XXX International Conference on
Surface Modification Technologies (SMT30)

29TH JUNE - 1ST JULY, 2016, MILAN, ITALY

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 which can drastically retard the growth rates of surface cracks. In addition, the induced high dislocation densities may increase the resistance to fatigue crack nucleation while the typically accompanied high surface roughness has the opposite effect. The present work aimed at studying the effect of coverage and peening angle effects in shot peening on fatigue crack nucleation and micro-crack growth. The coverage was varied to a wide extent ranging from 20% to 1200% and the peening angle from 90 to 30 degrees. Fatigue performance of shot peened rotating bending hour-glass shaped and flat bending fatigue specimens was studied and compared to an electrolytically polished or machined reference. The results indicate that low (20%) coverage peening leads to a loss in HCF strength presumably, caused by insufficient residual compressive stress fields which cannot compensate the early crack nucleation caused by the high roughness. In contrast, full (100%) up to a high (1200%) coverage was found to result in a marked increase in HCF strength. The variation of peening angles was investigated by keeping the Almen intensity to the same level which resulted in a clearly induced surface waviness at impact angles <90 degrees. HCF fatigue results over all impact angles at full and high coverage showed no significant differences.

Keywords: Ti-6Al-4V; HCF Fatigue; Coverage; Shot Peening; Roughness; Shot Hardness; Impact Angle

Introduction

The α+β Ti-6Al-4V is widely used in aerospace industry, specially aero engine components like blades, disks, drums or state of the art blisks. Shot peening is a common and broadly used post-surface treatment that increases the overall fatigue performance and/or eliminates the detrimental effects or variances caused by the manufacturing processes. Shot peening induces compressive residual stresses in near-surface regions that can drastically retard the growth rates of fatigue cracks [1]. In addition, the induced high dislocation densities may increase the resistance to fatigue crack nucleation while the typically accompanied high surface roughness can have the opposite effect.

Fatigue performance of metallic parts can be markedly influenced by coverage degree in shot peening (SP) [2], [3], [4]. Low coverage degrees (<< 100%) led to fatigue lives even lower than in the untreated electropolished reference condition [5]. These results were explained by residual compressive stresses being not fully developed at low coverage degrees and, therefore, were not able to compensate the early fatigue crack nucleation caused by the high induced surface roughness from the shot peening process. The fully developed residual compressive stresses in minimum 100% coverage were then seen to drastically reduce micro-crack growth by which the early fatigue crack nucleation was much overcompensated leading to marked enhancements in the overall fatigue life.

Present work aims investigating the effects either of a realistic coverage of 20, 100 and 1200% and different impact angles of 90, 60, 45 and 30 degrees that can occur on Ti-6Al-4V aerospace parts within shot peening in

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new manufacturing and/or following maintenance, repair and overhaul (MRO) treatments applied during the lifetime of such a component.

Material & Experimental Metods

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. The chemical composition and tensile properties are listed in Tables 1 and 2.

Table 1: Chemical composition

Element	Al	Cu	Fe	Mo	Ni
wt.%	6.68	<0.005	0.1581	<0.01	0.0115
Element	Si	Sn	V	Zr	Ti
wt%	0.0115	<0.01	4.114	<0.003	89.0

Micrographs of the α+β Ti-6Al-4V are showing typical globular microstructure with no marked texture (Figure 1). The tensile properties are listed in Table 2.

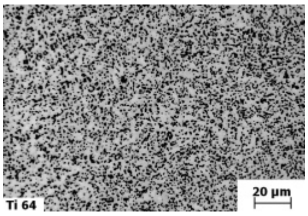


Fig. 1: Micrograph of the globular microstructure

Table 2: Tensile properties

Rp0.2 [MPa]	Rm [MPa]	A [%]	E [GPa]
990	1035	17.4	101

For fatigue testing the 20, 100 and 1200% coverage, hour-glass shaped specimens (6 mm minimum cross section diameter) were machined (Figure 2(a)). 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 were removed from the as-machined surface resulting in the same very smooth surface condition as observed in EP condition.

Fatigue tests were performed in stress controlled rotating beam loading (R = -1) in air at a frequency of 50 s^{-1}.

For the testing of the 90, 60, 45 and 30 degrees impact angle at 100 and 1200% coverage flat shaped fatigue samples (Figure 2(b)) have been machined and shot peened. The fatigue testing was carried out in a stress 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.

(a) (b)

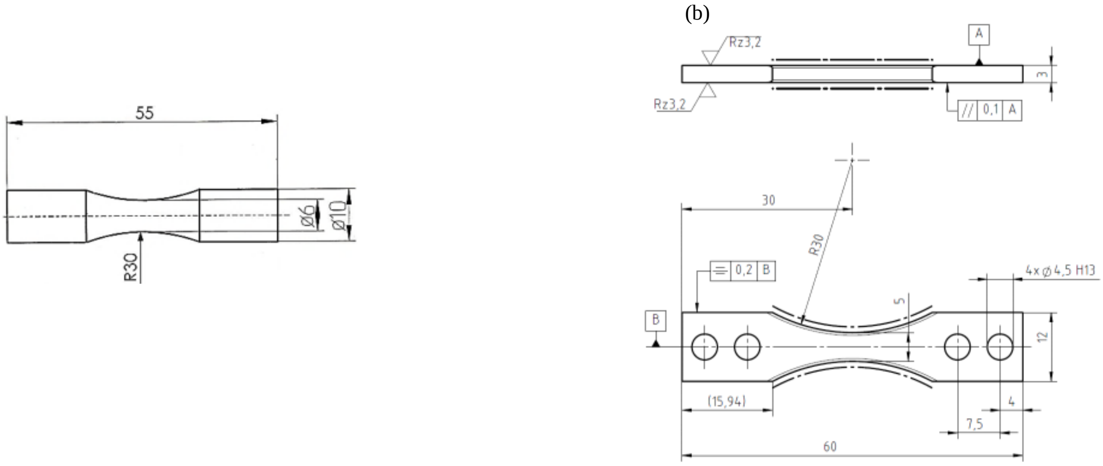


Fig. 2 : (a) Hour-glass shaped fatigue sample; (b) flat shaped fatigue sample

Shot Peening

Shot Peening was carried out using a direct pressure blast system at an angle of attack close to 90 degrees from horizontal for the hour glass shaped fatigue samples and with 30, 45, 60 and 90 degrees for the flat shaped fatigue sample. Three peening media were used for this study: SCCW14, ASR110 and ASH110 with an average diameter of 0.35 and 0.3 mm, respectively. The chemical composition of the thee shot media are listed in Table 3.

Table 3: Chemical composition of peening shots

Shots type	Chemical composition [wt.%]	Average diam. [mm]	Hardness [HV0.3]	Density [g/cm^3]
SCCW14	0.57 C, 0.67 Mn, 0.22 Si; P, S $\leq$ 0.25	0.35	675	7.8
ASR110	1.02 C, 0.5 Mn, 0.41 Si; P, S $\leq$ 0.03	0.3	500	7.5
ASH110	1.09 C, 0.48 Mn, 0.51 Si; P, S $\leq$ 0.025	0.3	652	7.5

The microscopic pictures of all three shot are shown in Figure 3. The micrographs reveal the perfect circular shape of the ASR110 and ASH110 shots compared to SCCW14 shots. This visual difference in roundness results from the different manufacturing methods.

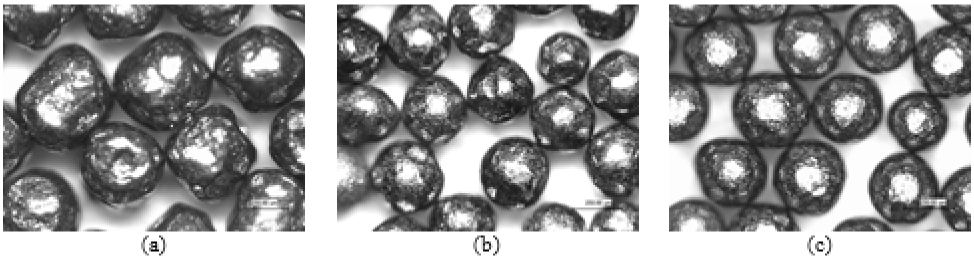


Fig. 3: Magnification (200x) of the (a) SCCW14, (b) ASR110 and (c) ASH110

The target Almen intensity for all samples was 0.20 mmA which represents a very common intensity for the present shot size and materials to be applied on aerospace components made of Ti-6Al-4V. The Almen intensity was set-up in accordance to the SAE J443 [6], [7] by using a saturation curve solver software.
Only exception in terms of Almen intensity was the 30 degrees flat shaped fatigue sample (Table. 4) with a maximum intensity of 0.16 mmA limited by the maximum available pressure in the machine configuration.

Table 4: Impact angle in relation to pressure and Almen intensity for shot typeASR110

Impact angle [degrees]	Pressure [bar]	Almen intensity [mmA]
90	3	0.20
60	4.7	0.20
45	6.7	0.20
30	7.5 (max available pressure)	0.16

Peening was carried out at two coverage degrees of 100% and 1200% on the flat shaped fatigue samples and a third 20% coverage on the hour glass shaped rotating bending fatigue samples. All three coverage degrees of 20%, 100% and 1200% represent actually occurring values in the industry e.g. in overspray areas with very low coverage rates in opposition to areas with e.g. ricochet peening or complicate geometries where coverage rates > 1000% can be reached. Coverage is defined in accordance to the SAE J227 [8] as the percentage of a surface that has been intended at least once by the peening media. “Full coverage” is therefore defined as being at least 98% denting of the surface to be peened. This full coverage is in the industry and also within this paper usually called 100% coverage. Based on the peening time to reach 100% coverage this time was multiplied by the factor 12 for 1200% coverage.
For the production of 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. The microscopic picture of the surface was transferred in a black and white picture to calculate and assure the target coverage of 20% (+/- 5%) (Figure 4).

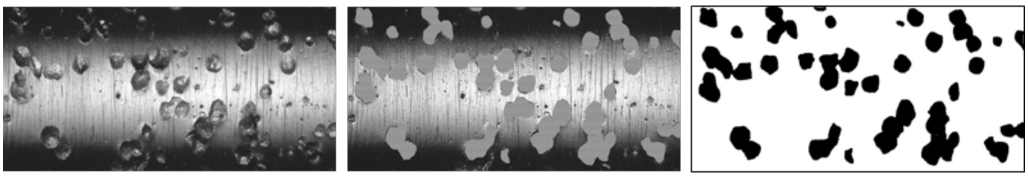


Fig. 4: Coverage determination procedures

Results

Hour glass shaped fatigue samples

Surface roughness:

Figure 5 shows the roughness in the EP, MP, as machined and the three different coverage conditions for all three shot types. The as machined value with a roughness of Ra 0.52 stays clearly lower than the maximum allowed Ra 1.6 specified in the most shot peening specifications [10], [11] before SP operation, issued by some leading aero engine manufacturers. The values in the SP condition were measured for both shot materials at 20%, 100% and 1200% coverage. Interesting to note are the higher roughness values of the ASH110 and even slightly more the SCCW14 shot using the same intensity as the ASR110. Reason for this is most likely the higher hardness of both shots and additional lower roundness (see Fig. 3) of the cut wire material (see Table 3) in comparison to the regular cast steel shot.

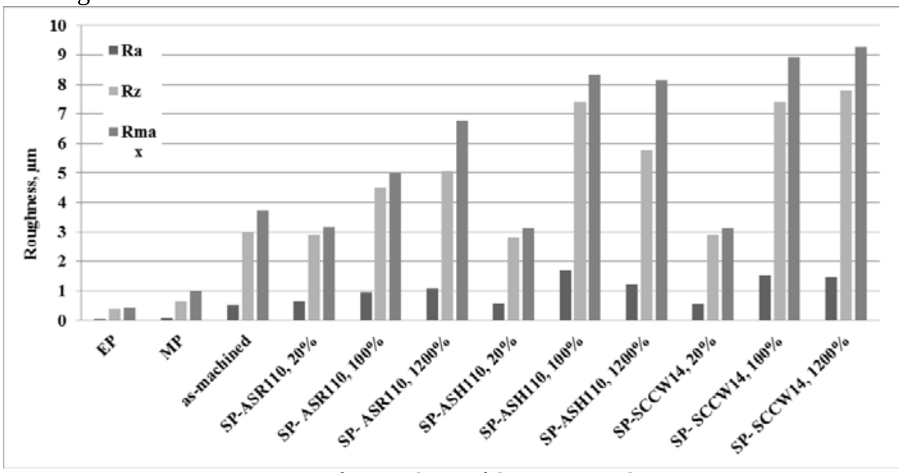


Fig. 5: Surface roughness of the various conditions

Fatigue:

The results of the fatigue tests 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 650MPa. 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 nucleation caused by the high roughness especially around single shot indents. Such a crack nucleation can be seen in Figure 7. In contrast, full (100%) coverage was found to result in a marked increase in HCF strength. This is explained by inducing near-surface regions residual compressive stresses which can drastically retard the growth rates of surface cracks. In addition, the induced high dislocation densities may increase the resistance to fatigue crack nucleation.

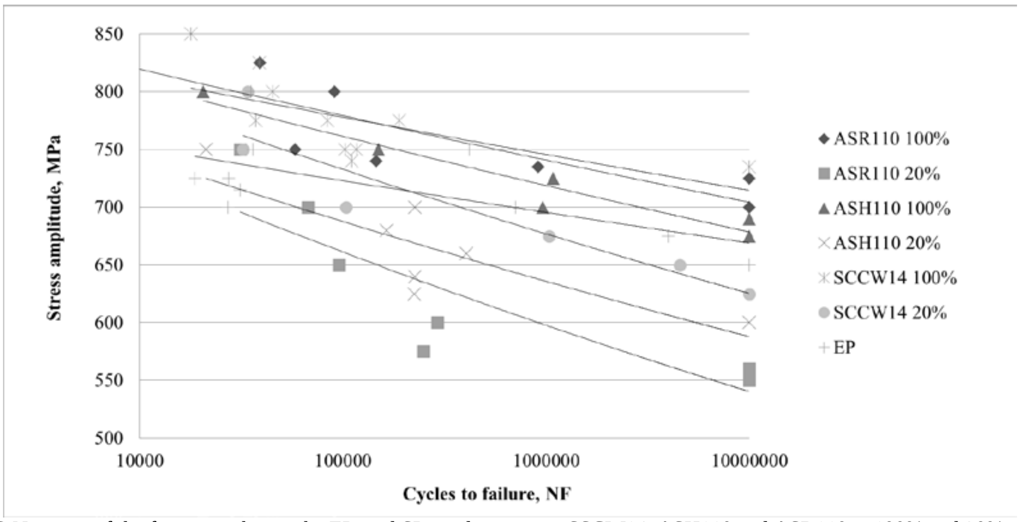


Fig. 6: S-N curves of the fatigue probes in the EP, and SP condition using SSCW14, ASH110 and ASR110 at 100% and 20% coverage

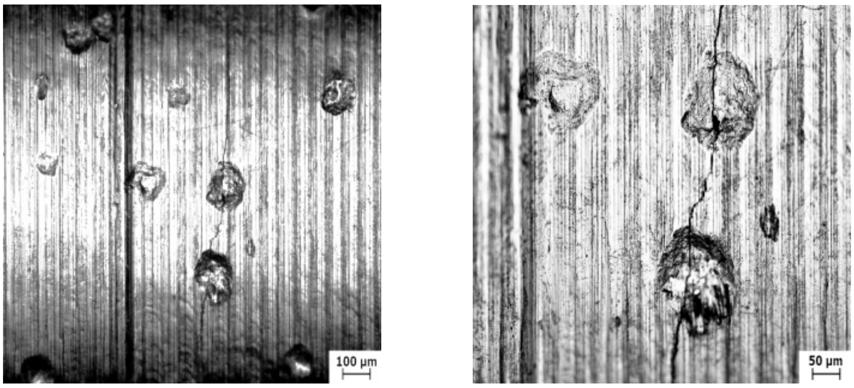


Fig. 7: Crack initiation from a single impact on the sample with 20% coverage

Flat shaped fatigue samples

Beside the variation of shot peening coverage a complex geometry of a workpiece (e.g. aero engine turbine disk or drum) can lead to a wide range of impact angles others than the ideal 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.
This is the background for the 4 different impact angles (90, 60, 45, 30 degrees) investigated in terms of resulting surface topography (roughness, waviness) and fatigue performance. The fatigue samples are described in Fig. 2(b).
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 0.20mmA. The increase of pressure and by this the speed of the ASR110 shot is needed to compensate the loss of impact energy due to the lower impact angle.

<u>Surface roughness:</u>
Fig. 8 shows the results of surface roughness over the 4 impact angles at 100% and 1200% coverage. Lowest roughness is produced at 90 degrees and 1200% coverage. This is lower than with 100% coverage which suggests that this call-out leads to a smoothening effect with increasing coverage rate.
The lower impact angles are generally resulting in a higher roughness tending to slightly increased values at higher coverage rates. The samples with an impact angle of 30 degrees and 1200% coverage showed the highest roughness even the shot peening intensity was 0.16mmA and herewith 0.04mmA (-20%) lower than for the other samples. Reason behind was the limitation of available air pressure in the used machine set-up.

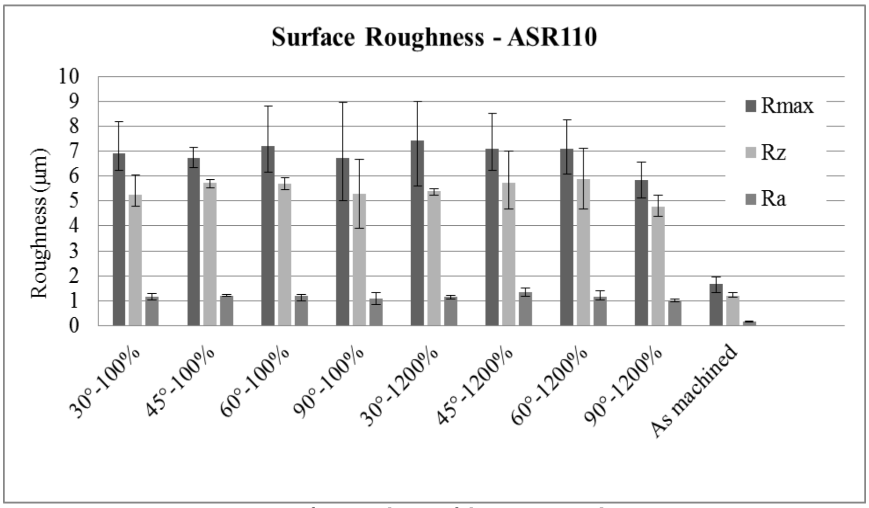


Fig. 8: Surface roughness of the various conditions

Beside the increased roughness with lower impact angles and increased coverage rates the samples showed a parallel increase of waviness (see Fig. 9) 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.

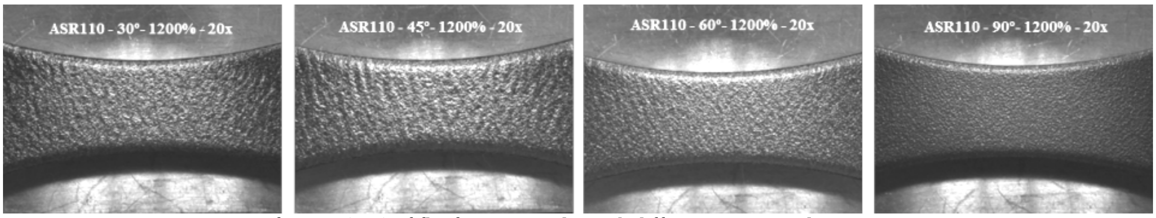


Fig. 9: Magnification (20x) of flat fatigue samples with different impact angles at 1200% coverage

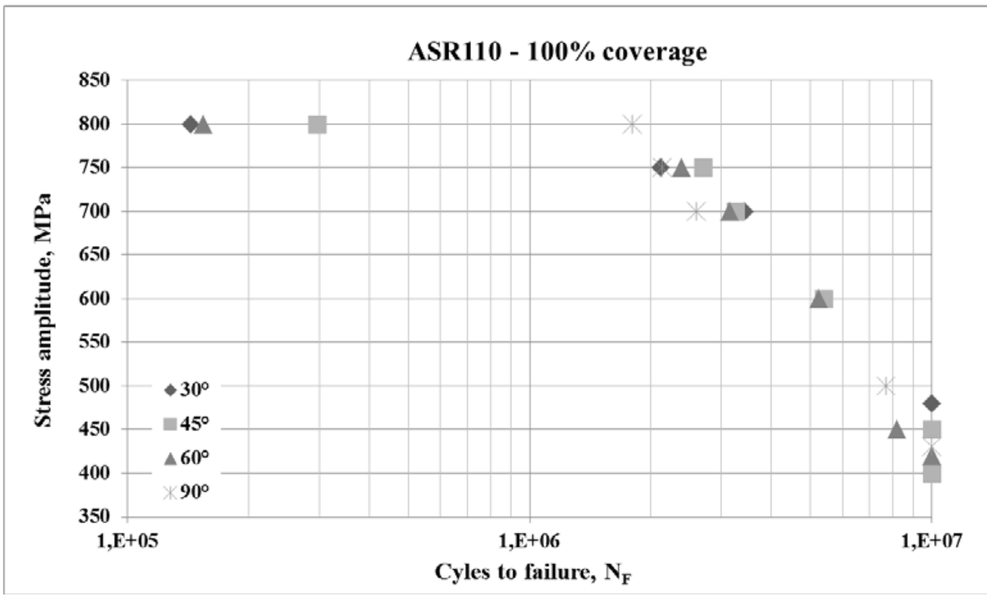
This waviness has its visual and measured maximum at 45 degrees and coverage of 1200% (see Fig. 9 and Table 5).
Due to the - caused by technical reasons - lower than targeted Almen intensity on the samples with 30º the resulting roughness and waviness must be considered separately.

Table 5: Waviness [Wt] of flat 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:
First results of the fatigue tests can be seen in Fig. 10. The samples with 1200 % coverage show a slightly increased fatigue performance whereas the results within the same coverage at different impact angles are showing a quite consistent performance. This result stands in contradiction to the increased roughness but especially the significant increased waviness (Table 5) and therefore material moving effects at lower impact angles.
A possible explanation for the consistent fatigue performance at different impact angles is presumably the adjustment of the targeted Almen intensity by control of air pressure and shot particle speed. The constant Almen Intensity at all impact angles (except for 30 degrees) makes sure that the same amount of impact energy for all impact angles is ensured. The resulting compressive stress and dislocation density - which will be investigated in the next future - seems to induce comparable residual compressive stresses and dislocation densities which are retarding the growth rates of surface cracks increase the resistance to fatigue crack nucleation.
The known negative effect of surface roughness and for lower impact angles additional waviness seems to be overcompensated by the beneficial compressive stresses and dislocation densities.

(a)



(b)

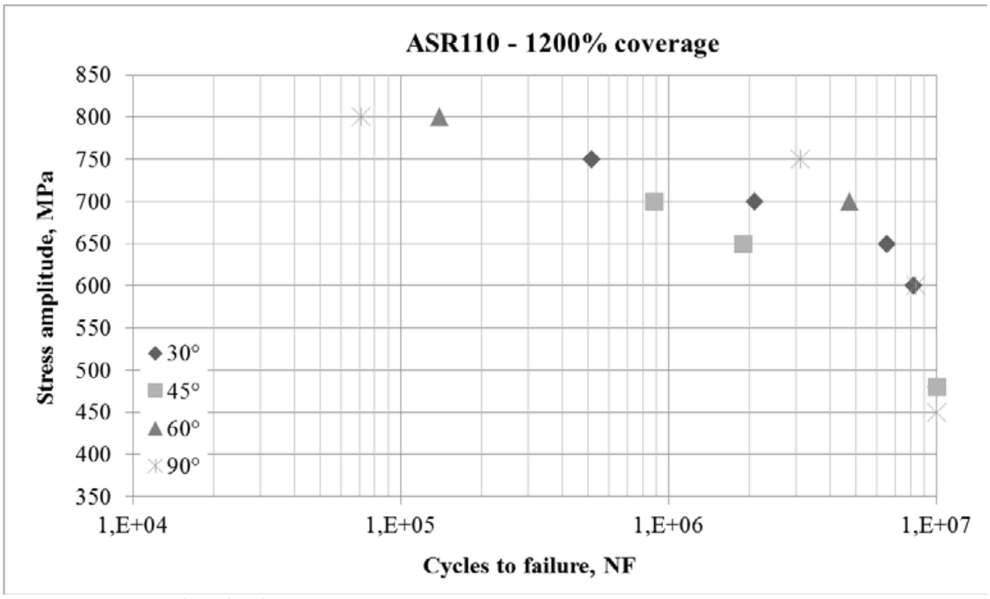


Fig. 10: S/N curves of the flat fatigue probes in the SP condition using ASR110 at 90, 60, 45, 30 degrees impact angle at (a) 100% and (b) 1200% coverage

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 SP 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 but no significant difference in fatigue behaviour. Even significantly increased roughness and creation of surface waviness under low impact angles resulted in consistent fatigue performances as long as the Almen intensity was kept to the same level.

Generally 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 shot.

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