Behavior of the Rate of Fatigue Crack Propagation after Shot Peening in Aluminum Alloy 2024 T3

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Abstract
Shot peening is a process that may induce improvements in the fatigue behavior of the material by inducing compressive residual stresses in their surfaces. This work studies the influence of the shot peening process on the rate of fatigue crack propagation in 2024-T3 aluminum alloy. Compact tension specimens were initially cracked in fatigue and then subjected to shot peening process on both sides. After application of shot peening process, the fatigue test was restarted. Tests with constant amplitude, the load ratios (*R*) of 0.1 and 0.5, in two thicknesses were conducted to examine the possible effects of stress state on the variation of the rate of crack propagation. The effects of two values of shot peening intensity are studied for both load ratios. Comparative curves of the behavior of the rate of fatigue crack propagation, with and without shot peening process, are presented and discussed their differences. The existence of the effect of shot peening process on the behavior of the rate of fatigue crack propagation is displayed when the compressive residual stresses induced by the process influence the value of the effective stress intensity factor range (ΔK_{eff}).

Keywords Shot peening, fatigue crack growth, aluminum alloy 2024-T3

Introduction
Some structural projects have considered during the service time the possibility of the presence of cracks and consequently, their effects on component failure. The possibility of failure increases with the use of high strength materials, especially in the aircraft industry in order to reduce the total weight structures [1]. Most aircraft structures are related to aluminum alloys, high-strength, among which stands out the 2024 [2]. Therefore, the control over the early initiation and propagation of surface cracks is important to prolong the fatigue life of the structural components. Shot peening is a process that induces compressive residual stresses on the surfaces of the components, which can alleviate the tensile stress of the cyclic request. This makes it possible to retard the initiation of surface cracks and/or complicate its propagation, thereby increasing the fatigue strength of the component [3,4,5,6]. Study of the effect of shot peening process during fatigue crack propagation is gaining more attention by the aircraft industry. One question that arises is the possibility of a surface treatment, such as shot peening process, being able to influence the propagation of an existing crack. Some researchers argued that the compressive residual stresses induced by shot peening process, causing a delay in the rate of fatigue crack propagation, but this issue is far from a consensus [7,8,9]. The aim of this work was to analyze the influence of shot peening process on the behavior of the rate of fatigue crack propagation from an existing crack of 4 mm for aluminum alloy 2024-T3. To this end, we used: a) Two thicknesses of material to analyze the effect of stress state; b) Two load ratios (0.1 and 0.5), to analyze the influence of ΔK_{eff}; c) Two shot peening intensities for each material thickness d) Two shot peened regions, behind and around the crack tip, for the plane stress state.

Experimental Methods
The chemical composition of aluminum alloy 2024-T3 used was 99.30Al–0.7 Si + Fe–0.10 Cu–0.05 Mn–0.10 Zn–0.05 V–0.013 Ti–0.03 others (each), wt%. The mechanical properties of this alloy are: yield strength of 270 MPa, tensile strength of 400 MPa, Young's modulus of 72.4 GPa and elongation of 10%. Compact tension specimen with width of 50 mm and thickness of 1.27 mm and 6.35 mm were machined from aluminum sheets (Fig. 1).

Tests of fatigue crack growth (FCG) were carried out at room temperature in laboratory air using a MTS servo-hydraulic machine and were performed with constant amplitude under force control. The test frequency was kept constant at 10 Hz and the loading 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. When the crack was grown about 4 mm (a/W=0.38), the fatigue test was interrupted for application of shot peening treatment in the regions shown in Fig. 1. Following shot peening, the test specimen was refatigued under the loading conditions similar to those prior to shot peening treatment. For each thickness and load ratio test unpeened specimens for comparison with test peened specimens were carried out. All numerical and experimental procedures were in accordance with standard test method for measurement of fatigue crack growth rates (ASTM E647 – $11^{\varepsilon 1}$). The fracture analysis was performed using a Scanning Electron Microscope (SEM).
Crack closure measurements were performed in order to allow ΔK_{eff} calculations to be used in FCG modeling according to Elber's approach [10]. 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

$$U = \frac{K_{\max} - K_{eff}}{K_{\max} - K_{\min}} = \frac{\Delta K_{eff}}{\Delta K} \tag{1}$$

Where K_{max} and K_{min} are the maximum and minimum stress intensity factors, respectively, and K_{eff} is the effective stress intensity factor.

The shot peening process was applied with glass beads, on both sides of the regions shown in Fig. 1. For specimens of 1.27 mm thick was used peening intensity 8 A behind the crack tip and peening intensity 6 N behind and around the crack tip. For specimens of 6.35 mm thick were used peening intensities 12 A and 10 N behind the crack tip.

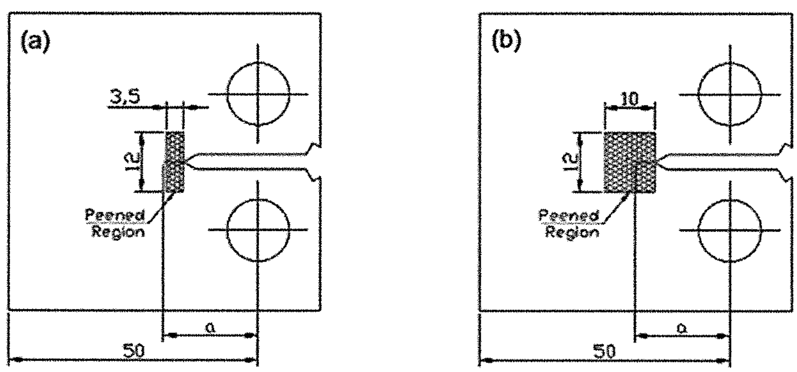

Figure 1. Shot peened regions: (a) behind the crack tip and (b) around the crack tip.

Results and Discussion

Fig. 2 shows the fracture surface of the region treated with shot peening behind the crack tip with intensity 6 N in specimen of 1.27 mm thickness and R=0.1. In general are transgranular fractures. 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.
Fig. 3 shows the results of the behavior of fatigue life between a/W=0.38 to fracture for specimens in plane stress state (1.27 mm thickness) in load ratios (R) of 0.1 and 0.5. Curves crack

length (a) vs. number of cycles (N) are shown of unpeened and peened specimens with two peening intensities, 6 N and 8 A, behind the crack tip (Fig. 1(a)) and a peening intensity, 6 N, around the crack tip (Fig. 1(b)). For the two conditions studied load ratio, the shot peening process showed differences in crack growth compared to unpeened specimen. For R=0.1 it was observed that shot peening process increased fatigue life of peened specimens behind the crack tip, especially for intensity 6 N. However, peened specimen around the crack tip there was no variation in the number of cycles from a/W=0.38 to fracture (Fig. 3(a)). For R=0.5 (Fig. 3(b)), the effect of shot peening occurred only for peened specimen behind the crack tip with intensity 8 A decreasing the number of cycles in the fatigue life.

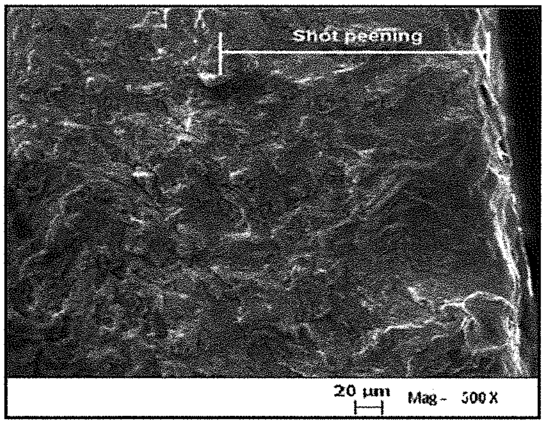

Figure 2. Fracture surface of a peened specimen behind the crack tip.

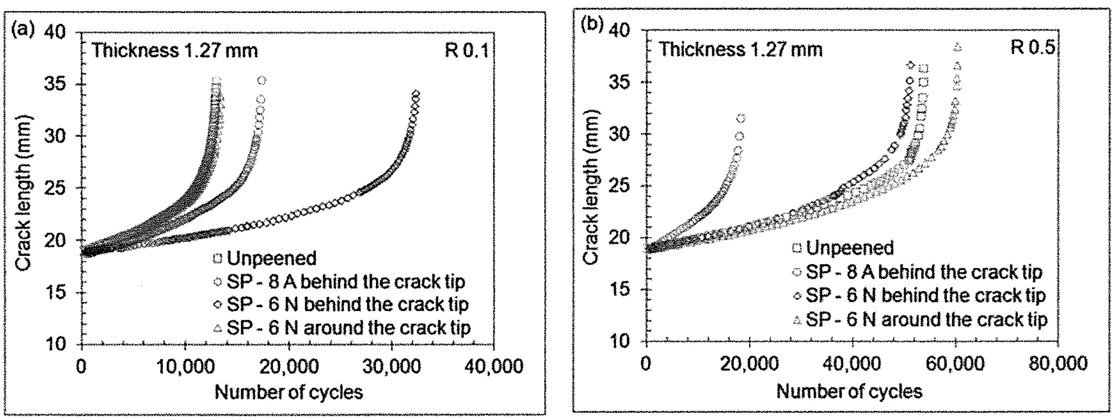

Figure 3. Behavior of the fatigue life for peened and unpeened specimens of 1.27 mm thickness for (a) R=0.1 and (b) R=0.5.

Fig. 4 shows 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 Fig. 3. Fig. 4(a) shows a decrease in crack propagation rate, for the peened specimen behind the crack tip with intensity 6 N, immediately after the shot peening treatment (15 MPa√m) compared to the unpeened specimen. For the condition peened behind the crack tip with intensity 8 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 R=0.5 (Fig. 4(b)) there is an increase in da/dN after shot peening process behind the crack tip with intensity 8 A 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. 3(b).
The results of the behavior of the fatigue life after a/W=0.38 for specimens in plane strain state (6.35 mm thickness) are shown in Fig. 5 to load ratios (R) of 0.1 and 0.5. Tests unpeened and peened specimens were carried out behind the crack tip, in two different intensities, 10 N and 12 A. It is observed in the Fig. 5, in plane strain state, the same behavior noted for peened

specimen behind the crack tip in plane stress state shown in Fig. 3. For R=0.1 the shot peening process tends to increase fatigue life. For R=0.5 condition, however, the shot peening process seems to reduce fatigue life of the component.

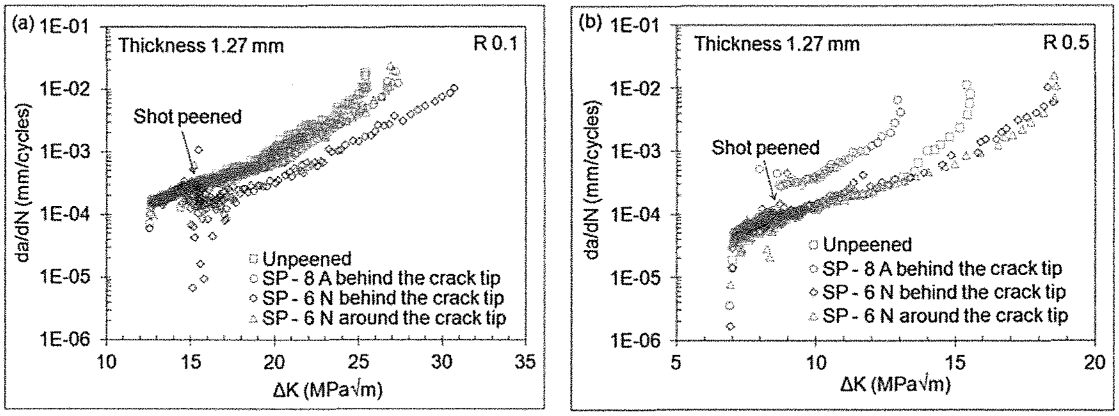

Figure 4. Behavior of the rate of fatigue crack propagation for peened and unpeened specimens of 1.27 mm thickness for (a) R=0.1 and (b) R=0.5.

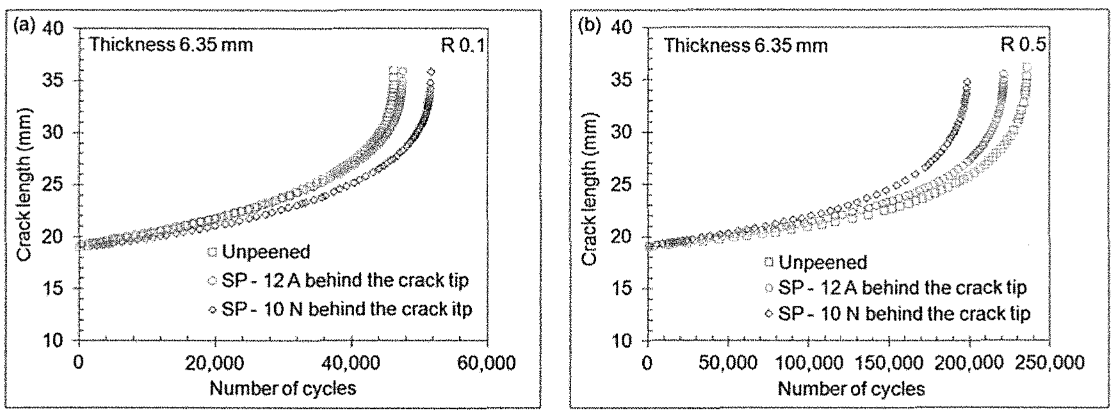

Figure 5. Behavior of the fatigue life for peened and unpeened specimens of 6.35 mm thickness for (a) R=0.1 and (b) R=0.5.

Fig. 6 shows the effect of shot peening on the rate of fatigue crack propagation (*da/dN*) versus stress intensity factor range (ΔK), the same tests shown in Fig. 5. Analyzing the curves of *da/dN* versus ΔK, there is no significant variation among these peened and unpeened specimens for all conditions studied. Everett et al. [9] shows, also studying the 2024-T3 aluminum alloy with a thickness of 6.35 mm, the influence of shot peening process where the treatment is applied at lengths crack shorter than 1.4 mm. He also shows that, under these conditions, the effect of shot peening occurs immediately after the process. Thus, one may speculate that the shot peening treatment is not able to change the rate of fatigue crack propagation, when there is a certain length crack in plane strain state. Future work with additional testing should be carried out to confirm these considerations.

Song [8] remarks that the shot peening process applied to an existing crack causes, in the material below the peened surface, strain and expansion towards the crack sides. The expansion gave rise to a larger plastic wake along crack sides for an increase in closure effect, i.e. increasing K_{eff}. To analyze the possible influence on the effective stress intensity factor, two results of the degree of crack closure (U) versus a/W were studied (Fig. 7). In Fig. 7(a) there are the results of tests on specimens of 1.27 mm thick and R=0.1 for unpeened and peened specimens behind the crack tip with intensity 6 N. In Fig. 7(b) the results in the same conditions are shown for R=0.5. In Fig. 7(a) is observed that the U value of peened specimen decreases after application of shot peening relative to the unpeened specimen. This decrease is constant until the fracture of the material. For the unpeened specimen decline in the U value occurs only after a/W=0.5. The influence of the closure tensions caused by shot peening process, explains the existence of the retardation in the rate of fatigue crack growth. In Fig. 7(b) it is shown that there was no change in the amount of U value in the same conditions for R=0.5, confirming once again that the shot peening process did not affect the crack propagation in this condition. In previous work [11] for aluminum alloy 2524-T3 was observed and measured a significant existence of closure for the tests performed at R-ratios of 0.05, 0.15 and 0.1, less pronounced closure at R=0.3 and virtually no closure occurred for R=0.5 and R=0.6. Therefore, since for R=0.5 no significant influence on ΔK_{eff}, it is expected that the shot peening process is unable to generate retardation effects on the rate of fatigue crack propagation.

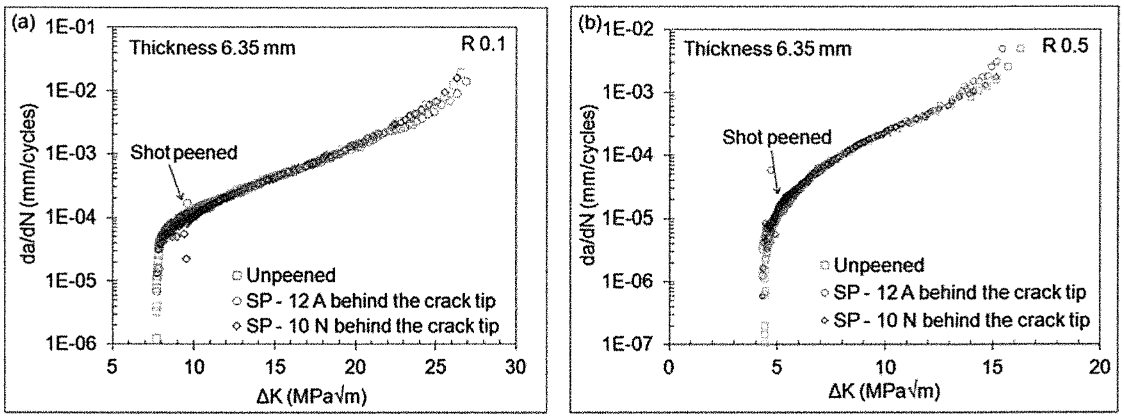

Figure 6. Behavior of the rate of fatigue crack propagation for peened and unpeened specimens of 6.35 mm thickness for (a) R=0.1 and (b) R=0.5.

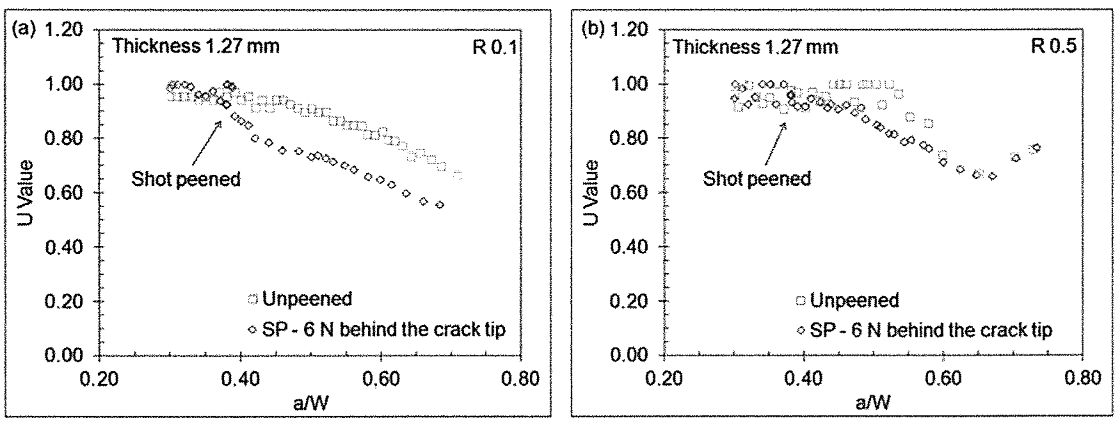

Figure 7. Behavior of the degree of crack closure to the unpeened and peened specimens behind the crack tip of 1.27 mm thickness for (a) R=0.1 and (b) R=0.5.

Conclusions

The shot peening process, when applied behind the crack tip, can influence the behavior of the rate of fatigue crack propagation for 2024-T3 aluminum alloy, occurring retardation or acceleration in the fatigue crack growth. On the other hand, the shot peening process was not found to influence the crack growth when applied around the crack tip.

The influence of shot peening on the propagation rate was most significant for fatigue crack in plane stress state.

The effect of retardation in the rate of fatigue crack propagation occurred when the compressive residual stresses induced by shot peening process can influence the behavior of crack closure.

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