Coverage and Peening Angle Effects in Shot Peening on HCF Performance of Ti-6Al-4V

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Abstract
Shot peening of titanium alloys is known to enhance the HCF performance by inducing in near-surface regions residual compressive stresses and increasing the dislocation density.
The present work aimed at studying the effect of coverage and peening angle effects in shot peening on cyclic fatigue performance on Ti-6Al-4V.
For shot peening a soft and hard type of cast steel shot and a comparable size conditioned cut wire shot have been used.
The coverage was varied from 20 % to 1200 % and the peening angle from 90 to 30°. Fatigue performance of shot peened rotating- and alternating-bending fatigue specimens was studied.
The results indicate that low (20%) coverage peening leads to a loss whereas full (100 %) up to a high (1200 %) coverage was found to result in a marked increase in HCF strength.
The variation of peening angles resulted in a significant beneficial effect on the fatigue performance in direction to increasingly flat angles and high coverages (1200 %) at constant Almen intensities of 0,20 mmA.
These results are even more interesting as those peened surfaces resulted in the highest surface roughness and a topography with a starting waviness.

Key Words – Shot Peening, Cyclic Fatigue, Impact Angle, Ti-6Al-4V, Waviness

Introduction

Ti-6Al-4V is a widely used Ti-alloy in aerospace industry and many of the components made from this are shot peened to increase the cyclic fatigue performance.
Nearly all existing fatigue data of shot peened components are based on the "idealized" conditions of ≥ 100 % coverage and an impingement angle of 90°. But due to complex geometries or the repeating repair of several of these components or areas it cannot be avoided that some of these surfaces will or must be shot peened with a much wider range of coverage and/or impingement angles.
Target of this work was to investigate the effect of shot peening with realistic ranges of coverage and impingement angles on the HCF performance of the Ti-6Al-4V material.

Material & Experimental Methods

Ti-6Al-4V was received as cylindrical rods Ø 12.7 mm. The used material was Grade 5 (3.7165) fulfilling the material specifications ASME SB348, ASTM B348, UNS R56400.

<u>Hour-glass samples for coverage investigations</u>
For fatigue testing the 20, 100 and 1200 % coverage, hour-glass shaped specimens (6 mm minimum cross diameter) were machined. Electrolytically polished (EP) and mechanically polished (MP) conditions were used as references to which the shot peening at various coverage degrees were compared. EP was done to remove about 100 μm from the as-machined surface to exclude any machining effects that could have masked the results. During MP, a surface layer of about 50 μm was removed from the as-machined surface resulting in the same smooth surface condition as observed in EP condition.
Fatigue tests were performed in load controlled rotating beam loading (R = -1) in air at a frequency of 50 s-1.

Flat-shaped samples for impingement angle investigations
For the testing of the 90, 60, 45 and 30 degrees impingement angle at 100 and 1200 % coverage flat-shaped fatigue samples have been machined and shot peened. The fatigue testing was carried out in a load-controlled fatigue machine where the force on the flat specimen is applied by a cam and linkage (R = -1) in air at a frequency of 8 s^{-1}.
All Specimens were considered as run outs after 10^7 cycles.

Shot Peening
Shot Peening was carried out using a direct pressure blast system using a single nozzle.

Three peening medias were used for this study: SCCW14, ASR110 and ASH110 with an average diameter of 0.35 and 0.3 mm (Fig. 1).

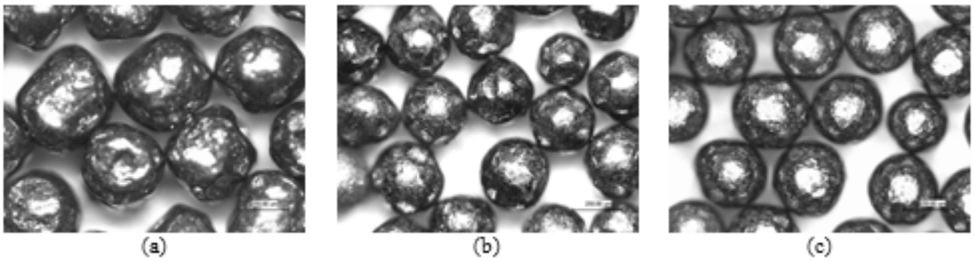

Fig. 1: Magnification (200x) of the shot material (a) SCCW14, (b) ASR110 and (c) ASH110

The target Almen intensity for all samples was 0.20 mmA.
Only exception in terms of used Almen intensity was the 30 degrees flat-shaped fatigue sample with a maximum shot peening intensity of 0.16 mmA limited by the maximum available pressure in the specific machine configuration.

All three coverage degrees (20, 100, 1200 %) and impingement angles (90, 60, 45, 30 degrees) represent occurring values in the industry e.g. in areas with very low coverage rates in opposition to areas with e.g. ricochet peening or complicate geometries where coverage rates > 1000 % and low impingement angles can be reached.

To produce 20 % coverage a rotating disc with a slit was used in between the nozzle and the sample ensuring that only for a short time a low amount of shot particles with the appropriate speed was impacting the surface of the rotating hour-glass shaped fatigue sample.

Experimental Results

Hour-glass shaped fatigue samples

Surface roughness
The roughness of all shot peened samples was increased in comparison to the electropolished (EP) and mechanically polished (MP) condition. The highest value was reached by using the SCCW14 at 1200 % coverage.

Fatigue:
The results of the fatigue tests (Fig. 2) confirm the experience [1] that the lowest performance in HCF fatigue can be seen in all samples peened with low coverage of 20 % followed by the stress-free EP condition. All versions covered with 100 % resulted in the highest fatigue performance. The Lowest fatigue strength at 20 % coverage showed the ASR110 with -15 % to the EP fatigue level followed by ASH110 and SCCW14 shot. On the upper side the SCCW14 showed the highest increase with +13 % followed by the ASR110 and the ASH110 in comparison to the EP level of 650 MPa. The obvious decrease of fatigue performance of the 20 % covered samples can be explained by the insufficient residual

compressive stress fields which cannot compensate the early crack initiation caused by the high roughness especially around single shot indents.

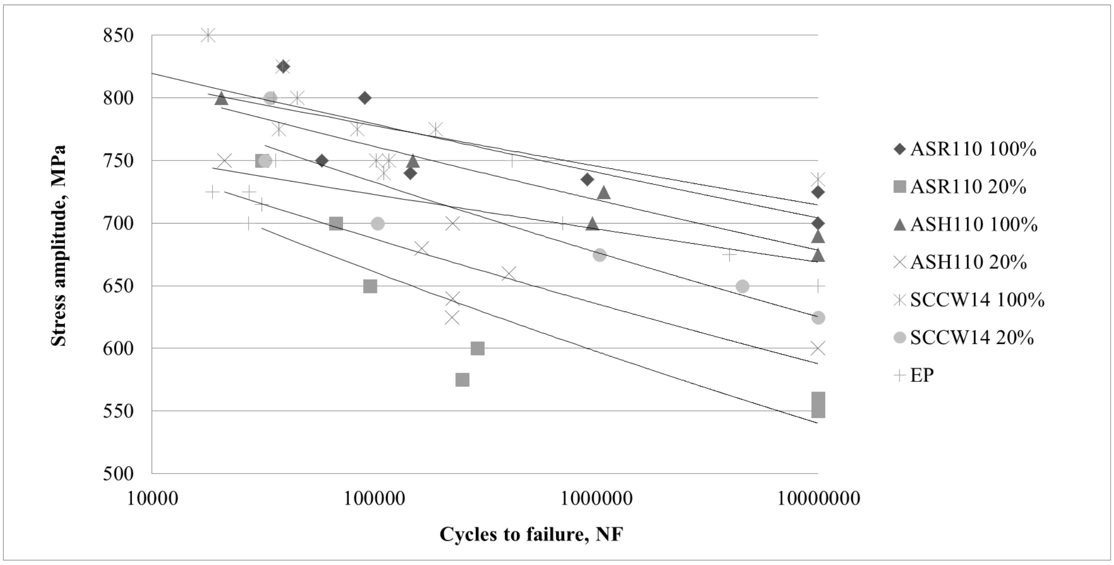

Fig. 2: S-N curves of the fatigue probes in different treatment conditions

Flat-shaped fatigue samples
A complex geometry of a workpiece can lead to a wide range of impact angles others than 90 degrees. Most aircraft and engine manufacturers [12-13] are limiting the angles in a range of 90 to 45 degrees whereas the SAE J443 [9] reduces the lowest possible angel of impact to a minimum of 30 degrees.
For this reason 4 different impact angles (90, 60, 45, 30 degrees) have been investigated in terms of resulting surface topography (roughness, waviness) and fatigue performance.
Important to notice is that for the trials on the flat-shaped fatigue samples peened with different peening angles the pressure was increased with lower angle of attack to keep the Almen intensity to or as close as possible to the target of 0.20 mmA.

Surface roughness/waviness:
Fig. 3 shows the results of roughness over the 4 impact angles at 100% and 1200 % coverage.

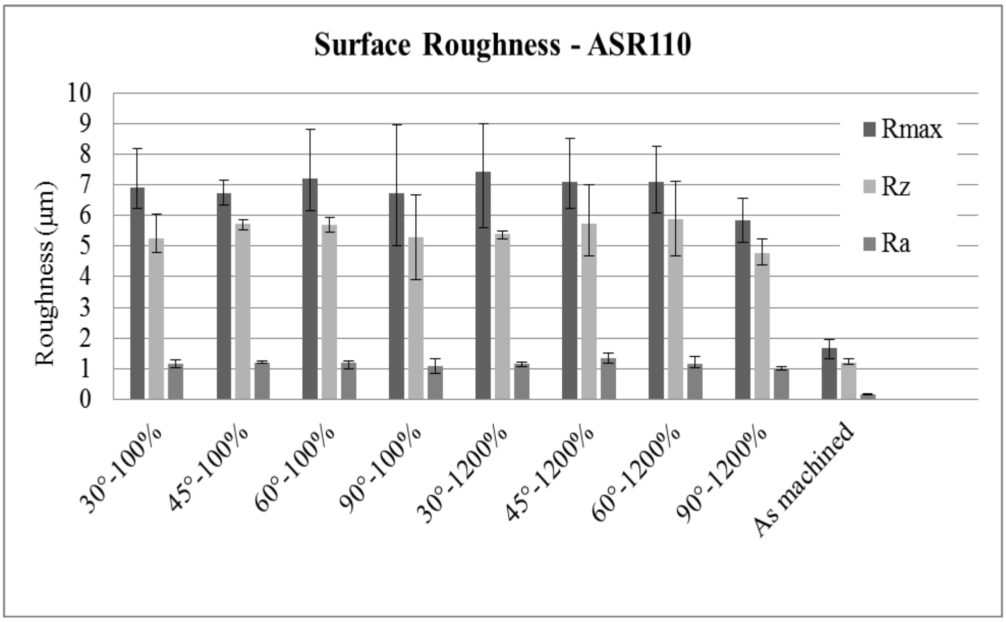

Fig. 3: Surface roughness of the various conditions

Beside the increased roughness with lower impact angles and increased coverage rates the samples showed a parallel increase of waviness which is obviously caused by the pushing movement of the material along the impact direction of the shot. Further amplifier for this deformation and material moving effect is the increasing shot speed at lower impact angles to keep the targeted Almen intensity at the same level.
This waviness has its visual and measured maximum at 45 degrees and coverage of 1200 % (see Fig. 4 and Table 1).

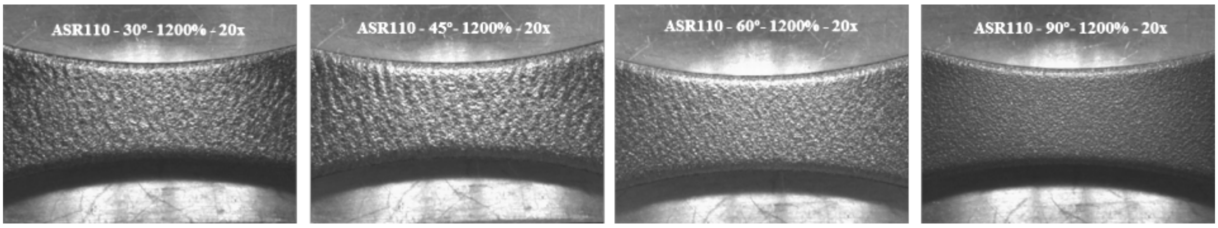

Fig. 4: Magnification (20x) of flat fatigue samples with different impact angles at 1200% coverage

Table 1: Waviness [Wt] of flat-shape fatigue samples with different impact angles

Impact angle [degrees]	Waviness [Wt in µm]	
	100 % coverage	1200 % coverage
90	2.50	3.25
60	2.53	5.93
45	5.00	13.67
30	3.71	6.15

Fatigue:
The results of the fatigue tests on the flat-shape samples can be seen in Fig. 5 for 100 % and 1200 % coverage over the 4 different investigated impact angles.

(a) (b)

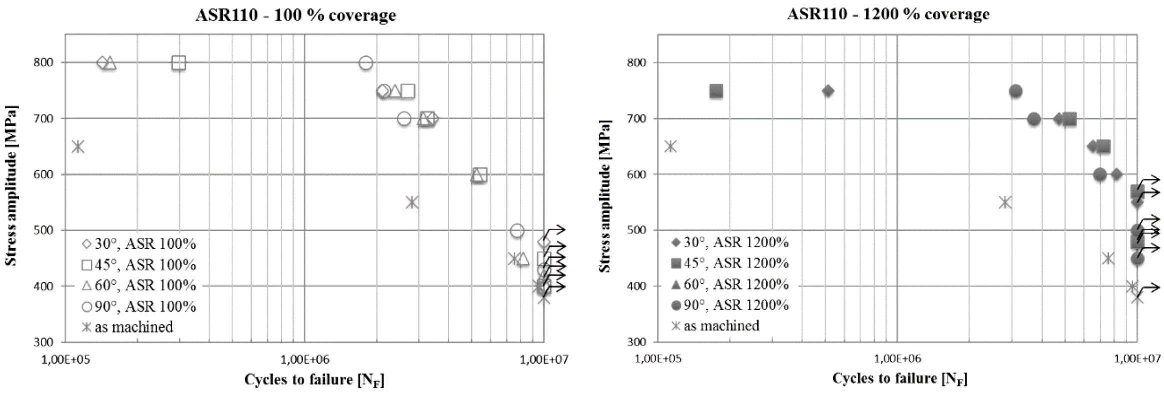

Fig. 5: S/N curves of the flat fatigue probes in the SP condition using ASR110 at 90, 60, 45, 30 degrees impact angle at (a) 100 % and (b) 1200 % coverage

All shot peened samples showed an increase in fatigue performance in comparison to the as machined condition. The samples with 1200 % coverage result in the highest increase.
Looking on the different impact angles the largest improvement can be found at an angle for 45 degrees at 1200 % coverage – but also the 30 degrees impact angle shows a significant increase even so the shot peening intensity here was due to machine reasons lower than for all other investigated impact angles.

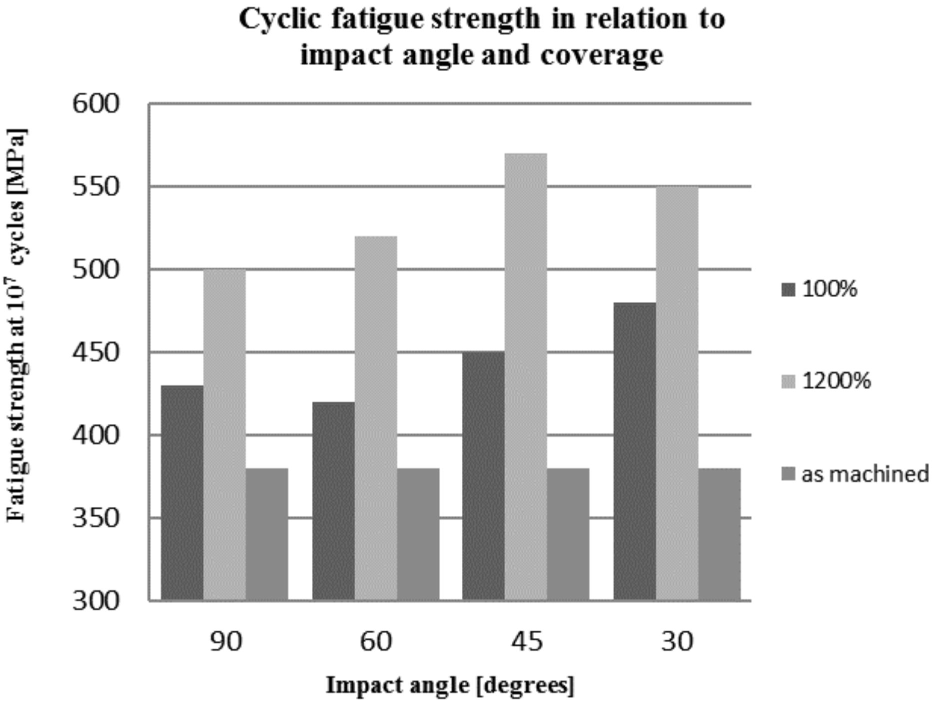

Fig. 6: Cyclic fatigue strength of the flat bending fatigue sample in relation to shot peening impact angle and coverage treated with ASR110

Fig. 6 shows that especially for the high coverages all impact angles smaller than 90 degrees show a larger increase in fatigue strength with a maximum at 45 degrees resulting in a 14% higher value than the shot peened version with same coverage at 90 degrees impact angle and 50 % higher strength than the as machined condition.

This result stands in contradiction to the increased roughness but especially the significant increased waviness (Table 1) caused by the shear plastic flow of the material at lower impact angles.

A possible explanation for the consistent fatigue performance at different impact angles is presumably the targeted constant Almen intensity kept by adjustment of air pressure and the resulting shot particle speed. The resulting compressive stress, dislocation density and material flow in the close surface area under shear plastic loading seems to induce comparable or even higher residual compressive stresses and dislocation densities which are retarding the growth rates of surface cracks increase the resistance to fatigue crack initiation (Fig. 7).

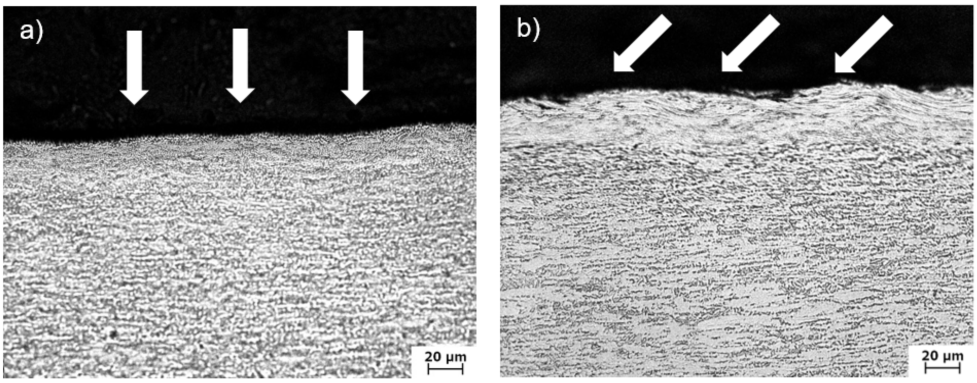

Fig. 7: Microsection of the flat bending fatigue samples shot peened with (a) 90 degrees and (b) 45 degrees

Conclusions

Shot peening increased the surface roughness compared to the reference as-machined conditions. However, the roughness values were still lower than the allowed roughness values as specified by many aerospace shot peening specifications.

Low coverage (20 %) resulted in a significant loss of fatigue performance. High coverages (1200 %) showed in the most cases a slight increase of roughness values and induced compressive residual stresses.

On the flat bending fatigue probes the highest fatigue strength was found with an increasing amount for the high coverages (1200 %) in direction to smaller impact angles than 90 degrees. Significantly increased fatigue strength values have been found for 45 degrees impact angle and 1200 % coverage although theses samples showed the highest roughness values and surface waviness.

The waviness causing deformation of the surface material texture orientated 90 degrees to the preferred cracking direction seems to be a further fatigue improving factor beside the well-known effects of residual compressive stress and increased dislocation density due to the shot peen treatment. Within the investigated range of shot peening intensities and coverages the resulting roughness and waviness seems to be a negligible detrimental factor for the resulting fatigue performance.

In all cases SP led to a marked improvement in the fatigue life compared to the EP and MP conditions. Using different SP media had no significant effects on the resulting fatigue life even a slight better fatigue performance can be seen using cut wire in comparison to cast steel shot.

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