Effect of shot peening on the fatigue life of AA 7050-T7451

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Introduction

Fatigue is a common cause of failure. A structure that undergoes fluctuating mechanical loadings becomes locally damaged. This weakness is caused by the nucleation and the growth of cracks at the microstructural scale. These cracks propagate until final fracture, when the material's toughness is reached. Shot peening is a surface treatment well-known to increase fatigue life. This process consists in impinging shots at high velocity onto a metal surface. The impacts strengthens the structure by delaying the initiation and growth of cracks through the introduction of residual stress, local hardening, and grain distortion [1, 2]. However, shot peening also introduces surface deterioration, which may accelerate crack initiation and growth. Even if the shot peening process has an overall beneficial effect on fatigue life, a potential increase of fatigue dispersion exists due to the stochastics nature of the process. Moreover, process reliability and its influence on fatigue dispersion remain unreported in the literature. The project described herein involves aerospace companies, for which reliability is an important criteria. Therefore, a probability study of shot peening effect on the fatigue life of AA 7050-T7451 at two stress amplitudes was undertaken.

Objectives

The main objective of this work was to study the effect of shot peening on the median of fatigue life, dispersion, and in terms of B-basis. B-basis is specified in the MMPDS standard [3] as a probabilistic value that gives 90% of survival rate with at a confidence level of 95%. In addition, fracture surface analysis was performed in order to explain the effect of shot peening on dispersion.

Methodology

Four shot peening conditions were studied, all at 100% coverage, namely, peening with CW14 at 8A intensity, peening with S230 at 8A intensity, and peening with Z425 at 4A and 8A intensities. The baseline was the As-Machined (AM) surface condition. Two stress amplitudes were studied, one in the Low Cycle Fatigue (LCF) regime and a second in High Cycle Fatigue (HCF) regime. All tests were conducted at room temperature, with a stress ratio of R=0.1 and a frequency of 20 Hz. Fatigue specimens were machined along the rolling direction, using a cylindrical gage section to avoid roll edge effects after shot peening. Ten fatigue specimens were tested per surface condition and per stress amplitude. All tests were axially loaded in the rolling direction until final fracture. Surface roughness measurements were performed on fatigue specimens for all surface conditions. For each set of tests, fracture surfaces of samples exhibiting maximum and minimum fatigue lives were analysed using a Scanning Electron Microscope (SEM).

Shot peening was achieved using a Canablast shot peening system. All fatigue specimens were cleaned with isopropyl alcohol before peening. Fatigue specimens peened with S230 and CW14 shots were cleaned afterwards with a solution of nitric acid and distilled water as specified in the AMS 2430T standard [4].

A probability analysis was performed on the AM and all shot peening conditions. First, a goodness-of-fit was conducted on different distributions, namely, gamma, generalized extreme value, log-normal, normal, and Weibull to identity the most representative. After which, tolerance limits were computed using the selected distributions.

Results and analysis
Probabilistic fatigue analysis
Quantiles are values that separates experimental data, or probability distribution into identical intervals. For instance, the median is the quantile that separates 50% of the population, and the 9th decile the quantile that separates 90% of the population, that are below the value, from the 10% above. Distributions estimating accurately experimental quantiles were selected to represent the data. The generalized extreme value and log-normal distributions were selected to model the HCF and LCF data, respectively. The generalized extreme value distribution is usually associated to an extreme phenomenon. In HCF, this phenomenon can be interpreted as the critical size defect that causes a single crack initiation. The log-normal distribution is usually associated with multiple independent phenomena that affect each other. In LCF, the high stress amplitude increases stress concentration induced by roughness and intermetallics, and also impacts plasticity behaviours. These different phenomena are inactive in the HCF regime. When combined, these phenomena led to several crack initiation criteria that trigger several crack initiations.

Figure 1 and 2 show probabilistic results computed using both mentioned distributions in HCF and LCF. The survival rate is the probabilistic value (n) under which n percentage of fatigue samples should not fail. The error bars represent the lower bound at 95% confidence. Therefore, the 50% survival rate is the median, and the 90% survival rate at 95% confidence level is the B-basis value.

In HCF, all shot peening conditions increased fatigue life time when compared to the AM condition. Samples peened at 4A intensity had the longest live at both 50% and 90% survival rates. However, the B-basis at 4A intensity provided a negative value. The large dispersion of samples peened at 4A intensity was the cause of this negative value. As a consequence, the peening process using Z425 shots at 4A intensity was unreliable. Peening at 8A with CW14, S230, and Z425 shots comparably increased the median of fatigue life and B-basis, when compared to the AM condition. Therefore, peening with Z425 shot at 8A intensity was the most reliable condition in terms of B-basis in HCF, since the error bars gave the highest value among all conditions.

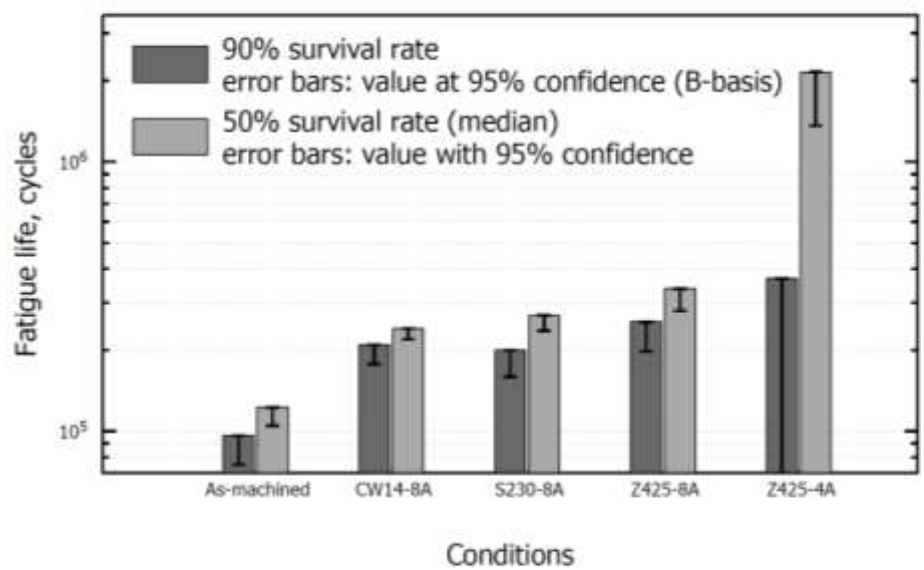


Figure 1. Fatigue life results for 50% and 90% survival rate for a 0.1 stress ratio in HCF. Errors bars are confidence intervals with a confidence level of 95%.

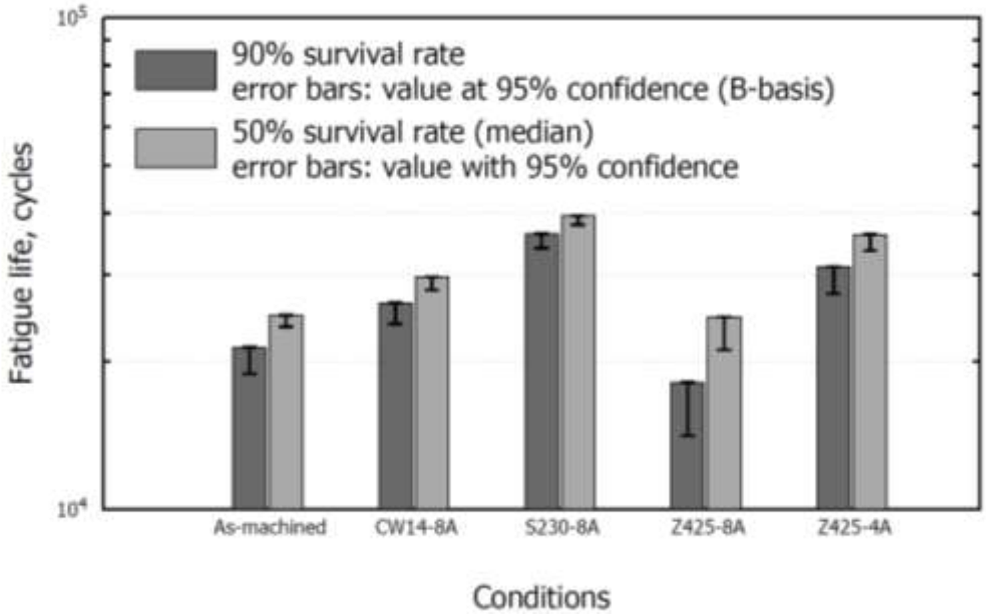


Figure 2. Fatigue life results for 50% and 90% survival rate for a 0.1 stress ratio in LCF. Errors bars are confidence intervals with a confidence level of 95%.

Table 1. Roughness measurements of the studied condition in the longitudinal direction. Ra is the arithmetic average. The values after the ± sign are the errors at 99.7% confidence using a normal distribution.

Condition	AM	CW14-8A	S230-8A	Z425-8A	ZA425-4A
Ra (µm)	9.7±1.0	62.0±2.7	36.7±2.4	41.5±2.8	18.3±1.7

In LCF, peening with CW14 shots increased the median and B-basis values when compared to the AM condition. Peening with S230 shots at 8A was the best process in terms of median and B-basis. Peening with Z425 shots at 8A intensity had the worst effect on the median and B-basis among all conditions. However, peening with the same shots at 4A intensity increased the B-basis value, when compared to AM.

Surface roughness modification

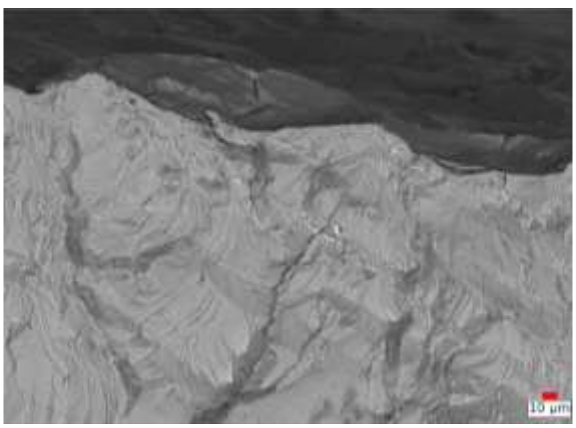
Table 1 provides the arithmetic average values along with the confidence intervals at 99.7%. All shot peening conditions increased surface roughness. Peening with CW14 shots at 8A had the highest deterioration. Surface roughness of samples peening with Z425 shots at 8A was double that of the 4A intensity.

Fracture surfaces analysis

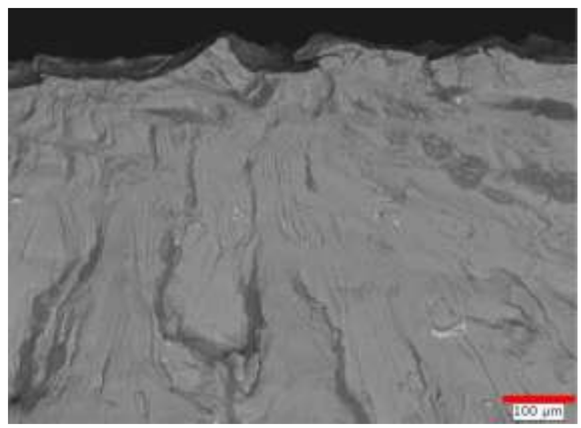
In HCF, most fracture surface observations revealed a single crack initiation. Two cracks within a few millimeters apart were observed only on the sample peened with CW14 exhibiting maximum life. Observations of fracture surfaces of the AM samples showed that the Al7CuFe intermetallic was the cause of initiation. Observation of samples peened with CW14 shots revealed that geometry discontinuity (dimples or overlap) was the cause of initiation. Observation of samples peened with S230 shots showed two close initiations, separated by few hundred microns that merged into a single crack. Initiations were caused by a large grain and an intermetallic. Fracture surface of samples peened with Z425 shots at both intensities revealed the same nucleation mechanism. Crack initiation was caused by a large dimple on the surface. Interestingly, specimens peened with Z425 shots revealed Zirconium contamination around the surface.

In LCF, several crack initiations were observed all around the fracture surfaces. The AM fracture surfaces had 6 initiations per sample. Initiations were caused by Al_7CuFe, Al_2CuMg, and Mg_2Si intermetallics. Samples peened with CW14 shots giving maximum and minimum fatigue lives had 3 and 5 crack initiations, respectively. Figure 3 shows typical fracture surface observations. Figure 3 (a) and (b) show observations of the CW14 samples in LCF. The same mechanism as observed on the CW14 samples in HCF was found. Samples peened with S230 shots giving maximum and minimum fatigue lives had 19 and 10 crack initiations, respectively. Two competitive mechanisms were identified: intermetallics, and geometry discontinuity (overlap and deep dimples).

Fracture surface of maximum and minimum fatigue lives samples peened with Z425 shots at 8A intensity led to 18 and 14 initiations, respectively. For both samples, the main crack was induced by a geometry discontinuity containing Zirconium shot contamination. Figure 3(c) shows the observed zirconium contamination. All the remaining cracks were induced by either intermetallics or geometry discontinuity. Observation of samples peened with Z425 shots at 4A intensity revealed 8 crack initiations per sample. The initiation causes were intermetallics and geometry discontinuities. Even though all the peened surface showed Zirconium shots contamination, no Zirconium was found on initiation sites as it was for the 8A intensity.



(a)



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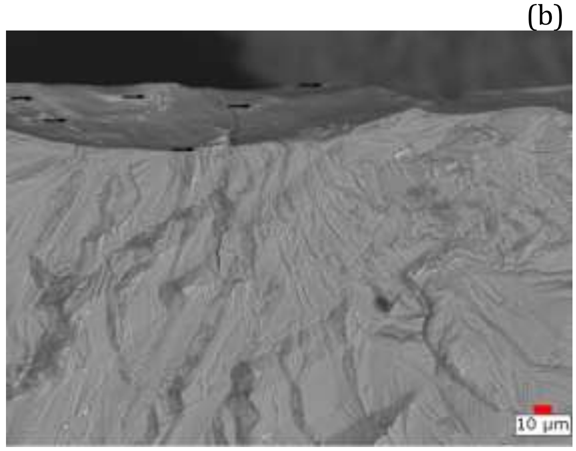

(c)

Figure 3. Typical observations of fracture surfaces. (a) and (b) are samples peened with CW14 shot at 8A intensity giving minimum and maximum in LCF, respectively. In (b) the crack initiated at an overlap, and in (c) the crack initiated at a large dimple. (c) Sample peened with Z425 shot at 8A intensity giving maximum fatigue life in LCF. The crack initiated at a large dimple contaminated by zirconium shots pointed by the black arrows.

Discussion

The physical interpretations of the selected distributions was in agreement with the fractography observations. In HCF regime, single cracks were observed on the fracture surfaces. The nucleation was then caused by a critical phenomenon. In LCF, observations revealed several crack initiation sites all around the surfaces. The crack initiations were caused by different phenomena that may have had coupled effects. The high stress amplitude found in LCF could explain this difference as multiple mechanisms are activated. These mechanisms were inactive in HCF regime.

In HCF, peening with Z425 at 8A intensity resulted in the best condition in terms of B-basis. Peening with the same shots at 4A intensity drastically increased fatigue life at a 90% survival rate, but the process was unreliable. The decrease of intensity increased fatigue life average and dispersion results. The roughness parameter of surface peened at 4A had a low dispersion, which involved a uniform peening. The fatigue life dispersion can be a consequence of the residual stress dispersion that may increase at lower intensity. More work are required to validate this hypothesis.
In LCF, peening with Z425 shots at 4A intensity increased median and B-basis values, when compared to peening with Z425 shots at 8A intensity, this is in opposition with results in HCF. At high stress amplitude a part of the residual stress have had relaxed, and the dispersion of residual stress could be less severe than in HCF. The better surface finish at 4A intensity, in combination with a relaxed residual stress profile may explained the improvement of fatigue life median and dispersion. In addition, peening with S230 shots at 8A showed the best results in terms of median and B-basis values. Peening with S230 shots at 4A intensity could improve fatigue results in LCF.

For both stress amplitudes and at 8A intensity, fatigue dispersion of samples peened with steel shots (S230 and CW14) were lower than samples peened with Z425 shots. Among the shot properties, S230 and Z425 shots have similar hardness (55-63), size (0.425-0.6 mm), and shape (spherical). The main difference was the relative density, 7.8 for steel shots versus 3.9 for Z425 shots. Shots density appeared to play an important role on dispersion.

Peening with Z425 shots at 8A increased and decreased B-basis values in HCF and LCF, respectively, when compared with AM condition. Precaution should be taken to avoid high stress amplitudes if a structure is peened with Z425 shots at 8A intensity.

Conclusions

Axial fatigue tests were performed on AM, and 4 shot peening conditions in low and high cycle fatigue. Probabilistic analysis was carried out on the fatigue results to identify the most reliable process using B-basis values. Higher shot density had lower dispersion. In HCF, B-basis results showed that peening with Z425 shots at 8A and 4A intensities were the best and the worst surface conditions, respectively. In LCF, B-basis results showed that peening with S230 and Z425 shots at 8A intensity were the best and the worst surface conditions, respectively. In LCF, peening with Z425 shots at 4A intensity was the second best surface condition in terms of B-basis. It appeared that switching from 8A to 4A intensity increased B-Basis results in LCF, while it drastically deteriorated it in HCF. In fact, peening with 4A in HCF provided the highest values of fatigue lives, about 10 times higher than 8A conditions. However, the high dispersion of these fatigue results did not provide enough reliability. Surfaces peened with Z425 shots showed zirconium contamination. Evidence of Zirconium contamination on crack sites was observed on fracture surfaces of samples peened at 8A intensity in LCF.

References

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