ESRF	**Experiment title:** Title **Residual stress investigation in laser shock peened (LSP) and foreign object damaged (FOD) aerofoil specimens after fatigue cycling**	**Experiment number:** MA793
Beamline: ID31	**Date of experiment:** from: 27/08/2009 at 08:00 to 01/09/2009 at 08:00	**Date of report:** 12-04-2010
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Report:

Aeroengine compressor fans and blades are subject to foreign object damage (FOD) that can substantially reduce low, high and combined (both high and low) cycle fatigue strength of the rotating engine components[1]. A crack growth inhibiting layer of compressive residual stress (CRS) has been shown to be a good way of improving fatigue tolerance to notches in many situations [2]. To introduce a CRS layer, Laser shock peening (LSP) has been proven to be particularly effective in enhancing the fatigue life of deep notched samples compared to shot peening [3]. In our previous study it has been found that FOD superimposes additional CRS directly below the notch to the pre-existing residual stress (RS) associated to LSP. In this context, it is important to evaluate the residual strain relaxation of the beneficial CRS associated with the prior LSP treatment, as well as the relaxation of the FOD related stress. The purpose of this experiment was to investigate the residual stress relaxation around 45° impacts due to the application of (i) only low cycle fatigue (LCF), (ii) combined cycle fatigue (LCF+HCF) and due to small crack growth.

The material studied is Ti-6Al-4V, which is currently used for compressor blades. The specimens were subsequently laser shock peened over the leading edge.

Fatigue testing and FOD simulation. After that foreign object damage was simulated by firing the edge of 3 mm hardened steel cubes towards the leading edge of the samples, at an angle of 45° and at a speed of 245 m/s. Fatigue experiments were carried out at room temperature under block loading of combined LCF and HCF cycles with 1000 HCF cycles superimposed upon 1 LCF cycle, representing a simplified flight spectrum. The crack growth was monitored using a direct current potential drop (DCPD) system with nano-voltmeters. The crack lengths were verified post testing from the fracture surfaces. Full experimental procedures may be found in [4].

High Energy Synchrotron X-ray Diffraction. Residual elastic strains were mapped around the FOD damage at ID31. A monochromatic synchrotron X-ray beam was used (50.8keV, 0.244Å), to ensure an optimised configuration of enough flux to get maximum possible counts and enough penetration to enable the measurement in transmission geometry. The diffracted beam was registered on the central detector of the 9 channel multianalyser stage. Three line scans were measured along the thickness direction: one along the mid thickness and the other two lines are 0.67 mm away from the surface of the sample on either side. A step-size of 0.4 mm and 0.075 mm was used in parallel and perpendicular to the leading edge, respectively. Strains were computed from the shift of the $(10\bar{1}2)$ diffraction peak from Ti-α phase. Data analysis was performed using Large Array Manipulation Program (LAMP).

Experimental Results

Residual Strain Maps. Figure 1 shows the residual strain line profiles in a direction parallel to the L.E. for 45° impacts: after the application of only LCF (a) at P_{max}=24kN, n=1000, (b) at P_{max}=27kN, n=100; and after subjecting to combined cyclic load (LCF+HCF) (c) at P_{max}=20kN, n=1000 block and (d) P_{max}=27kN, n=100 block (In one block, the ratio of LCF and HCF = 1:1000; and R = 0.1and 0.7 for LCF and HCF, respectively).

Three lines were collected for each sample and the additional line in each plot, in purple color, represents the residual strain distribution along the midthickness for a 45 degree impact in unfatigued condition. It can be observed that a substantial amount of residual strain has been relaxed at high level(27kN) of applied load as shown in Fig 1(b) compared to the low level (24kN) of applied load in (a), even though the sample was cycled 10 times more at 24 kN load. Comparison with the unfatigued condition might suggest that there is some relaxation. However, it should be noted here that, the difference in notch depth plays a significant

role in introducing the peak stress into the sample, as shown elsewhere [5], the notch depth for the sample in unfatigued condition is 0.2 mm deeper than the fatigued case. Therefore, it can be argued that due to the smaller notch depth the initial residual strain in these samples before applying LCF was lower compared to the unfatigued condition showed here.

In combined cyclic loading as shown in Fig 1(c) there is no significant strain relaxation observed at low applied load; when load is 35% increased, 37% strain was relaxed.

Conclusion

Applied load seems to have maximum effect on the residual strain relaxation compared to the no. of cycles in both LCF and CCF condition. Through thickness resolved strain measurement suggest that the deeper notch side experiences maximum level of strain relaxation in both LCF and CCF loading condition.

Acknowledgements

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References

[1] B. L. Boyce, X. Chen, J. W. Hutchinson, and R. O. Ritchie: *Mechanics of Materials*, Vol. 33 (8)(2001), p.441-454.

[2] P.J. Withers: Rep. Prog. Phys., Vol. 70 (2007), p. 2211–2264.

[3] G. Hammersley, L.A. Hackel, and F. Harris: *Optics and Lasers in Engineering*, Vol. 34 (2000), p. 327-337.

[4] R Hall, J Byrne, J Tong : *Fracture Fatigue Engng Mater Struct*., Vol. 31(2008), p.386-397.

[5] S. Zabeen, M Preuss, P.J. Withers, S. Spanrad, J. Tong and J. Schofield: Mat. Sci. Forum (Sub. 2010)

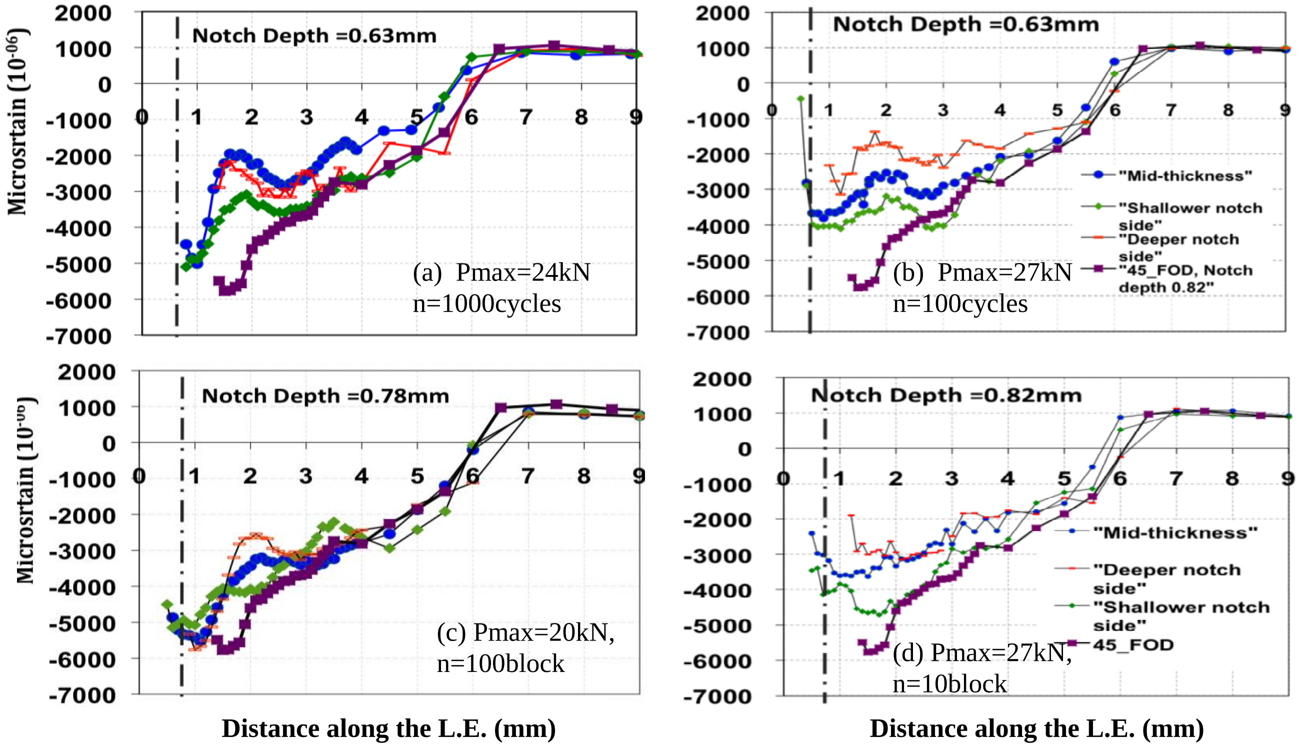
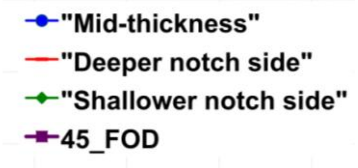


Figure 1: Residual elastic strain profiles parallel to the leading edge: (a) LSP+FOD, after applying only LCF, n=1000, P_{max}=24kN R=0.1,12.5s (b) LSP+FOD, after combind fatigue cycling LCF+HCF, n=100 blocks (LCF:HCF=1:1000, P_{max}=19.8kN and R_{LCF} = 0.1and R_{HCF} =0.7) and (c) LSP+FOD+Crack , Δa=1 mm, combined fatigue loading blocks (LCF:HCF=1:1000, P_{max}=27kN and R_{LCF} = 0.1and R_{HCF} =0.7).



Implications of the results

This results will be compared to the peredicted results from FEM to improve the models predicting remnant fatigue life with greater accuracy and reliability so that airfoils can be safely removed from the service before FOD induced failure.

Publications

[1] M.M. Attallah, S. Zabeen, R.J. Cernik and M. Preuss: Materials Characterization, Volume 60, Issue 11, November 2009, Pages 1248-1256,

[2] S. Zabeen, M Preuss, P.J. Withers, S. Spanrad, J. Tong and J. Schofield: Mat. Sci. Forum (Sub. 2010)