HCF Performance of the Shot Peened Ti-6246– Effects of Test Temperature

S. Yang, L. Wagner and M. Wollmann

Institute of Materials Science and Engineering, TU Clausthal, Germany

Abstract

The paper presents results on duplex microstructure of Ti-6246 which is used in compressor parts of aircraft engines. Shot peening (SP) was applied on axial fatigue specimens. Electrolytically polished specimens were prepared as reference. Surface properties of peened and reference conditions, such as surface roughness, cold work and residual stress (RS) were characterized using profilometer, microhardness tester and hole drilling method. High cycle fatigue behaviour of the peened specimens was examined under axial load at both room temperature (RT) and 450°C in contrast to the reference. It was found that shot peening could bring out a moderate enhancement in high cycle fatigue (HCF) strength at RT. With the increase in test temperature to 450 °C, fatigue limit in peened condition was maintained at the reference level, whereas lifetimes deteriorated at high stress amplitude regime. This is explained by the more marked effect of the increased surface roughness on acceleration of crack nucleation at elevated temperature where more than 40% RS relaxation occurred during the tests.

Keywords

Ti-6246, high cycle fatigue, Shot-peening, elevated temperature, residual stress relaxation

Introduction

Ti-6Al-2Sn-4Zr-6Mo (Ti-6246) is an important material for forging components in intermediate-temperature sections of aero-engines, particularly in compressor disks and blades. This alloy combines virtues of the long-term, elevated-temperature strength properties of Ti-6Al-2Sn-4Zr-2Mo-0.08S and much improved short-term strength levels of a fully hardened (α + β) alloy. Long-term load-carrying applications are considered at temperatures up to 400°C and short-term load-carrying applications up to 540°C [1]. Considering the working environment in fatigue failure-critical aero-engines, attempt to improve the HCF performance by means of surface mechanical treatment will be made.

Shot peening is a one of the most widely applied mechanical surface treatments to improve HCF performance in a wide variety of industrial components. It is employed to impart RS and cold work in the near surface region. RS could counteract the effective applied stresses of the components, which reduces the stress concentration at the crack tip and thus retards the fatigue crack propagation (FCP), extending fatigue lifetimes [2–4]. Cold work leads to a retardation of fatigue crack nucleation (FCN) due to the increase in strength [5]. Meanwhile the concomitant increase in surface roughness results in acceleration in FCN, because surface defects such as notches and dimples induced by SP serve as stress raiser at which cracks may easily nucleate due to stress concentration. Experimental studies on various titanium alloys [6–10] confirm the improvement in HCF by SP at RT. Namely, the benefits owing to the RS and cold work overcompensate the detrimental effect of the increased roughness. Whereas the influence of SP on HCF of this alloy during application at elevated temperatures are not fully studied. Further, investigation on relaxation of RS and variation in cold work under thermal exposure are of great importance to elucidate the effect of test temperature on fatigue behaviour of the peened Ti-6246.

Hence, the HCF behavior of peened specimens and electro-polished references will be examined isothermally at both RT and 450°C (representative for elevated temperature application). Besides, it is also obliged to study the SP-induced changes in surface properties, and their evolvement during the thermal exposure to 450°C for various durations.

Experimental methods

The tested material is in duplex microstructural condition, as presented in Fig. 1.a and b. It has a low volume fraction of equiaxed primary α grains (α_p), approximately 10 %. Hence it is designated as D10/ AC. The grain size is about 3 µm. Higher resolution micrograph in Fig. 1.b displays a very fine particulate transformed β matrix, unlike the lamellar matrix in duplex structures reported by T. Krull [11] and C.J. Szczepanski [12].

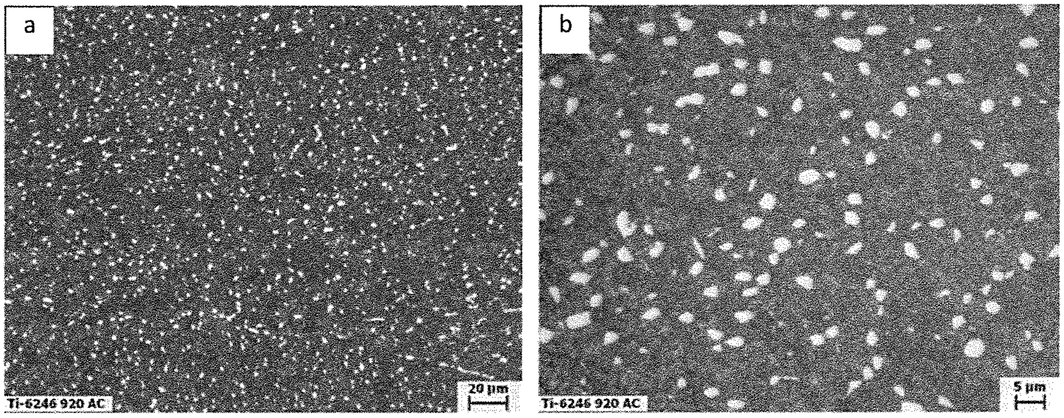

Figure 1, Microstructure of D10/ AC: (a) duplex structure with about 10 % α_p, (b) high resolution micrograph indicating fine grain size and transformed β matrix.

The hour-glass shaped axial fatigue specimens with gage diameter of 3 mm were first low stress ground, then shot peened to intensity of 0.22 mmA. Other ground specimens were electro-polished to generate RS free surfaces, serving as references. The load controlled axial HCF tests were conducted at 50Hz and load ratio $R = -1$ on an Instron 8801 servohydraulic machine which is facilitated with a three-heating stage furnace. Test temperatures were set up at RT and 450°C, respectively for both peened and reference conditions.

For tests at 450°C, the specimens were first mounted into the servohydraulic machine at RT and enclosed within the furnace. Thermal couples were attached at the specimens to control the temperature. The preheat to 450°C includes 2.5 hours heating-up and another 1.5 hours soaking to eliminate the temperature gradient before starting the isothermal HCF tests.

Surface roughnesses of the EP and SP specimens were measured using a stylus contact-type profilometer. In order to determine the influence of test temperature on stability of RS and cold work produced by SP, heat treatment at 450°C on the peened flat specimens (20 × 20 × 8 mm^3) for RS and cold work measurement were carried out in the three-heating stage furnace at different durations, including the preheat (SP + Preheat), preheat + 1 hour soaking (SP + preheat + 450°C/1 h) and preheat + 55.6 hours (SP + preheat + 450°C/55.6 h), corresponding the run out duration (10^7 cycles at 50Hz). The as peened conditions were also prepared as reference (SP). RS measurements were accomplished using hole-drilling methods. Microhardness-depth profile was used to display the variation of cold work in the near surface region of the specimens treated in the above four conditions.

Experimental results

The fatigue behavior of the shot peened condition at RT is shown in Fig. 2.a, contrasting to EP reference. SP could improve the fatigue limit of the reference from 500 to 550MPa. Moderate increase by 50 MPa in strength level and prolongation of fatigue lifetimes could be provided by SP, especially in higher stress amplitude regime. However, with the increase of test temperature to 450°C, the fatigue performance of shot-peened condition turned inferior to EP (Fig. 2.b). Reduction of fatigue lifetimes at low cycle regime (~ 10^5 cycles) appeared, particularly, at low stress amplitude range, where lifetimes of fatigued specimens were within 0.56 hour. At high cycle regime, the S-N curve of SP almost converged with EP. The strength level of the peened recovered to the reference state, 450MPa. The benefit of SP at elevated temperature vanished.

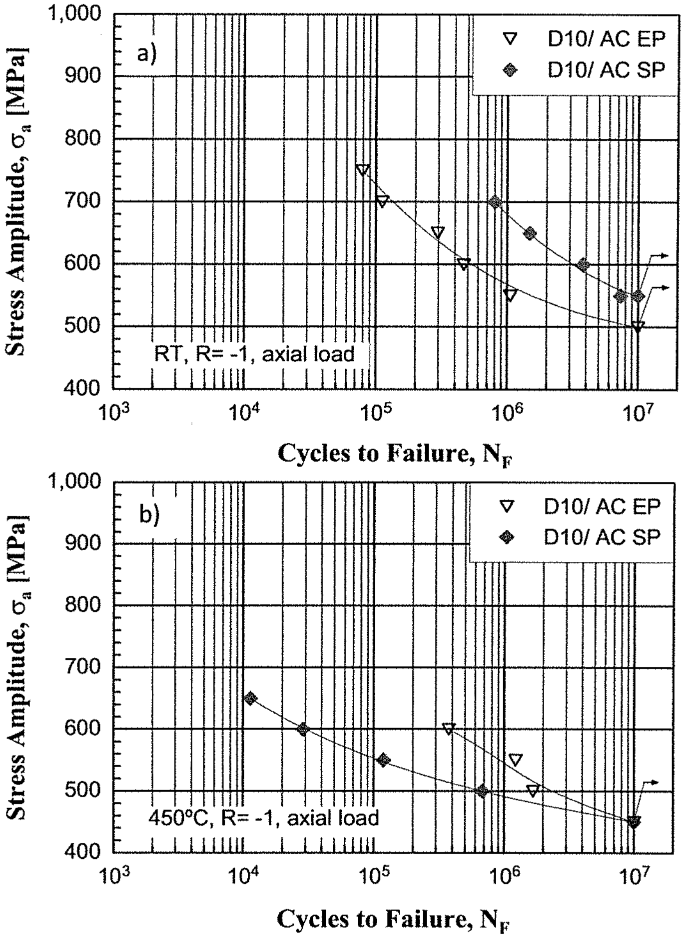

Figure 2, HCF performance of D10/ AC: (a) at RT, (b) at 450°C.

Surface profile and roughness of D10/ AC after EP and SP are compared in Fig. 3. The EP surface is rather smooth, serving as reference free from surface defects. The roughness of shot peened condition increases in comparison with EP. SP brings out evident deterioration of the surface finishing because of the plastic deformation during SP. The uneven surface after SP provides micro-notches which might act as crack initiation sites, and further accelerate the process of FCN.

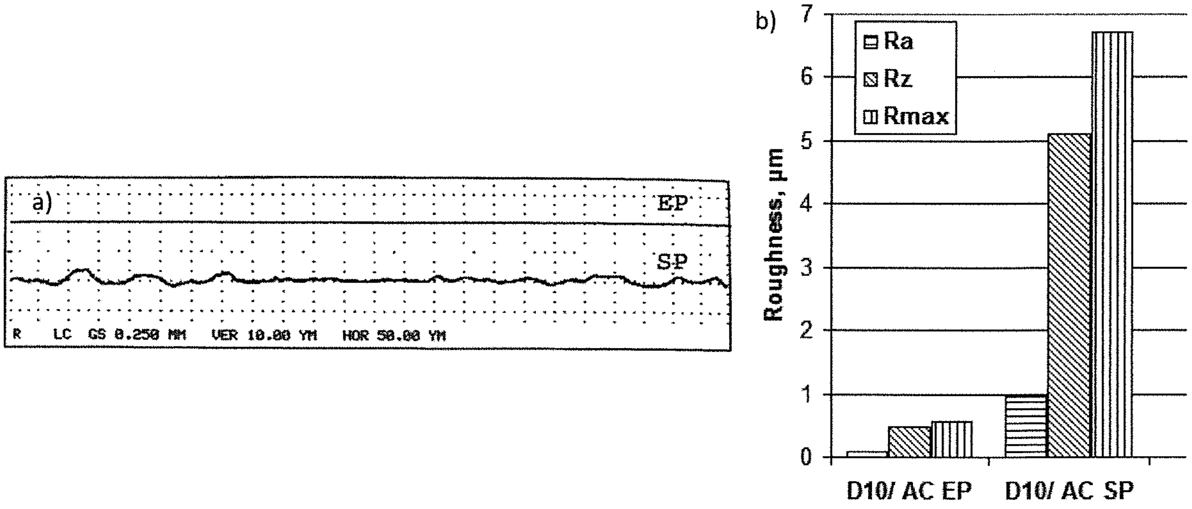

Figure 3, Surface finish after EP and SP: (a) surface profile, (b) roughness.

The microhardness-depth profiles of peened conditions heat-treated for different durations are displayed in Fig. 4.a. In the near surface region, the as peened one exhibit enhancement in microhardness. This confirms the SP-induced work-hardening effect (cold work) due to the increase in dislocation density. The maximal hardness was found at the surface at around 490 HV. SP induced cold-worked zone spans to the depth of 0.6 mm. Beyond the influenced zone, the bulk status reveal the original hardnesses of the unpeened condition, about 445 HV. Maximum increase in hardness resulting from SP reaches 10 %. Besides, SP produced RS gradient, with maximum values of about -910 MPa at the surface. It could be inferred that the improvement of HCF behaviour could be ascribed to SP induced-work hardening and RS at the surface layer, as the increased cold work and RS are proved to be able to retard the fatigue crack initiation and decelerate crack growth.

After preheat, maximum microhardness at the surface decreased to around 480 HV. Meanwhile, the influenced zone shrank. It suggests that cold work is partially recovered as a response to the thermal exposure. Additional soaking at 450°C for 1 hour led to further drop of the hardness to about 460 HV and shrinkage of the affected zone (~200 µm). This is also confirmed by the results after 55.6 hours soaking. The two profiles converge, as no much reduction of hardness could be observed after keeping at 450°C for 55.6 hours. Thus, it could be concluded that cold work recovered significantly during the first hour after starting the HCF tests at 450°C, and only a small portion of the work-hardening effect was retained during long term test (~10^7 cycles). The influence of the maintained cold work might be rather minor on the HCF. On the other hand, RS relaxed due to the thermal exposure. After preheat, the maximal RS decreased to -535 MPa. The relaxation ratio compared to as peened condition corresponds to 41 %. The effective zone lies in the same area as that of the peened profiles, down to 200 µm under the surface. SP + preheat + 450°C/1 h results in very slight drop in stress profile. Further prolongation of heat-treatment duration to 55.6 h also could cause no more stress relaxation. The maximum RS kept stable at -520 MPa up to the run out test, corresponding to a relaxation ratio of 43 %. This is approaching to the result of R. John [13] at 47 % which was obtained on the specimen after exposure to 399°C for 100 hours. This proof confirms that the thermal relaxation in RS happened mainly during the first 1 hour after preheat, consisting with the cold work response to the heat treatment duration.

Besides, most SP specimens failing at 450°C fatigued from surface cracks regardless of the RS retained at the surface layers, as the surface is roughened due to SP (Fig. 3). Therefore, it is evident that at 450°C the detrimental influence of increased surface roughness due to SP overwhelms the benefits of retained RS, accelerating the crack nucleation. That is the reason why the lifetimes of fatigued SP specimens at 450°C which mainly happened during the first 1 hour test were shortened. While, for the run out specimens which lasted for 10^7 cycles, the RS in the near surface region might compete with the roughness for a higher probability of subsurface FCN, thus result in comparable strength levels in SP condition and the reference.

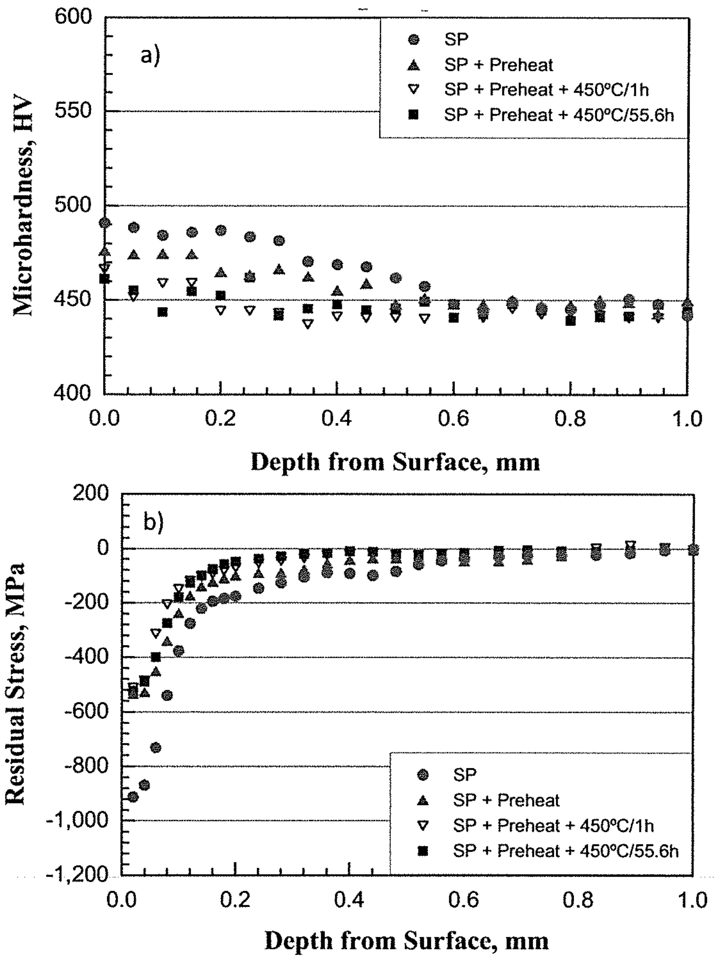

Figure 4 Variation in surface properties after different heat treatments at 450°C: (a) RS-depth profiles, (b) microhardnesses-depth profiles.

Disscussion and conclusions

This study demonstrates the beneficial effects of mechanical surface treatment as SP on improving fatigue lifetimes and strength level at RT, and the mechanisms concerning the induction of RS and cold work. Meanwhile, the HCF behaviour of shot peened material at elevated temperature was characterized, and interpreted by means of identifying the surface properties such as roughness, thermal stability of RS and cold work. It is found that the interaction between the surface properties should be taken into account in explaining the influence of SP on HCF. The main conclusions are summarized as following:

- SP could induce raised surface roughness, RS and cold work gradient zones in the near surface regions of the specimens. The RS could reach maximal 910 MPa at the surface, and inhabit an influenced zone with depth of 200 µm. Meanwhile, mild work hardening effect could be achieved with a maximal value 490 HV at the surface, compared to the bulk hardness of 445 HV.
- At RT, SP could introduce extension in fatigue lifetimes and moderate improvement by 50 MPa in fatigue strength, owing to the enhancement in resistance to crack initiation and propagation because of RS and cold work at surface layers of specimens.
- 41% RS relaxation occurred during preheat. During 1 hour soaking after preheat, 43% RS and most amount of work-hardening effect were observed to have relaxed or recovered. Thereafter both stabilized till the end of run out test duration.
- At 450°C, fatigue strength of peened condition is maintained at the reference level. Life times of peened ones at high stress amplitude regime deteriorated, probably due to the overwhelming effect of deteriorated roughness against the greatly relaxed RS.

Reference

[1] G. Welsch, R. Boyer, E. Collings, Materials properties handbook: titanium alloys, ASM International, 1994.

[2] J. Hack, G. Leverant, Influence of compressive residual stress on the crack-opening behaviour of part-through fatigue cracks, in: Residual stress effects in fatigue: A symposium, American Society for Testing and Materials, Philadelphia, Pa. (1916 Race St., Philadelphia 19103), 1982, pp. 204–223.

[3] J. Hack, G. Leverant, Fatigue microcrack behaviour under the influence of surface residual stresses, 1982.

[4] D. Löhe, K.-H. Lang, O. Vöhringer, Residual stress and fatigue behaviour, in: G.E. Totten, Howes, Maurice A. H, T. Inoue (Eds.), Handbook of residual stress and deformation of steel, ASM International, Materials Park, OH, 2002, pp. 27–53.

[5] L. Wagner, Mechanical surface treatments on Titanium alloys: Fundamental mechanisms, in: J.K. Gregory, H.J. Rack, D. Eylon (Eds.), Surface performance of titanium: Proceedings of a Symposium on Surface Performance of Titanium sponsored by the Titanium Committee of TMS, held at the 1996 Fall TMS Meeting in Cincinnati, Ohio, October 7-9, 1996, Minerals, Metals & Materials Society, Warrendale, Pa, 1996, pp. 199--215.

[6] T. Ludian, L. Wagner, Mechanical surface treatments for improving fatigue behaviour in titanium alloys, Advances in Materials Sciences 8 (2008) 44–52.

[7] J. Müller, H.J. Rack, T. Ludian, L. Wagenr, Microstructureal and mean stress effects in fatigue performance of shot peened Ti-6Al-4V, in: M. Niinomi (Ed.), Ti-2007 science and technology: Proceedings of the 11th World Conference on Titanium (JIMIC5), held at Kyoto International Conference Center, Kyoto, Japan, 3-7 June 2007, Japan Institute of Metals, Sendai, Japan, 2007, pp. 375–378.

[8] K. Zay, S. Yang, Y. Kosaka, L. Wagner, Shot peening and ball-burnishing to improve HCF strength of the new titanium alloy TIMETAL-54M, in: J. Champaigne (Ed.), Proceedings of 11th international conference on shot peening, 2011, p. 303.

[9] K. Zay, E. Maawad, H.-G. Brokmeier, L. Wagner, C. Genzel, Influence of mechanical surface treatments on the high cycle fatigue performance of TIMETAL 54M, Materials Science and Engineering: A 528 (2011), pp 2554–2558.

[10] H. Polanetzki, J. Ehrl, I. Stoll, L. Wagner, Influence of surface enhancement processes on mechanical properties of the titanium alloys Ti6246, in: J. Champaigne (Ed.), Proceedings of 11th international conference on shot peening, 2011.

[11] T. Krull, Bruch- und Ermüdungsverhalten der β-Titanlegierung Ti-6246 bei sehr hohen Festigkeiten, PhD thesis, Shaker, Aachen, 2007.

[12] C. Szczepanski, S. Jha, J. Larsen, J. Jones, Microstructural Influences on Very-High-Cycle Fatigue-Crack Initiation in Ti-6246, Metall and Mat Trans A 39 (2008), pp 2841–2851.

[13] R. John, D.J. Buchanan, S.K. Jha, J.M. Larsen, Stability of shot-peened residual stresses in an α + β titanium alloy, Scripta Materialia 61 (2009), pp 343-346