Optimization of shot peening parameters on beta titanium alloy Ti10V-2Fe-3Al in order to improve fatigue behaviour

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Abstract
Shot peening is a mechanical surface treatment widely used in industry to improve the fatigue properties of components. It appears that the parameters of this process must be adjusted to new alloys and/or manufacturing techniques to reach even better fatigue properties. The purpose of this study is to determine the optimal shot peening conditions for the beta titanium alloy Ti10V-2Fe-3Al in order to optimize fatigue life, taking into account different machining conditions. This development was carried out during CONDOR project.

Keywords: Shot peening, Fatigue, beta titanium, Ti 10V-2Fe-3Al, fractography, surface roughness

Introduction

The near-β titanium alloy Ti 10V-2Fe-3Al is highly used in airframe forging applications such as landing gears and rotor systems. It's been widely demonstrated that the introduction of residual compression stresses near the surface through shot peening increases the components fatigue lifetime [1-3]. This process is widely used in industry. However today the parameters are not always adapted to the specific alloy. In particular, titanium alloys, which are generally used in aeronautical applications, are often shot peened like steel alloys. The aim of this study is to determine the optimal shot peening conditions for the titanium alloy Ti10V-2Fe-3Al in order to enhance fatigue properties.

Experimental Methods

Specimens of near-β Ti10V-2Fe-3Al presenting bimodal microstructure were machined from a 135mm diameter billet. A large fatigue test campaign was performed in order to determine the best parameters combination regarding fatigue lifetime. A Design of Experiment (DOE) was set up to take into account different initial surface conditions generated by 3 different sets of milling parameters (see table 1) as well as different shot peening parameters (size and hardness of shots, intensity and coverage - see table 2). The optimization of the DOE was performed by the statistical program minitab. This reduced the number of fatigue tests from 1100 to 245.

Table 1. Surface roughness after machining for the three conditions of study

Milling conditions	Roughness after machining (Ra)
A	0,8 µm
B	1,6 µm
C	3,2 µm

The 4-point bending fatigue tests were carried out at a frequency of 10 Hz at room temperature according to standard EN 6072 [4]. Three levels of fatigue were evaluated (R = 0.1): a level close to the endurance limit (HCF), a stress level above the elastic limit of the material (LCF regime) and an intermediate level. The condition for stopping the tests is $2x10^6$ cycles. The analysis of the results was carried out using the minitab statistical software. Afterwards, fracture surfaces of failed samples were analyzed to determine the failure mechanisms.

Table 2. Surface roughness after machining for the three conditions of study

Shot peening parameters	Values
Shot's size	AS 130 and AS 230
Shot's hardness	Regular (R) and High (H) hardness
Almen intensity	Low and High AI
Coverage	Low and High Cov

In addition, analyses were carried out to characterize roughness and residual stress profiles generated by shot peening. The 3D roughness parameters S_a, S_v, S_p and S_z were measured without cut off in a GT contour microscope from Bruker. Residual stress profiles were determined by ray diffraction using Cu-Kα radiation.

Experimental Results and Discussion

The test campaign results are shown in figure 1. To evaluate the impact of the different parameters on fatigue life, it was chosen to evaluate the residuals of each point compared to the minimum Wöhler curve. This curve is determined from the average Wöhler curve of all the tests of the experimental campaign, from which 3 times its standard deviation is withdrawn.

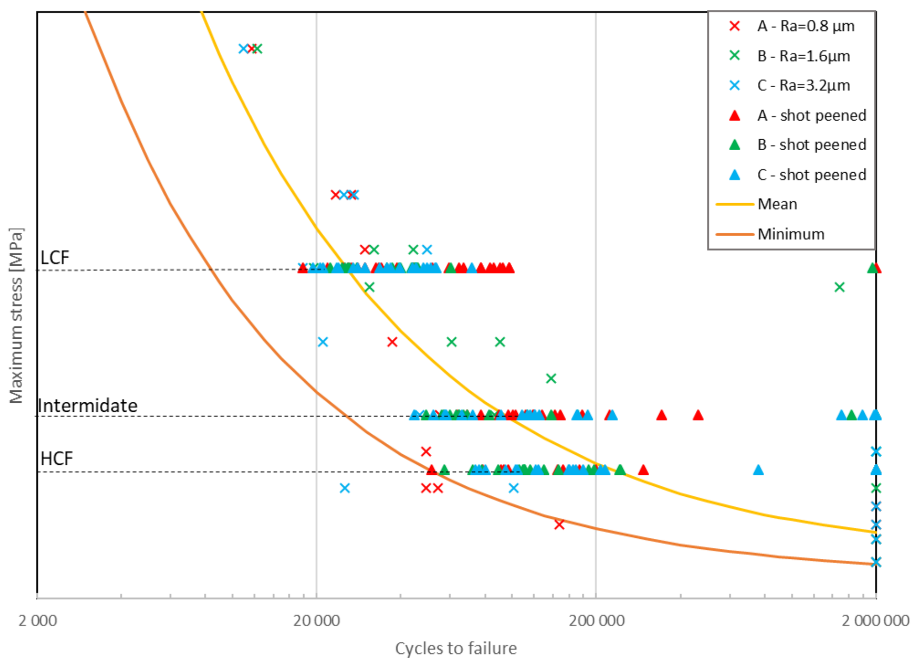
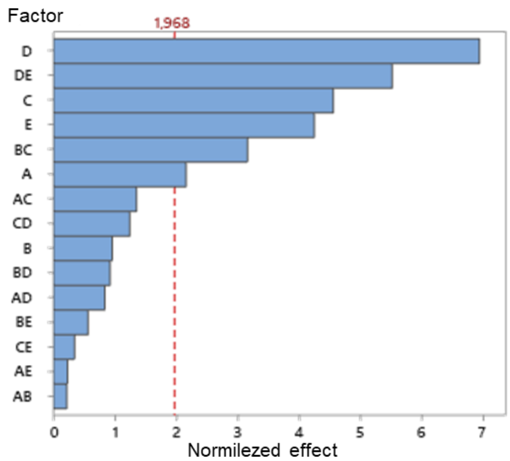


Figure 1. Fatigue results of all tested coupons (reference and shot peened following different conditions). This graph also displays the mean and minimum fit in S-N curves for fatigue data.

The Pareto diagram in figure 2 shows the effect of the different parameters on the fatigue life. All parameters with a normalized effect greater than 1,968 are considered to have a significant impact on the fatigue behaviour. This corresponds to the P value of the experiment plan using an alpha coefficient of 5%. The only impacting parameters without being combined are the Almen intensity (D), the diameter of the shot (C), coverage and roughness before shot peening (A). The Almen intensity alone and coupled with the coverage are the two elements having the most effect on the fatigue life. The shot hardness alone has no significant effect.



Factor	Parameter
A	Surface roughness before SP
B	Media hardness
C	Media diameter
D	Almen Intensity
E	Coverage

Figure 2. Pareto diagram of DOE on shot peening

Fractography analysis identified two types of cracking initiation sites: surface initiation sites (94% of analyzed sites) and sub-surface initiation sites (6% of analyzed sites). Test coupons that have the highest number of cycles before failure exhibited sub-surface sites that are between 50 µm and 100 µm below the surface. They also exhibited limited surface roughness as a consequence of low Almen intensity during SP. On the other hand, the shortest fatigue lives are consequence of a crack initiation from a surface defect created by shots impact. An example is shown in Figure 3. In these cases, the surface defects were due to the high intensity used during shot peening. This type of defect acts as a stress concentrator, reducing the fatigue life.

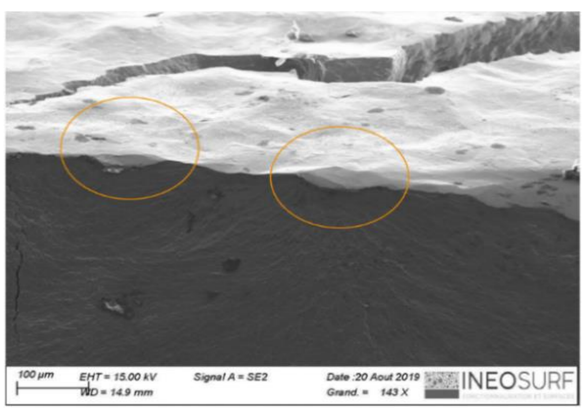


Figure 3. Crack initiation sites as a consequence of a surface defect introduced by shot peening

The impact of the different machining and shot peening conditions on the surface topography is shown in figure 4. In general, roughness measurements confirm that Almen intensity has the predominant role on surface finish. For the same initial topography (A, B or C), using a high intensity leads to higher values of S_a, S_p, S_v and S_z compared to a low almen intensity. As expected, the media hardness also has an influence on the final surface roughness. Regular hardness shots are generally associated with lower roughness values. The influence of the size of the shots is more relevant when using a hard media. In general, higher roughness values are observed when using smaller shots for the same intensity and hardness.

All residual stress profiles measured in shot peened specimens are shown in Figure 5. This graph highlights that the different shot peening and machining conditions induce very different residual stress profiles. As expected, the Almen intensity is the parameter that has the most influence on the affected depth and the maximum residual compressive stress (MRCS). The hardness and size of shots also affect the value of the MRCS and affected depth, but their influence is more moderate and not always obvious. The association of a large size and high hardness of shots induces the highest residual stresses and affected depths at isoalmen. However, it should be noted that there is a great dispersion between profiles corresponding to the same shot peening conditions. This is due to variations of the initial mechanical state caused by the different machining conditions. This implies that a good knowledge of milling conditions is important when choosing shot peening parameters for the same material.

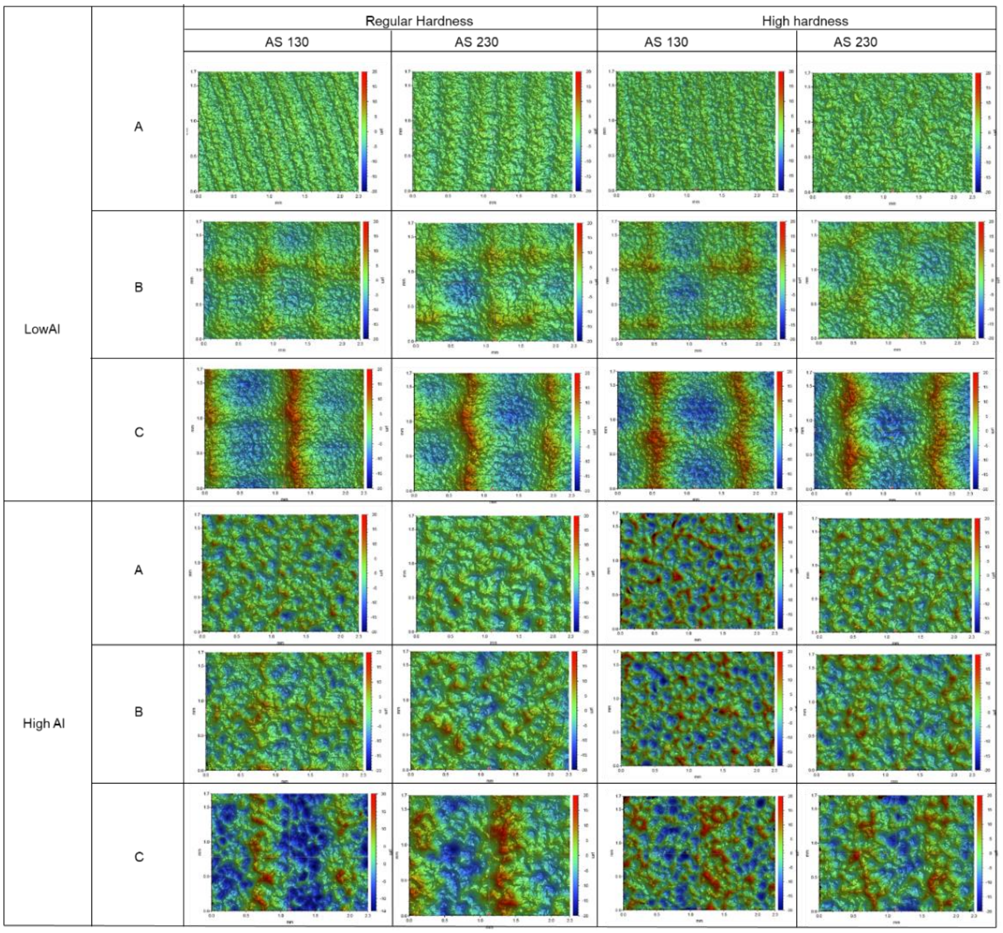


Figure 4. Topography of surfaces issued from different machining and shot peening conditions

The improvement in fatigue life due to the presence of residual compressive stresses introduced by shot peening has been widely demonstrated in the literature [5,8]. However, the graph (a) in Figure 6 shows that there is almost no correlation between the MRCStress and the number of cycles to failure (N). Table 3 shows that is also the case for the affected depth. This is explained by the fact that the peening conditions which introduce the most intense residual stress profiles also produce the most degraded surface finish. On the other hand, the conditions which produce the smoothest surface finish, do not always introduce enough residual stress to delay crack initiation. However, the correlation coefficient between Sa and N is also low (table 3). Coupons with very different surface roughness (S_a or R_a) have similar fatigue lives for a given level of stress. Consequently, the value of S_a nor MRCStress alone does not make it possible to predict the number of cycles to failure.

To evaluate the combined contribution of residual stresses and surface roughness on fatigue life, the correlation coefficient between different combinations of parameters and N was compared. An exponential equation was fitted to the data each time, each point represents the mean life and mean parameter for each set of conditions (machining and shot peening). Table 3 shows the evaluated parameters and the correlation coefficient for all the HCF tests.

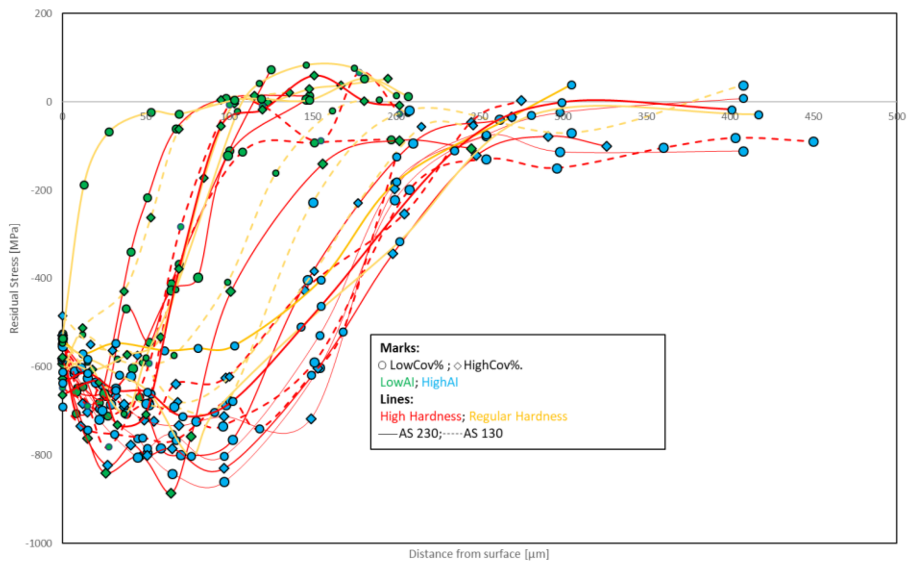


Figure 5. Residual stress profiles induced by different shot peening conditions.

Here, a new parameter (R_{local}) is proposed to characterize the maximum height of defects introduced by shot peening in comparison to the mean roughness, given by: $R_{local} = 0.5*S_z\text{-}S_a$, where $0.5*S_z$ is equal to the mean of the absolute values of S_p and S_v. This new parameter presents the highest correlation coefficient of all surface parameters.

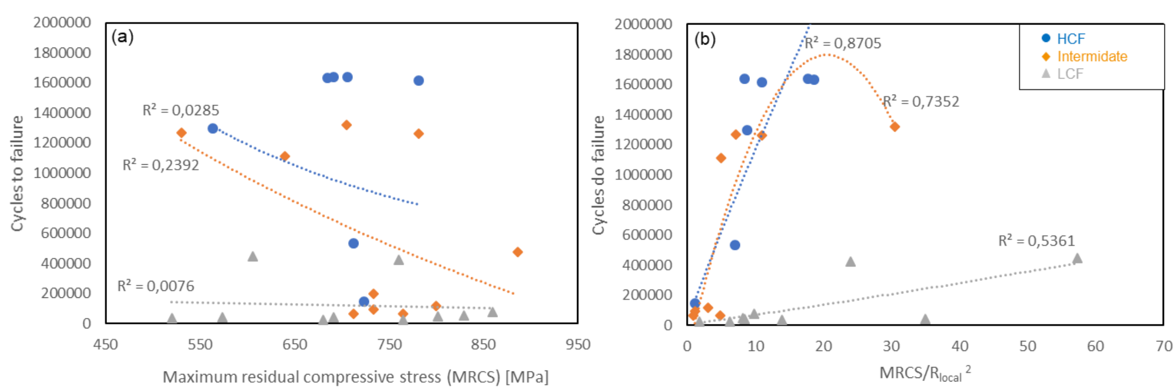


Figure 6. Service life as a function of (a) the maximum residual stress and (b) the ratio between the maximum residual stress and the square of the local roughness (difference between the mean of Sp and Sv (0.5Sz) and Sa - 0 , 5 Sz-Sa). Values correspond to means for each set of parameters

The ratio $\frac{\mathrm{MRCS}}{(\frac{1}{2}S_z - S_a)^2}$ presents the best correlation coefficient (see table 3 and Figure 6b) of all evaluated parameters. This brings out the existing competition between the surface finish and the residual stresses, being the local roughness the most influential parameter. Different studies [9,12] associate a stress concentration factor K_t with the roughness parameter R_z. Therefore, certain shot peening conditions neutralize the beneficial effects of the residual compressive stresses by creating surface defects which increase the stress concentration factor. This demonstrates the importance of reducing dispersion, as generating a surface as uniform as possible is more effective to enhance fatigue life, regardless the average roughness (R_a or S_a).

It should be noted that the correlation coefficient increases with the reduction of fatigue stresses, which indicates that the surface condition and residual stresses are more important when coupons approach the endurance limit (HCF), which agrees with the literature [7,8].

Table 3. Correlation coefficient (R^2) between different parameters and N for HCF solicitations.

Evaluated parameter	**R^2**
N=f(Sa)	0,318
N=f($S_{a\ normalisé}$= (S_a/S_a before SP))	0,0198
N=f($S_{a\ normalisé}$= ((S_a-S_a before SP)/S_a before SP))	0,0512
N=f(S_z)	0,7979
N=f(S_v)	0,7421
N=f(S_v-S_a)	0,8292
N=f(R_{local}= 0,5*S_z-S_a)	0,8463
N=f(MRCS)	0,0285
N=f(affected depth)	0,2618
N=f(MRCS/S_a)	0,3382
N=f(MRCS/S_z)	0,7683
N=f(MRCS/S_a*S_z)	0,5686
N=f(MRCS/Rl_{ocal})	0,8473
N=f(MRCS/R_{local}^2)	0,8705
N=f(affected depth/Rl_{ocal})	0,103

Conclusions

The test campaign demonstrated a significant increase in fatigue life for the sets of peening conditions which preserve a regular roughness through samples surface, while introducing residual compressive stresses at depth. This was the case when low Almen intensity was applied with AS H 230 shots. Analyses showed the great influence of local defects, which can be assessed through the roughness parameter S_z. Fractography analysis showed that the shot peening parameters optimization lead in a shift of the crack initiation sites from the surface to the core of the samples, and subsequently increasing the number of cycles to failure. These results show that the competition between the final surface finish and the residual stresses introduced by shot peening is a key element to enhance fatigue life.

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