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Effect of laser shock peening and cold expansion on fatigue performance of open hole samples

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Abstract. Mechanical fastening is still one of the main methods used for joining components. Different techniques have been applied to reduce the effect of stress concentration of notches like fastener holes. In this work we evaluate the feasibility of combining laser shock peening (LSP) and cold expansion to improve fatigue crack initiation and propagation of open hole specimens made of 6061-T6 aluminum alloy. LSP is a new and competitive technique for strengthening metals, and like cold expansion, induces a compressive residual stress field that improves fatigue, wear and corrosion resistance. For LSP treatment, a Q-switched Nd:YAG laser with infrared radiation was used. Residual stress distribution as a function of depth was determined by the contour method. Compact tension specimens with a hole at the notch tip were subjected to LSP process and cold expansion and then tested under cyclic loading with R=0.1 generating fatigue cracks on the hole surface. Fatigue crack initiation and growth is analyzed and associated with the residual stress distribution generated by both treatments. It is observed that both methods are complementary; cold expansion increases fatigue crack initiation life, while LSP reduces fatigue crack growth rate.

Keywords: fatigue test; laser shock processing; residual stress

1. Introduction

Laser Shock Peening (LSP) is a relatively new surface treatment technique and has been shown to be effective in improving the fatigue properties of a number of metals and alloys. Potential applications are directed to aerospace and automotive industries. Peyre (1995) reviews the data on LSP and provides deep revision of trends related to the physics, the mechanics and the applications involved. The beneficial effects of LSP on static, cyclic, fretting fatigue and stress corrosion performance have been demonstrated for different materials. For aluminum alloys, Yang *et al.* (2001) demonstrated the effectiveness of LSP on the fatigue behavior of specimens with a fastener

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hole, multiple crack stopholes and single-edge notch. The fatigue behavior improvements on samples were attributed to a combination of increased dislocation density and compressive residual stress induced by the laser shock waves according to results reported by Hong and Chengye (1998). A comparison of LSP and Shot Peening (SP) was made by Rankin *et al.* (2003), residual stress 0.1 mm from the surface due to LSP and SP were comparable and the depth of the compressive stress for LSP was far greater than for SP. Rubio-Gonzalez *et al.* (2004) demonstrated that LSP reduces fatigue crack growth and increases fracture toughness in an aluminum alloy; and in a duplex stainless steel (Rubio-Gonzalez *et al*. 2011) while wear rate decreases by using LSP as shown by Sanchez-Santana *et al.* (2006). The effect of an absorbent overlay on the residual stress field induced by LSP was analyzed by Rubio-Gonzalez *et al.* (2006), it was observed that the overlay makes the compressive residual stress profile move to the surface. On the other hand, for steels and nickel-based alloys, beneficial effects provided by LSP have been reported. Tsay *et al.* (2003) evaluated the fatigue crack growth behavior of laser-processed 304 stainless steel in air and gaseous hydrogen, for both cases a lower fatigue crack growth was observed. The effects of LSP and shot peening on the microstructure, microhardness, and residual stress of low carbon steel were studied by Chu *et al.* (1999), LSP induced plastic deformation causing extensive formation of dislocations. Lavender *et al.* (2008) used the LSP process to increase life of pilger dies made of A2 tool steel by imparting compressive residual stresses to failure prone areas of the dies. The fatigue behavior improvement of LSP treated aluminum friction stir welded joints has been also evaluated by Hatamleh *et al.* (2007) and Hatamleh (2009), the results indicate a significant reduction in fatigue crack growth rates using LSP compared to SP and native welded specimens. However, at cryogenic temperature, it was difficult to discern a trend between residual stress treatment and crack growth rate data as demonstrated by Hatamleh *et al.* (2009); laser peening over the friction stir welded material resulted in the fatigue crack growth rates being comparable to those for base material. Since laser beams can be easily directed to fatigue-critical areas without masking, LSP technology is expected to be widely applicable for improving the fatigue properties of metals and alloys, particularly those that show a positive response to shot peening.

One of the main methods used for joining components is still mechanical fastening, which has the advantage of no special surface preparations, easy disassembly and inspection. Holes in components will create stress or strain concentrations and therefore will reduce load capacity. According to statistic information from Huang *et al.* (1998) fatigue fracture of fastener holes account for 50-90% of fracture of aging planes, and surface finish of fastener holes have direct effect on usage and reliability of aircraft. It is well-known that cracks initiate at the fastener holes in aircraft structures under fatigue loading. It is also known that stopholes can be used to arrest fatigue cracks and to extend the fatigue life of structures. In practice, one stophole at each end of a fatigue crack is usually used to immediately slow down its propagation rate for tolerable cracks. Compressive residual stresses are beneficial as they tend to cancel with the stress resulting from external loading thus reducing the effective stress concentration at the hole edge and the likelihood of fatigue crack initiating under fluctuating loading is reduced.

The effects of various laser shock peening patterns on the residual stress distribution and fatigue performance of Ti-6Al-4V open hole fatigue samples has been investigated by Cuellar *et al.* (2012). The contour method was used to determine the residual stress induced by LSP. A correlation between the residual stress distribution and fatigue performance was established. The effect of laser shock peening on the fatigue behavior of 2024-T3 aluminum alloy with a fastener hole, multiple crack stopholes and single-edge notch was investigated by Yang *et al.* (2001). Ivetic *et al.* (2012) evaluated the effect of the sequence of operations on the effectiveness of LSP treatment in improving the fatigue performance of open hole aluminum specimens. Negative effects on fatigue lives were found on the specimens with the hole already present, while positive effect was observed in specimens in which LSP was applied before drilling the hole.

Numerical simulations of the LSP have been demonstrated to be useful in order to evaluate the effect of changing process parameters and analyze the response on different materials. Ocaña *et al.* (2004) developed a FE model to estimate residual stresses and surface deformation induced by LSP using different process parameters. Ivetic (2011) used a 3D FE analysis to determine the response of aluminum alloy thin plates including the effect of wave reflections from the plate back side. A FE simulation of multiple LSP impacts was presented by Ding *et al.* (2006) to estimate the magnitude and distribution of residual stresses on steel samples. A numerical analysis of an open hole specimen subjected to LSP was conducted by Ivetic *et al.* (2011), the effect of the induced residual stress field on the fatigue life of the specimen was investigated.

Over the last 30 years the cold expansion process has been used widely to improve the fatigue life of components containing fastener holes without any weight penalty. To achieve cold expansion an oversized ball or a mandrel is forced to pass through the hole yielding locally the material and creating a plastic region. The fatigue life improvement of cold expanded fastener holes is attributed to the presence of compressive residual stress around the hole surface. Different numerical and experimental studies have been conducted to analyze the effect of process parameters, sequence of operation during the process and load spectrums. Residual stress measurements were made Liu *et al.* (2008) on aluminium alloy open holes after cold expansion, the results revealed that direct cold expansion technique could elevate about six times fatigue life; in addition, they observed that after cold expansion, fatigue crack of open holes always initiates on entrance face. The effectiveness of a direct cold expansion technique on the fatigue strength of fastener holes was also addresses by Chakherlou and Vogwell (2003). Minguez and Vogwell (2006) investigated the influence of cyclic temperature variation on the fatigue life of fastener holes in an aerospace aluminium alloy after cold expansion. Longer fatigue lives of specimens with cold expanded holes were obtained provided that the applied load ratio was less than 0.7, and the maximum applied stress was less than 0.5 of the yield strength according to the results reported by Lacarac *et al.* (2000). Amrouche *et al.* (2003) quantified the effect of the cold expansion on the initiation and the propagation of the fatigue crack, they showed that the degree of cold expansion has an influence on the size of the zone of compressive residual stresses but it has no influence on the level of the maximum residual stresses. Fatigue crack growth from an expanded hole was simulated by Semari *et al.* (2013), the residual stresses were superposed with the applied stresses field in order to estimate crack growth with a linear 3-D model. A simulation of the residual stress field resulting from the cold expansion of two adjacent fastener holes was conducted by Papanikos and Meguid (1999); the results revealed the important role played by the geometry of the workpiece and the expansion parameters upon the quality of the treatment. The application on fatigue-aged fastener holes has also been reported by Zhang and Wang (2003). Ghfiri *et al.* (2000) addressed the cold expansion method as a reparation technique of cracked component, it was demonstrated that fatigue initiation life after the reparation increases with the degree of cold expansion of the stophole. The distribution of tangential residual stress obtained from a finite element analysis shows that it is not uniform throughout the thickness of a cold expanded plate (Chakherlou and Vogwell 2003). The tangential residual stress is less compressive at the pin entrance face than at the mid-plane and the exit face. This was confirmed by fatigue tests since all fatigue cracks initiated and propagated at, or near, the entrance face in the cold expanded specimens. Aid *et al.* (2014) observed good agreement between FEM simulation and experimental

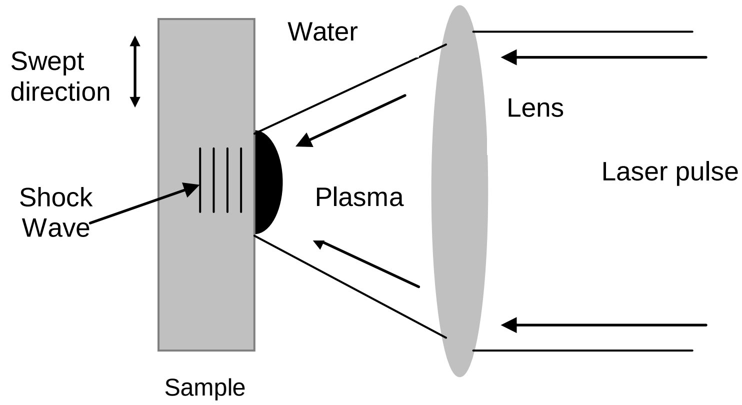


Fig. 1 Pinciple of laser shock processing

results of crack growth on expanded hole samples.

It is known that the residual stress field due to LSP is extremely sensitive to geometric features (Cuellar *et al*. 2012) and it is well understood that geometric features, such as notches or holes, are typical fatigue crack initiation points because they act as stress concentrations. However, little information has been published regarding the residual stress induced by LSP in different geometries. In addition, no previous work has been reported on the open literature to evaluate the effect of combining LSP and cold expansion on the fatigue behavior of open hole specimens.

The aim of this paper is to analyze the combination of LSP and cold expansion to improve fatigue crack initiation and propagation of open hole specimens made of 6061-T6 aluminum alloy. Residual stress distribution as a function of depth is determined by the contour method. Compact tension specimens with a hole at the notch tip were subjected to LSP process and cold expansion and then tested under cyclic loading; fatigue cracks emanating from the hole surface were then monitored. Fatigue crack initiation and growth is analyzed and associated with the residual stress distribution generated by both treatments.

In the laser shock processing of metals, the sample is either completely immersed in water or in air. A water jet may be used also to produce a water wall with constant thickness on the sample. The laser pulse is then focused onto the sample. The schematic of how the process works in water is shown in Fig. 1. When the laser beam is directed onto the surface to be treated, it passes through the transparent overlay and strikes the sample. It immediately vaporizes a thin surface layer of the overlay. High pressure against the surface of the sample causes a shock wave to propagate into the material. The plastic deformation caused by the shock wave produces the compressive residual stresses at the surface of the sample. Laser pulse may come directly from the laser apparatus or may be delivered using an optical fiber.

2. Experimental procedure

2.1 Material

Plates of 6061-T6 aluminum alloy with thickness of 6.3 mm were machined to obtain the specimens. The T6 condition consists of a solution treatment and artificial aging. The mechanical

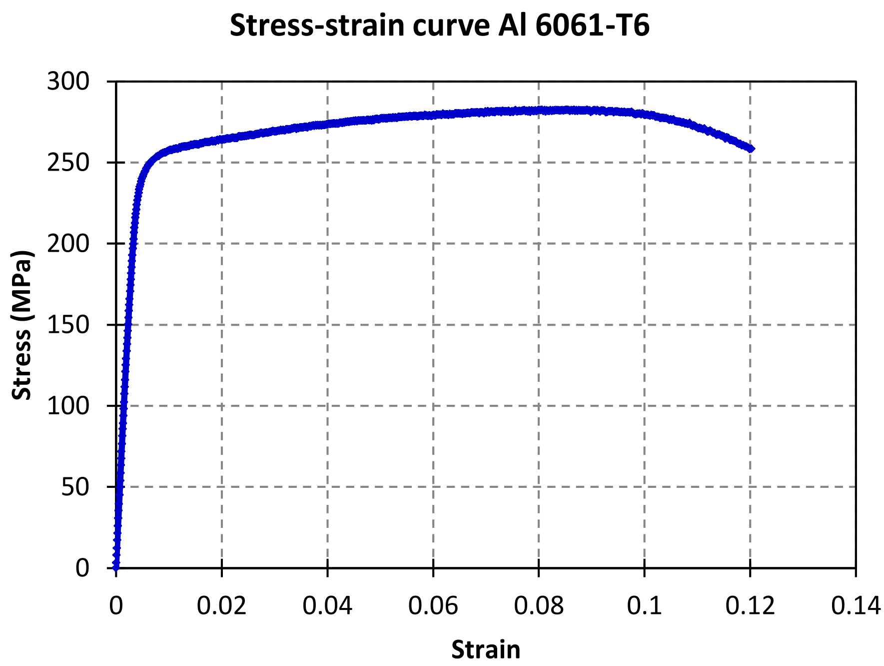


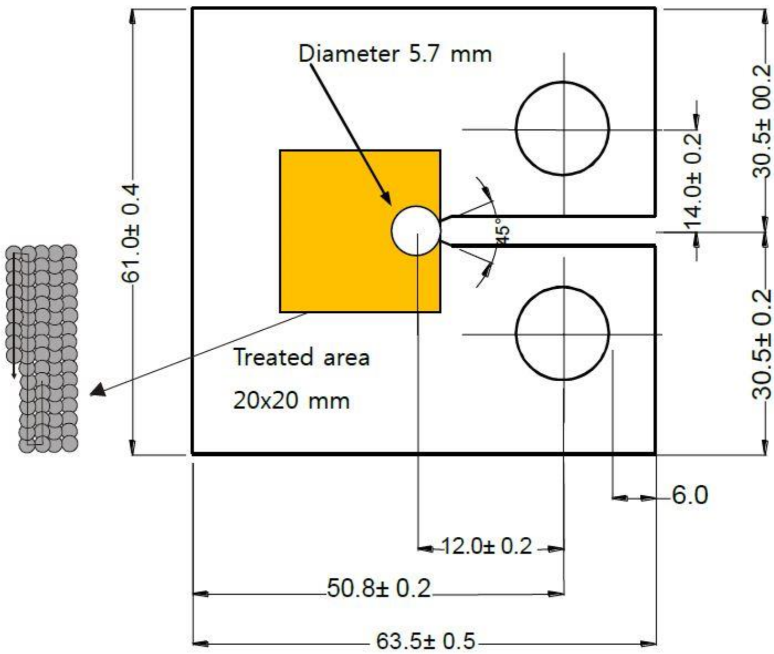
Fig. 2 Stress-strain curve of 6061-T6 aluminum alloy under tensile loading conditions

properties were determined using dog-bone type specimens. Results are shown in Fig. 2. The offset tensile yield stress is 241 MPa, ultimate tensile strength 282.5 MPa and elastic modulus 67.6 GPa.

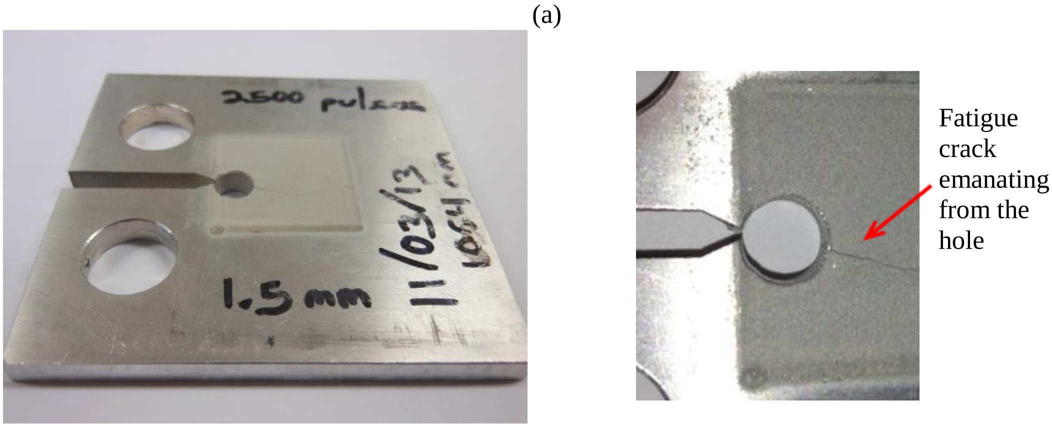
The specimens used for residual stress measurement were blocks of 50×50×5 mm with LSP on only one side. The specimen used for fatigue crack growth tests were compact tension specimens as illustrated in Fig. 3. All fatigue crack growth tests specimens were machined with the loading axis parallel to the rolling direction. Fig. 3(a) also illustrates pulse swept direction. The thickness of all specimens was reduced from 6.3 mm to 5 mm (or 4.8 mm for compact tension specimens) by machining the specimen faces to eliminate the manufacturing effect of the original plates.

2.2 Laser shock processing

The LSP experiments were performed using a Q switched Nd:YAG laser operating at 10 Hz with a wave length of 1064 nm, the FWHM of the pulses was 6 ns. A convergent lens was used to deliver 0.9 J/pulse. Spot diameter was 1.5 mm. Pulse density was 2500 pul/cm^2. A special device to produce a controlled water jet has been implemented to form a thin water layer on the sample to be treated. Specimen treated area was 20x20 mm on both sides of the compact tension specimen. CT specimens were used for fatigue crack experiments. A 2D motion system was used to control specimen position and generate the pulse swept as shown in Fig. 3. Controlling the velocity of the system, the desired pulse density was obtained. No protective coating was used during LSP (Rubio-Gonzalez *et al*. 2006). Fig. 3(b) shows a photograph of a compact tension specimen with LSP applied after the hole was introduced.



(a)



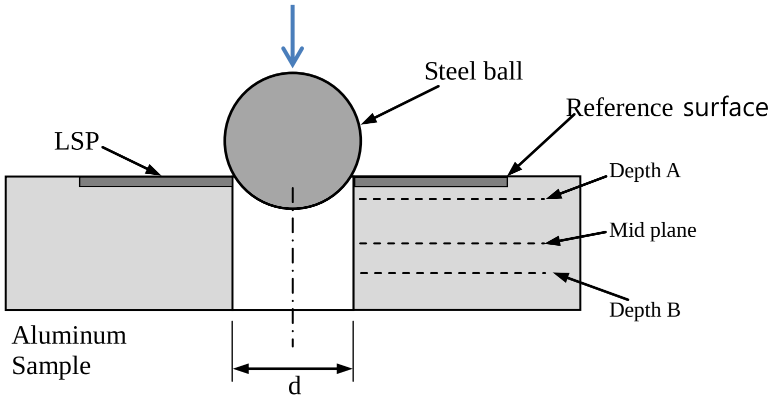
(b)

Fig. 3 Compact tension test specimens used in the fatigue crack growth tests (a) Specimen illustration with dimensions in mm. Specimen thickness was 4.8 mm (b) Real specimen

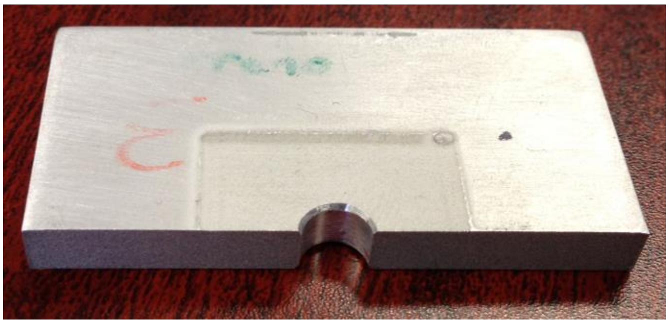
From the practical point of view, it would be convenient to evaluate the feasibility of applying LSP on components already with holes that may be assembled later, where it is not possible to apply LSP before the hole is made, because the manufacturing process may not allow modifying the sequence. This is the motivation for the sequence chosen in this work.

2.3 Cold expansion

An initial hole was drilled (diameter 5.7 mm) with center at the notch end of the compact



(a)



(b)

Fig. 4 (a) Illustration of the Cold Expansion process. (b) Photograph of the specimen used for residual stress measurement

specimen. The Cold Expansion process was carried out by inserting a high strength steel ball of 6 mm diameter through the hole using a hydraulic machine with oil as a lubricant. These diameters give a percentage of cold expansion of 5.2%. Fig. 4(a) shows a schematic illustration of the cold expansion process and Fig. 4(b) shows a photograph of the specimen used for residual stress measurements. For the specimen with LSP and cold expansion, the entrance face corresponds to the face treated with LSP. On specimens used for residual stress measurements LSP was applied only on one face.

2.4 Fatigue crack growth test

Fatigue crack growth tests were performed on a MTS 810 servo-hydraulic system at room temperature in the air. Load ratio $R=P_{min}/P_{max}$ was maintained at R=0.1. Frequency of 20 Hz with a sine wave form was used in the experiments. Each specimen was tested to maximum load of 3500 N. Crack lengths were measured using the crack compliance method. Fatigue crack initiation life was considered when a small crack of about 2 mm long appeared on the surface; that is, crack length measured from the load line was about 17 mm.

Stress intensity factor KI due to external load P was determined using the following equation (Anderson 1995)

$$K_I = \frac{P}{B\sqrt{W}} \frac{2+\frac{a}{W}}{\left(1-\frac{a}{W}\right)^{3/2}} \left[0.886 + 4.64\left(\frac{a}{W}\right) - 13.32\left(\frac{a}{W}\right)^2 + 14.72\left(\frac{a}{W}\right)^3 - 5.60\left(\frac{a}{W}\right)^4\right] \tag{1}$$

which is also the equation used in the ASTM E647 standard.

2.5 Residual stress measurement

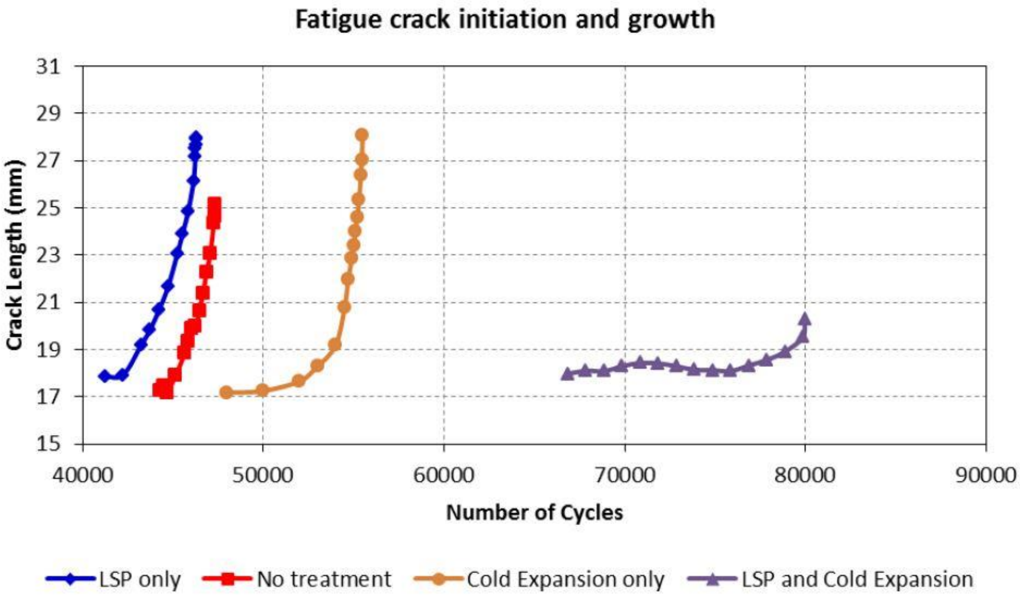
Residual stress component perpendicular to the swept direction was measured using the contour method (Prime 2001) on the treated specimen cross section. This was carried out by cutting specimens along the measurement plane with an EDM wire. Before the specimens were cut, they were fixed to a rigid backing plate in order to minimize movement during the cutting process. The deformed surface shape, resulting from the relaxed residual stresses, was measured on the cutting surface using a coordinate measuring machine. The displacements from the cutting surface were filtered by fitting to a smooth analytical surface. Finally, the original residual stresses were calculated from the measured contour using a finite element model. Fig. 4(b) shows a photograph of a specimen used for residual stress measurement; this specimen was subjected to LSP and cold expansion.

3. Results and discussion

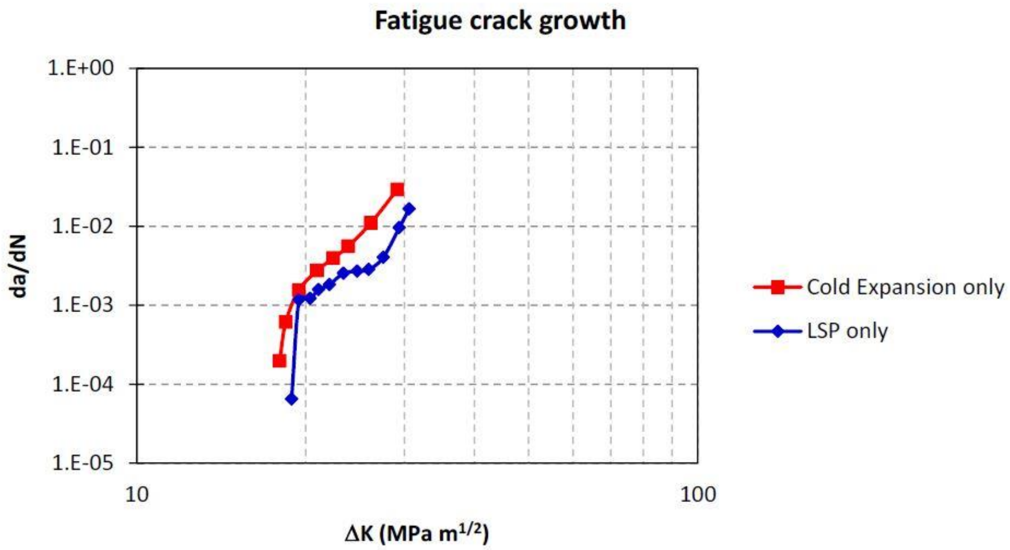
Fig. 5(a) shows fatigue crack growth curves of specimens with different treatments. Note that specimens with and without LSP treatment have no much difference on fatigue crack initiation, moreover, LSP has a small detriment on fatigue life as has been observed by Ivetic *et al*. (2012) when holes are drilled before LSP. However, Cold Expansion has a beneficial effect on fatigue crack initiation as shown in the same figure (label "Cold Expansion only"). Finally, the combination of LSP and Cold Expansion is shown to increase fatigue crack initiation life even more and reduce fatigue crack growth rate, in this last case the crack growth presented a bifurcation, for this reason the crack length monitoring was stopped and fatigue crack growth rate was not calculated. In Fig. 3(b) the zoomed image shows a fatigue crack emanating from the hole surface. Fig. 5(b) shows the fatigue crack growth rate as a function of the stress intensity factor range, it demonstrates that the advantage of LSP compared with Cold Expansion is on reducing fatigue crack propagation rate.

Figs. 6-8 show the residual stress distribution on the specimen cross section obtained by the contour method on open hole specimens. The calculated stress corresponds to the circumferential component around the hole. Distance is measured from the hole surface. Specimens with different treatments were considered. Stress profiles were calculated at three different depths; as illustrated in Fig. 4(a), Depth A is an imaginary line at approximately 1 mm from the reference surface, Mid plane is a line at the middle of the thickness and Depth B is a line approximately 3.7 mm from the reference surface. Position of these imaginary lines is arbitrary; the purpose is just to identify any difference on the residual stress profiles. The reference surface is either the LSP surface or the entrance surface for cold expanded specimens.

Fig. 6 shows the residual stress profiles for the specimen treated with LSP only. As it is expected, LSP has a local effect close to the treated surface; compressive residual stress is



(a)



(b)

Fig. 5 (a) Fatigue crack growth of aluminum samples with different treatments, LSP and Cold Expansion (b) Fatigue crack growth rate. Cracks emanating from the hole surface

observed at Depth A and Mid plane. Residual stress measurements for the specimen subjected to LSP and cold expansion are shown in Fig. 7, while Fig. 7(b) shows a color-map illustrating the residual stress distribution. Note that LSP improves the effect of cold expansion, that is, generates more compressive residual stress over a bigger region, bringing down the stress profile. Recall that LSP was applied on one specimen surface only. Fig. 8 shows the residual stress profiles forspecimen with cold expansion only. Note that stress profile is more compressive close to the exit face (Depth B) in agreement with the usual results as pointed out by Liu *et al*. (2008).

In order to make a comparison of the residual stress profiles obtained by the contour method, a

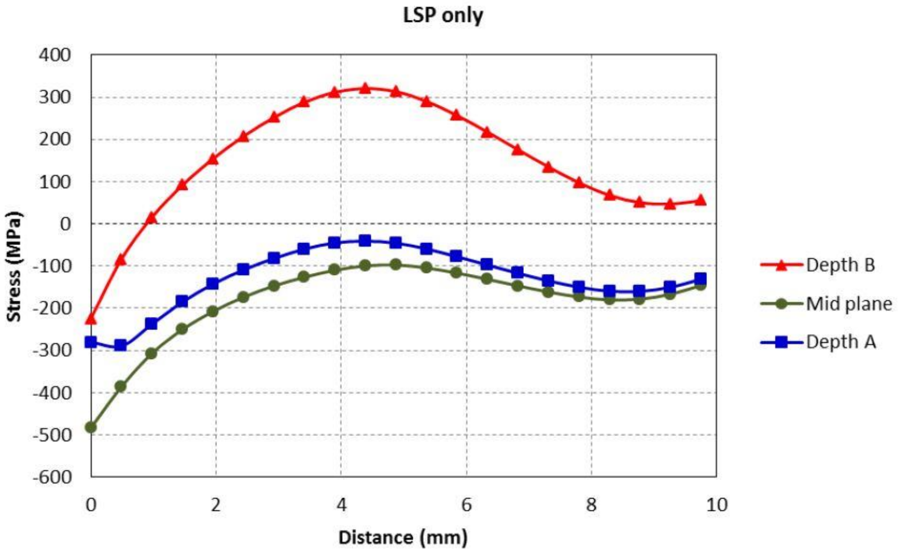
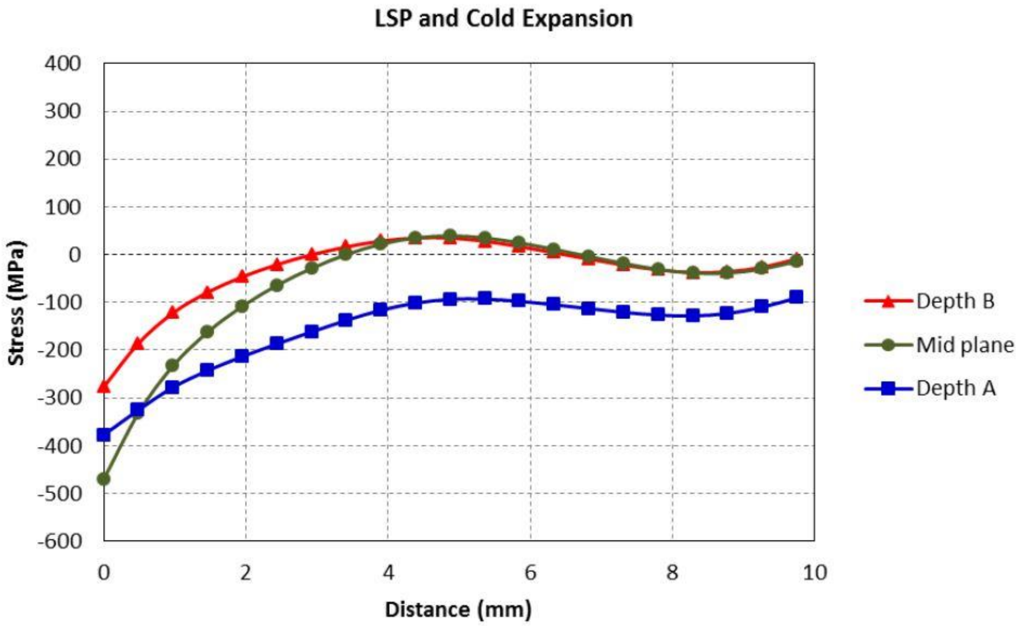
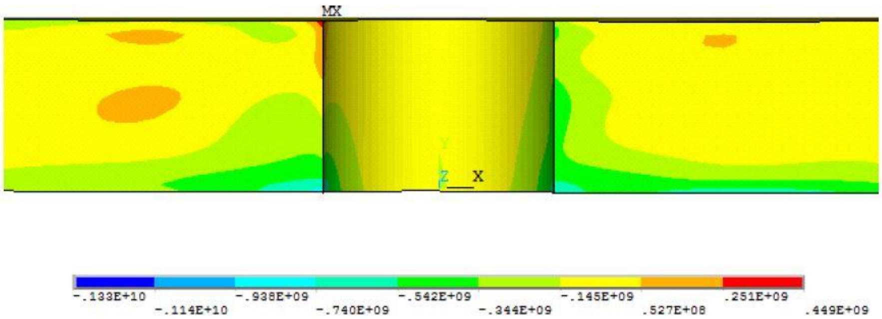


Fig. 6 Residual stresses profiles at different depths. LSP only. Distance is measured from the hole surface



(a)

Fig. 7 (a) Residual stresses profiles at different depths, LSP and Cold Expansion. (b) Residual stress contour map in Pa



(b)

Fig. 7 Continued

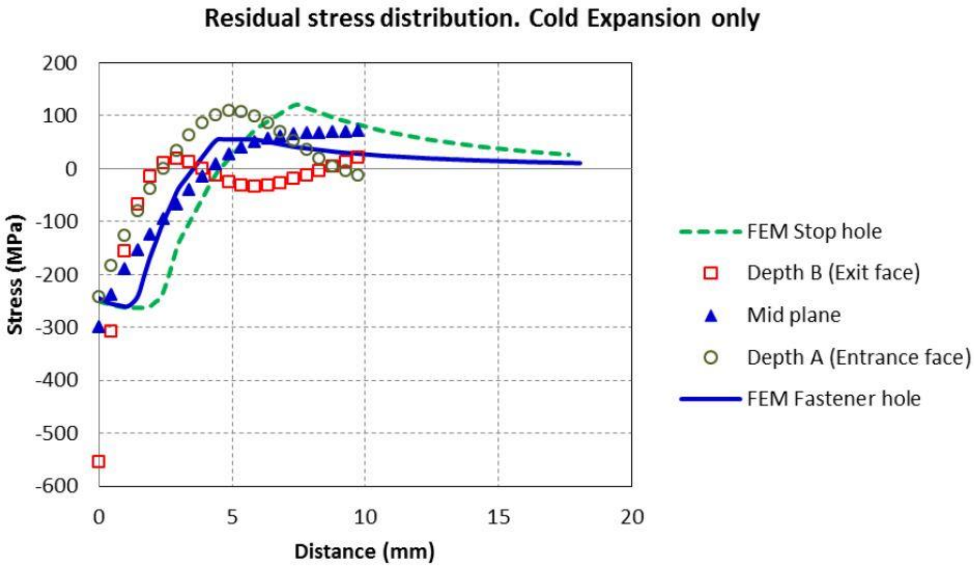
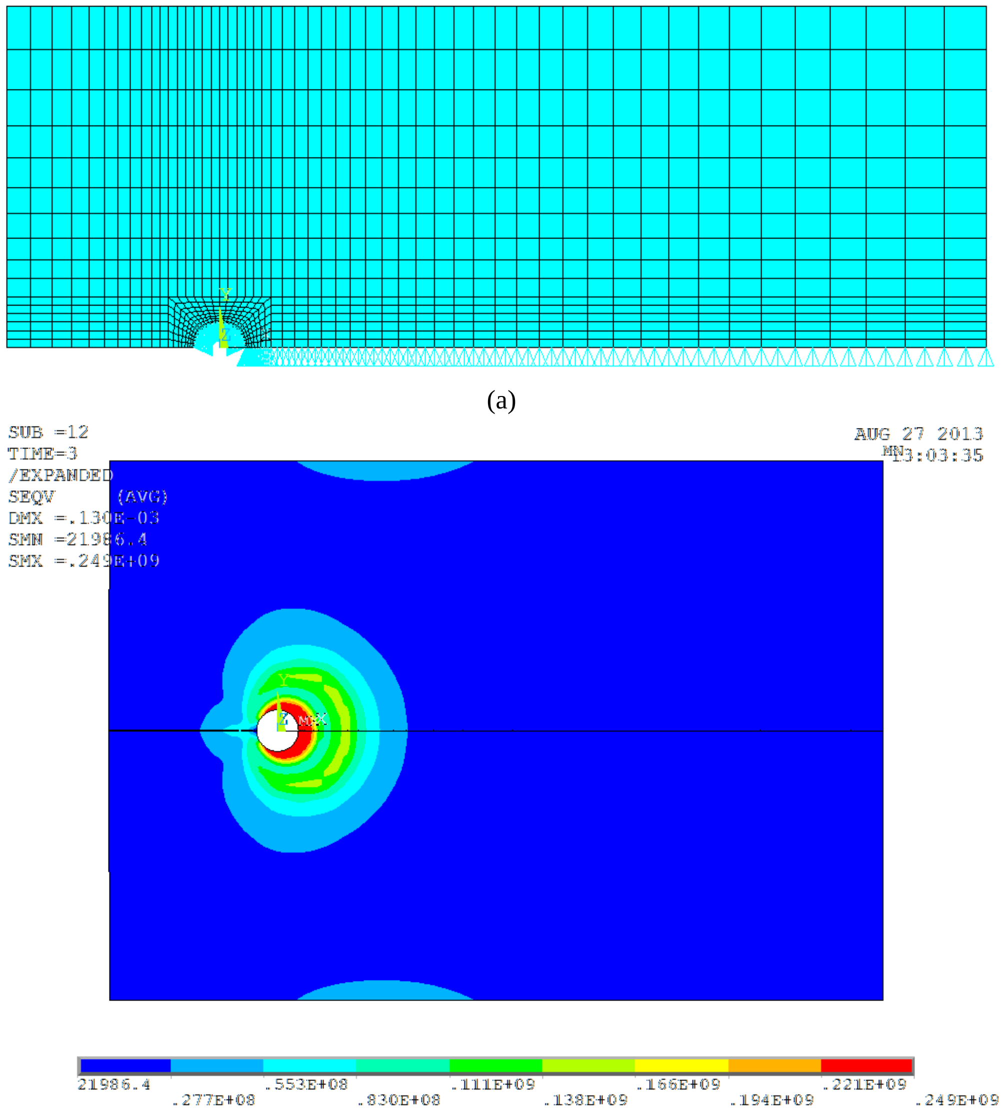


Fig. 8 Comparison of residual stress profiles at different depths determined by the contour method and those obtained by a FE simulation. Cold Expansion only

simplified finite element simulation of the cold expansion process was performed. Even though a 2D FE model is not capable to accurately predict the residual stresses because its variation on the thickness direction; it is used in this work just for comparison with the results obtained by the contour method. A nonlinear analysis using the code ANSYS was conducted. Two dimensional isoparametric elements with eight nodes were used. Plane stress conditions were assumed. A multilinear model of the experimental stress-strain curve was considered along with the kinematic hardening rule. The mesh is shown in Fig. 9(a); because of symmetry, only the upper half part is considered. Fig. 9(b) shows the von Mises residual stress distribution. Fig. 9(a) shows the boundary condition for the stophole case; however the fastener hole case may also be obtained by constraining displacement on the crack face; both situations were analyzed. Fig. 8 shows the tangential residual stress component obtained by the 2-D finite element analysis for both configurations: fastener holes and stop holes. It is worth noting a good agreement between the Mid



(b)

Fig. 9 (a) 2-D Finite element discretization of the half specimen. (b) Residual stress field (von Mises) after cold expansion of an arresting crack hole

plane stress profile measured by the contour method and the 2-D finite element analysis for the fastener hole case.

4. Conclusions

It has been demonstrated that the laser shock processing (LSP) is an effective surface treatment technique to improve fatigue properties of 6061 aluminum alloy. It may be a good complement of

Cold Expansion for fatigue life enhancement of metallic components. It has been shown that the LSP and cold expansion are suitable treatments to improve fatigue crack initiation and propagation of open hole specimens made of 6061-T6 aluminum alloy. The beneficial effect of cold expansion is mainly in increasing fatigue crack initiation life, while the advantage of LSP is primarily in reducing fatigue crack growth rate. This is due to the residual stress field induced on the hole surface (cold expansion) and sample faces (LSP).

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