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Department of Materials Science and Engineering,
University of California at Berkeley

On the Fatigue Behavior and Associated Effect of Residual Stresses in Deep-Rolled and Laser Shock Peened Ti-6Al-4V Alloys at Ambient and Elevated Temperatures

I. Altenberger[1], R. K. Nalla[1], U. Noster[2], B. Scholtes[2], and R. O. Ritchie

[1]Department of Materials Science and Engineering,
University of California, Berkeley, CA 94720-1760, U.S.A.

[2]Institute of Materials Technology, University Gh Kassel, Germany

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On the Fatigue Behavior and Associated Effect of Residual Stresses in Deep-Rolled and Laser Shock Peened Ti-6Al-4V Alloys at Ambient and Elevated Temperatures

I. Altenberger[1], R. K. Nalla[1], U. Noster[2], B. Scholtes[2], and R. O. Ritchie[1,3]

[1]*Department of Materials Science and Engineering*
University of California, Berkeley, California 94720-1760

[2]*Institute of Materials Technology, University Gh Kassel, Germany*

ABSTRACT

Mechanical surface treatments, such as deep rolling, shot peening and laser shock peening, can significantly improve the fatigue behavior of highly stressed metallic components. Deep rolling is an especially attractive technique since it is possible to generate deep, near-surface compressive residual stresses and work hardening while retaining a relatively smooth surface finish. Indeed, this technique is best known for increasing the fatigue strength and lifetime of steel components such as crankshafts. Although most work on deep rolling has been on steels, recently it has also been applied with reasonable success to titanium alloys. Accordingly, in this investigation, we examine the effect of deep rolling on the high-cycle fatigue behavior of Ti-6Al-4V, with particular emphasis on the thermal and mechanical stability of the residual stress states and near-surface microstructures. Preliminary results on laser shock peened Ti-6Al-4V are also presented for comparison. In addition, we examine whether these surface treatments are effective in retaining fatigue strength at the higher temperatures of 300 to 450°C. Based on the cyclic deformation and stress/life behavior, together with the X-ray and microstructural observations, it is found that deep rolling can be quite effective in retarding the initiation and initial propagation of fatigue cracks in Ti-6Al-4V at such higher temperatures, despite the almost complete relaxation of the residual stresses at the surface. This clearly implies that, in addition to residual stresses, near-surface microstructures, which in Ti-6Al-4V consist of ultrafine near-surface nanostructures, play a critical role in the enhancement of fatigue lifetimes by mechanical surface treatments.

Keywords: fatigue, titanium alloy, Ti-6Al-4V, surface treatment, deep rolling, laser shock peening

INTRODUCTION

Deep rolling and laser shock peening are two mechanical surface treatment methods that are increasingly used for enhancing the strength and endurance of metallic materials. These treatments can substantially increase resistance to wear and stress corrosion, and in particular enhance the fatigue strength. Near-surface compressive residual stresses and cold work are the predominant mechanisms for these effects, and can be related to a improved resistance to surface crack initiation and near-surface fatigue-crack growth (e.g., [1-3]). Deep rolling (DR) is commonly used for components that are rotationally symmetric (e.g., shafts) and is especially useful in overcoming the highly detrimental effects of notches. Besides near-surface compressive residuals stresses and cold work, DR can also reduce the surface roughness [4]. Laser shock peening (LSP), on the other hand, is not limited by component geometry. This treatment is known to be capable of introducing high levels of compressive residual stresses and high levels of cold work in the near-surface layers as a result of the

[3]Corresponding author: Tel: (510) 486-5798; Fax: (510) 486-4881.
E-mail address: roritchie@lbl.gov (R. O. Ritchie).

elastic-plastic shock-wave induced during such processing. However, the surface roughness is generally not markedly influenced by the LSP process [5].

An important issue in the context of such induced compressive stresses is their relaxation with increasing temperature. This raises questions regarding the efficiency of such mechanical surface treatments for lifetime improvement at higher temperatures which are commonly encountered by many structural components. In the present investigation, we examime the effect of deep rolling and laser shock peening on the fatigue properties of an α+β titanium alloy Ti-6Al-4V, commonly used as blade and disk material in aircraft engines at service temperatures of ~300°C or higher [6,7]. To assess the effectiveness of mechanical surface treatments on fatigue lifetimes at such temperatures, the stability of the near-surface properties as well as the cyclic deformation behavior is investigated after deep rolling and laser shock peening for fatigue behavior from ambient to 450°C.

EXPERIMENTAL PROCEDURES

The material investigated was a Ti-6Al-4V alloy, of composition (in wt.%) 6.3 Al, 4.17 V, 0.19 Fe, 0.19 O, 0.013 N, 0.0041 H, bal. Ti [9], which was supplied by Teledyne Titanium (Pittsburgh, PA). The original bar-stock (63.5 mm in diameter) was sectioned into segments 400 mm long, preheated to 940°C for 30 min and forged into 400 x 150 x 20 mm plates. These plates were solution-treated at 925°C for 1 hr, fan air cooled and then stabilized at 700°C for 2 hr. The as-received microstructure of the alloy was in the bimodal condition (also termed solution-treated-and-overaged), and consisted of colonies of equiaxed primary-α and lamellar α+β (transformed-β), with an average grain size of ~20 μm (Fig. 1). Mechanical properties of this alloy are listed in Table I.

Cylindrical samples, with a gauge length 7 mm in diameter and 15 mm long, were used to determine stress/life behavior. After machining, specimens were carefully stress relieved *in vacuo* for 2 hr at 700°C.

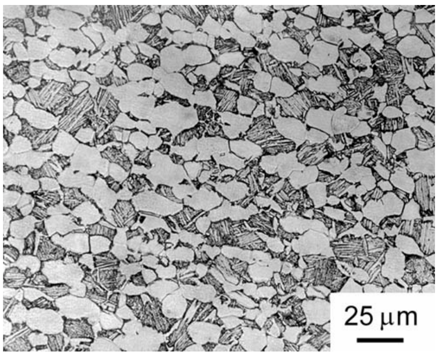

Fig. 1: Optical micrograph of the bimodal (solution treated and overaged, STOA) Ti-6Al-4V microstructure investigated. Etched for ~10 s in 5 parts 70% HNO_3, 10 parts 50% HF, 85 parts of H_2O.

Table I: Uniaxial Tensile and Toughness Properties of Ti-6Al-4V

Microstructure	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Reduction in Area (%)	Fracture Toughness K_{Ic} (MPa√m)
Bimodal	930	978	45	64
Lamellar	975	1055	10	100

For deep rolling, a hydrostatically-seated spherical rolling element (6.6 mm diameter) was used with a feed rate of 0.1125 mm per revolution and a rolling pressure of 150 bar. Laser shock peening (LSP) was carried out with a power density of 7 GW/cm^2 and a coverage of 200%. Subsequent tension-compression fatigue tests were performed at room temperature and at 450°C (homologous temperature, T/T_m = 0.43, where T_m is the melting point) using an automated servo-hydraulic testing machine operating under load control at a load ratio (minimum load/maximum load) of R = -1 and a frequency of 5 Hz. For the tests at temperature, specimens were heated to the required levels in an air furnace. During fatigue, strains were monitored using a capacitative extensometer. Residual stress distributions were measured using standard X-ray diffraction techniques; lattice strain measurements were carried out using Cr-K_α radiation at the {201}-planes of the hexagonal α-phase. For residual stress evaluation, the well-known $\sin^2\psi$-method was applied and the X-ray elastic constant for Ti of $\frac{1}{2}s_2$ = 12.09 x 10^{-6} mm^2/N was used for this purpose. Residual stress depth profiles were determined (without correction for stress relief) by successive removal of material electrochemically. Near-surface work hardening was characterized by the hardness measurements as well as by the full width at half maximum (FWHM) distributions of the X-ray Bragg peaks. Transmission electron microscopy (TEM) was carried out on cross-sections of the direct surface regions using a 200 kV JEOL microscope; further details are given elsewhere [8]. Striation spacings on the post-fracture surfaces were also measured using scanning electron microscopy (SEM) during fractographic observations.

RESULTS AND DISCUSSION

While laser shock peening did not result in any significant alteration of the surface topography, deep rolling, as expected, led to a marked decrease in the surface roughness (untreated: surface roughness R_z = 1.7 µm, deep rolled: R_z = 0.8 µm). The Vickers hardness of the untreated specimens was about 330 VPN; both DR and LSP mechanical surface treatments resulted in an increase in the near-surface hardness by about 10% (Fig. 2).

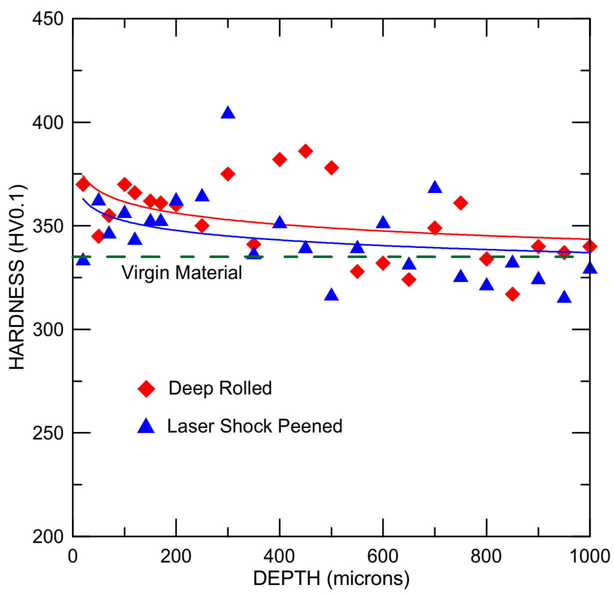

Fig. 2: Near-surface hardness depth profile of deep rolled and laser shock peened Ti-6Al-4V.

From the X-ray diffraction measurements, it was observed that both treatments introduced compressive residual stresses at the specimen surface and in the near-surface regions. Fig. 3 shows typical residual stress and FWHM depth distributions after DR and LSP. After DR, maximum compressive residual stress levels of up to 930 MPa were detected immediately below the surface, with the residual stress levels decreasing to zero at a depth of about 0.5 mm. In the case of LSP, the average compressive residual stress levels were much lower; however, the residual stress "case" was considerably deeper. In fact, there was no significant reduction of the residual stress levels up to a depth of 0.5 mm. Similar observations of deep residual stress "cases" after LSP, which incidentally are sample thickness dependent, have been reported for the same material in ref. [9]. In general, the residual stress levels as well as the increase in FWHM are much less pronounced after LSP than after DR. It should be noted that the residual stress distributions and FWHM states after deep rolling correspond qualitatively to those found after shot peening (see results for Ti-6Al-4V in ref. [10]). Furthermore, in addition to the hardness increase after mechanical surface treatment, FWHM distributions indicate the presence of a work hardened layer at the surface of the material.

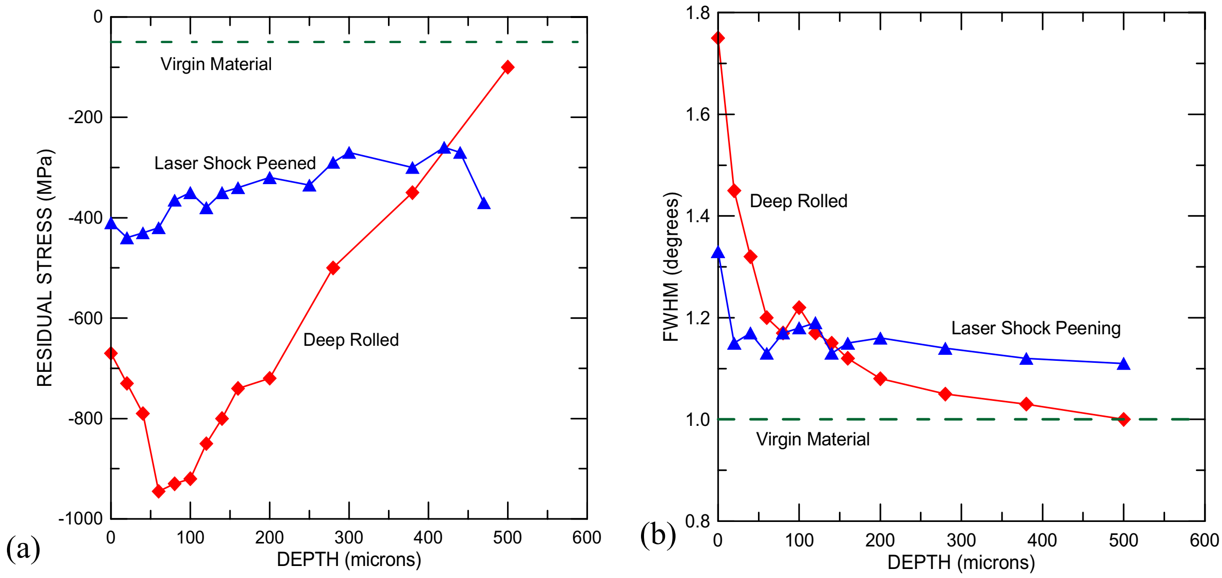

Fig. 3: Near-surface residual stresses and FWHM-values of deep rolled and laser shock peened Ti-6Al-4V.

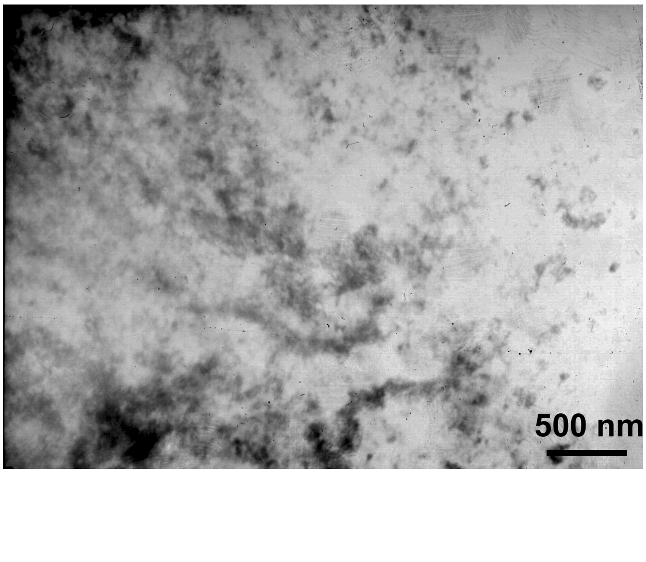

Fig. 4: TEM micrograph of direct surface regions of deep rolled Ti-6Al-4V (rolling pressure 150 bar).

In the case of deep rolling, the near-surface microstructure was further investigated by TEM. Fig. 4 shows a typical TEM micrograph of the near-surface deep rolled Ti-6Al-4V. It can be seen that deep rolling led to the formation of highly tangled dislocation arrangements; in addition, the first stages of a diffuse subgrain structure are formed, typical of the early stages of mechanically-induced nano-crystallization resulting from severe plastic deformation [11].

Fig. 5 shows the stress-controlled stress-life (*S/N*) fatigue behaviour of the untreated and the deep rolled surface conditions at temperatures of 25 and 450°C. It can be seen that deep rolling leads to a significant enhancement in fatigue life at room temperature which is still evident, although reduced, at 450°C. The effect, however, is more pronounced in the high-cycle fatigue (HCF) regime than in the low cycle (LCF) regime, as is typcial of many surface-treated materials. Due to the decrease of the yield strength with increasing temperature, in general, fatigue lives are considerably lower at 450°C than at 25°C.

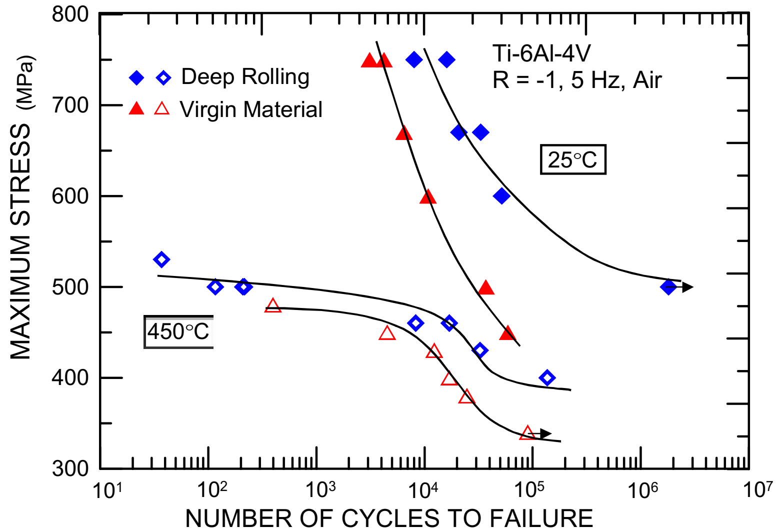

Fig. 5: Stress-life plots for untreated and deep rolled Ti-6Al-4V at 25°C and at 450°C.

Fatigue lifetimes were also obtained for laser shock peened samples at specific stress levels. Fig. 6 illustrates typical lifetimes for all three surface states at 25 and 450°C at stress amplitudes close to the yield strength, i.e., $\sigma_a/\sigma_{yield} \approx 0.7$ and 0.8, respectively. It is clear that there is an enhancement in fatigue life due to mechanical surface treatment at both temperatures, with the deep rolling process being considerably more effective.

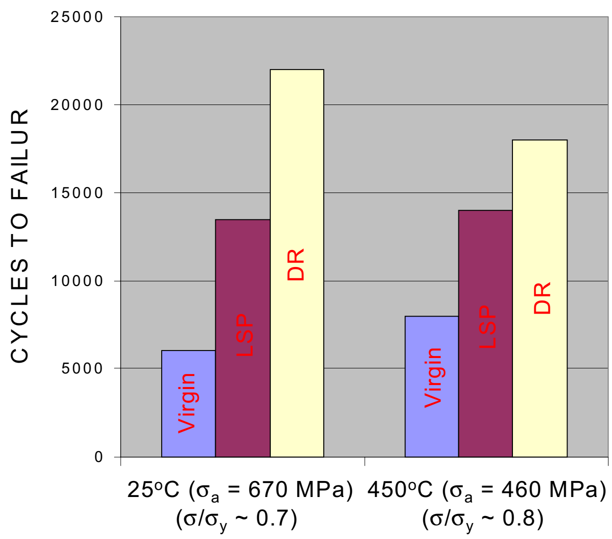

Fig. 6: Fatigue lifetime enhancement by deep rolling and by laser shock peening for test temperatures of 25°C and 450°C and stress amplitudes of 750 MPa and 400 MPa, respectively.

The plastic strain amplitude can be considered as a measure of damage during the fatigue of ductile materials [12,13]. In Fig. 7, such amplitudes, measured during fatigue cycling at a temperature of 450°C, are given as a function of the number of the applied cycles. Compared to the untreated material, deep rolling was observed to lower the plastic strain amplitude throughout the majority of the lifetime; this would be expected to result in extended lifetimes. For all the material conditions at 450°C, an initial increase (cyclic softening) and a subsequent decrease (secondary cyclic hardening) in the plastic strain amplitude was always observed, although a quasi-elastic "incubation" period prior to cyclic softening was seen in the untreated material. The absence of this incubation phase for the deep rolled surface treated material, where the material cyclically softened from the very first cycle, is most likely the result of the significantly higher dislocation density in the work hardened surface layers [14]. At room temperature, conversely, all conditions showed this incubation period followed by cyclic softening until fracture; however, the start of the softening was delayed in the mechanically surface treated samples.

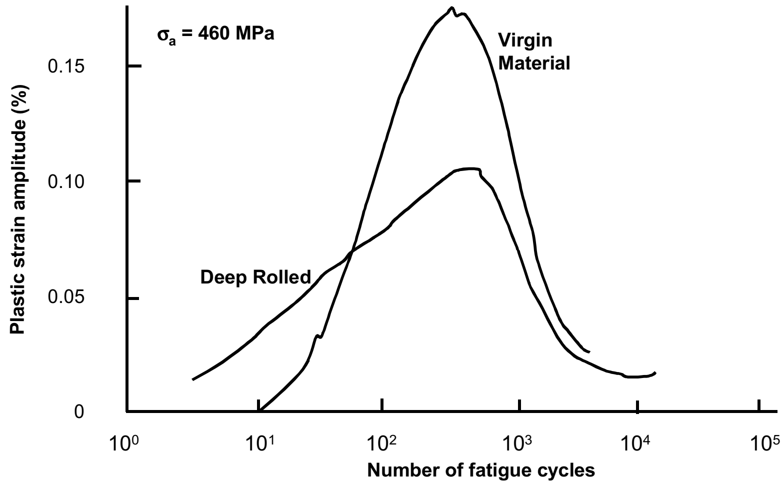

Fig. 7: Cyclic deformation curves for the untreated and deep rolled surface conditions at 450°C at a stress amplitude of 460 MPa.

In addition to their effect on the total fatigue life (*S/N* behavior), the effect of mechanical surface treatments on fatigue-crack propagation behavior is also of interest. In this context, the fracture surfaces of the failed specimens were examined using scanning electron microscopy to measure the size of the fatigue striations. Fig. 8 shows the local crack-growth rates estimated from such measurements on the fracture surfaces of untreated and deep rolled Ti-6Al-4V at 25 and 450°C. (Note that for crack-growth rates in the range of 10^{-7} to 10^{-5} m/cycle, fatigue striation spacings in Ti-6Al-4V are reasonably representative of the macroscopic crack-growth rates). Results in Fig. 8 give a clear indication that deep rolling significantly reduces the fatigue-crack growth rates compared to behavior in the untreated materials. In addition, it is important to note that, as with the *S/N* behavior, the beneficial effect of the mechanical surface treatment is realized at both 450°C as well as at room temperature.

The observed improvement in the fatigue lifetime due to mechanical surface treatment depends predominantly on the stability of the induced residual stresses and the work hardening in the near-surface region [15]. However, it was observed that after thermal annealing for 40 min at 450°C, the residual stresses in both the DR and LSP conditions were markedly reduced (Figs. 9,10). Furthermore, it is evident from these results that cyclic loading led to additional residual stress relaxation as compared to the heat treated (annealed) condition. More specifically, for both the surface treatments investigated in this study, after half the number of cycles to failure, residual stresses were reduced to nearly the same levels as at the surface (~ –200 MPa). This agrees with the commonly held notion that residual stresses relax if the sum of the residual and applied stresses exceeds the material yield strength [16]. Also, in both cases, increased FWHM values measured immediately at the surface indicate that significant amounts of work hardening still exist after fatigue cycling; indeed, this appears to be the more important factor responsible for the observed alteration of the cyclic deformation behavior and in the increase in fatigue lifetime. The higher near-surface work hardening after fatigue in the deep rolled condition also is consistent with the superior fatigue lifetimes as compared to laser shock peened material. Based on these results, we conclude that mechanical surface treatments can be a useful methods to enhance high temperature fatigue behavior and lifetimes of Ti-6Al-4V alloys.

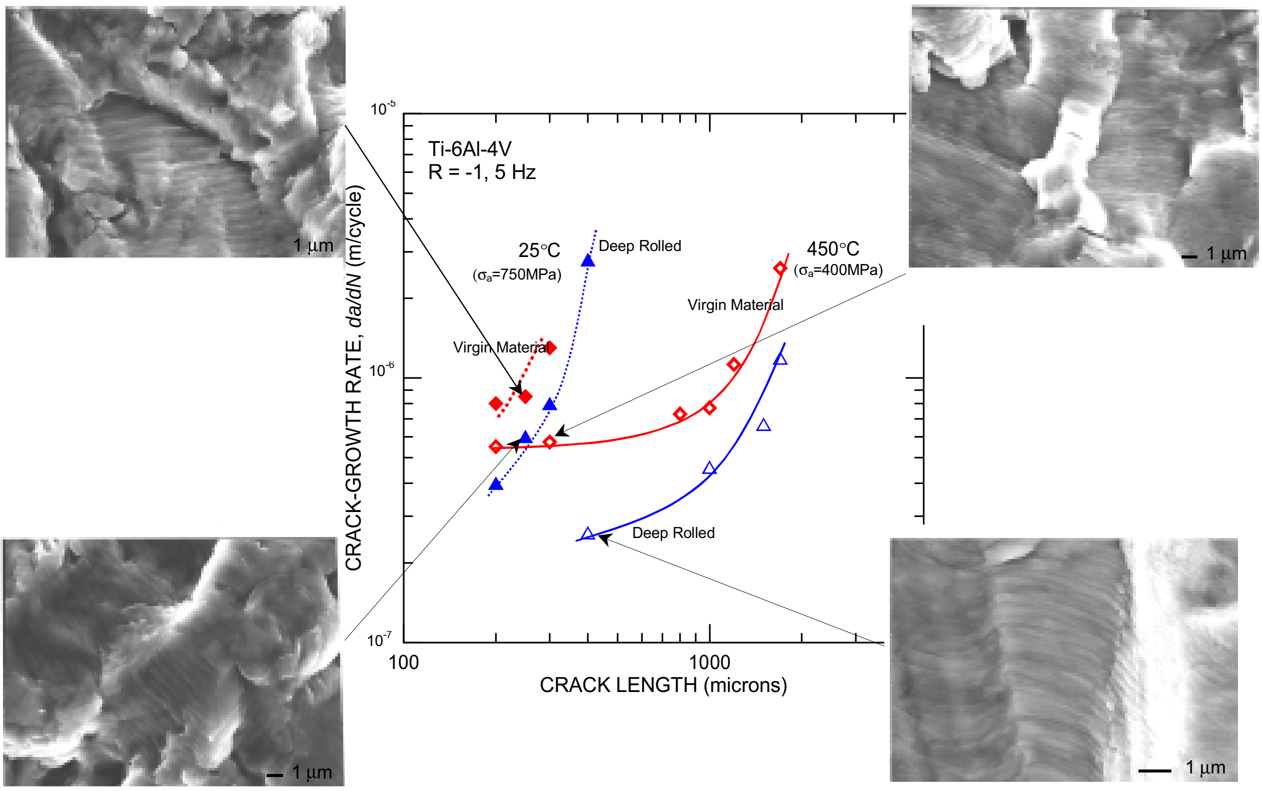

Fig. 8: Local crack-growth rates, estimated from striation spacings measurements on fracture surfaces of untreated and deep rolled Ti-6Al-4V.

CONCLUSIONS

Mechanical surface treatments (deep rolling and laser shock peening) of the titanium alloy Ti-6Al-4V have been shown to lead to alterations of the near-surface microstructure and residual stress states which have a significant effect on subsequent fatigue behavior. For the surface conditions investigated, laser shock peening was found to induce lower near-surface

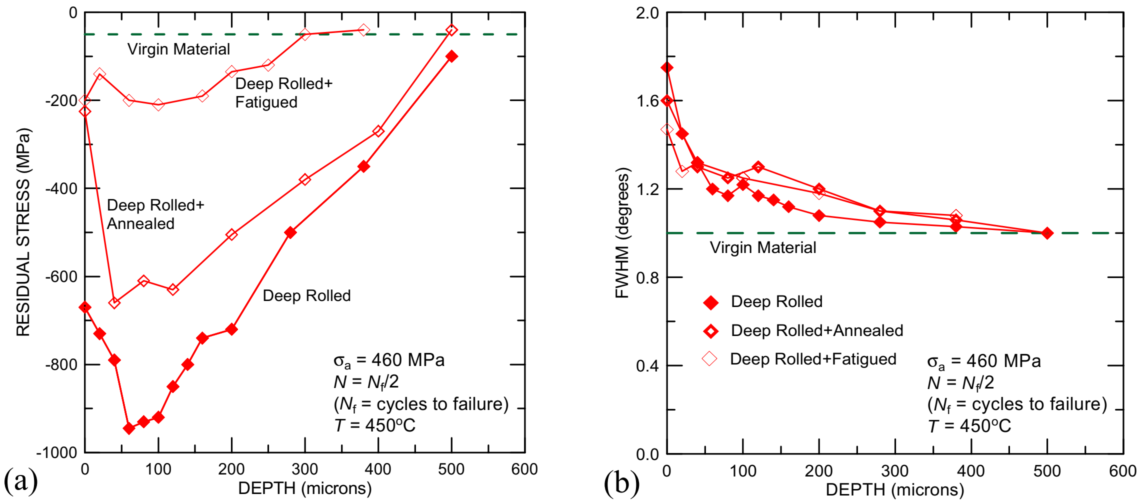

Fig. 9: Thermo-mechanical relaxation of near-surface residual stresses and FWHM-values in deep rolled and fatigued Ti-6Al-4V at 450°C.

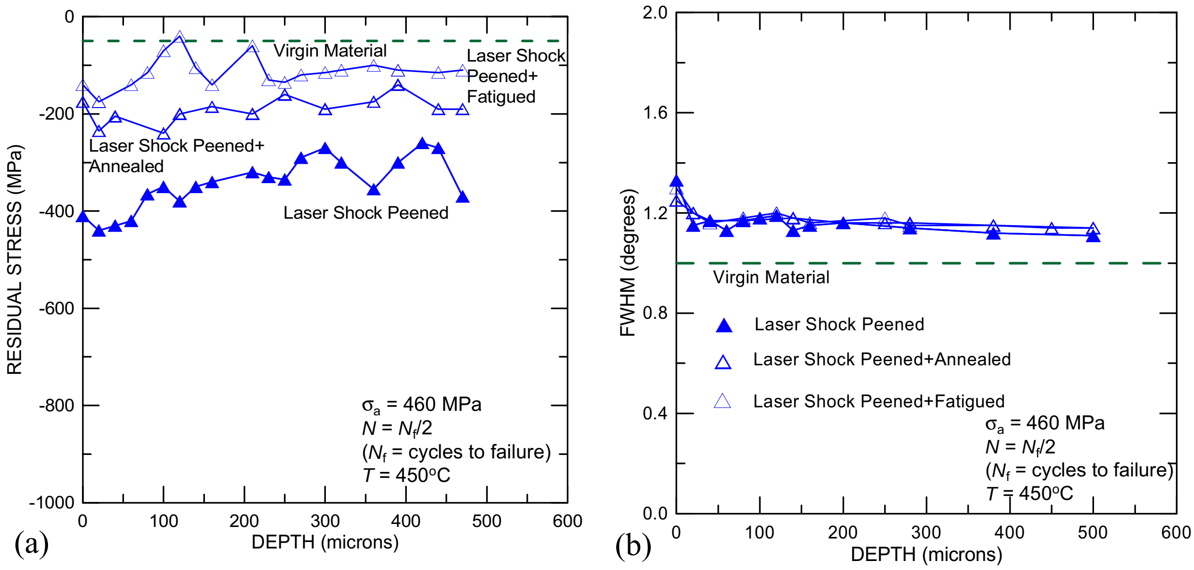

Fig. 10: Thermo-mechanical relaxation of near-surface residual stresses and FWHM-values in laser shock peened and fatigued Ti-6Al-4V at 450°C.

compressive residual stresses and work hardening than deep rolling; however, the depth of the affected near-surface layer was larger. In terms of fatigue behavior, deep rolling was correspondingly found to lead to superior increases in fatigue life compared to laser shock peening at ambient temperature. More importantly, this benefical effect on life was also observed at elevated temperatures, specifically at 450°C, although the degree of life enhancement was reduced compared to that at 25°C. It was found that although fatigue cycling at 450°C caused the near-complete relaxation of the near-surface compressive residual stresses, there was nevertheless an increase in fatigue lives and a decrease in crack-propagation rates in the surface treated material, a fact that is believed to be associated with the more stable work hardened material and corresponding fine-grained microstructure created in the near-surface layers. This implies that even at elevated service temperatures, mechanical surface treatments of Ti-6Al-4V can be used effectively to improve the high-cycle fatigue properties of these alloys.

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