Investigation of residual stress, stress relaxation and work hardening effects induced by shot peening on the fatigue life of AA 6005-T6 aluminum alloy

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Abstract
Fatigue strength improvement of mechanical components is one of the most challenging problems in engineering. One of the known ways to improve fatigue life is by using the shot peening process. However, it is complex to define the optimum shot peening parameters to different materials due to the interaction of several variables. This work aimed to investigate the effect of the complex interaction of surface roughness, the residual stresses induced, the stability of the compressive residual stresses during fatigue cycles, and the work hardening of the surface layers induced by the shot peening process on the fatigue behavior of AA 6005-T6 aluminum alloy at room temperature. Rotating bending fatigue tests \((R = -1)\) were carried out on specimens in the as-machined, as-ground, and shot peened with two different intensities \((0.006 \text{ N and 0.007 A})\) conditions. The results indicate that both shot peening conditions were capable of improving fatigue life compared to as-machined condition. However, the best fatigue behavior was achieved for the more severe condition \((0.007 \text{ A})\), which was capable of shifting the crack source to beneath the surface, as observed through scanning electron microscopy. Although the maximum compressive residual stress was higher for the more severe condition, it was observed a relaxation of the compressive residual stresses after rotating bending fatigue cycles. It was demonstrated that, despite the stress relaxation and the surface damage induced by shot peening, the work hardening generated by the more severe condition nearby the surface was determinant to the efficiency of the process.

1. Introduction

Age-hardenable aluminum alloys are widely applied in structural components in many industrial segments due to their high strength to weight ratio \([1]\), which is combined with other desirable properties such as good plasticity, resistance to atmospheric corrosion and easy processing \([2]\). AA 6xxx series is widely used in the construction and transportation industries. AA 6005, an Al-Mg-Si alloy, is used in the automotive industry for applications that require moderate mechanical strength and great resilience \([2, 3]\). The mechanical properties of this alloy are interesting for applications where the structure may be subjected to occasional overloads \([4]\). However, the automotive components are frequently subjected to vibratory loads and cyclic stresses, which may result in fatigue failure. The fatigue strength improvement to avoid fatigue failure or increase the service life of mechanical components is considered one of the most challenging problems in engineering.

One of the known ways to improve fatigue strength is by using the shot peening (SP) process. SP is a cold-working process that consists of impacting the surface of a component with ceramic, glass or metallic spherical media \([5]\). The SP intensity is measured by flat standardized plates called Almen strips (types N, A and C).
Almen strips are placed parallel to the treated component and, therefore, receive the same treatment. The strips bend during the process, and the arc height is the Almen intensity [6]. The thicknesses of Almen strips N, A and C are 0.79 mm, 1.29 mm and 2.39 mm, respectively [7]. Therefore, Almen strips A and C are used for measuring more severe SP intensities than Almen strip N. For example, the strip N deforms about 3 times more than strip A for the same shot peening stream. In this study, the SP intensities analyzed were measured using Almen strips N and A.

The SP process induces plastic deformations on the surface layers of the material. Since these layers must remain coherent with the elastic substrate material, it generates a compressive residual stress field (CRSF) on the surface and below [5, 8]. The CRSF has a positive impact on fatigue life since it can hinder fatigue crack nucleation and propagation [9]. The effect of the CRSF induced by SP in increasing fatigue life was reported in the literature for different materials [10–12].

The SP efficiency is usually attributed frequently only to the induction of a CRSF. However, the CRSF may suffer relaxation during fatigue cycles. The possibility of stress relaxation in the CRSF induced by treatments at high temperatures is well known [13]. Stress relaxation at room temperature is not usually considered in mechanical projects and was initially identified by Bignonnet [14] and Torres & Voorwald [5]. Currently, the analysis of the stress relaxation of the CRSF induced by SP during the fatigue process at room temperature is more frequent [15–17].

Besides the effect of the CRSF on fatigue life, SP can also produce the work hardening of the surface layers [16, 18–20]. It has been demonstrated that the ultra-fine particles peening treatment on the 5056 aluminum alloy significantly increased the surface hardness [16]. Another study showed that the work hardening generated by shot peening treatment was important to the fatigue life enhancement of 6082-T6 aluminum alloy [18].

The increase of the SP intensity increases the CRSF [5] and the hardness of the surface layers [16]. However, the surface roughness also increases [21], which is detrimental to the fatigue behavior. Furthermore, the CRSF induced may not be stable during fatigue cycles. Hence, there is not a direct correlation between the SP intensity increase and the fatigue strength improvement. The optimum combination of those variables results in the fatigue life improvement of materials. It has been demonstrated in previous work that the efficiency of the SP process is related to the capacity of the CRSF to protect the surface from fatigue crack nucleation, pushing the crack source beneath the surface [5].

The complexity of the effects induced by different SP parameters leads to frequent discussions and divergences regarding the optimum SP intensity for different materials. For aluminum alloys, the military standard MIL-S-13165C recommends Almen strip N intensities with nonmetallic sphere shots or strip A intensities with metallic or ceramic sphere shots [22], the standard ASTM B851 suggests Almen strip A intensities with stainless steel shots [7] and the standard SAE J443 proposes Almen strip A intensities with glass sphere shots [23]. Gonzales et al [24] obtained an improvement of about 28% in the rotating bending fatigue strength for $3 \times 10^6$ cycles of the AA 6063 alloy with a shot peening intensity of 13 A. Benedetti et al [25] studied the AA 7075 aluminum alloy in pulsating fatigue tests with $R = 0.005$ after shot peening intensities of 4.2 N and 12 N with glass and ceramic sphere shots, respectively, finding the best fatigue behavior for the less severe intensity. Trško et al [12] studied the same material, AA 7075 aluminum alloy, in axial fatigue tests with $R = -1$ and shot peening intensities of 9.6 N and 14.9 A. Similar fatigue results for both shot peening parameters were obtained up to $10^7$ fatigue cycles, and the improvement of 9.6 N condition with respect to the base material was observed only from approximately $10^8$ fatigue cycles (very high-cycle fatigue).

The present research aims to investigate the complex interaction of the variables induced by the shot peening process through the study of the effect of two different SP intensities (N and A) on the fatigue strength of AA 6005-T6 aluminum alloy tested in rotating bending fatigue loading ($R = -1$). For this purpose, the fatigue behavior is discussed with respect to the following variables induced by SP: (a) surface roughness, (b) the CRSFs before and after cyclic loading, (c) the microhardness profile near the surface, and (d) the crack initiation points.

2. Experimental procedure

The chemical composition of AA 6005 aluminum alloy used was 0.30 Cu, 0.40–0.70 Mg, 0.50 Mn, 0.20 Zn, 0.35 Fe, 0.10 Ti, 0.50–0.90 Si, 0.30 Cr, and 0.15 other components, wt%. The heat treatment condition was T6, consisting of solution treatment ($580\,^\circ\text{C}/15\text{ min}$) and artificial aging ($180\,^\circ\text{C}/6\text{ h}$). The mechanical properties of the alloy were yield strength of 256 MPa, ultimate tensile strength of 286 MPa, and Young’s modulus of 65.7 GPa. The specimens were machined according to figure 1 from extruded cylindrical rods with a diameter of 10 mm. The material was machined on a CNC lathe following the guidelines suggested by standard ASTM E466 in Appendix X1 to assure that surface residual stresses were minimized.

After machining, the specimens were divided into three groups: base material (as-machined and as-ground), shot peened with N order of magnitude Almen intensity (SP 0.006 N), and shot peened with A order of
magnitude Almen intensity (SP 0.007 A). The surface grinding treatment was conducted by using 400, 600, 800 and 1200 mesh sandpapers. The SP intensities were determined considering the SP parameter possibilities presented in standards and the literature. The parameters of the SP 0.006 N condition were glass microsphere media, shot stream angle to the surface of 90°, blast media size ‘AC’, air pressure of 20 psi, and coverage of 100%. The parameters of the SP 0.007 A condition were glass microsphere media, shot stream angle to the surface of 90°, blast media size ‘AC’, air pressure of 100 psi, and coverage of 200%.

The specimens were tested in rotating bending fatigue tests (R = −1) at room temperature with a frequency of 30 Hz. The S-N curves were determined according to ASTM E739. The fracture surfaces were examined using scanning electron microscopy (SEM) to identify the crack initiation points.

The CRSF induced by shot peening was determined by x-ray diffraction method, using the Raystress equipment with a stress measurement accuracy of ±20 MPa. The method sin² ψ was applied in the measurements using five angles for each measurement. The parameters used are given in table 1. The stress measurement was performed in a modern portable stress analyzer Xstress3000, with a collimator of Ø 1.0 mm (30 kV and 6.7 mA). The software XTronic V1-0 Standard was used to perform the stress calculation. In addition, the layers of specimens were removed by electrolytic polishing with a non-acid solution to obtain the stress distribution by depth. Mathematical models to correct the measured residual stresses were not necessary since the residual stress variation was insignificant, considering the high ratio between the thickness of specimens used and the thickness of the removed layers [26].

In order to evaluate the possible residual stress relaxation during the fatigue process at room temperature, the CRSF was measured in shot peened specimens (SP 0.006 N and SP 0.007 A) before fatigue tests and after 10⁴ rotating bending fatigue cycles at a maximum stress level of 191 MPa. The CRSF measurements after 10⁴ fatigue cycles were performed on non-fractured specimens after stopping the fatigue tests.

The mean and maximum superficial roughness of the base material and shot peened specimens were measured with a mobile roughness measurement instrument model Marsurf M300. The microhardness profile was measured with loads of 0.25 N applied for 10 s in the cross-sectional area of the base material and shot peened specimens after the fatigue tests.

### 3. Results and discussions

#### 3.1. Fatigue

Figure 2 exhibits the fatigue test data and the S-N curves of the AA 6005-T6 aluminum alloy for the base material and shot peening conditions analyzed. Two S-N curves are presented for the base material: as-machined and as-ground. Table 2 shows the mean roughness resulting from the machining and grinding processes. Suraratchai et al (2008) showed the significant influence of surface roughness resulting from machining in the fatigue behavior of aluminum alloys [27], which is also important to the fatigue life of 6xxx series aluminum alloys [28]. According to Novovic (2004), machined surface roughness in excess of 0.1 μm Ra has a strong influence on fatigue life [29]. Thus, the difference in the fatigue behavior of as-machined and as-ground conditions possibly occurred due to the reduced surface roughness after grinding.

As it is possible to observe in figure 2, both shot peening conditions increased the fatigue strength compared to the base material as-machined. However, the more severe intensity (SP 0.007A) resulted in better fatigue behavior than the SP 0.006 N condition. For SP treatment effectiveness, two variables are commonly analyzed: the CRSF and the roughness induced by the process. As SP intensity increases, the maximum compressive
residual stress and the depth of the CRSF usually increase. However, the surface roughness also increases (table 2). The balance between the CRSF beneficial effects and the worsening of the surface finish usually defines the optimum SP intensity [5, 30].

The fatigue strength improvement of the SP 0.006 N condition occurred for all stress levels compared to the base material as-machined. Nevertheless, the SP 0.006 N was less efficient than the grinding for fatigue life improvement, especially for high-stress levels. In comparison to the ground specimens, the SP 0.007 A was capable of improving the fatigue performance for all the stress levels analyzed. In order to understand this issue, the following sections present a discussion of the effects of the CRSF, the microhardness profile, and the fatigue crack initiation points on the fatigue results.

3.2. Compressive residual stress field (CRSF)

The CRSFs induced by the two different shot peening intensities (SP 0.006 N and SP 0.007 A) are shown in figure 3. The surface residual stresses for both shot peening conditions are almost similar. Studies have revealed that the residual stress at the surface is more dependent on the material properties than the shot peening intensity [31]. However, the evaluation of the residual stress in the subsurface layers is necessary for a better understanding of the fatigue behavior. The CRSF can be expressed by the following characteristic parameters: the surface compressive residual stress (CRS), the maximum CRS, the depth of the maximum CRS, and the depth of the CRSF [32].

The SP 0.007 A condition generated a greater maximum CRS than the SP 0.006 N condition at a similar depth (figure 3), which would explain the better fatigue performance of the material subjected to this treatment. The improvement of the fatigue life by the CRSF induced by the SP process is explained by one or more of the following effects: (i) the CRSF increases the number of cycles required to nucleate a crack from the surface; (ii) once a crack has initiated at or beneath the surface, the CRSF increases the propagation number of cycles by decreasing the mean stress on the surface layers [25]; (iii) the CRSF pushes the crack origin to subsurface layers by protecting the surface of the component. Previous work has correlated the last possibility with the SP process effectiveness [5]. However, the stability of the CRSF during fatigue loading, especially for \( R = -1 \), may be affected during the fatigue process [5, 14–16].

| Residual | As-machined | As-ground | SP 0.006 N | SP 0.007 A |
|----------|-------------|-----------|------------|------------|
| CRS (MPa)| 130 ± 0.23  | 130 ± 0.23| 130 ± 0.23 | 130 ± 0.23 |
| depth (μm)| 20 ± 0.5 | 20 ± 0.5 | 20 ± 0.5 | 20 ± 0.5 |

Figure 2. S-N comparative curves for the base material and shot peening conditions.
3.3. Analysis of the CRSF stability during fatigue tests

The CRSFs induced by SP 0.007 A and SP 0.006 N shot peening conditions were measured again after $10^4$ rotating bending fatigue cycles at an intermediate stress level (191 MPa), and the results are shown in figure 4. A relaxation of the CRSF was observed for both conditions. Benedetti et al [11] carried out reverse bending fatigue tests on 7075-T651 aluminum alloy after shot peening and observed that the relaxation of the CRSF occurs in the first fatigue cycles.

The CRSF relaxation can be explained due to the superposition of (i) the compressive residual stresses generated by the shot peening process and (ii) the rotating bending fatigue compressive stresses. The stress superposition exceeded the material yield strength and caused a stress redistribution, resulting in the relaxation of the original CRSF [5]. This effect depends on the type of loading to which component will be subjected since the CRSF tends not to be affected by the fatigue process for loadings without compressive stresses [10]. Hence, the stress relaxation of the CRSF is directly related to the rotating bending fatigue loading. It is noteworthy to mention that the effect of stress relaxation resulted in similar stress levels for both peening conditions (figure 4), which suggests a stress stabilization level. Considering similar CRSFs achieved during fatigue tests for both shot peening conditions and a higher surface roughness for the more severe shot peening intensity, it would be expected that the SP 0.006 N would result in better fatigue behavior than the SP 0.007 A condition. However, the best fatigue performance was achieved for the SP 0.007 A condition, as previously discussed in section 3.1.
Basically, the shot peening process induces three effects in the material: the generated CRSF, the increase of the surface roughness, and the work hardening of the superficial layers. Since the CRSF was not the principal cause of fatigue behavior improvement in the SP 0.007 A treatment, and certainly neither was the increase of the surface roughness, the possible superficial work hardening induced by shot peening was investigated.

3.4. Work hardening

The microhardness profile was measured in the transversal section of the base material as-machined and shot peened (SP 0.006 N and SP 0.007 A) to evaluate the work hardening caused by the shot peening process, as illustrated in figure 5. It is possible to observe similar microhardness profiles for the SP 0.006 N condition and the base material. Therefore, the fatigue strength increase of the material treated with SP 0.006 N compared to the base material (figure 2) was directly related to the CRSF induced by the treatment, in spite of the compressive stress relaxation after cyclic loading (figure 4). Therefore, the surface roughness increase caused by SP 0.006 N condition (table 2) was overcome by the positive effect caused by the induced CRSF (figure 2).

A significant work hardening of the surface layers was observed for the SP 0.007 A condition, mainly in depths up to 0.03 mm (figure 5). It is interesting to notice that this result was achieved only by the more severe shot peening intensity (SP 0.007 A). Severe shot peening conditions may introduce high plastic deformation on the surface and a high density of crystal lattice defects, particularly dislocations, in the microstructure [24]. Abeens et al [33] related the hardness improvement of the AA 7075- T651 aluminum alloy after laser shock peening to the grain refinement and dislocation strengthening that result from the severe plastic deformation. The increase of dislocation density due to shot peening provides a good resistance to fatigue crack nucleation [34]. Furthermore, the work hardening induced by SP process can increase the fatigue crack nucleation life due to a higher resistance to the formation of persistent slip bands [25].

Considering that the CRSFs induced by the shot peening process during fatigue tests were similar in both conditions analyzed, as discussed in section 3.3, and that the surface roughness of the SP 0.007 A condition is higher than the SP 0.006 N condition (table 2), the fatigue performance improvement of the SP 0.007 A is attributed mainly to the work hardening caused by the treatment. The analysis was only made possible by the study of the combination of surface roughness, residual stress, stress relaxation, and work hardening effects on the fatigue behavior of the material.

3.5. Crack initiation points

The crack initiation points were investigated using scanning electron microscopy to understand the fatigue behavior of all the conditions analyzed (figure 2) and to determine the shot peening process capability of protecting the surface from fatigue crack nucleation.

Figure 6(a) shows the typical fracture surface presented by the base material as-machined, depicting the fatigue cracks originated at the surface (indicated by arrows). Figure 6(b) shows a magnification of the crack initiation site highlighted with a circle in figure 6(a). For the as-ground samples, the crack nucleation also occurred at the surface for all the stress levels studied (figure 7). The fatigue crack nucleation at the surface is expected considering (i) the highest stress on the surface due to the rotating bending loading, (ii) the stress...
concentrations resulting from the surface finish, and (iii) the reduced constraint to plastic deformation of the surface [35].

Figures 8 and 9 show the typical fracture behavior found for the samples treated with SP 0.006 N. For high-stress levels, the crack always originated at the surface (figure 8). The compressive stresses created by shot peening were not able to supplant the high applied tensile stress combined with the roughness increase induced by shot peening. For low-stress levels, the crack initiation occurred beneath the surface (figure 9). Hence, the CRSF created by SP 0.006 N condition seems to be sufficient to push the crack initiation beneath the surface for low-stress levels.

Figures 10 and 11 show the typical fracture surfaces found in SP 0.007A samples tested at maximum stresses of 208 MPa and 173 MPa, respectively. For all stress levels, the crack initiation occurred beneath the surface, demonstrating that the CRSF and the work hardening generated by the SP 0.007 A condition were capable of protecting the surface, moving the crack initiation site beneath the surface. Gao et al found that the shot peening of 40CrNi2Si2Mo2V steel was capable of moving the crack initiation into the interior beneath the hardened layers [36]. The greater capacity of pushing the crack beneath the surface of condition SP 0.007 A in comparison to SP 0.006 N seems to confirm the better effectiveness of the more severe intensity treatment, despite the increase of the surface roughness.

From the analysis of the results obtained in this work, the literature [5, 11, 12, 24, 25], and shot peening standards [7, 22], the following analysis can be made:

(a) The variables that can influence the fatigue strength through the shot peening treatment are the surface roughness, the induced CTRC, the hardness increase in the surface layers and the type of loading applied.
Figure 8. Overview of fatigue fracture surface of SP 0.006 N condition tested in maximum stress of 208 MPa (254,600 cycles).

Figure 9. (a) Overview of fatigue fracture surface of SP 0.006 N condition tested in maximum stress of 173 MPa (472,000 cycles). (b) Detail of the crack initiation site highlighted.

Figure 10. (a) Overview of fatigue fracture surface of SP 0.007 A condition tested in maximum stress of 208 MPa (667,300 cycles). (b) Detail of the crack initiation site highlighted.
Loadings that contain compressive stresses may result in stress relaxation of the CRSF, reducing the relevance of this variable to the fatigue results.

(b) For high strength materials, the roughness and the CRSF are expected to be more important than the increase of the surface hardness in the fatigue behavior of the material. In this work, the material analyzed has good work hardening capability and moderate mechanical strength in comparison to 2xxx and 7xxx series aluminum alloys, and, consequently, the increase in hardness resulting from the more severe shot peening process was more relevant than the other variables studied, especially considering the type of loading applied $(R = -1)$, which caused the relaxation of the induced CRSF.

(c) Studies that do not take into account all the variables previously listed in item (a) may exhibit divergences regarding the most efficient shot peening parameters. The efficiency of shot peening parameters for the same material may be divergent for different types of loading, and the possibility of relaxation of the CRSF should be considered. Usually, standards that specify the shot peening process do not take into account the type of loading that the component will have to withstand during the operation to suggest the suitable shot peening intensities.

(d) The capability to push the crack source beneath the surface is directly related to the shot peening treatment effectiveness.

4. Conclusions

The effects of surface roughness, residual stress, stress relaxation and work hardening induced by shot peening on the fatigue behavior of AA 6005-T6 aluminum alloy were discussed. The following conclusions can be drawn from the analysis made and data obtained:

- The shot peening intensities tested, 0.006 N and 0.007 A, were capable of improving the fatigue life of AA 6005-T6 aluminum alloy compared to the base material. However, the best fatigue performance was obtained for the more severe shot peening intensity, 0.007 A.

- The fatigue life increase provided by the shot peening process with 0.006 N intensity was not significant considering the almost similar fatigue results obtained after grinding the base material.

- The maximum compressive residual stress was higher for the more severe shot peening intensity (SP 0.007 A). However, after rotating bending fatigue cycles, the CRSFs induced by both shot peening conditions relaxed to similar stress levels. This showed that the CRSF was not the main parameter for the difference in the fatigue behavior of the two shot peening conditions tested.

- It was demonstrated that the work hardening due to the more severe shot peening intensity condition (SP 0.007 A) was the determinant factor in the fatigue life improvement of AA 6005-T6 alloy.

- The shot peening intensity condition that results in better fatigue life, SP 0.007 A, was the one capable of transferring the crack nucleation to beneath the surface for all stress levels analyzed.
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