Ultrasonic Shot Peening (USP) on Ti-6Al-4V and Ti-6Al-2Sn-4Zr-6Mo Aero Engine Components

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Abstract

Bladed disks (Blisks) have been developed and applied in the compressor sections of modern aero-engines to reduce the component weight and improve efficiency. Over time, the blisk design has been further optimized with respect to weight reduction resulting in thinner geometries in the web area of the disk. Consequently, precautions have to be taken into account to avoid stress induced distortion in thin walled areas during the peening process.

MTU has therefore implemented ultrasonic shot peening as an alternative to the conventional shot peening process. For safety reasons detailed knowledge about the effect of this process on the properties of the blisk material, especially the fatigue behavior is a necessity.

Most known is the conventional shot peening process, where the peening media is accelerated by pressurized air. A new method of this mechanical strengthening process is shot peening using bearing balls accelerated by an ultrasonic vibrating plate. The bearing balls are surrounded by a closed chamber that fits the geometry of the part to be peened. Only a very small amount of bearing ball peening media is needed. To understand the mechanics of this rarely researched process, extensive experiments were performed at MTU.

The effect of Ultrasonic Shot Peening compared to conventional shot peening on the near surface area – surface roughness, residual stress - of Ti-6Al-4V (Ti64) and Ti-6Al-2Sn-4Zr-6Mo (Ti6246) was investigated using common methods. The resulting fatigue behavior including fracture characterization for both materials was studied in detail comparing both mechanical strengthening processes.

Keywords
Ultrasonic Shot Peening, Ti-6Al-4V, Ti-6Al-2Sn-4Zr-6Mo, residual stress, surface roughness, fatigue behavior, fracture characterization, BLISK

Introduction
In the compressor section of jet engines at operating temperatures <450 ° C, titanium alloys are used due to their low density, high strength and good corrosion resistance [1, 2]. The most frequently used alloys in the compressor are Ti-64 and Ti6246 . In operation, these rotor parts are exposed to high temperatures and cyclic loads. For many components local crack initiation and propagation of surface cracks are life limiting [3].
Therefore it is necessary to implement a process which is not only cost-effective but also produces a very high surface quality in serial production. Surface treatment processes such as

shot peening are able to shift the crack initiation from the surface to sub-surface regions which leads to significantly higher fatigue life of the component [4, 5]. Shot peening has been used for many years as the standard process in the final surface treatment of rotating and static engine components [6].
For specific reasons (weight reduction, elimination of assembly costs) in modern aero-engines, blisks (bladed disks) made from titanium alloys are commonly used in the compressor section. blisks are integral components of rotor blades and disks (see Figure 1).

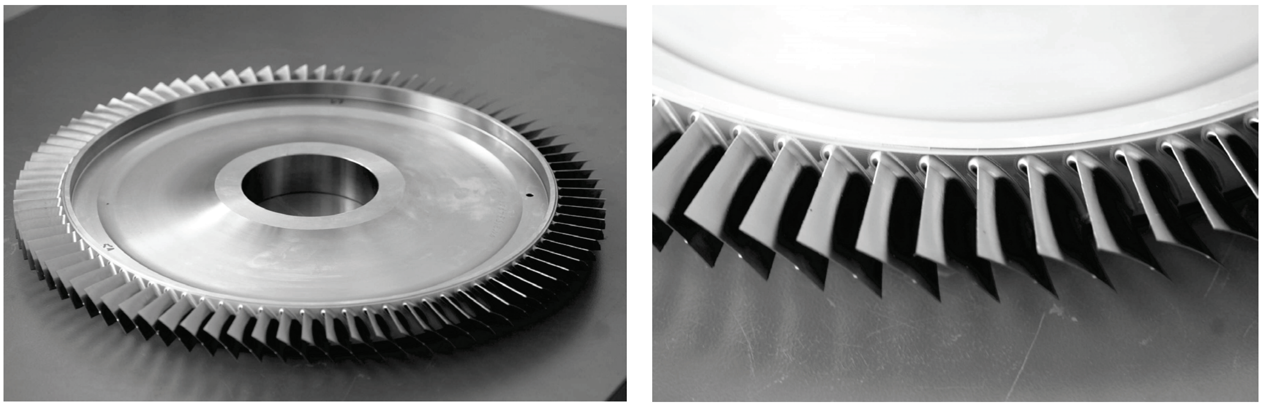


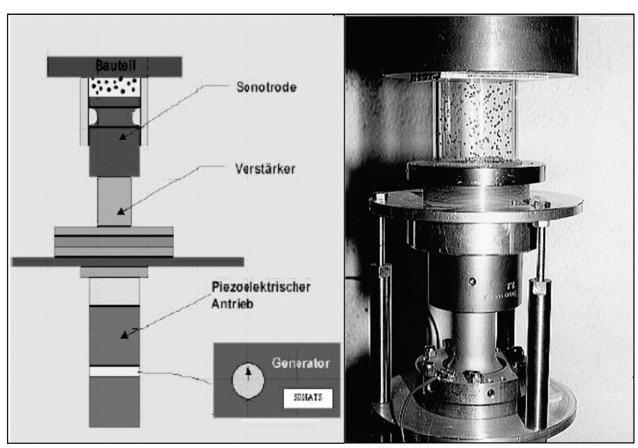
Figure 1. Picture of a BLISK part [MTU Aero Engine].

These components are either produced by milling from the solid or by linear friction welding [7]. For further weight and cost savings, the BLISK should be manufactured exhibiting thinner wall thickness in the disk area. During the conventional shot peening process of such a blisk distortion may occur due to the directionally focused beam of peening media and the reduced wall thickness of the part. MTU has therefore implemented ultrasonic shot peening as an alternative to the conventional shot peening process. In addition to some other benefits of ultrasonic shot peening, lower distortion of thin-walled parts are expected as a result of the randomly distributed peening media during the ultrasonic shot peening process.

Ultrasonic Shot Peening

Ultrasonic waves are generated by means of a piezoelectric excited oscillator and transmitted by an acoustic amplifier on the sonotrode. The acceleration of the peening balls occurs by kinetic energy transfer during collision of the shot with the continuously vibrating sonotrode. In case of ultrasonic shot peening the peening media consists of perfectly spherical bearing balls having a diameter several times larger than that of conventional shot peening media. Peening media and the component sealed off in the peening chamber. Due to reflection of peening media on the component, chamber walls and the sonotrode, randomly distributed collisions between the peening media and the part, e.g. the blisk can be realized.

Figure 2 shows the operating principle of a ultrasonic shot peening facility.



Experimental Methods

To measure the effects of shot peening using different peening processes on the near surface zone, two different experimental methods were employed: Roughness measurement and residual stress measurement by means of X-ray diffractometry.

Fatigue tests were carried out using smooth LCF and HCF tests under axial loads well as LCF rotating bending tests for Ti6246.

The surface of all samples were modified by conventional or ultrasonic shot peening with a low Almen intensity (0,10mmA) and a high Almen intensity (0,23mmA for Ti64 / 0,2mmA for Ti6246) for LCF tests. HCF tests representing the blade area of a blisk were conventionally shot peened using glass beads as peening media or ultrasonic shot peened using bearing balls with Almen intensities of 0,18N or 0,27N. The coverage was 100% in all cases.

Experimental Results

Roughness

Comparing the surface roughnesses of ultrasonic shot peened and conventionally shot peened specimens peened with the same Almen intensity and coverage, it is obvious that conventional shot peening results in surface roughness values much higher than ultrasonic shot peening. This behavior is observed on both Ti64 (Figure 3) and Ti6246 (Figure 4). For Ti64, the absolute value of surface roughness is higher.

Figure 3. Roughness measurements Ti64.

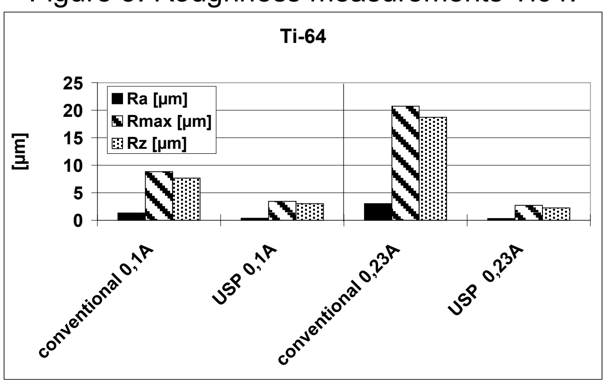
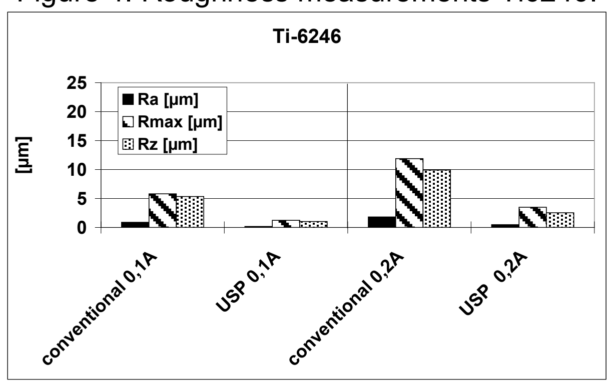


Figure 4. Roughness measurements Ti6246.



Residual stress measurements

For both alloys, the resulting compressive residual stresses at the surfaces for conventional shot peened specimens are higher than for ultrasonic shot peened ones. For a given alloy, both methods result in a similar location of the subsurface compressive residual stress maximum as well as comparable penetration depths. For Ti6246, the penetration depth is lower than for Ti64 as shown in Figure 5 and Figure 6

Figure 5. Residual stress measurements Ti64.

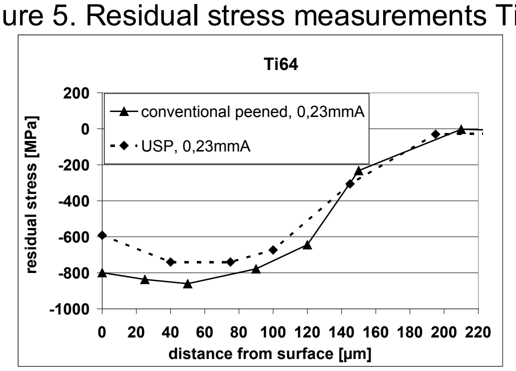
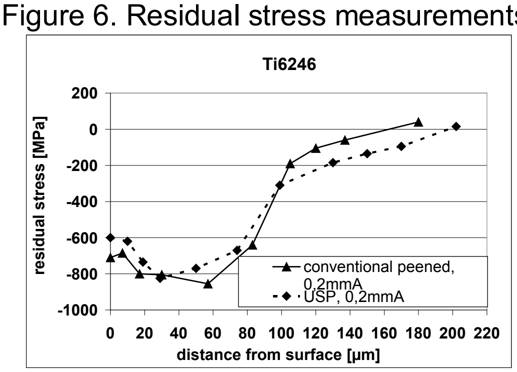


Figure 6. Residual stress measurements.



LCF Fatigue Life

For Ti64, ultrasonic shot peening and conventional shot peening lead to higher LCF life compared to the unpeened condition indicated by the fatigue results at 0.9% strain range. The peening benefit of ultrasonic shot peened specimens is lower than for conventional shot peened specimens if both are tested at high strain ranges. For lower strain ranges, the resulting LCF life is comparable (see Figure 7). SEM investigations show surface failures for the unpeend (Figure 8) and the ultrasonic shot peened specimens at high strain ranges (Figure 9). At lower strain ranges, conventional shot peening (Figure10) and ultrasonic shot peening (Figure 11) result in a shift of the crack initiation site from the surface to subsurface regions.

Figure 7. LCF test results Ti64.

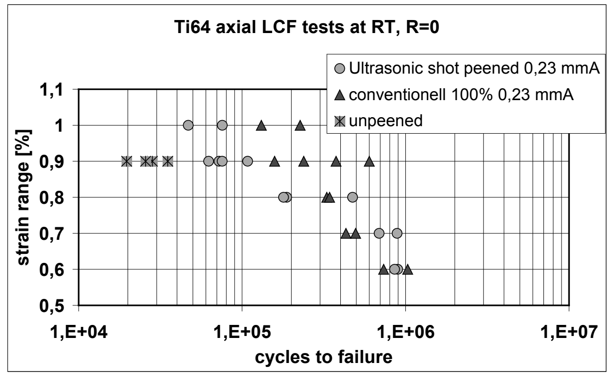


Figure 8: unpeened

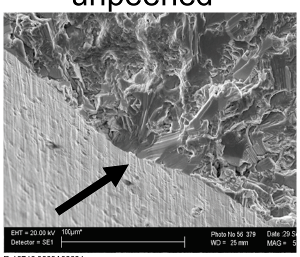


Figure 9: USP (high strain rate)

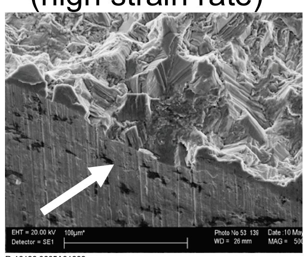


Figure 10: conv. shot peened

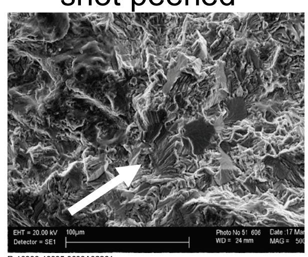
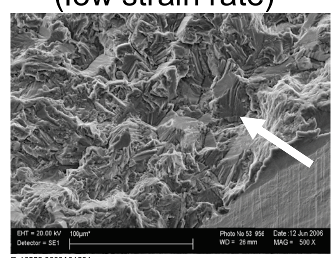


Figure 11: USP (low strain rate)



For Ti6246, conventional shot peening leads to LCF lives under rotating bending significantly higher than that of the unpeened condition. Ultrasonic shot peening still gives a life benefit compared to the unpeened condition but exhibits significantly lower LCF lives than conventional shot peening (Figure 12). Crack intitiation sites at the surface were detected by SEM investigations for all unpeened specimens (Figure 13). For ultrasonic shot peening, crack inititation sites were observed at both locations, surface and subsurface (Figure 14, 15). Conventional shot peening (Figure 16) generally shifted the crack initiation to subsurface regions.

Figure 12. LCF rotating bending at RT Test results Ti6246.

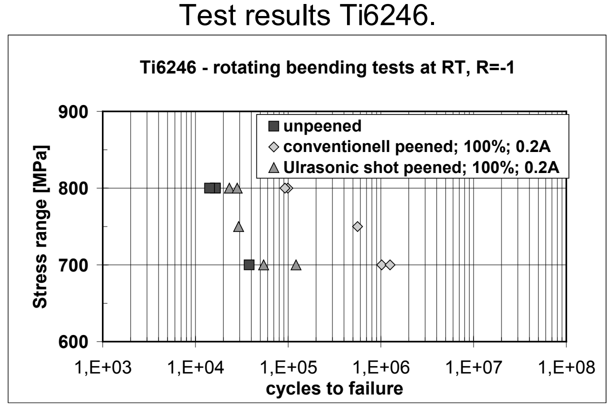


Figure 13: unpeened

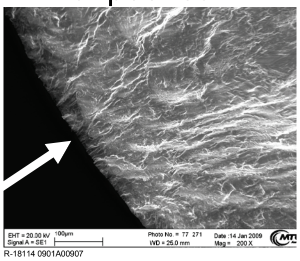


Figure 14: USP surface failure

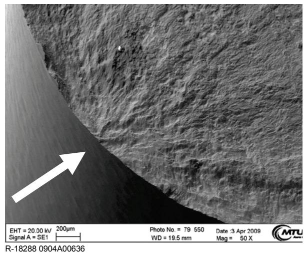


Figure 15: USP subsurface failure

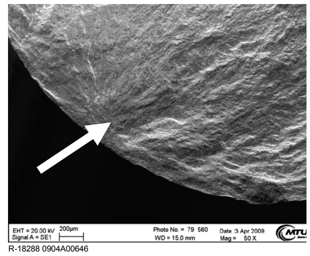
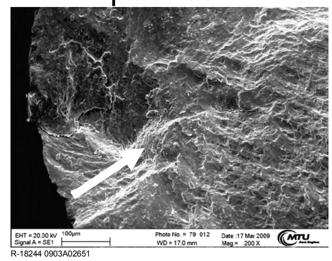


Figure 16: conv. shot peened



HCF Fatigue Life – Comparison of glass peening and ultrasonic shot peening

Shot peening of Ti64 gives similar HCF life for conventional glass peening and Ultrasonic shot peening. In case of Ultrasonic shot peening with a high Almen intensity value, the scatter can be reduced.

Compared to the unpeened surface condition, all tested peening processes and Almen intensities show an increase of the HCF life about one magnitude.

SEM investigations indicate surface failures for the unpeened condition and subsurface failures for all peened specimens (Figure 18, 19, 20).

Figure 17. HCF Test results Ti64.

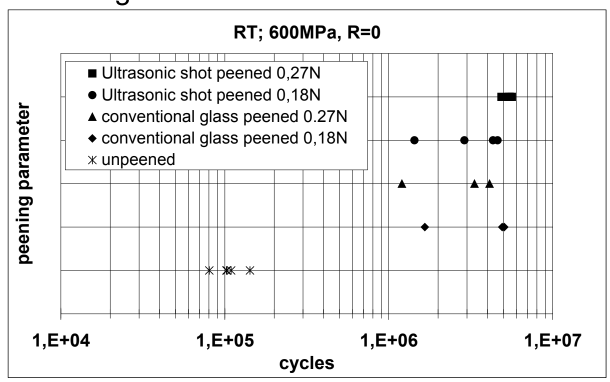


Figure 18: unpeened

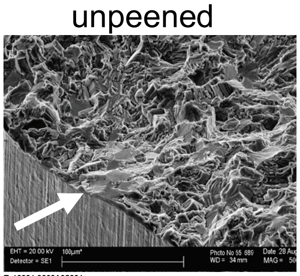


Figure 19: conv. glass peened

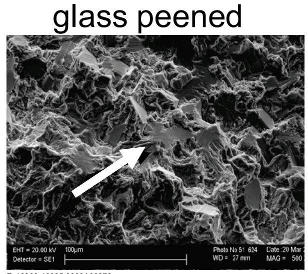
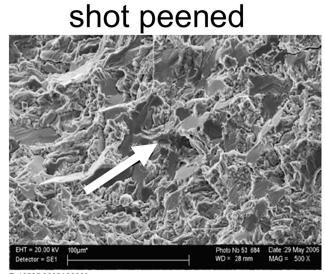


Figure 20: Ultrasonic shot peened



Shot peening of Ti6246 also leads to similar resulting HCF life for conventional glass peening and Ultrasonic shot peening. Compared to the unpeened surface condition specimens peened with the higher Almen intensity show a slightly improved HCF life whereas peening with low Almen intensity leads to HCF life which is more or less comparable to unpeened surfaces (Figure 21).

SEM investigations indicate surface failures for the unpeened condition and subsurface failures for all peened specimens (Figure 22, 23, 24).

Figure 21. HCF Test results Ti6246.

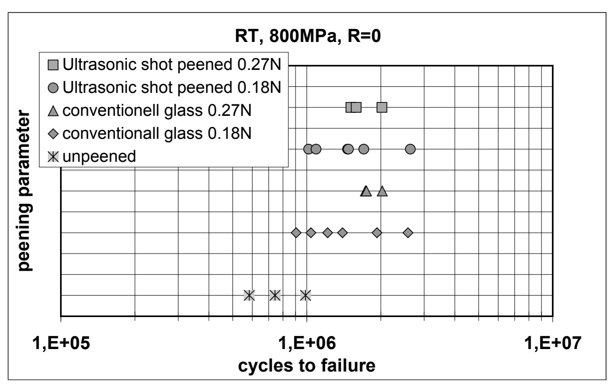


Figure 22: unpeened

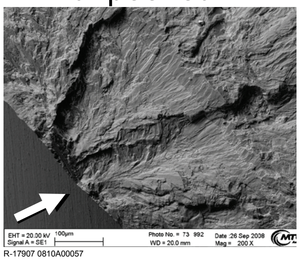


Figure 23: conv. glass peened

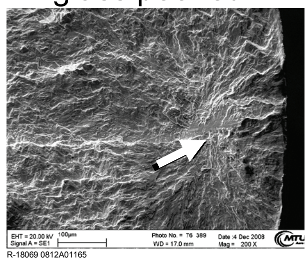
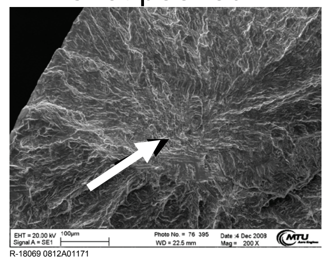


Figure 24: Ultrasonic shot peened



Discussion and Conclusions

Conventional shot peening leads to higher surface roughness and higher resulting compressive residual stresses at the surface than Ultrasonic shot peening using same Almen intensity. This characteristic can be shown for Ti64 as well as for Ti6246. The location of the compressive residual stress maximum under the surface as well as the penetration depth is comparable for both methods.

The lower surface roughness and penetration depth for Ti6246 compared to Ti64 can be explained by the lower deformation resistance of Ti64.

The resulting LCF life of peened surfaces depends on the pening process. Conventional shot peening leads to higher LCF life than for the unpeened condition of the same alloy for all tested almen intensities. SEM investigation show that conventional shot peening is able to shift the crack initiation from the surface to the subsurface region. Therefore crack initiation occurs under vacuum giving a substantial contribution to life improvement. Additionally, life extension due to crack growth under vacuum must be considered. For ultrasonic shot peened Ti64 specimens this behavior takes place only at low strain rates, while at higher strain rates crack initiation occurs again at the surface results in lower LCF life. Ti6246 specimens with ultrasonic shot peened surface condition exhibits lower LCF life compared to specimens with conventional peened surface.

The resulting HCF life for peened specimens is comparable for both investigated peening processes. The life benefit of peened Ti64 specimens is nearly one magnitude. Ti6246 specimens hardly show a life improvement for both shot peening methods. This difference to Ti64 may be explained by less sensitivity of Ti6246 to crack initiation at laboratory air.

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