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AN EVALUATION OF THE EFFECT OF SHOT PEENING ON THE FATIGUE CRACK GROWTH IN ALUMINUM ALLOY 2024 – T3

Douglas Henrique da Silva Costa
IAE/DCTA – Institute of Aeronautics and Space, Aeronautical Systems Division, S.J. Campos/SP, Brazil
doug_feg@yahoo.com.br

Marcelo Augusto Santos Torres
FEG/UNESP – College of Engineering Campus Guaratinguetá, Departament of Mechanics, Guaratinguetá/SP, Brazil
mastorres@uol.com.br

Carlos Antonio Reis Pereira Baptista
EEL/USP – School of Engineering of Lorena, Departament of Materials Engineering, Lorena/SP, Brazil
baptista@demar.eel.usp.br

Abstract. *The shot peening is a process that induces compressive residual stresses on the surface of a component and may improve the fatigue strength. However, studies of its effect on a pre-existent crack are scarce. This paper studies the effect of the shot peening process in the propagation rate of a fatigue crack in the high strength aluminum alloy 2024-T3. Compact Tension (CT) specimens were initially cracked by fatigue with two crack sizes and then shot peened on both sides behind the crack tip. After peening, the tests were resumed under the same conditions. Tests were carried out under constant amplitude at two load ratios. The results showed that, for stage II cracks, the shot peening process has greater influence on the growth rate at the lower load ratio. For cracks approaching stage I of propagation, the shot peening process induced a delay in their growth for all studied conditions. The retardation on fatigue crack propagation occurred only when the plastic deformation and compressive residual stresses induced on the surface by the shot peening process was able to affect the crack closure and therefore the effective stress intensity factor,* ΔK_{eff}.

Keywords: *Shot peening, fatigue crack propagation, 2024-T3 aluminum alloy.*

1. INTRODUCTION

The finding that, especially in high-strength materials, a large part of the total service life of a component can be consumed in fatigue crack propagation, intensified the interest of the mechanisms involved in the phenomenon. The presence of a crack in the structure does not mean that it will fail or be impaired in its use, provided the crack behavior during the components life is known. Therefore, control over the initiation and propagation of cracks is of fundamental importance for the aircraft industry to extend the fatigue life of structural components.

Shot peening is a cold working process consisting of repetitive blasting with steel, ceramic or glass shot stream, on the surface of parts. The features of shot peened surfaces include compressive residual stress and high dislocation density in the surface layers, resulting in heterogeneous plastic deformation (Torres and Voorwald, 2002). It is possible to achieve an improvement in fatigue strength by employing the shot peening process, mainly due to the introduction of compressive residual stresses in the surface layers (Gao and Wu, 2011; Hong *et al*., 2008). In general, the compressive residual stresses can delay the initiation of a crack and/or influence its propagation (de los Rios *et al*., 1995).

In most of the works related to effect of shot peening on fatigue behavior or crack propagation, the shot peening treatment is performed before the component being subjected to cyclic loading. Situations with and without treatment are often compared (Houjou *et al*., 2013; Miková *et al*., 2013; Ali *et al*., 2007; Mehmood and Hammouda, 2007). However, the use of the shot peening process to interfere on the propagation rate of an existing crack has been little explored. Some examples are the papers presented by Černý *et al*. (2014), Černý (2011) and Everett Jr. *et al*. (2001).

The aim of the present work is to study the possibility of employing the shot peening process after a crack has started, as a procedure to decrease the rate of growth of the fatigue crack, thus increasing a component’s residual life. For this, aircraft aluminum alloy 2024-T3 specimens were previously cracked and then shot peened with two peening intensity values. The effect of shot peening on the fatigue crack growth rate was assessed for two crack sizes under constant amplitude loading with two distinct load ratios (min/max).

2. MATERIALS AND EXPERIMENTAL PROCEDURE

The high strength aluminum alloy 2024-T3, widely used in the aircraft industry, was chosen for the present work.

The chemical composition and mechanical properties of the alloy are shown in Tabs. 1 and 2, respectively. Compact tension (CT) specimens with 50 mm in width and thickness of 1.27 mm were machined from the aluminum plate.

Table 1. Chemical composition of aluminum alloy 2024-T3.

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
Weight (%)	0.07	0.16	4.01	0.44	1.28	0.004	0.07	0.01

Table 2. Mechanical properties of aluminum alloy 2024-T3.

Yield strength (MPa)	Tensile strength (MPa)	Young's modulus (GPa)
327	432	62

Fatigue crack growth (FCG) tests were carried out at room temperature in laboratory air using a MTS servo-hydraulic machine and were performed with constant amplitude loading under force control. The test frequency was kept constant at 10 Hz and the waveform was sinusoidal. The following load ratios (min/max) were adopted for the tests: R = 0.1 and R = 0.5. The compliance method of crack length monitoring was used during the tests and the five point incremental polynomial technique was employed for computing the crack growth rate. The specimens were initially cyclically loaded up to a crack growth of about 1 mm (a/W = 0.32) or 4 mm (a/W = 0.38) and then subjected to shot peening treatment in the regions shown in Fig. 1. The shot peening was applied with glass shot, on both sides of the specimens. The adopted peening intensities were 6 N and 8 A, behind the crack tip. Following shot peening process, the fatigue tests were resumed under the same loading conditions until the fracture. For each load ratio unpeened specimens were tested for comparison with peened specimens results. All numerical and experimental procedures were in accordance with standard test method for measurement of fatigue crack growth rates (ASTM E647 – 13a$^{\varepsilon 1}$, 2014). The fracture analysis was performed using Scanning Electron Microscopy (SEM).

Crack closure measurements were performed in order to allow ΔK_{eff} calculations to be used in FCG modeling according to Elber's approach (Elber, 1970). The linear-quadratic spline method in which the ''load versus COD'' plots are modeled using two-section least square fit curves, was employed in closure calculations. The degree of crack closure is quantified in terms of fraction U, see Eq. (1), where K_{max} and K_{min} are the maximum and minimum stress intensity factors, respectively, and K_{eff} is the effective stress intensity factor.

$$U = \frac{K_{max} - K_{eff}}{K_{max} - K_{min}} = \frac{\Delta K_{eff}}{\Delta K} \quad (1)$$

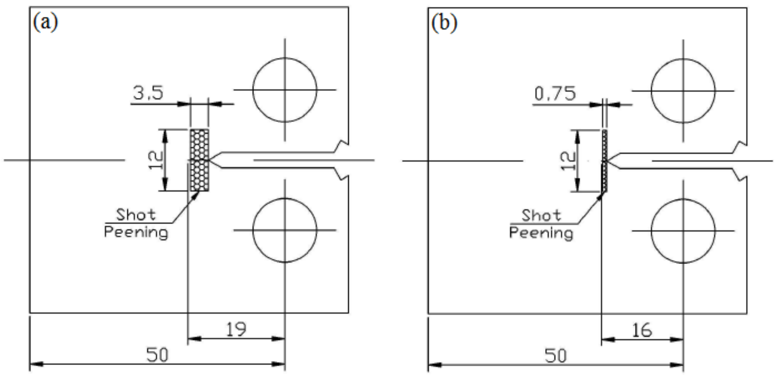

Figure 1. Shot peening process behind the crack tip in (a) a/W = 0.38 and (b) a/W = 0.32.

3. RESULTS AND DISCUSSION

The microstructural and surfaces analysis were especially conducted to characterize the surface layer after the shot peening process. Figure 2 shows a comparison of the surface and subsurface microstructure without and with shot peening in the analyzed intensities. The plane in which the microstructures were examined is the same plane of crack propagation. As expected, the deformation effect of the shot peening process on the surface microstructure was clearly more significant to the most severe intensity (8 A). It can be seen that the cladding layer is deformed by the shot peening process. Could not through the optical microscope to observe changes in the microstructure under the cladding layer treated by shot peening. Surfaces treated with shot peening, in the intensity 6 N, resulted in similar changes in the surface microstructure compared to that found for the most severe intensity, but as expected, much less intense. A comparison of the reliefs of the unpeened and peened surfaces in the intensities studied is shown in Fig. 3. It can be seen that the most severe intensity (8 A) caused greater deformation on the surface compared with lower intensity (6 N).

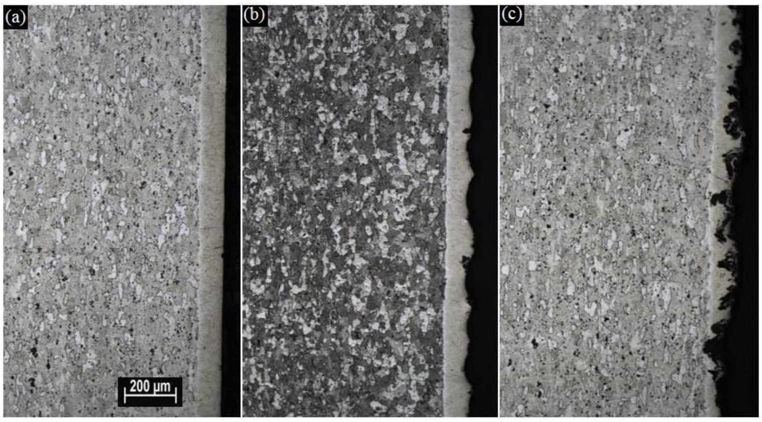

Figure 2. Comparison of microstructures: (a) unpeened and peened specimens with intensities (b) 6 N and (c) 8 A.

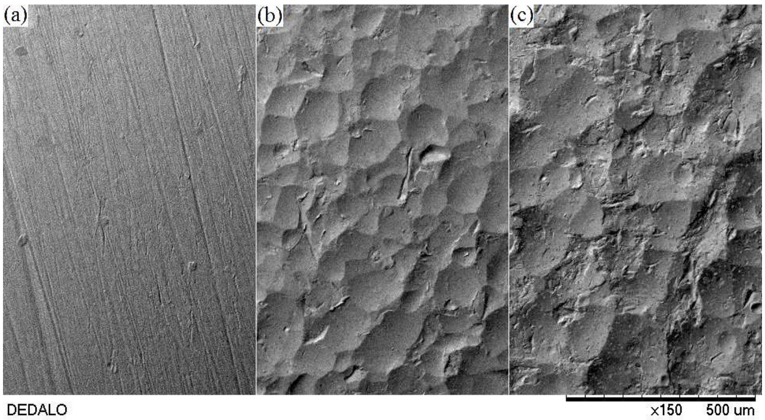

Figure 3. Comparison of the surface between (a) unpeened and peened specimens with intensities (b) 6 N and (c) 8 A.

Figure 4 shows the fracture surface of the region treated with shot peening behind the crack tip at a/W = 0.38 with intensity 6 N and R = 0.1. In general there are transgranular fracture mechanisms. It is observed, in the region that was not affected by shot peening process, cavitation by detachment of particles arising probably from the solution and aging treatment, subcritical crack, cleavage facets and a set of grooves with different orientations, spacings and located fractures between grooves. In the region that is subjected to compressive residual stress induced by shot peening process, facets and cavitation were observed, but there is no clear formation of grooves. There is evidence of plastic strain very close to the surface with shot peening treatment.

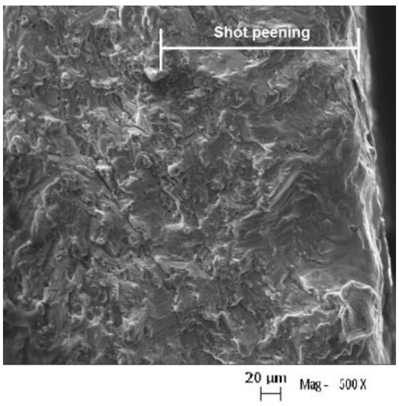

Figure 4. Fracture surface of a peened specimen behind the crack tip in a/W = 0.38.

Figures 5 and 6 show the results of the behavior of fatigue life between *a/W* = 0.38 (*a* = 19 mm, stage II propagation) and *a/W* = 0.32 (*a* = 16 mm, close to the stage I propagation) to fracture for specimens in plane stress state (1.27 mm thickness) under load ratios (*R*) of 0.1 and 0.5, respectively. Plots crack length (*a*) versus number of cycles (*N*) are shown for unpeened and peened specimens with two peening intensities, 6 N and 8 A. For the two studied load ratio conditions, the shot peening process showed differences in crack growth compared to unpeened specimens. For *R* = 0.1 (Fig. 5) it was observed that shot peening process increased fatigue life of peened specimens with intensity 6 N. However, apparently, there was no changes in the number of propagation cycles for peened specimens with intensity 8 A. For *R* = 0.5 (Fig. 6), the effect of shot peening occurred only for peened specimens in *a/W* = 0.32, increasing the fatigue life in terms of the number of propagation cycles.

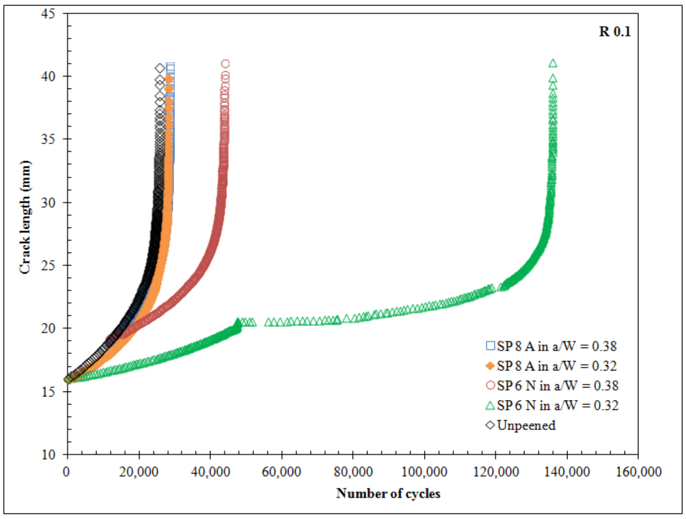

Figure 5. Fatigue crack growth plots for unpeened and peened specimens with intensities 6 N and 8 A for *R* = 0.1.

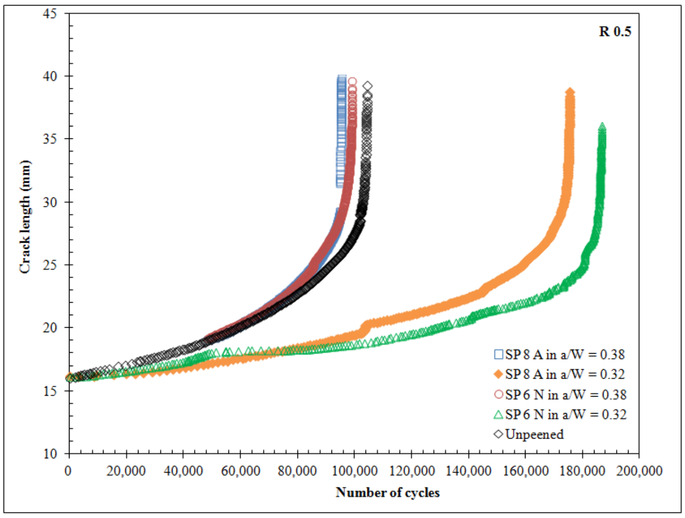

Figure 6. Fatigue crack growth plots for unpeened and peened specimens with intensities 6 N and 8 A for *R* = 0.5.

Figures 7 and 8 show the effect of shot peening on the rate of fatigue crack propagation (*da/dN*) versus stress intensity factor range (ΔK), the same tests presented in Figs. 5 and 6, respectively. Figure 7 (*R* = 0.1) shows a decrease in crack propagation rate, for the peened specimens with intensity 6 N, immediately after the shot peening treatment (15 MPa√m for *a/W* = 0.38 (Fig. 7(a)) and 13 MPa√m for *a/W* = 0.32 (Fig. 7(b))) compared to the unpeened specimen. For the condition peened with intensity 8 A in *a/W* = 0.38 (Fig. 7(a)), no significant change in *da/dN* was observed soon after the process. Greater decrease of *da/dN* occurred only in ΔK = 20 MPa√m for this condition, which in principle can not be credited to the shot peening used. For peened specimen with intensity 8 A in *a/W* = 0.32 (Fig. 7(b)), there has been a small decrease in *da/dN* after the shot peening process, presenting a small increase in fatigue life for this condition, which could not be observed in the Fig. 5. For *R* = 0.5 (Fig. 8) there is a decrease in *da/dN* after shot peening process in *a/W* = 0.32 (ΔK = 7 MPa√m (Fig. 8(b))) for two peening intensities used compared to the unpeened specimen. For other conditions, no change in the crack propagation rate was observed after shot peening treatment, thus confirming the results shown in Fig. 6.

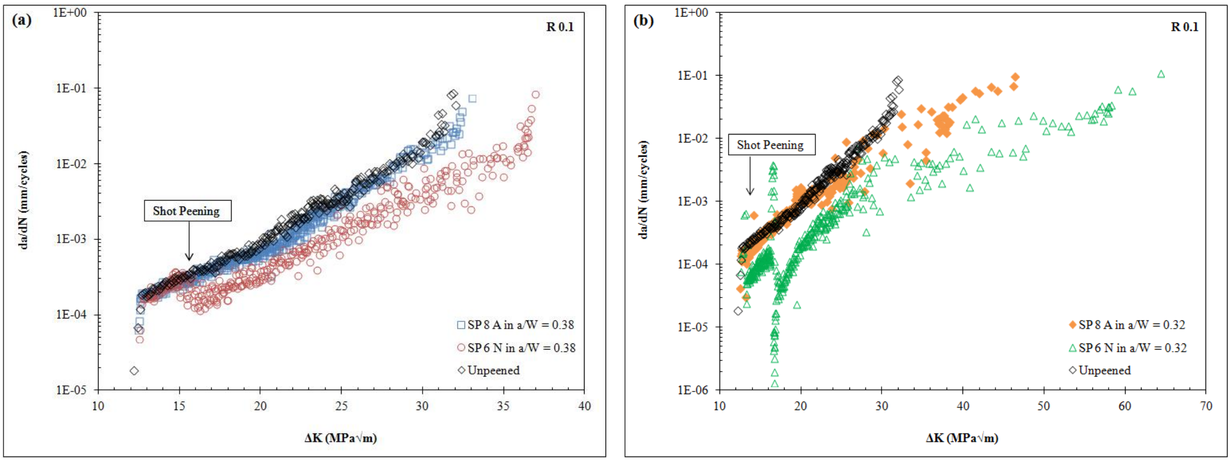

Figure 7. Behavior of the rate of fatigue crack propagation for unpeened and peened specimens in (a) a/W = 0.38 and in (b) a/W = 0.32 for R = 0.1.

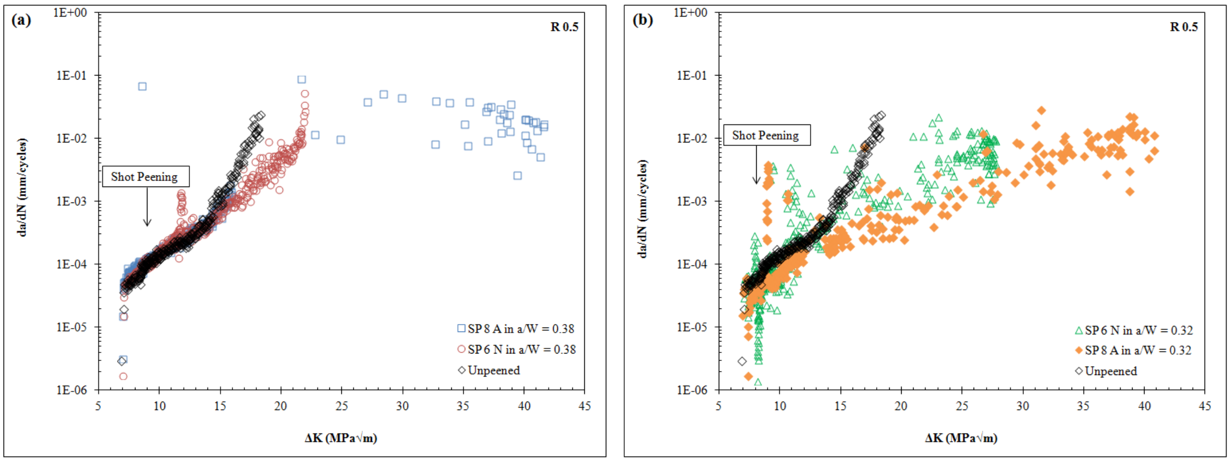

Figure 8. Behavior of the rate of fatigue crack propagation for unpeened and peened specimens in (a) a/W = 0.38 and in (b) a/W = 0.32 for R = 0.5.

According to Zhu and Shaw (1995), shot peening process causes a decrease in fatigue crack propagation rate when the crack closure phenomenon is intensified. Song and Wen (1999) also showed the importance of increasing the crack closure stress in order to obtain a delay on crack propagation rate after shot peening process. To analyze the possible influence of shot peening process on the effective stress intensity factor, results of the degree of crack closure ($\Delta K_{eff}/\Delta K$) versus a/W were studied (Figs. 9 and 10). Figures 9 and 10 show the effect of the shot peening process on the crack closure under the same conditions shown in Figs. 5 and 6, respectively. For R = 0.1 (Fig. 9), it is observed that crack closure of the peened specimens with intensity 6 N is intensified after applying the shot peening process, both for a/W = 0.38 (Fig. 9(a)) and a/W = 0.32 (Fig. 9(b)), in relation to the unpeened specimen. For a/W = 0.38 (Fig. 9(a)), there is a steady decrease of the normalized effective stress intensity factor until fracture occurs, whereas for a/W = 0.32 (Fig. 9(b)), the amount of $\Delta K_{eff}/\Delta K$ decreased up to a/W = 0.40, explaining the increase in fatigue life for this condition. For peening intensity 8 A in a/W = 0.32 (Fig. 9(b)), it is observed a reduction in the amount of $\Delta K_{eff}/\Delta K$ after the shot peening process. However, contrary to what happened for the peened specimen with intensity 6 N, was not a steady decrease, which explains the slight delay in the propagation rate shown in Fig. 7(b). For the unpeened and peened specimens with intensity 8 A in a/W = 0.38 (Fig. 9(a)), there is no difference in the crack closure degree throughout the whole propagation life.

For R = 0.5 (Fig. 10), no change is observed in the crack closure degree after applying the shot peening process on the intensities 6 N and 8 A in a/W = 0.38 (Fig. 10(a)), confirming the previously discussed results showing no influence of shot peening under these conditions. Baptista *et al.* (2012) studied an aluminum alloy 2524-T3, measured and observed a significant crack closure on stage II propagation for load ratio (R) values of 0.05, 0.1 and 0.15, a less pronounced closure for R = 0.3. For R = 0.5 and R = 0.6 no closure was observed. Therefore, since for R = 0.5 no significant influence is expected on ΔK_{eff}, it can be assumed that the shot peening process does not produce delayed effects on the rate of fatigue crack propagation, when applied to a crack on the stage II as is this situation (a/W = 0.38). For a/W = 0.32 (Fig.10(b)), it is observed that, after the application of shot peening process, there was a decrease in the value of $\Delta K_{eff}/\Delta K$ of peened specimens in the two intensities used, justifying the delays in crack propagation rate found in Fig. 6. So for the plane stress state and R = 0.5, the shot peening process influenced the rate of fatigue crack propagation, only when applied in smaller crack sizes (close to the stage I of propagation).

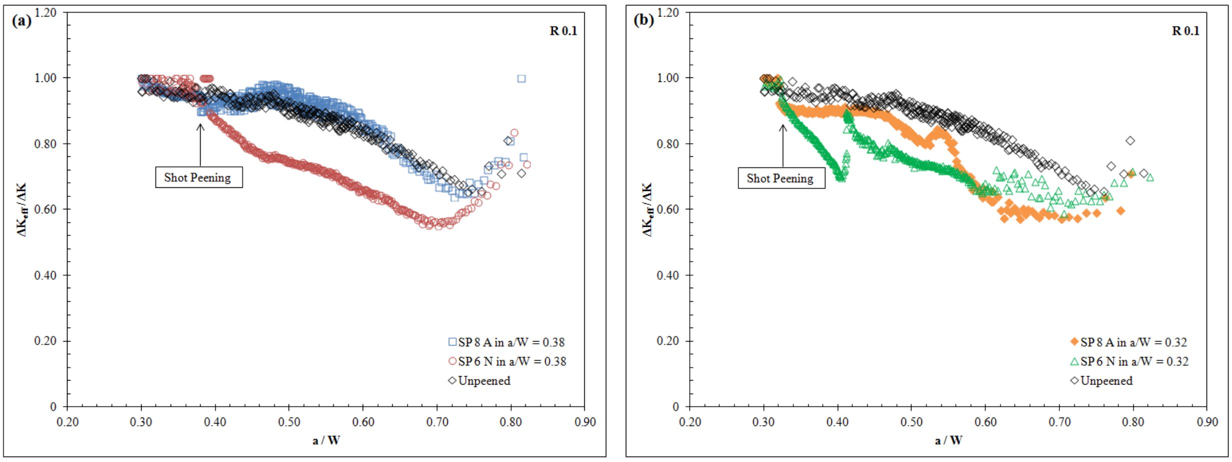

Figure 9. Behavior of the degree of crack closure for unpeened and peened specimens in (a) a/W = 0.38 and in (b) a/W = 0.32 for R = 0.1.

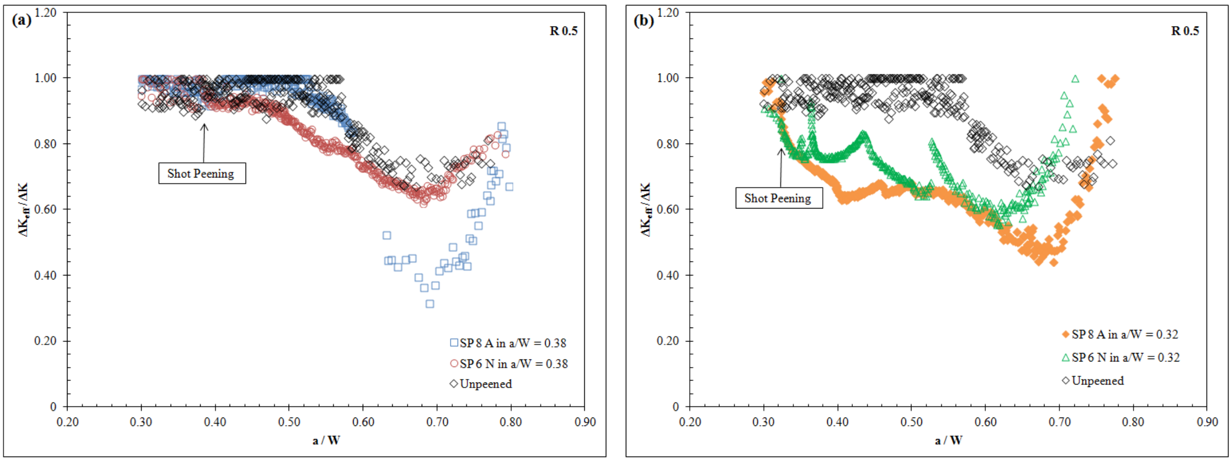

Figure 10. Behavior of the degree of crack closure for unpeened and peened specimens in (a) a/W = 0.38 and in (b) a/W = 0.32 for R = 0.5.

Masuda *et al*. (2014), using CT specimens of aluminum alloy 6061-T6, showed that the plastic zone (in plane stress conditions) on the material surface is an important factor in the plasticity-induced fatigue crack closure. This may explain why the shot peening process, despite being a surface treatment, produces a delay effect on the rate of propagation of fatigue cracks. As the stress state on the surface seems to be the most important factor affecting the crack closure, it is expected that higher compressive stresses in the surface, induced by shot peening process, have increased the ability to induce a delay in the rate of fatigue crack propagation. According to Trško (2013) and Vielma *et al*. (2014), the more severe shot peening intensities create fields of deeper compressive residual stresses, but lower values of compressive residual stresses on the surface. This may help explain why the lower shot peening intensity (6 N) has obtained the best delay effects on fatigue crack propagation rate when compared to the more severe (8 A).

4. CONCLUSION

It was shown that the shot peening process, although being a surface treatment, can affect the propagation rate of a pre-existing fatigue crack in 2024-T3 aluminum alloy specimens, increasing the residual life of a component.

Smaller initial crack size (close to stage I propagation) was more sensitive to the effects of shot peening process than the longer crack (stage II propagation) and presented larger delays in the propagation rate.

The delay effect on fatigue crack propagation rate only occurred when the shot peening process was able to influence the crack closure behavior and therefore ΔK_{eff} values.

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6. RESPONSIBILITY NOTICE