Influence of different Surface Enhancement Processes on Mechanical Properties of the Titanium Alloy Ti6246

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Abstract

Titanium alloys are used in aircraft engines mostly in compressors at lower temperatures up to 500 °C. The main reason for its use is the high strength to weight ratio. The titanium alloy Ti-6Al-2Sn-4Zr-6Mo has a specific strength which is approximately 8.5 % higher than that of the commonly used titanium alloys Ti-6Al-4V and that of Ti-6Al-2Sn-4Zr-2Mo at a temperature of 450 °C. This property allows a lower part weight due to the possible reduction of wall thickness in the layout design. The alloy Ti-6246, which has been investigated in the present work, was forged above the β-transus temperature, (α+β) annealed and subsequently age-hardened. The microstructure consists of elongated β-grains with coarse primary α-plates and fine secondary α-plates.

In the present work, the effects of various mechanical surface treatments including deep rolling, conventional shot peening and ultrasonic shot peening on the change in surface and near-surface properties as well as on the HCF performance were studied. For the shot peening processes, various Almen intensities were being used. Regarding deep rolling, the rolling ball diameter, hydrostatic pressure, rolling speed as well as the overlap of adjacent rolled lines (coverage) were varied. Surface roughness and residual stress measurements were performed to characterize surface and near-surface properties.

Fatigue tests were done in rotating beam loading (R = -1) at T = 450 °C at a frequency of about 100 Hz in air.

Keywords Ti6246, shot peening, deep rolling, residual stress, rotating bending loading

Introduction

Titanium alloys have been used for decades in the aircraft engines. The main reason for this application is the combination of high quasi-static and cyclic strength as well as good oxidation resistance at elevated temperatures. Titanium alloys are divided in α-, (α+β)- and β-alloys. Among these all alloy groups, (α+β)-alloys are mostly used in engine components. The most important (α+β)-alloy is Ti-6Al-4V having a maximum operating temperature of about 300 °C [3]. In order to sustain temperatures in the excess of 300 °C, so called near-α alloys were developed having a lower content of β-stabilizers such as Mo, V and Nb. These near-α alloy combine the high creep resistance of the α-alloys with the higher strength of the there are still titanium alloys which are kept in the neighborhood of α- alloys based on their α+β-alloys. Best known examples of near-α alloys are Ti-6242 and TIMETAL 834 with maximum operating temperatures of 550 °C and 600 °C, respectively [1].

Recently, the high-strength metastable β-alloy Ti-6246 has received much attention in aero engine application because it can be heat treated to strength levels significantly higher than those achievable in Ti-6Al-4V. With maximum tensile strengths of up to 1400 MPa [2], a further weight saving over Ti-6Al-4V is possible. In the present investigation, the influences of shot peening and deep rolling on potential improvements in the elevated temperature fatigue performance was examined on Ti -6246.

Experimental Methods

All test specimens were machined from IBR blanks (**I**ntegrated **B**laded **R**otor). Flat samples were used for the determination of surface roughness, metallographic examination of the near-surface microstructures and to measure residual stress-depth profiles. Shot peening was performed on CNC-shot peening pressure type equipment. As shot peening media CCW14 (conditioned cut wire) with a nominal diameter of 0.35 mm and a hardness of 50 – 62 HRc was used. Deep rolling was carried out with hydrostatic rolling tools in conjunction with a high pressure pump unit using hydraulic fluid. Flat specimens were rolled on a CNC controlled mill whereas for the fatigue specimens a lathe was used. In order to make sure that only one process parameter at the time was varied, the degree of rolling track overlap (*RO*) was introduced [4]. *RO* can be determined according to equation (1) and **Figure 1**. *W* represents the width of a single rolling track and *f* equals the feed rate at which the tool is moved across the surface. By using *RO* instead of feed rate, the actual width of the rolling track is taken into account and therefore, it is possible to compare surfaces manufactured with different tools or using various hydrostatic pressures. To determine *RO* the width of a single rolling track needs to be measured before processing the whole surface. This is done using an optical microscope in conjunction with digital picture analysis software. Turning speed and feed rate on the lathe were adjusted to match the process parameters used for the flat specimens.

$$RO = \frac{w-f}{w} * 100\%, \quad 0 < f \le w \tag{1}$$

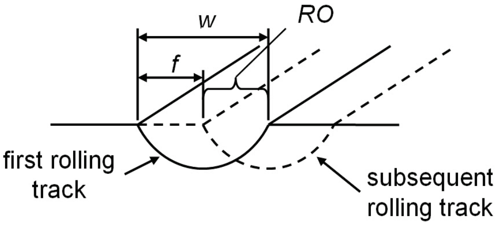

Figure 1: Illustration of feed rate, and degree of rolling track overlap

Before applying shot peening or deep rolling, the test surfaces on the flat and round specimens were turned and milled, respectively and subsequently low stress ground. From the industrial point of view this as-machined surface condition can act as a suitable reference to which the various mechanically surface strengthened conditions will be compared. Residual stress measurements were performed on a X-ray diffractometer using the $\sin^2\Psi$ method. For low stress ground and deep rolled specimens, the measurements were carried out at 0° and 90° relative to the working direction which is defined by the grinding pattern. Shot peened specimens were measured in 0° direction only.

Hour-glass shaped rotating beam specimens with a minimum diameter of 6 mm were used to determine S-N curves.

Experimental Results

Residual Stress Measurements

The residual stress measurements (RSM) are shown in reference to the as-machined condition. As seen in **Figure 2,** the reference state exhibits only low residual compressive stresses which are limited to a depth of about 75 µm. The absolute stresses are higher in the 90° direction. The differences gradually level off with increasing distance to the surface. No such directionality of the compressive residual stresses was observed after shot peening. The variation of the intensity has no influence on the maximum value of the compressive stresses. However, increasing Almen intensities lead to a shift of the location of the maximum value into greater depths (**Figure 2**).

For deep rolling, directionality in residual compressive residual stress profiles is evident (**Figures 3, 4, 5**). The absolute values of the near-surface residual compressive stresses measured in perpendicular direction are about 100 to 300 MPa higher than those measured in parallel direction. At depths beyond the location of residual stress maxima, these differences disappear.

Residual stress profiles for various degrees of rolling track overlap as shown in **Figure 3** are essentially the same. The Hertzian contact between surface and rolling ball results in a stress distribution below the surface which affects an area that is wider than that of a single rolling track. Therefore, no further strengthening is achieved by increasing the overlap while slight changes in surface waviness may still occur.

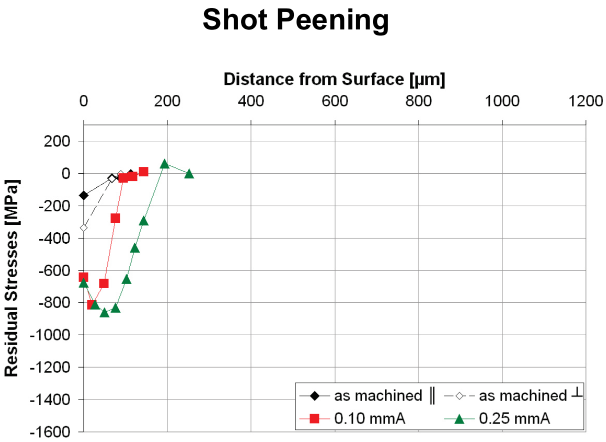

Figure 2: RSM for various Almen Intensities in shot peening

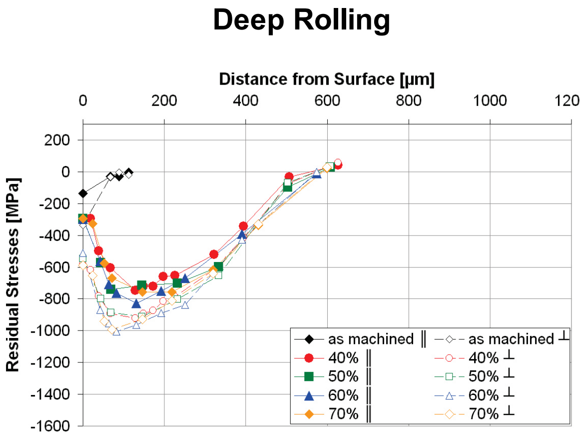

Figure 3: RSM for different degrees of *RO* in deep rolling

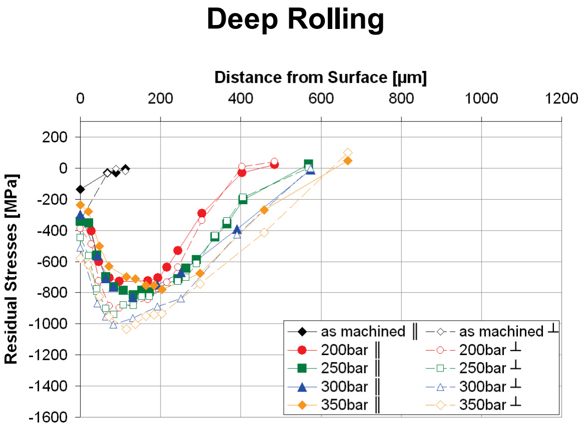

Figure 4: RSM for various hydrostatic pressures in deep rolling

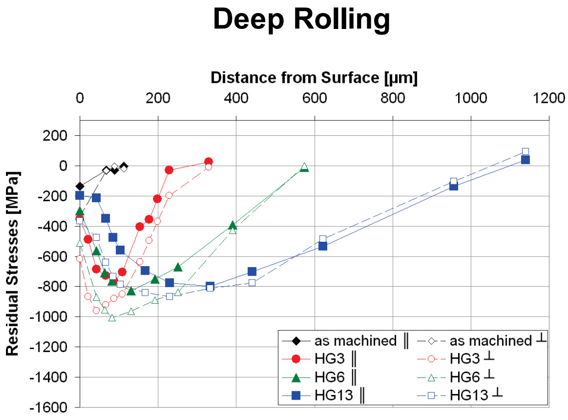

Figure 5: RSM for various ball diameters in deep rolling

The influence of hydrostatic pressure on the residual stress profiles is shown in **Figure 4**. There is no significant shift in the depth of the maximum stress level but the overall effective depth of the compressive residual stresses until the zero-crossing increases with rising pressure.

By increasing the ball size diameter in deep rolling (**Figure 5**), the maximum residual compressive stresses are shifted deeper below the surface. This is due to the increased rolling force resulting from the bigger cross sectional area on which the hydrostatic pressure is exerted. The depth of the maximal residual compressive stress observed for the smallest ball (Ø 3mm) in deep rolling is approximately the same as observed for the higher Almen intensity in shot peening.

Fatigue Results

S-N curves from rotating bending testing of the various shot peened conditions are illustrated in **Figure 6**. All tests were carried out at the maximum operating temperature of T = 450 °C for this alloy.

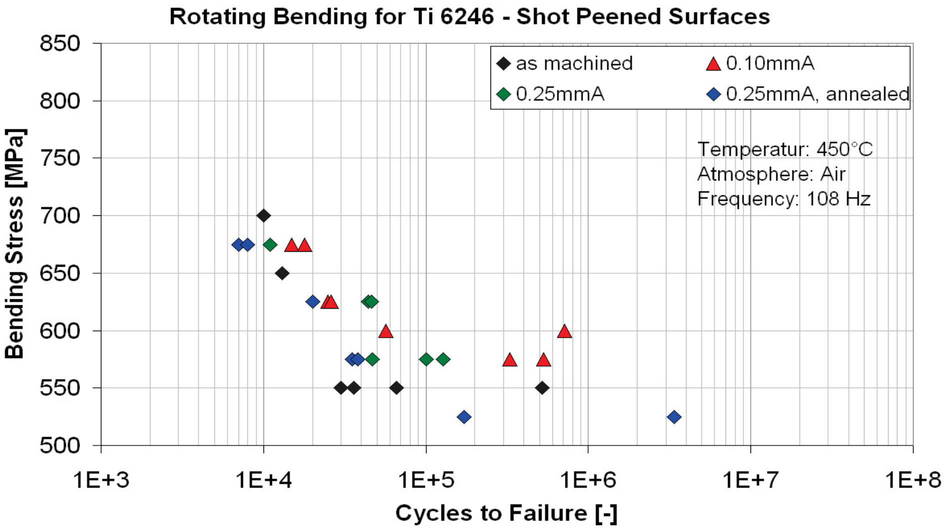

Figure 6: Fatigue results for rotating bending tests of shot peened surfaces

There is no significant difference in fatigue life between the as-machined and the shot peened specimens. Apparently, peening with lower intensity results in a small improvement in fatigue life as opposed to specimens peened with higher intensities. Annealing of high intensity shot peened specimens results in clear decrease of the fatigue life compared to the baseline levels.

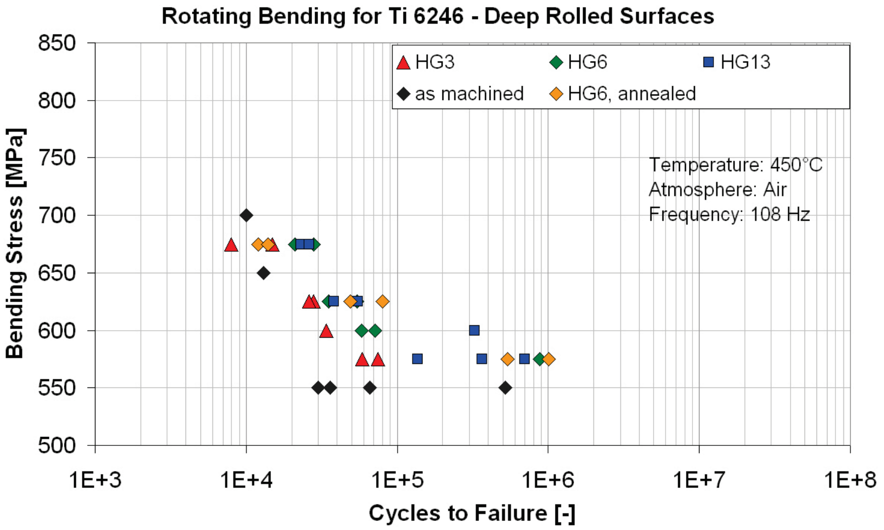

Figure 7: Fatigue results for rotating bending tests of deep rolled surfaces

In **Figure 7** the results of rotating beam tests after deep rolling with different ball diameters are presented. Again, the reference as-machined condition is also shown. Deep rolling of the specimens with the smallest ball diameter yielded only a modest improvement in fatigue life compared to the reference condition while deep rolling with the larger size lead to significantly higher fatigue life. However, differences between the larger diameters cannot be determined. Subsequent annealing of HG6-rolled samples showed that the fatigue life did not change in comparison to only deep rolled specimens. At higher stress amplitudes, no significant differences in fatigue life of the various surface conditions exist. However, the deep rolled specimens have longer fatigue life at low stress amplitudes.

Figures 8 to 10 illustrate SEM pictures of typical fatigue crack nucleation sites of the various conditions tested. In all examined samples, independent of the surface treatment, crack nucleation occurred at the surface of the specimens.

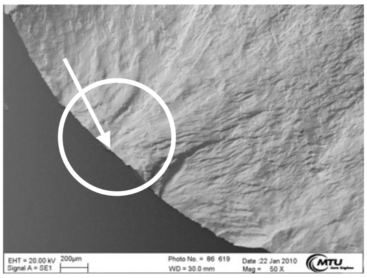

Figure 8: as-machined

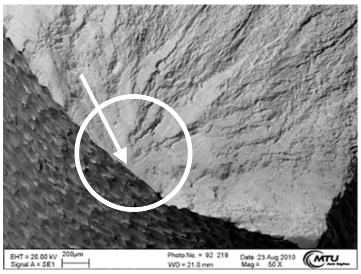

Figure 9: shot peened, high Almen intensity

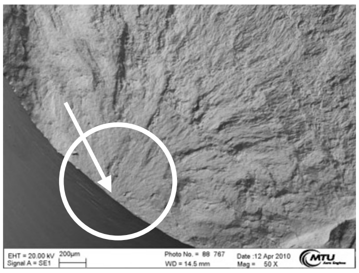

Figure 10: deep rolled, medium ball size

Conclusion

The fatigue life of Ti-6246 at elevated temperatures can be improved due to strengthening processes such as shot peening and deep rolling. The rotating beam tests also show that an annealing treatment after deep rolling has no influence on the fatigue life of Ti-6246. The positive effect of shot peening can be reversed by subsequent solution treatment again. It is also remarkable that crack initiation is always located at the surface of the specimens. This is not the case with the previously used Ti alloys such as Ti-6242.

References

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