Advanced Materials Research *Online: 2014-08-11*
ISSN: 1662-8985, Vol. 996, pp 775-781
doi:10.4028/www.scientific.net/AMR.996.775

Fatigue Crack Growth in Laser Shock Peened Thin Metallic Panels

TROIANI Enrico[1, a *], TADDIA Sara[1,b] , MENEGHIN Ivan[2,c]
and MOLINARI Gianluca[2,d]

[1]University of Bologna, Forlì, Italy

[2]Rücker Aerospace GmbH, Augsburg, Germany

[a]enrico.troiani@unibo.it, [b]sara.taddia4@unibo.it, [c]ivan.meneghin@googlemail.com,
[d]gmolinari79@gmail.com

Keywords: Residual Stress, Thin Panels, Laser Shock Peening, FEA, Fatigue Crack Propagation, Analytical Predictions.

Abstract. Flat thin aluminum panels with centered crack have been Laser Shock Peened along straight patterns perpendicular to the crack. Despite of the locally induced compressive residual stresses, the experimental tests showed the negative effect of the LSP on the fatigue crack propagation performances of panels. Starting from the numerical assessment of the self-balancing residual stress distribution along the entire panel width, the fatigue crack growth through the panels has been analytically evaluated and compared with experimental results, showing a good agreement. The comparison highlights the sensitivity of the fatigue crack propagation life to the selected LSP pattern configuration (i.e. the width of the LSP treated strip and the relative position to the crack centre) which have to be accurately setup in order to exploit the full potentiality of the LSP process in increasing the fatigue life and avoid undesired reduction of the component performances.

Introduction

A proven method for reducing the fatigue related problems in metallic structures is to drive compressive residual stresses into the affected area by means of Laser Shock Peening (LSP) [1]. This surface treatment is very effective in bulk structures, improving life performances of fatigue sensitive aeronautical components, such as jet engines turbine blades or helicopter gearboxes.

The LSP process is based on a high-power pulsed laser beam of very short duration (1 to 10 ns) focused on the surface to be treated, which is covered by a coating (ablative layer, usually black paint or a very thin aluminum foil), as shown in Fig.1. The laser beam hits the ablative layer, which partially evaporates into the plasma state. A transparent layer, usually water, is required over the coating and prevents the plasma expansion, thus resulting in a compressive shock wave propagating into the metal. The shock waves are essential for locally inducing plasticization of the metal and the establishment of the compressive residual stresses.

Test results available in the bibliography show that the residual compressive stresses induced by LSP increase the fatigue life of bulk metallic components [1], whereas quite limited studies have been presented on the fatigue crack growth in thin components [2,3]. The beneficial effect of LSP in terms of fatigue crack growth on compact tension specimens with crack tips very close or inside to the laser shot pattern has been assessed [4,5,6], while an investigation on the effect of the LSP on the fatigue crack propagation of a macro-crack approaching the LSP treated area is still missing. As a consequence of the self-balancing residual stress field induced by the LSP in the thin-gauge panel, the chosen LSP pattern configuration (distance of the crack tip to the laser shot, width of the laser pattern) can affect significantly the fatigue crack propagation performances of the panel.

Therefore, the aim of this work is to investigate the effect of the residual stress distribution introduced by the LSP on the crack growth in thin panels. These stress distributions are assessed by means of experimental tests and finite element simulations. Their effects on the crack growth has been analytically evaluated to perform a sensitivity study in order to determine which LSP parameters can influence the crack growth rate.

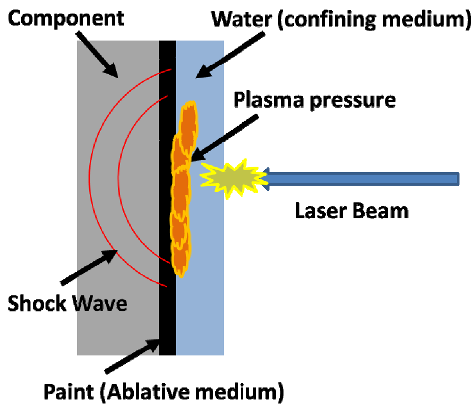

Fig. 1. LSP process

Geometry definition and experimental procedure

Three M(T) central cracked aluminum panels 2mm thick have been used in this investigation [7]. The panels, 160mm wide and 400mm long, have been LSP treated along two straight patterns, 10mm wide and 100mm long, located 50 mm from the specimen centerline, as shown in Fig. 1. The panels have been subjected to LSP treatment before the introduction of the central crack by the Universidad Politecnica de Madrid (UPM) with a Q switched Nd:YAG laser with 2.5 mm spot diameter, 178 pulse/cm^2 density and 0.75 mm shot overlapping were used to perform the LSP process.

The central cracks has been machined as saw cuts perpendicularly to the LSP patterns into the panels which have been subjected to a pre-fatigue loading to achieve realistic sharp tip crack geometry before the fatigue crack propagation tests.

The fatigue crack propagation tests have been performed by Airbus Group Innovations on the aforementioned three panels identified as 2.1, 2.3 and 2.4. A constant amplitude fatigue load with R = 0.1 has been applied uniaxially perpendicular to the central crack.

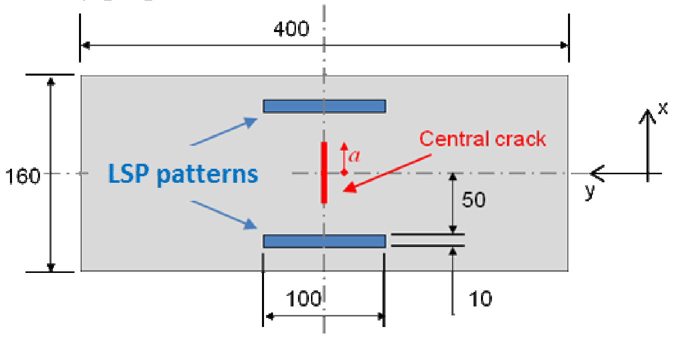

Fig. 2. FCP Specimens configuration (in mm)

The experimental crack growth rate data as a function of the Stress Intensity Factor (SIF) are reported in Fig.3 for the three investigated specimens. The LSP influence can be evaluated via comparison with a baseline, relative to the non-treated material. The baseline behaviour has been extrapolated by means of the Paris “C” and “n” material coefficients calculated at the linear part of the Fig.3 curves (C = 2.10e-11; n=2.71) and taking into account the effect of the finite-width of the panel expressed by the geometry factor below *β(a)*.

$$\beta(a)=\sqrt{\sec\frac{\pi a}{W}} \tag{1}$$

where a is the semi-crack length of the crack and W is the panel width.

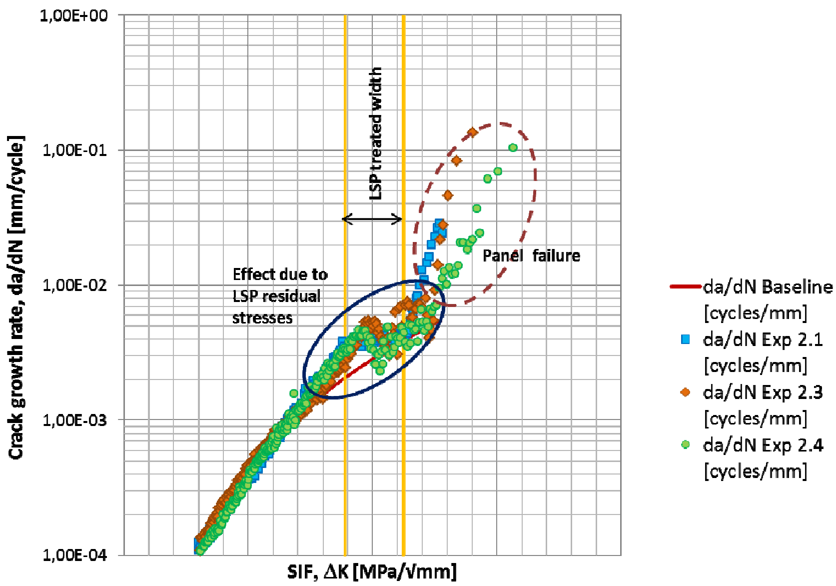

Fig.3. Fatigue Life, Paris Curve; experimental LSP coupon vs Baseline

A comparison of the experimental half-length crack vs fatigue cycles curves with baseline is shown in Fig.4. A crack growth slowdown due to the laser peening has been highlighted in the crack propagation rate experimental data at the middle of the treated pattern. At the same time, a steep increase in the crack growth rate is evident before and after the shot pattern. This effect can be due to both the onset of plastic collapse and the self-equilibrating tensional residual stress accumulated in this area. The crack growth results show an overall negative effect of the laser shock peening process in comparison to the non-treated solution, because the crack growth rate is in every case higher that the baseline. The chosen geometric configuration, i.e. the relative position between the laser pattern and crack origin and the shot width, is unable to exploit the benefit of the compressive residual stress field induced by the LSP. Furthermore, this configuration had a detrimental effect on the fatigue crack propagation performance of the cracked panel.

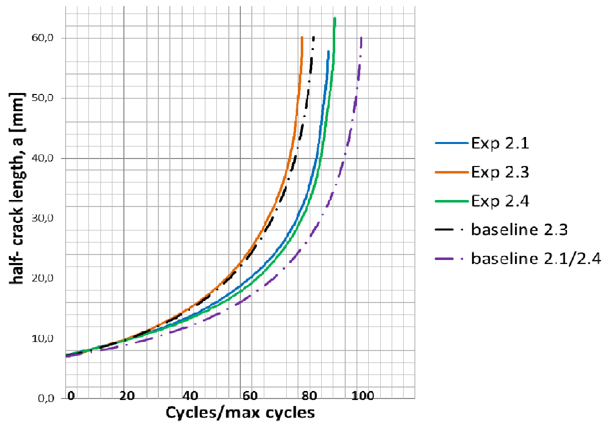

Fig.4: Non-dimensional a/N curves, compared with baseline.

The different behavior shown in Fig.4 is due to the fact that, while in coupon 2.3 the crack propagates along the x horizontal axis, in the specimens 2.1 and 2.4 it develops with an angle of 45 degrees with respect to the previously mentioned axis. The 2.1-2.4 reference baselines have been evaluated taking into account the effect of the angled propagation expressed by a geometry factor [8] in addition to the aforementioned finite-width geometry factor in expression 1.

FEM analysis and analytical models of Laser Shock Peening

In order to predict how the laser pattern dimension and location affect the fatigue crack propagation performances of a thin-walled cracked panel, is fundamental to describe the self-balancing residual stress distribution along the entire panel width.

An all explicit finite element model (Abaqus Software), which already proved to be effective in making such predictions [9,10,11], has been applied. The stress profile reported in Fig.5 for half of the investigated panel has been obtained along the entire crack path.

On the basis of the residual stress profile we have obtained using the finite element modeling is then possible to predict the fatigue crack propagation performances of the investigated panels by means of analytical models.

The SIF [$K_{Res}(a)$] of a crack propagating through a residual stress field can be calculated by the Eq.2 [12]:

$$K_{Res}(\pm a) = \frac{1}{\pi a}\int_{-a}^{+a} \sigma_{y\_Res}(\xi)\sqrt{\frac{a \pm \xi}{a \mp \xi}}\,d\xi \tag{2}$$

where the function $\sigma_{y\_Res}(\xi)$ describes the profile of the residual stress component orthogonal to the crack path.

Tada in [13] proposed an analytical formulation of the residual stress profile established in a welded panel across the welding bead

$$\sigma_{y\_Res}(x) = \sigma_0 \frac{\left[1 - \left(\frac{x-L}{c}\right)^2\right]}{\left[1 + \left(\frac{x-L}{c}\right)^4\right]} \tag{3}$$

By means of an accurate selection of the shape parameters "c", "L" and "σ_0" of the Tada equation, the analytical formulation can describe accurately the residual stress profile calculated numerically for the LSP treated panel (Fig.4). "L" is the distance between the crack centre and the LSP pattern centreline, "c" is representative of the point in which the residual stress field changes from tensile to compressive and "σ_0" is the compressive peak stress value.

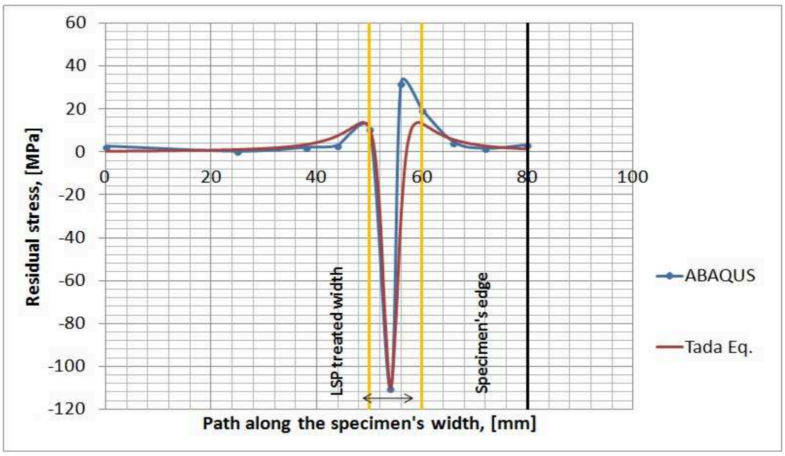

Fig.5: Numerical and analytical evaluation of Residual Stress Field

In Fig.5 a mismatch of the numerical residual stress profile and its analytical representation is evident at the LSP pattern side close to the panel edge. This is due to the edge effect captured by the finite element model and not taken into account by the analytical formulation. Moreover, tensile residual stresses are established in both the sides of the LSP pattern in order to restore the global stress equilibrium of the panel.

The tensile stresses predicted at the inlet to the shot pattern are lower than that at the exit, explaining the moderate acceleration in crack propagation shown by the tests' results, in respect to the baseline, before reaching the pinned line, and subsequently slowing down in the central area, before the final sharp increase of the FCP.

The prediction of fatigue crack propagation behaviour of the investigated panels with the aforementioned SIF model for the residual stress field taking into account the finite-width of the panel, has been compared with the experimental measurements (Fig.6), showing good agreement.

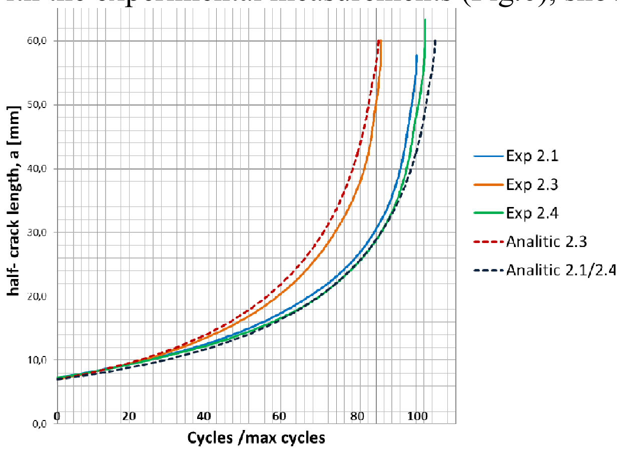

Fig.6: Effect due to LSP, comparison between the test results and the analitical evaluations

Parametric analysis on geometric parameters influence

A parametric analysis on the effect of the LSP pattern position and width on the FCP performances has been carried out. The proposed analytical crack propagation model implementing the Tada´s residual stress distribution has been used, with the following parameters:

- laser pattern width of 10 mm; compressive residual stress of -100MPa and -150 MPa; distance between crack origin and peened area of 15 mm, 26.5 mm and 50 mm.
- laser pattern width of 33 mm; compressive residual stress of -100MPa and -150 MPa; distance between crack origin and peened area of 26.5 mm and 61.5 mm.

The results are shown in Fig.7 and summarized in Table 1. An increase in FCP life is achieved only when the peening pattern is closer to the initial crack origin, at 15mm. Similarly, a larger laser shot width and higher compressive residual stresses were producing the best results in terms of FCP. The lack of benefit in the actual experimental configuration can be explained with the effect of the balancing tensile field before the shot pattern that, acting to a long crack, provides a significant contribution to the crack driving force. As a consequence, the tensile residual stress field before the shot path counteracts the subsequent compressive stresses in retarding the crack propagation.

Table 1. Percentage variation of the fatigue life referred to the baseline

Crack origin – LSP distance [mm]	15	26.5	50	61.5
RS = -100 MPa Shot pattern = 10 mm	23.7	0.04	-1.77	
RS = -100 MPa Shot pattern = 33 mm		47.5		-11.9
RS = -150 MPa Shot pattern = 10 mm	74.98	7.9	-2.43	
RS = -150 MPa Shot pattern = 33 mm		291.18		-15.52

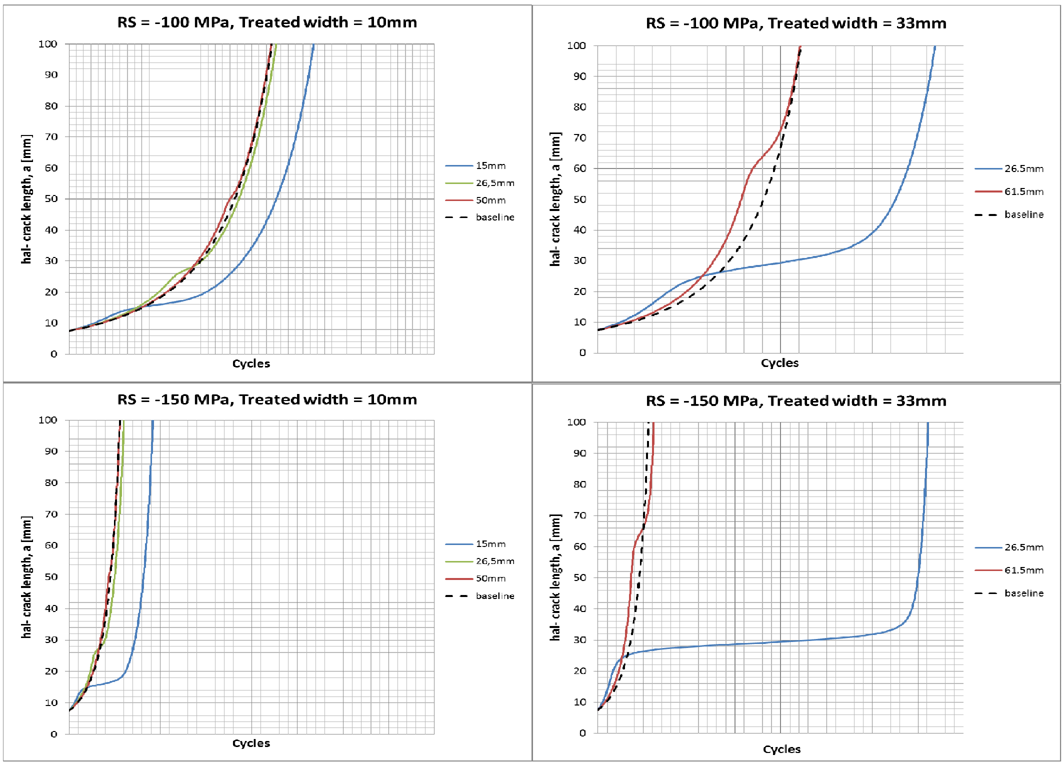

Fig.7. Fatigue Life Estimation with Terada and Tada modeling technique

Conclusions

The objective of this work was to investigate the enhancement in fatigue crack propagation performances induced by LSP on structures which are representative of aircraft fuselage skin. The experimental data obtained on simple specimen show no improvement achieved with the selected configuration of the LSP treated pattern. Using a previously validated FEM approach to predict the residual stress profile along the entire width of the LSP treated specimen, together with an analytical crack propagation model, a comparison of the FCP predicted performances has been done with the experimental data available, showing a good agreement. The model was then used to make predictions about the best peening configuration to achieve benefit in terms of fatigue crack propagation life after LSP treatment. This lead to the conclusion that, to extend component fatigue crack propagation life, the laser shot has to be placed close to the crack origin and a larger shot pattern has to be used. In this case, LSP can be very effective in enhancing fatigue life performances.

References

[1] U. Heckenberger, E. Hombergsmeier, V. Holzinger, W. von Bestenbostel, Advances in Laser Shock Peening theory and practice around the world: present solutions and future challenges, in G. Ivetic (Ed.) Proceedings of the 2nd International Conference on Laser Peening, Emerald Group Publishing Ltd., Bradford, 2011, p. 22-33.

[2] G. Ivetic, I. Meneghin, E. Troiani et al., Fatigue in laser shock peened open-hole thin aluminium specimens, Materials Science and Engineering A 534 (2012) 573-579

[3] G. Ivetic, E. Troiani, I. Meneghin et al., Characterization of fatigue and crack propagation in laser shock peened open hole 7075-t73 aluminium specimens, in Proceedings of ICAF 2011 Symposium, Montreal, Canada, 2011.

[4] C. Rubio-Gonzalez, J.L. Ocana, G. Gomez-Rosas, C. Molpeceres, M. Paredes, A. Banderas, J. Porro, M. Morales, Effect of Laser shock processing on fatigue crack growth and fracture toughness of 6061-T6 aluminium alloy, Material and Science Engineering A 386 (2004) 291-295.

[5] S. Huang, J.Z Zhou, J. Sheng, K.Y. Luo, J. Z. Lu, Z. C. Xu, X. K. Meng, L. Dai, L. D. Zuo, H. Y. Ruan, H. S. Chen, Effects of Laser Peening with different coverage areas on fatigue crack growth properties of 6061-T6 aluminium alloy, International Journal of Fatigue 47 (2013) 292-299.

[6] S. Huang, J.Z Zhou, J. Sheng, J. Z. Lu, G. F. Sun, X. K. Meng, L. D. Zuo, H. Y. Ruan, H. S. Chen, Effect of Laser Energy on fatigue crack growth properties of 6061-T6 aluminium alloy subjected to multiple laser peening, Engineering Fracture Mechanics 99 (2013) 87-100.

[7] D. Furfari, N. Ohrloff, E. Hombergsmeier, U. Heckenberger, V. Holzinger, Enhanced Fatigue and Damage Tolerance of Aircraft Components by Introduction of Residual Stresses – A Comparison of Different Processes, in A. Brot (Ed.), Proceedings of ICAF 2013 Symposium, Jerusalem, Israel, 2013.

[8] P.C. Paris, H. Tada, G. Irwin, The Stress Analysis of Cracks Handbook, 3rd edition, p.127, ASME Press, New York, 2000

[9] S. Taddia, E. Troiani, C. Crudo, Numerical Investigations on Laser Peening Process, in J.L. Ocana (Ed.), Proceedings of the 4th international conference on laser shock peening and related phenomena, Madrid, Spain, 2013

[10] E. Troiani, C. Crudo, G. Molinari, S. Taddia, Investigations on Laser Peening Capability by finite element simulations, in A. Brot (Ed.), Proceedings of the ICAF 2013 Symposium, Jerusalem, Israel, 2013.

[11] G. Ivetic, I. Meneghin, E. Troiani, Numerical analysis of Laser Shock Peening as a process for generation of compressive residual stresses in open hole specimens, Materials Science Forum 681 (2011) 267-272

[12] H. Terada, Stress Intensity factor analysis and fatigue behaviour of a crack in the residual stress field of welding, Fatigue of aircraft structures 1 (2011) 5-15.

[13] H. Tada, P.C. Paris, The stress intensity factor for a crack perpendicular to the welding bead, International Journal of Fracture 21 (1983) 279-284