in the form of a 2 mm thick plate, was cut using electrical discharge machining (EDM) to obtain the compression samples in cylindrical form of 4 mm diameter and 2 mm thickness. These samples were placed in between the incident and transmission bars of 150 mm diameter. Electrical current is conducted directly through the sample using the bar ends as electrodes. Owing to the large difference in the sample and bar cross-sectional areas and the very short heating times involved, the sample alone heats up while the bars themselves remain cool, with a less than 25 °C temperature rise even

while the samples heated to 1000 °C [4]. In this series of experiments, the total heating time, which includes a transient heating period followed by a hold period, is limited to 3.5 seconds.

The temperature of the sample is monitored through three signals: a thermocouple spot welded onto the sample surface and two fast response infrared spot pyrometers focused on opposite sides of the sample surface. During heating by the electrical current, the thermocouple signal gets affected by electromagnetic interference. Hence one of the pyrometers is used as a feedback sensor to a specialized power supply that controls the sample temperature. The second pyrometer is used to monitor temperature uniformity. The pyrometer signal measures only the radiance temperature of the specimen. The thermodynamic, or true, temperature is determined from the thermocouple signal, which takes a few milliseconds to settle after the current is turned off. Hence compression pulse is timed to arrive about 20 ms after the current is switched off so a clean thermocouple signal can be obtained prior to impact. Just at the time of impact, the pyrometer signals could also be used to obtain radiance temperature, but after impact the specimen moves out of the view of pyrometers and the signals are lost. The radiance and true temperatures at impact, plotted in Figure 1, are linearly correlated, indicating that even using the pyrometer as the feedback control signal, good true temperature control is possible.

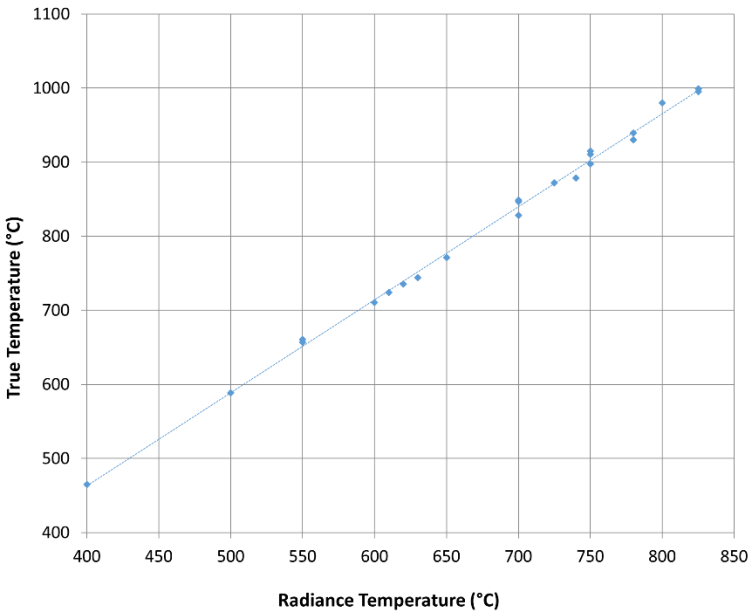

Fig. 1: Thermodynamic or true temperature measured by the thermocouple and the radiance temperature measured by the pyrometer at the time of impact show a strong correlation between 400 °C and 1000 °C.

The usual analysis method for deducing dynamic stress-strain from strain gauge signals is performed with a correction for the presence of graphite foils used for uniform contact conductance between the sample and the bars. The foil and the sample are treated as separately deforming elements and the foil response is deducted from the overall contraction between the compression bars to obtain the sample contraction. The detailed analysis for this deduction of dynamic stress-strain curves is presented elsewhere [4].

RESULTS AND DISCUSSION

The dynamic true stress- true strain curves from compression tests conducted at temperatures ranging from 23 °C to 1008 °C under a strain rate of 2200 s^{-1} (± 800 s^{-1}) are depicted in Figure 2. The total time of heating is 3.5 seconds before the sample is impacted. The test temperature quoted is the true temperature measured using the thermocouple at the moment the first compression pulse hits the sample.

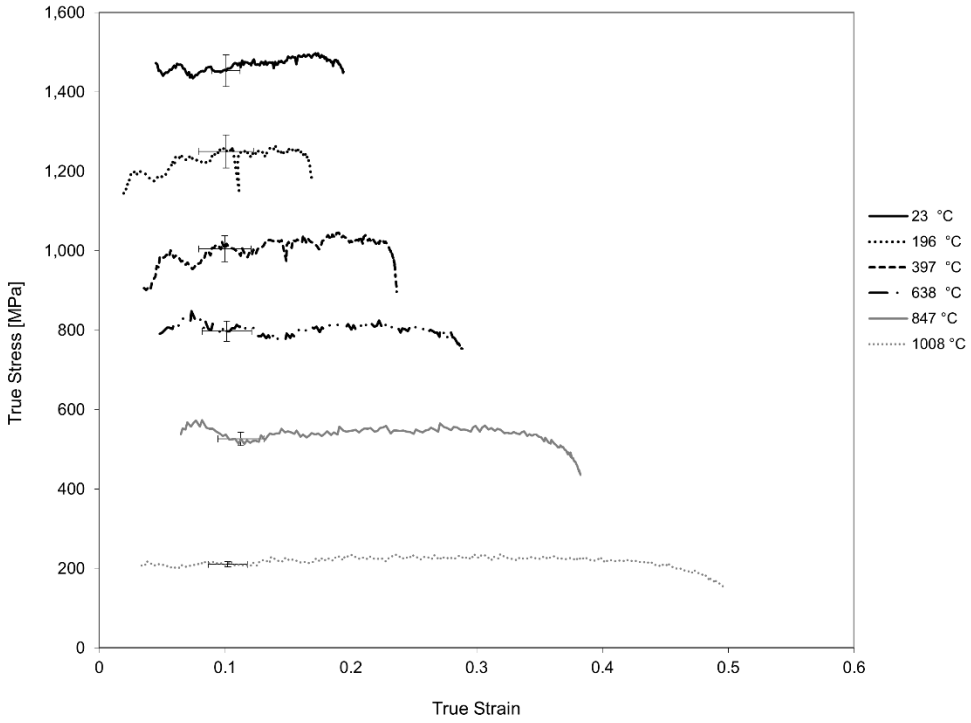

Fig. 2: Dynamic true stress – true strain graphs of Ti-6Al-4V alloy undergoing compression under a strain rate of 2200 s^{-1} (± 800 s^{-1}) at temperatures between 23 °C and 1008 °C.

Thermal softening is evident, as the flow stress decreases significantly with increase in temperatures. The flow stresses at 0.1 and 0.15 true strains are plotted as a function of test temperature in Figure 3 (a). The Johnson-Cook empirical equation is often used to describe material response as a function of plastic strain, strain rate and temperature [9]:

$$\sigma\left(\varepsilon_p,\ \dot{\varepsilon}_p, T\right) = \left[A + B\left(\varepsilon_p\right)^n\right]\ \left[1 + C\ ln\left(\ \dot{\varepsilon}_p{}^*\right)\right]\ [\ 1 - (T^*)^m\ ] \qquad (1)$$

where thermal softening is encompassed by the last term, $[\ 1 - (T^*)^m\ ]$. T* is the homologous temperature given by $(T-T_{ref})/(T_{melt}-T_{ref})$. In an attempt to describe our results similarly, the normalized flow stresses $\sigma(T)/\ \sigma(T_{ref})$ at 0.15 true strain are plotted as a function of T* with the reference temperature, T_{ref} = 23 °C, and melting point, T_{melt} = 1630 °C. This graph in Figure 3(b) shows that the data could be well described by the Johnson-Cook equation for temperatures below 650 °C with a thermal softening parameter *m* of value 0.8. Similar values of *m* have been reported in other high strain rate investigations such as: Seo et al [3] whose *m* was 0.7 while Johnson [10] reported *m* =0.8. Dorogoy et al [11] have reported a similar *m* of 0.8 from quasi-static loading conditions as well. At temperatures higher than 650 °C however, there is a steeper reduction in the flow stresses.

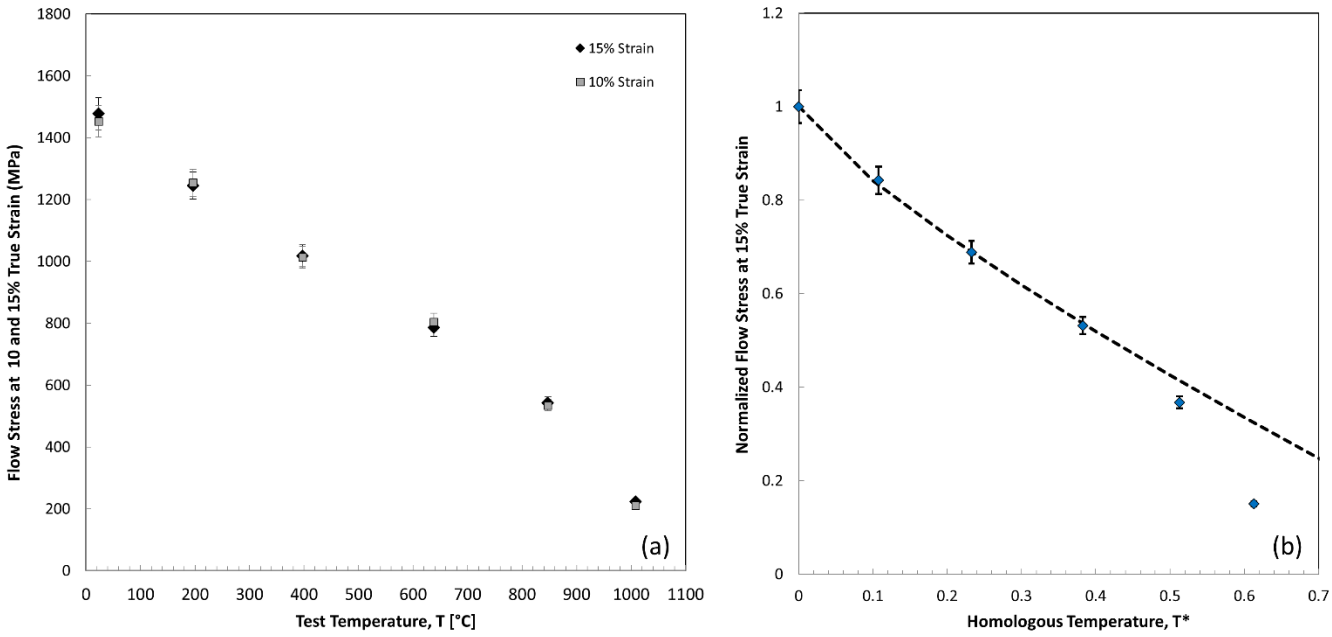

Fig. 3 (a) Flow stresses at 0.1 strain and 0.15 true strain plotted as a function of thermodynamic temperature. **(b)** Normalized flow stresses $\sigma(T)/\sigma(T_{ref})$ at 0.15 true strain plotted as a function of homologous temperature $T^* = (T-T_{ref})/(T_{melt}-T_{ref})$, with T_{ref} = 23 °C, T_{melt} = 1630 °C.

This behavior can be a result of the ongoing allotropic transformation in Ti-6Al-4V. At room temperature, pure Titanium exists in hcp (α) crystal structure and when heated to 882 °C, it changes into bcc (β) [7]. The alloy Ti-6Al-4V containing both α-stabilizing Aluminum and β-stabilizing Vanadium elements does not have a sharp transition point, instead there is a temperature range in which there is a gradual transformation. The start temperature α-transus is lower than room temperature, and the β-transus is about 995 °C [8]. At room temperature, the alloy contains both α and β. At higher temperatures, α starts transforming into β, increasing the β phase fraction. The increase in β volume fraction is insignificant below 600 °C, after which it starts to rise slowly initially and becoming rapid at elevated temperatures, especially closer to the β-transus. The α phase is known to show better high-temperature strength than the β phase [12], so at temperatures above 600 °C, it can be expected that the flow stresses show a more rapid decline with increasing temperature.

It has to be considered here that the heating time involved in our tests is only 3.5 seconds. Whether this time is sufficient for the α->β transformation needs to be verified before concluding that the low flow stresses observed are a result of the allotropic transformation. Confirmation of this transformation will be found in the microstructure of post-compression specimens. The electrical-pulse heated Kolsky Bar allows rapid cooling rates of about 1000 °C/s owing to the swift heat transfer from the hot specimen to the cool bar ends once the heating current is turned off. If the test temperature is higher than the martensitic start temperature M_S, this quenching causes any new β produced by the α->β transformation on heating to transform into martensitic acicular α′ [12].

Figure 4 compares the microstructure of the as-received material with the microstructure of a post-compression specimen, tested at 850 °C, both etched with Kroll's Reagent. Figure 4 (a) depicts the initial/ as-received microstructure consisting of globular α grains (bright contrast) in a matrix of β (dark contrast). At room temperature, the phase distributions consists of about 90 % α and 10 % β by volume. Figure 4 (b) shows a region in the post-compression specimen tested at 850 °C consisting of a large area of acicular α′. According to the phase diagram [12], the phase composition at 850 °C is expected to be 66 % α and 34 % β. When quenched from this condition, the volume fraction of primary α remains the same, but the β starts to transform into acicular α′. Since the martensite finish temperature M_F is lower than room temperature, the transformation is incomplete, leaving some β remaining in the microstructure. The quenched microstructure can therefore be expected to contain about 66 % primary α, 24 % α′ and 10 % β. Acicular α′ is easily distinguishable from the equiaxed primary α as can be seen in Figure 4(b), and hence its appearance confirms the allotropic transformation.

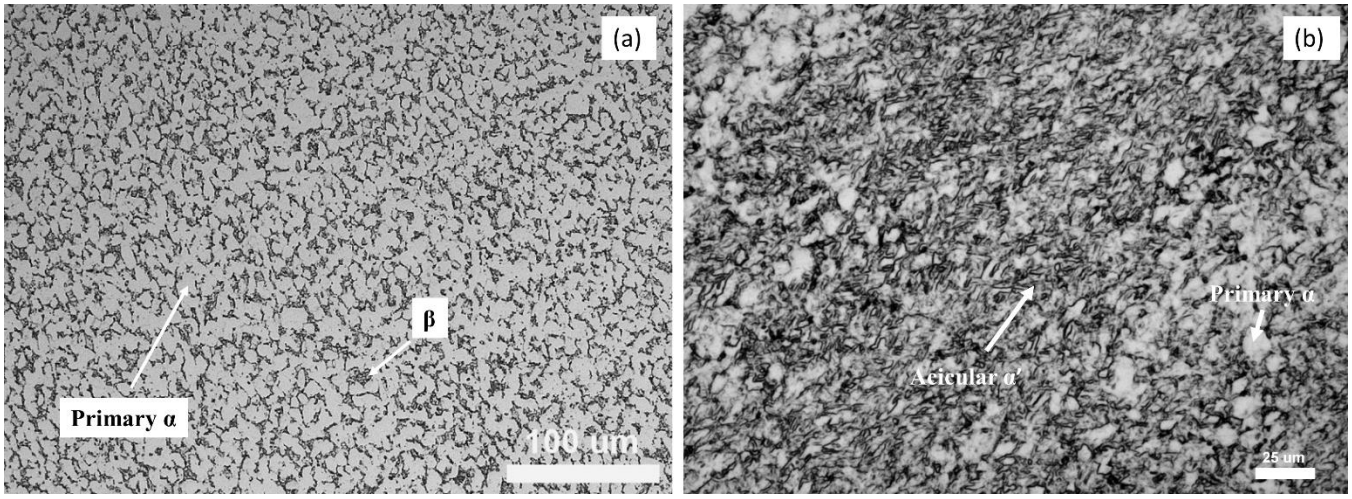

Fig. **4 (a)** Microstructure of as received Ti-6Al-4V **(b)** Microstructure of Ti-6Al-4V post-compression specimen tested at 850 °C.

The initial results indicate that the constitutive response of Ti-6Al-4V from the pulse heated Kolsky Bar system is comparable to the behavior reported by other investigators [1, 3, 14] from room temperature to about 650 °C. However, at higher temperatures we observe the thermal softening could not be similarly described using Johnson-Cook's equation owing to the allotropic transformation, which has not been considered by most of the other studies [1, 3, 14]. Modifications to the Johnson-Cook equation are often made to account for phase transformation [12], but they are essentially step functions only suitable for well-defined transformation temperatures. But in a material such as Ti-6Al-4V, where there is a continual phase transformation in a two-phase field, they are not ideal. A new modification to the Johnson-Cook equation is therefore essential to describe thermal softening in Ti-6Al-4V, one that considers the changing phase fractions together with the difference in the high temperature strengths. We propose to conduct more experiments in the 700 °C to 1000 °C range with smaller temperature steps to more completely describe Ti-6Al-4V's thermal softening behavior through the transition region.

CONCLUSIONS

A compression Kolsky Bar system, which directly pulses electrical current through samples for achieving high temperature, is used to study the widely used Titanium alloy Ti-6Al-4V. The first results from this investigation where compression tests were conducted at about 2200 s^{-1} strain rate at temperatures ranging from 23 °C to 1008 °C are reported in this paper. The results show that the dynamic response of the material has a strong dependence on temperature. The thermal softening occurs more rapidly above 650 °C, and is attributed to allotropic transformation from hcp (α) to bcc (β) crystal structure. Evidence of this transformation is discovered in the microstructures of post-compression specimens, which show an acicular α′ phase formed from quenching of β when the test temperatures are above martensite start, M_S. Further data is essential, especially in the 700 °C to 1000 °C temperature range, to develop a new modification to the Johnson-Cook equation, which considers the changing phase fractions as a function of temperature to be able to describe the Ti-6Al-4V's mechanical response.

DISCLAIMER

REFERENCES

[1] Lee WS, Lin CF (1998) Plastic deformation and fracture behavior of Ti-6Al-4V alloy loaded with high strain rate under various temperatures. Materials Science and Engineering A241:48-59.

[2] Seo S, Min O, Yang H (2005) Constitutive equation for Ti-6Al-4V at high temperatures using the SHPB technique. International Journal of Impact Engineering 31 (6): 735-54.
[3] Gray GT III (1990) Classic Split Hopkinson pressure bar testing, ASM Handbook 8: 462 – 476. Materials Park, Ohio.
[4] Mates S P, Rhorer R, Whitenton E, Burns TJ (2008) A pulse-heated Kolsky Bar Technique for Measuring the Flow Stress of Metals at High Loading and Heating rates. Experimental Mechanics 48:799-807.
[5] Basak D, Yoon HW, Rhorer R, Burns TJ, Matsumoto T (2004) Temperature control of pulse heated specimens in a kolsky bar apparatus using microsecond time resolved pyrometry. International Journal of Thermophysics 25 (2):561-574.
[6] Wood RA (1972) Titanium Alloy Handbook. Metals and Ceramics Information Center Battelle Publication No. MCIC-HB-02.
[7] Froes FH (2015) Titanium – Physical Metallurgy, Processing and Applications. ASM International.
[8] Semiatin SL, Seetharaman V, Weiss I (1997) The thermomechanical processing of Alpha/Beta Titanium Alloys. JOM 49:33-39.
[9] Johnson GR, Cook WH (1983) A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures. Proceedings of the 7th International Symposium on Ballistics Vol. 21:541-547.
[10] Johnson GR (1985) Strength and fracture characteristics of a titanium alloy (0.6Al, 0.4V) subjected to various strains, strain rates, temperatures and pressures. Technical report TR 86-144, Naval Surface Warfare Center.
[11] Dorogoy A, Rittel D (2009) Determination of Johnson-Cook material parameters using the SCS specimen. Experimental Mechanics 49: 881.
[12] Donachie MJ (2000) Titanium: A Technical guide. ASM International.
[13] Andrade U, Meyers MA, Vecchio KS, Chokshi AH (1994). Dynamic recrystallization in high strain, high strain rate plastic deformation of copper. Acta Metallurgica et Materialia 42: 3183-95.
[14] Nemat-Nasser A, Guo WG, Nesterenko VF, Indrakanti SS, Gu YB (2001) Dynamic response of conventional and hot isostatically pressed Ti-6Al-4V alloys: experiments and modeling. Mechanics of Materials 33 (8): 425-39.