ASSESSMENT OF FATIGUE BEHAVIOR FROM THE ALUMINUM ALLOY SHOT PEENED SPECIMENS

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Abstract. *Shot peening is an effective technique of surface treatment in engineering components widely used for the introduction of residual stresses and improving the fatigue strength. The present research has evaluated the fatigue behavior from the Al 7050-T7451aluminum alloy. Shot peening process was carried out to create residual stresses using ceramic and glass shots. Axial fatigue tests were performed with base material and base material shot peened from longitudinal and transversal directions. In order to study the influence of residual stresses on fatigue life, the compressive residual stress field was measured by an X-ray diffraction method. The performance of glass shot peened Al 7050-T7451 specimens is better in comparison to ceramic shots, for longitudinal and transversal conditions. The decrease in axial fatigue strength associated to the ceramic shot process may be attributed to higher surface roughness, which acted as stress concentrators. Despite partial relaxation of the compressive residual stress for both shot peening process, they still found a beneficial effect on fatigue live for 7050-T7451 aluminum alloy.*

Keywords*: Shot peening, compressive residual stress profile, aluminum alloy*

1. INTRODUCTION

Recently, the increasingly design requirements for modern engineering applications have driven the development of new materials with improved physical and mechanical properties. In particular the 7000 series wrought aluminum alloys are used for structural applications because of their combination of high fatigue strength, stress-corrosion cracking resistance and toughness. To improve design metals and alloys for aerospace applications, investigations are aimed to strengthening mechanisms, phase transformations, plasticity, creep, fatigue, environmental effects and dynamic and static fracture (Carvalho and Voorwald, 2007).

Shot peening is an effective technique of surface treatment in engineering components widely used for the introduction of residual stresses and improving the fatigue strength. This is particularly the case of the aeronautical industry where structural components from high strength alloys are shot peened in accordance with their specific requirements (Levers, 1998 and Wang et al. (1998a)). Increase in fatigue life due to the shot peening process is associated to compressive residual stresses induced in the surface and subsurface layers. The surrounding elastic material, on attempting to return the yield surface to its initial shape, creates residual compressive stress field within the cold work-hardened surface layer Wang et al. (1998b). Surface roughening, strain hardening and residual stresses are surface modifications produced by shot peening Curtis et al. (2003). On the other hand, surface damage produced by the shot peening process during overpeening may result in fatigue failures (Mutoh et al. (1987), and Tekeli, 2002). The shot peening intensity that produces best results in fatigue life is influenced by the relaxation of induced compressive stresses during the fatigue process, by surface conditions created by shot peening and the possibility of the compressive residual stress field to push the crack source beneath the surface (Torres and Voorwald, 2002). Experimental evidence assumed that the increase in fatigue strength associated to shot peening is related to the residual stress ability to arrest crack propagation. The stability of these residual stresses at purely mechanical or thermal as well as superimposed mechanical and thermal loadings is of decisive importance. The aim the present work was investigated to evaluation of fatigue behavior from the 7050-T7451 aluminum alloy under surface treatment of shot peening carried out to create residual stresses using ceramic and glass shots. S–N curves were obtained in axial fatigue testing and, in order to study the influence of residual stresses on fatigue life, the behavior of compressive residual stress field was measured by an X-ray tensometry.

2. EXPERIMENTAL PROCEDURES

The material used in this investigation was a plate of 7050-T7451 aluminum alloy. The chemical composition is (in wt%): 6.06% Zn, 2.19% Cu, 1.90% Mg, 0.15% Zr, 0.10% Mn, 0.04% Cr, 0.12% Si, 0.14% Fe, 0.06% Ti. Mechanical properties obtained from tensile testing were: elastic modulus 65 GPa and 69 GPa, yield stress 429 MPa and 439 MPa, ultimate tensile strength 502 MPa and 504 MPa and elongation 10% and 12% in the longitudinal (L) and transversal (T to the rolling plane) directions, respectively. Analysis by light microscopy revealed microstructure of the partially

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recrystallized regions that are large elongated course grains surrounded by finer grains that consist in the equiaxed grain population and uniformly distributed fine precipitates of η and ή, that lead to precipitation hardening. Aluminum alloy specimens were grinder machining which represent surface roughness equal to 0.89 ± 0.32 μm.

2.1. Shot peening

S–N curves were obtained for the aluminum alloy treated with two intensities of shot peening: 0.022 N (35 psi) and 0.013 N (30 psi), using ceramic and glass shots, respectively. The shot used was (∅ 0.4 mm) with coverage of 120% for both conditions and carried out on an air-blast machine according to standard MIL-S-13165. The shot peening treatment was performed with high quality control, in which the shots were automatically selected and kept in perfect conditions.

2.2. Fatigue testing

Axial fatigue testing (according to ASTM E-466) were performed using an electrohydraulic servo controlled MTS with constant amplitude load control, and R = 0,1 with a frequency of 30 Hz at room temperature. S/N curves for all conditions studied were obtained by average results of four specimens in each stress level, in which each estimated point corresponds to P = 50% of failure probability in the Weibull Distribution.

2.3. Residual stress measurement

The compressive residual stress field induced by shot peening was determined by X-ray diffraction method, using the ray stress equipment: ψ goniometer geometer, Cr-K_α radiation and registration of {222} diffraction plane for aluminum. The accuracy of the stress measurement was $\Delta\sigma= \pm 20$ MPa. In order to obtain the stress distribution by depth, the layers of specimens were removed by electrolytic polishing with a non acid solution.

3. RESULTS AND DISCUSSION

The fatigue life behavior of Al 7050-T7451 alloy for the longitudinal and transversal directions for the base material, ceramic and glass shot peened base material can be observed in Fig. 1. Comparison between longitudinal and transversal directions on fatigue strength in Fig.1 shows higher number of cycles to failure for the transversal condition. It is absolutely clear the increase in axial fatigue life due to the shot peening effect, for ceramic and glass shots, in both directions. The performance of glass shot peened Al 7050-T7451 specimens is better in comparison to ceramic shots, for longitudinal and transversal conditions, in all maximum stresses studied. Based on data from Fig. 1, it should be noted that for base material, number of cycles to failure for transversal specimens is higher than those for longitudinal ones, up to 260 MPa (approximately 60% rys). While, for ceramic shot peened the transversal direction shows fatigue life values higher when compared with longitudinal direction at 304 MPa and 260 MPa, respectively. However, an inversion in the fatigue life behavior occurs at 239 MPa stress as showed in Fig. 1, the longitudinal direction has a better fatigue behavior than the T direction. The same behavior is observed for glass shot peened condition fatigue strength for longitudinal condition is higher than for the transversal, exception made for maximum stress 304 MPa.

It is important to observe that the peening intensities are shown in Tab. 1. The decrease in axial fatigue strength associated to the ceramic shot process may be attributed to higher surface roughness, as indicated in Tab.1, which acted as stress concentrators. This mechanism was investigated by Mutoh et al. (1987) that observed that the reduction in fatigue life in the peened specimens could be attributed to acceleration in the crack initiation process by stress concentrations on the roughened surface, specially at fold defects. In (Tekeli, 2002) it is also shown that a higher surface roughness will accelerate fatigue crack nucleation and, consequently, reduce fatigue life. From Table 1 and Figure 2, it is possible to observe higher surface roughness for ceramic shot peening and greater depth and width of the compressive residual stress field for the glass shot peening, respectively. These conditions contributed for better base material glass shot peened axial fatigue performance in comparison to ceramic shot.

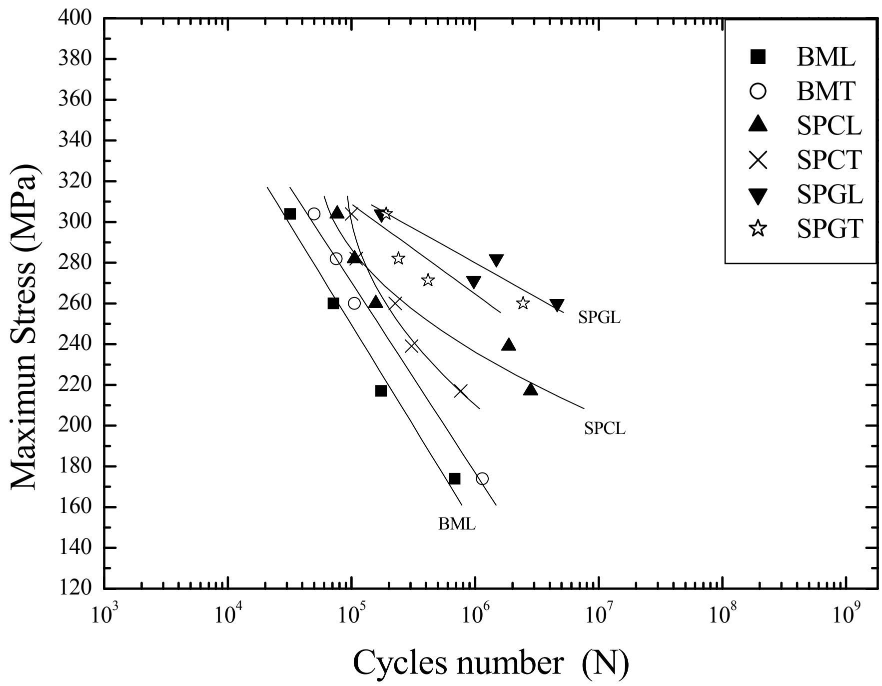

Figure 1. Axial fatigue S–N curves, from the base material, ceramic and glass shot peened base material, longitudinal and transversal directions.

The surface roughness will accelerate the nucleation and early propagation of cracks. On the other hand, strain hardening may retard crack propagation increasing the resistance to plastic deformation and the residual stress profile will reduce the driving force for crack propagation Curtis et al (2003). Turnbull et al. (1998) investigated that the increase in fatigue resistance can be improved by increasing the shot peening intensity. In the present research, the ceramic shot condition employed higher peening intensity but was not necessarily the one that showed the better fatigue resistance. This observation indicates that an overpeening may have occurred which produced damages (craters and folds) on the ceramic shot peened surface. This result agrees with the observations made by (Mutoh et al, 1987, Tekeli, 2002, Carvalho and Voorwald, 2007).

Table 1. Shot peening process parameters.

shot	Average ϕ	press	distance	intensity	coverage	roughness
	(mm)	(psi)	(mm)	Almen	(%)	Ra (μm)
glass	0.4	30	200	0.013 N	120	2.09
ceramic	0.4	35	80	0.022 N	120	5.54

It is well known the importance of the residual stresses stability that are purely mechanic, in front of the external loading superposition. Depending on the superposition level of the residual stresses on surface, it will undergo several degrees of stresses redistribution, inclusive relaxation of the compressive residual stresses (Torres and Voorwald, 2002). This relaxation is on account of the cyclic loading that is affected mainly by: (a) initial magnitude and gradient of the residual stress field and degree of cold working; (b) fatigue stress amplitude, mean stress ratio and number of cycles, and (c) material cyclic stress–strain response and degree of cyclic work hardening/softening (Zhuang and Halford, 2001). Figure 3 shows the residual stress profile from a specimen glass shot peened. The compressive residual stress at surface is −280 and −458MPa at 0.08mm depth. The maximum applied stress in the axial fatigue testing (Fig. 3) was

271MPa and 282MPa. Let us make a simple comparative analyzes of the superposition between the compressive and applied stress (271MPa) during the fatigue test: the residual stress at surface is -9MPa (271MPa-280MPa) and at 0.08mm depth, -187MPa (271MPa-458MPa). If results from superposition are sufficiently significant, plastic deformation will occur with consequently a stress redistribution (relaxation) of the original compressive residual stress; even though in the present work low cyclic fatigue testing were not performed. It is well known that the same undergo cyclic softening. The cyclic yield stress of the Al 7050-T7451 alloy is certainly lower than the monotonic yield stress of 429 and 439MPa for the longitudinal and transversal directions, respectively. Recent work (Carvalho and Voorwald, 2009) have reported to the influence of stresses superposition in the compressive stress field profile for ceramic and glass shot peening after reverse bending fatigue cycles. Namely, a gradient of the compressive residual stress underwent relaxation (redistribution) in relation to the original stress field.

Broadly speaking, the extent of stress relaxation depends on applied loads and on the tendency of many materials to exhibit cycle-dependent softening in the surface layer because the intense cold working introduced by shot peening. Normally, the cold work produced by shot peening is highest in the surface and decreases through the thickness of the material Benedetti et al (2004). That is, high compressive residual stresses are confined to a shallow surface layer, for instance around depth 0,08mm (Fig. 2), while low tensile residual stress spreads deeper through the cross-section.

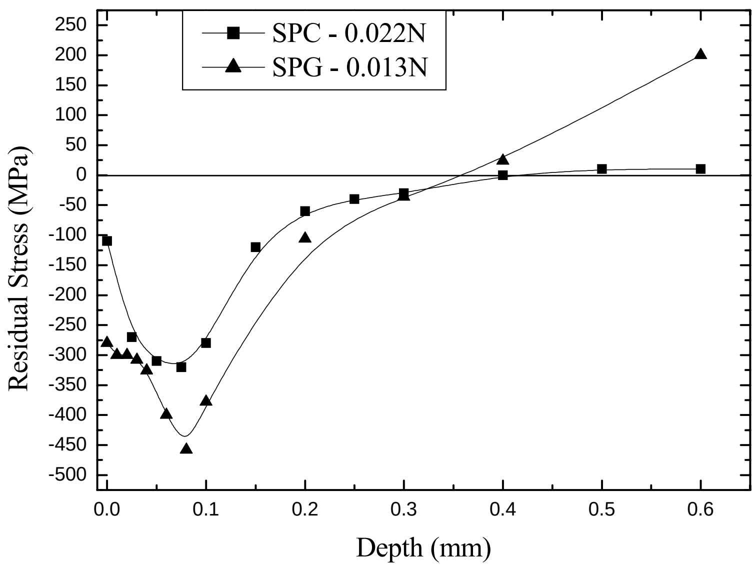

Figure 2. Residual stress compressive profile introduced by shot peening process using ceramic (SPC) and glass (SPG) shots.

Therefore, there are local yield strength gradients in the components after surface treatment by shot peening, namely, cold working effect on the yield strength. For instance, while more compressive cold working (introduce by shot peening) increases the compressive yield strength, the local initial tensile yield strength after compressive cold working is actually reduced. Thus the greater the compressive cold working will produce the lower the tensile yield strength. This phenomenon is known as the Bauschinger effect. This suggests that relaxation mechanics have took place for both shot peening processes, as can be seem in Figs. 3 and 4 is associated degree of cold working from the shot peening process. In Figure 3 shows the stress field profile for glass shot peening after $8x10^5$ and $2.9x10^6$ axial fatigue testing cycles at 271MPa and 282MPa, respectively. It is possible to notice in Fig. 3 a gradient of the compressive residual stress that undergo a relaxation (redistribution) in relation to the original stress field for SPGL and SPGT conditions. The same characteristic in the cyclic loading also occurred for the ceramic shot peening process, as indicated in Fig. 4. It is possible to observe in Fig. 3 that the relaxation effect of residual stresses was practically identical for longitudinal and transversal directions, and (Carvalho and Voorwald, 2007) have found same behavior for reverse bend fatigue testing. This is not in accordance with results from Holzapfel et al. (1998), which informed that the residual stresses in the transversal direction always relax more slowly than in the longitudinal direction. Besides, (Zhuang and Harlford, 2001) have reported that the compressive residual stress in the first load cycles can be relaxed by more than 50%. This feature only was found for glass shot peened conditions, which the compressive residual stress at surface was -280MPa and after fatigue cyclic changed to -210MPa and -180MPa, corresponding at 33% and 55% that were relaxed, respectively. While, for ceramic shot peened condition, the relaxation effect at surface layer does not occur, but throughout thickness, as can be drawn in Fig. 4.

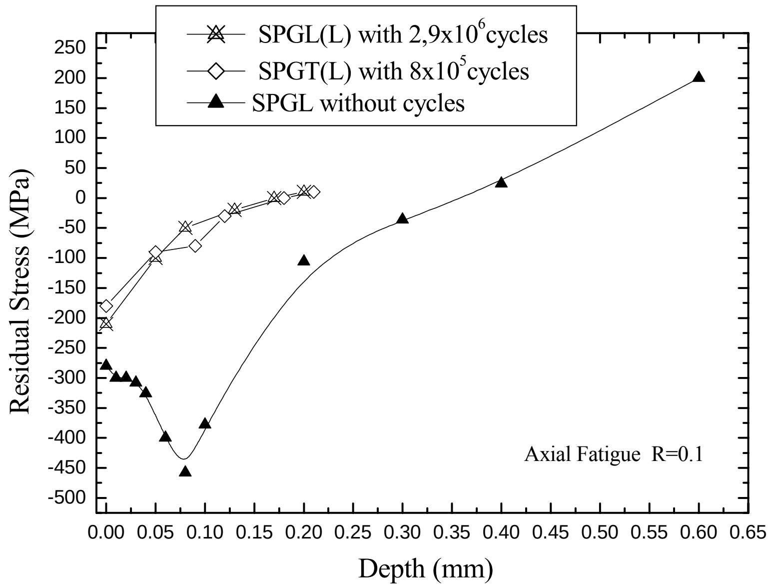

Figure 3. Residual stress compressive profile from glass shot peened specimens, after $8x10^5$ and $2.9x10^6$ axial fatigue cycles at 271MPa and 282MPa, respectively.

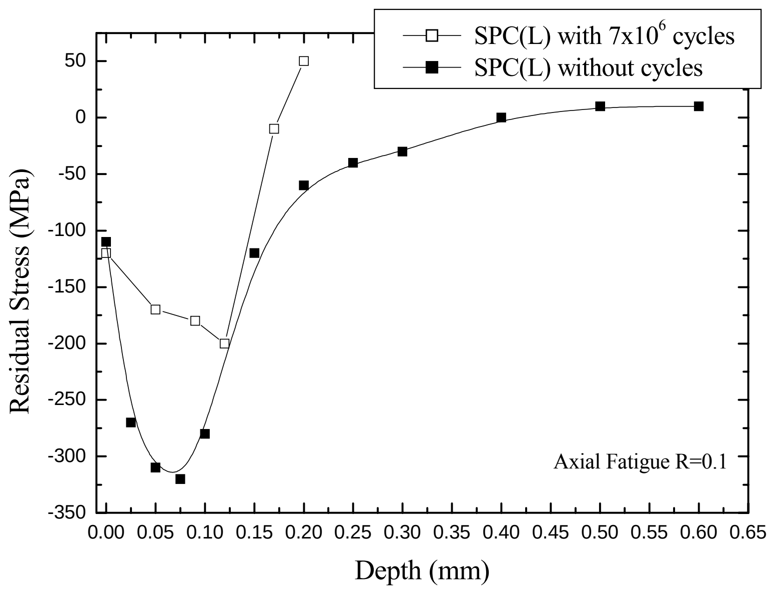

Figure 4. Residual stress compressive profile from ceramic shot peened specimens, after $7x10^6$ axial fatigue cycles at 239MPa.

4. CONCLUDING REMARKS

The present work has investigated fatigue behavior from 7050-T7451 aluminum alloy shot peened specimens using ceramic and glass shots. The results obtained can be summarized as follows:

The performance of glass shot peened Al 7050-T7451 specimens is better in comparison to ceramic shots, for both longitudinal and transversal conditions. The decrease in axial fatigue strength associated to the ceramic shot process may be attributed to higher surface roughness, which acted as stress concentrators. Residual stresses for ceramic and glass shot peened base material indicate greater depth and width of the compressive residual stress field, for glass shot peened aluminum alloy. On surface, residual stresses for glass and ceramic shots were -280 MPa and -110 MPa, respectively. Despite partial relaxation of the compressive residual stress for both shot peening process, they still found a beneficial effect on fatigue live for 7050-T7451 aluminum alloy. Accordingly, their fatigue lives were underpredicted if residual stress relaxation was not taken into consideration.

5. ACKNOWLEDGEMENTS

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