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Michele Angelo Attolico, Claudia Barile, Caterina Casavola, Vincenzo Moramarco, Gilda Renna. Fatigue performance enhancement of laser peened aircraft components. ICERS 11 - The 11th International Conference of Residual Stresses, SF2M; IJL, Mar 2022, Nancy, France. <hal-03997999>

HAL Id: hal-03997999

<https://hal.science/hal-03997999v1>

Submitted on 20 Feb 2023

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FATIGUE PERFORMANCE ENHANCEMENT OF LASER PEENED AIRCRAFT COMPONENTS

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ABSTRACT

The effects of the Laser Shock Peening (LSP) process and Tartaric-Sulfuric Acid Anodizing (TSA) treatment on the fatigue behavior of 7050-T7451 aluminum alloy were investigated through four-point bending fatigue tests. Anodizing processes, including TSA, are widely used in aerospace applications to increase components corrosion and wear resistance, but at the same time result in a significant reduction in fatigue properties of the base material. The possibility of combining the anodizing process with laser peening treatment allows this drawback to be overcome by exploiting the unique properties of the residual stress fields induced by the optimized LSP process to increase the fatigue life of the component.

To better understand the mechanisms and application possibilities of these two surface treatments, morphological and microstructural analyses were carried out on anodized and laser peened components, and the residual stress field induced by a specific laser shock peening process for the pre-treatment of the anodized surface was evaluated. The results showed that TSA resulted in an appreciable reduction in the fatigue life of the material especially at lower values of stress amplitude, due to the presence of defects at the interface between the substrate and the anodic layer which act as stress concentrators and promote the nucleation of fatigue cracks. The compressive residual stress field induced by the laser shock peening process used as a pre-treatment to anodizing can compensate for the negative effects introduced by anodizing and at the same time offer greater safety margins useful for the design of critical aeronautical structures.

Keywords: Residual stress; Laser Shock Peening; Tartaric-Sulfuric Acid Anodizing; Fatigue; Aircraft

1. Introduction

The aerospace industry commonly uses 7xxx-series aluminum alloys for fatigue-critical structural parts due to their high specific mechanical performance compared to other aluminum alloys. However, aeronautical components are often subjected to extreme service conditions characterized by high-temperature gradients and the presence of chemical media, and therefore require the use of protection systems able to ensure protection and efficiency during their entire life cycle [1]. For this reason, anodizing surface treatments are often employed: these involve the formation of an artificial stable layer of oxide on the surface of the component to guarantee enhanced wear and corrosion resistance. However, the benefits in terms of corrosion resistance are offset by a reduction in the fatigue strength of the component associated with three main causes: the fragility and porosity of the anodic layer, which cracks easily under the action of

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cyclic loads, the generation of residual tensile stresses following the anodizing process and the presence of pit-like defects in the subsurface region of the component which act as stress concentrating factors [2-3, 4-5].

Until now, numerous anodizing treatments have been studied in association with the use of aluminum alloys for aeronautical applications. The most commonly used anodizing process is certainly Chromic Acid Anodizing (CAA) [2, 4-6, 7]; however, the restriction imposed on the use of hexavalent chromium compounds by the European Union Regulation on the Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) has led to a sharp turn towards the development of alternative anodizing treatments, such as Tartaric-Sulfuric Acid Anodizing (TSA) [1], characterized by a lower environmental impact but still able to guarantee essential design requirements. Few studies in the scientific literature have focused on the effects of the TSA treatment on the mechanical behavior of the component following anodizing, but the available results [8-9] have shown that the tensile and fatigue properties are comparable with those of components with CAA coatings and, in particular, the fatigue life undergoes a more or less significant reduction depending on the morphology and thickness of the anodic layer. The detrimental effects of anodizing on the fatigue life of components can be conveniently overcome by using a surface peening process as a pre-treatment to anodizing [10]. The compressive residual stress field introduced by the peening process, such as Laser Shock Peening (LSP) [11-12], allows to counterbalance the tensile residual stresses induced by the anodizing process and, in addition, offer further fatigue protection by slowing down the crack propagation phase or even preventing crack nucleation. If the anodizing process is carried out before the LSP treatment, it is possible that the anodic layer will be damaged by the subsequent peening process, causing a reduction in corrosion resistance.

To the best of the authors' knowledge, the combination of the tartaric-sulfuric acid anodizing process with a suitably optimized laser shock peening treatment is unprecedented in the scientific literature and can be considered as an environmentally friendly and highly efficient solution for fatigue critical structural parts.

This research activity aims to investigate the effects of residual stresses induced by anodizing and laser peening processes on the fatigue behavior of components made of aluminum alloy 7050-T7451. Specifically, the possibility of using laser shock peening as a pre-treatment to anodizing will be verified to compensate for the reduction of fatigue life due to the formation of the anodic layer. Initially, a study of the residual stress field induced by an optimized laser peening process for aeronautical applications will be carried out to compliance with the design requirements, then the microstructure and morphology of the anodic layer will be analyzed to identify the causes correlated to the reduction of the fatigue life of the components. Finally, the results of four-point bending fatigue tests conducted on prismatic bending bars in untreated, anodized, and peened-anodized conditions will be proposed and discussed.

2. Materials and Methods

2.1. Materials

In this study, two different types of specimens were considered: square-shaped blocks (Type A) for the evaluation of the residual stress profile induced by the LSP process; prismatic bending bars (Type B) for the execution of four-point bending fatigue tests aimed at determining the life curve of the components. Both types of specimens were obtained from a 30 mm thick laminated plate made of aluminum alloy 7050-T7451. The chemical composition of the alloy used in this study is reported in Table 1. The geometry and main dimensions of both types of specimens are shown in Figure 1.

Table 1: Chemical composition (Weight Percent, wt%) of AA 7050-T7451

Zn	Mg	Cu	Fe	Si	Mn	Cr	Ti	Others
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5.7-6.7 1.9-2.6 2.0-2.6 Max 0.15 Max 0.12 Max 0.10 Max 0.04 Max 0.06 0.15

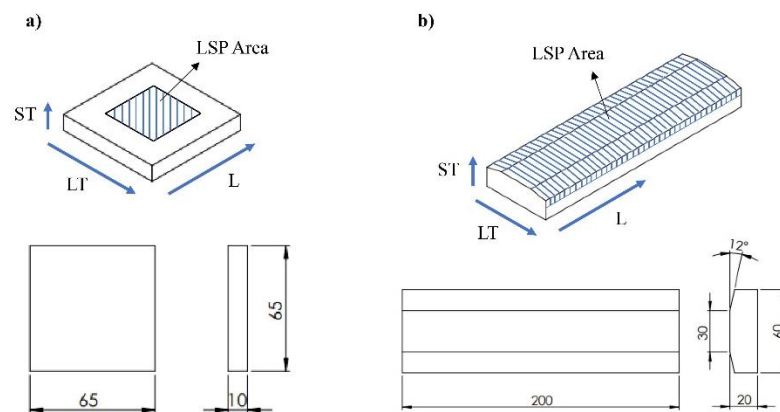


Figure 1: Isometric and front view of a) Square-shaped block (Type A) for residual stress investigation and b) Prismatic flexural bar (Type B) for 4PB fatigue tests (all dimensions in mm).

2.2. Laser Shock Peening Process

Both types of specimens were subjected to the LSP process: specifically, in the case of type A samples, peening only involved a square region (35x35 mm) within one of the two main faces of the sample, identified by the L-LT plane (see Figure 1); in the type B samples, the entire region subject to tensile stresses and a portion of the lateral surfaces (L-ST plane, see Figure 1b) extended up to half the thickness of the sample were subjected to peening. A black vinyl tape was placed over the regions affected by the peening process to promote energy absorption and act as an ablative material, while a layer of water was flowed over the region of interest to provide confinement to the high-pressure plasma expansion that is generated as a result of the energy input. A YLF:Nd laser with a wavelength of 1053 nm and operating at a pulse frequency of 10 Hz was used for the peening process. The process parameters adopted derive from an extensive campaign of experimental tests aimed at identifying an optimum compromise between the required characteristics of the induced residual stress field and the lowest possible impact on the surface integrity of the component [13]. The parameters thus obtained are summarized in Table 2. The overlap rate in the X and Z directions indicates the existing overlap between two adjacent laser spots in the X and Z direction respectively (Figure 2); on the other hand, the offset parameter refers to the percentage deviation of two consecutive laser patterns (i.e., layers) along with both X and Z directions.

Table 2: Definition of process parameters for laser shock peening treatment

Power Density (GW/cm ²)	Spot Diameter (mm)	X-Overlap (%)	Y-Overlap (%)	Offset (%)	Number of layers
3.5	2.0	33	33	33	3

2.3. Tartaric-Sulfuric Acid Anodizing

Type B specimens, following laser shock peening treatment, were subjected to the sulfuric-tartaric acid anodizing process. After a preliminary surface preparation phase, anodizing was carried out in a solution consisting of sulfuric acid, with a concentration of 40 g/l, and tartaric acid, with a concentration of 80 g/l, at a temperature of 40°C and applying a voltage of 15 V for a total duration of 20 min.

2.4. Residual stress analysis methodologies

The analysis of residual stresses induced by the LSP process on type A specimen was carried out using both the X-Ray Diffractometry (XRD) technique and the Hole Drilling Method (HDM). The Xstress 3000 G3R (Stresstech) X-ray diffractometer instrumented with a Cr tube ($\lambda=0.2291$ nm) and a 2 mm collimator operating at a voltage of 30 kV and a current intensity of 8 mA was employed. At each evaluation point, the stress state was calculated along with the scanning and stepping directions of the laser (Figure 2) using a tilt oscillation of $\pm 3^\circ$ and an exposure time of 25 seconds. XRD in-depth measurements were performed after removing the material by an electrochemical attack with a Movipol-3 Struers and A2 electrolyte using a voltage of 70 V and a current intensity equal to 0.8 A. Stresses were assessed at twenty different penetration depths with a step size ranging progressively from 10 to 250 μm . HDM was carried out by using the SINT Technology Hole Drilling system, according to the ASTM E837-13. Type B strain gauge rosette (CCW) was applied in the middle of the treated region and oriented in such a way as to obtain information about the local state of tension along with the scanning and stepping directions. The hole extends to a depth of 1 mm and was drilled in 20 steps according to a polynomial distribution. A tungsten carbide end mill, TiAlN coated, inverted cone-shaped 1.6 mm diameter was used. The rotation speed was set to 400000 rpm.

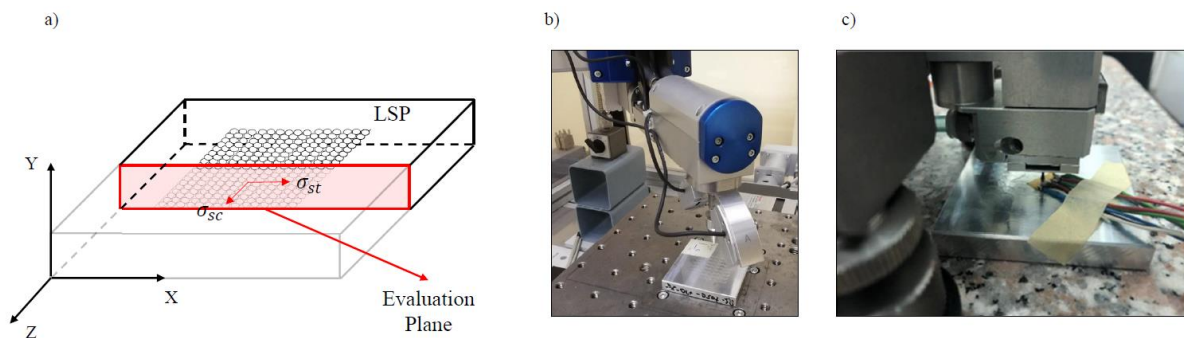


Figure 2: Residual stress measurements setup: a) Definition of scanning and stepping directions; b) X-Ray Diffraction setup and c) Hole Drilling Method setup.

2.5. Morphology and microstructure of anodic layer

The morphological analysis of samples surface in the longitudinal section (L-LT plane) was performed by conventional analytical techniques, such as stereomicroscope (Nikon SMZ800N) and Zeiss Evo MA 10 Scanning Electron Microscope (SEM). The thickness of anodic oxide film on 7050-T7451 samples was revealed in the Short Transverse-Long Transverse plane (ST-LT), after standard metallographic procedures, by SEM examination.

2.6. Evaluation of fatigue behavior of LSP + Anodized samples

To obtain a comprehensive account of the effects induced by the laser peening and anodizing processes on the fatigue behavior of the material, specimens made of base material, specimens subjected to anodizing treatment, and specimens subjected in series to laser peening and anodizing were fatigue tested.

The fatigue properties of the material following laser shock peening and sulfuric acid anodizing treatments were evaluated by performing four-point bending fatigue tests on type B specimens. The tests were carried out on a 4-point bending test fixture equipped with loading and support rollers (15 mm diameter) mounted on sliding supports to allow their correct positioning with respect to the specimen. The maximum initial tensile stress σ_{max} within the loaded specimen was calculated using the Euler-Bernoulli theory of slender beams. The test setup is shown schematically in Figure 3: $L_i = 60$ mm and $L = 170$ mm indicate respectively

the distances between inner and outer rollers, while F is the applied load. Tests were conducted using a stress ratio of 0.1 and a maximum load frequency of 10 Hz. The tests were interrupted when 3×10^6 cycles were reached without any sign of cracking and when the failure occurred or cracks were visually observed.

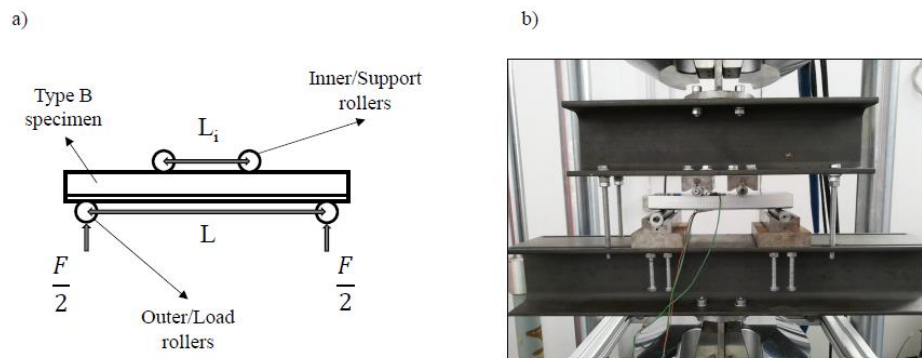


Figure 3: Four-point bending fatigue tests: a) testing fixture configuration and b) photo of the loading system during the test run.

3. Results

3.1. Surface morphology

Figure 4a-f shows the surface morphology in the longitudinal section of the untreated sample (AM) (fig. 4a, b), treated by anodizing process (AM+TSA) (fig. 4 c, d), and the one treated by laser peening before the anodizing process (AM+LSP+TSA) (fig. 4 e, f).

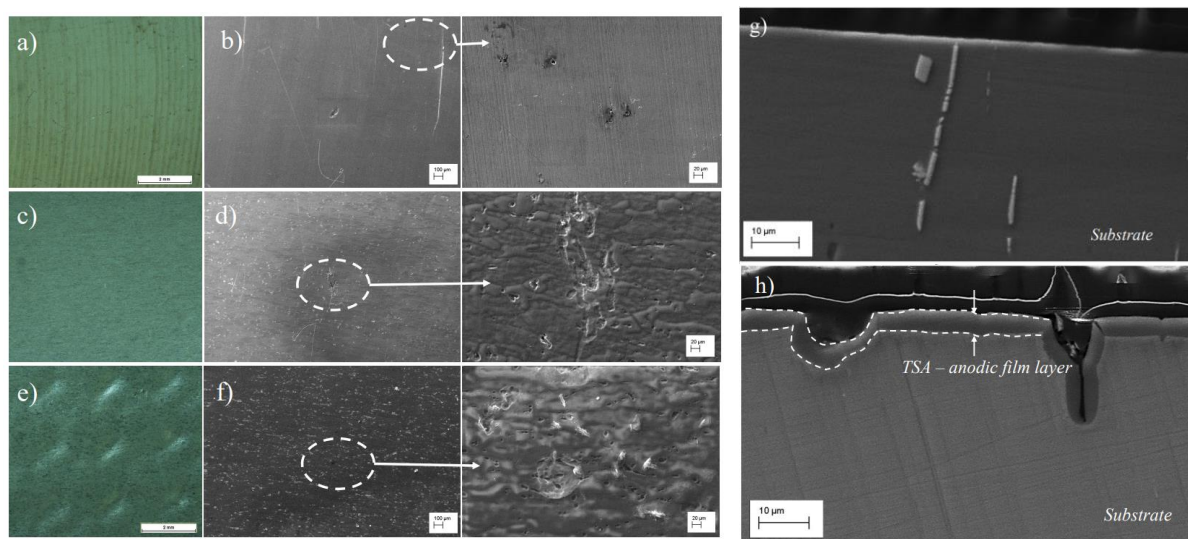


Figure 4: a-f) Longitudinal-section morphology of the 7050-T7451 samples. Overview of the longitudinal section of the samples (a, c, e) and SEM micrographs (b, d, f) of the sample surface: a and b) untreated as-machined (AM), c and d) treated by anodizing process (AM+TSA), and e and f) treated by laser peening and anodizing process (AM+LP+TSA). SEM micrograph of cross-section (ST-LT plane) of g) AM sample and h) AM+LSP+TSA sample showing the anodic film formed in TSA bath.

The AM sample surface was rather uniform and contains some small defects, i.e., pin-holes or local chippings (see fig. 4b and the enlarged image of the spot fringe). Generally, these imperfections result from the standard mechanical preparation of the surface, performed before the anodizing treatment. Moreover, the texture of scratches produced by the milling machine is clearly visible (fig. 4 a, b). Although, the surface of the AM+TSA sample appears

morphologically smoother and homogeneous than the AM surface (compare fig.4a and 4c), the SEM analysis reveals an anodic layer morphologically tailored to bond well with the sample surface characterized by several small cavities and micro-pores with 0.6 - 20.5 μm in diameter (see fig. 1d and the enlarged image of the spot fringe). The formation of these cavities is mainly due to the preferential dissolution, during anodization, of the particles enriched with Cu and Mg (Al_2CuMg) present in the 7050 alloy. In addition, it is also interesting to note that these defects are not uniformly distributed on the surface but they appear grouped in some areas, forming clusters. Unlike the AM+TSA sample, the surface morphology of the AM+LSP+TSA sample changed slightly. Both the typical shocks pattern appearance produced by the laser penning process and the anodic layer superimposed on the previously treated surface are clearly visible in fig. 4e. In particular, it can be observed that the laser pulses are repeated in a raster fashion over the surface with slightly overlapping shots to ensure complete coverage. Moreover, the AM+LSP+TSA sample surface shows shallow, pock-like marks in isolated circular areas (enlarged image of the spot fringe of fig. 4f) roughly 60 μm across. While the anodic layer in AM+LSP+TSA samples shows similar features of AM one (fig. 4f): a dense and a rather uniform layer with several micro-porosities.

Fig. 4g and h show the SEM micrographs of the cross-section of the AM and AM+LSP+TSA specimens, respectively. SEM observations of the AM+LSP+TSA sample cross-section show significant changes compared to the AM one. The specimen surface is relatively smooth in the AM cross-section, without waviness (fig. 4g). In LSP+TSA, the SEM micrograph shows a dense anodic layer forming along the surface of the sample substrate (top) (fig. 4g). It can be observed that that anodic layer has perfectly inherited the relief of the sample surface. The anodic film thickness was about $4 \pm 0.4 \mu\text{m}$. Furthermore, the pock-like marks and a smaller, pointed pit that is a diameter of 10 μm and a depth of about 8 μm can be clearly seen in fig. 4g.

3.2. Residual stresses analysis

Figures 5a and 5b show the residual stress profiles obtained by XRD and the HDM respectively. The trends and values of residual stresses observed are perfectly consistent with those found in studies conducted on the same material and at comparable combinations of process parameters [14-15].

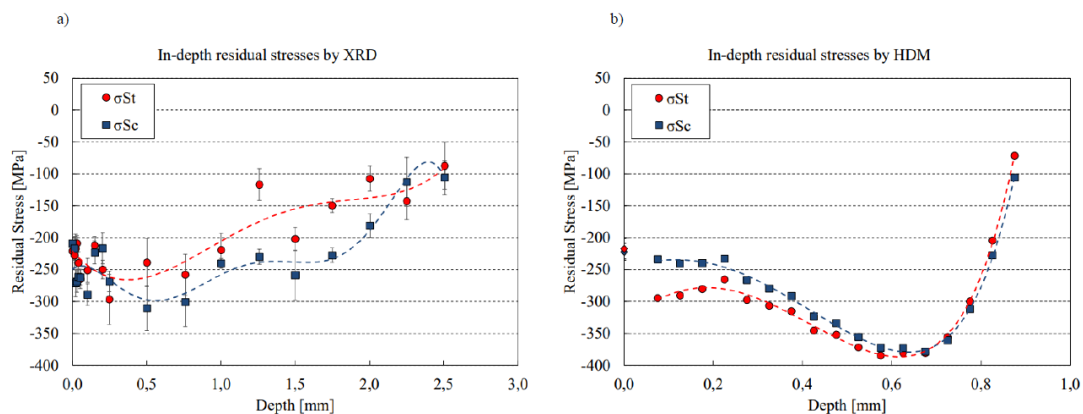


Figure 5: Compressive residual stress field caused by laser shock peening: a) profiles obtained by XRD and b) profiles obtained by HDM.

A first analysis of the profiles highlights some relevant aspects: the stresses measured along with the two directions of laser scanning and stepping present comparable trends, indicating the absence of distortion of the part following the laser peening process. The use of vinyl tape as an ablative material prevented the occurrence of local burns which could have led to the development of residual tensile stresses at the surface of the component and, on the contrary, guaranteed the presence of a compressive stress state as a result of the plastic deformation

caused by the propagation of the elastic wave; the peak of residual stresses is recorded at a depth of about 0.5-0.6 mm from the surface and has an intensity of approximately 350 MPa, equivalent to about 75% of the yield strength of the treated aluminum alloy. Concerning the position of the trend reversal point, the measurements made by XRD and HDM are apparently discordant: in the first case, permanence in the compression regime is observed up to depths of more than 2.5 mm, with a much lower stress growth rate towards positive values compared to what emerges from the analysis of the profiles obtained by HDM, where instead a rapid growth towards positive values of residual stresses is observed immediately after reaching the peak.

This discordance can be associated with the loss of reliability of the HDM residual stress measurement for depths greater than 0.8 mm and errors introduced during material removal when performing depth XRD. In any case, to improve the fatigue properties of the component, it is of fundamental importance that the residual stress field presents a stable or increasing trend in the surface and sub-surface region, i.e., those primarily involved in the nucleation and propagation phenomena of fatigue cracks, ensuring the achievement of higher performance standards.

3.3. Fatigue evaluation

Fatigue curves for untreated, anodized, and both laser shock peened and anodized specimens are shown in Figure 6. Looking at the curves for the untreated and anodized specimens, a reduction in the fatigue life of the material is immediately observable. As evidenced by the micrographic observations, this reduction can be attributed to the presence of cavities at the interface between the anodic layer and the substrate which can act as stress concentrators and thus favor the nucleation and propagation processes of fatigue cracks. As shown in other studies conducted on different anodizing processes [3, 9-10, 16], within the fatigue life of a component the crack nucleation process is dominant at lower maximum stress regimes, so the presence of local stress concentrators favoring crack nucleation has a significantly greater impact in this region of the fatigue curve.

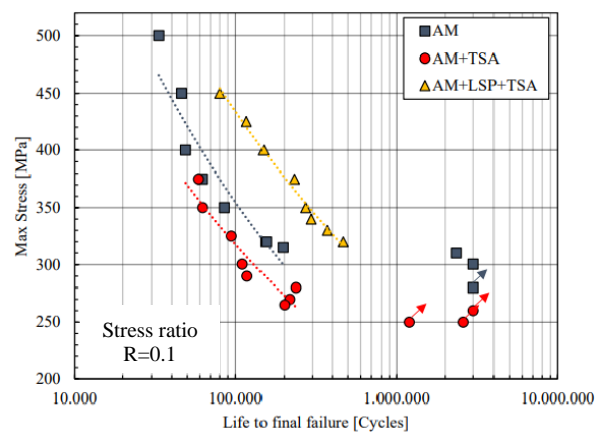


Figure 6: Four-point bending fatigue tests results: S-N curves for untreated, anodized and both laser peened and anodized specimens.

The fatigue strength of the material is reduced by approximately 10% as a result of the anodizing treatment. The extent of this reduction is directly influenced by the thickness of the anodic layer: an anodic layer thickness of 4 microns, as obtained in this research activity, can be considered an optimum compromise in terms of corrosion resistance and fatigue strength for critical aeronautical applications. Using laser shock peening as a pre-treatment to the anodizing process makes it possible to offset the reduction in fatigue life caused by the anodizing process alone. From a quantitative point of view, considering the regression lines in the region of the finite life of the material, the laser shock peening process determined an increase in fatigue life

of 2.5 compared to the untreated specimens and of about 4.5 compared to the anodized specimens. This improvement is undoubtedly due to the residual stress field induced by the laser shock peening treatment, whose intensity and depth of penetration made it possible to mitigate the local effects of the defects caused by the anodizing process and at the same time provided additional protection against the phenomena of fatigue crack generation.

4. Conclusions

The possibility of using laser shock peening as a pre-treatment to an anodizing process was evaluated to compensate for the reduction of the fatigue strength of the component caused by the presence of the anodic layer. The following points can be highlighted:

- The morphology of the anodic oxide layer was dependent on the Al substrate. The anodic layer on the 7050-T7451 alloy showed the presence of some defectiveness. The formation of defects was mainly attributed to the difference in reactivity of intermetallic particles present in the alloys.
- The residual stresses induced by the laser shock peening process present a similar trend in the scanning and stepping directions of the laser and remain in the compression regime beyond the depth of 1 mm from the surface of the component. The peak of compression occurs at a depth of about 0.5 mm, at which the stresses assume a value of about 75% of the yield strength of the aluminum alloy considered.
- The fatigue results showed a reduction in the fatigue life of the material following the application of the sulfuric-tartaric acid anodizing process: in particular, a more marked reduction is observed in correspondence with higher values of maximum stress. The laser shock peening treatment determines a significant increase in the fatigue life of the material, both compared to the untreated base material and the anodized component.

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