# An Experimental Study of the Influence of Laser Shock Peening on Fatigue Crack Growth

**A. Chahardehi[1], F. P. Brennan[2] and A. Steuwer[3]**

[1] Cranfield University, Cranfield, Beds, MK43 0AL, UK, a.chahardehi@cranfield.ac.uk
[2] f.brennan@cranfield.ac.uk
[3] ESS Scandinavia, Stora Algatan 4, 22350 Lund, Sweden and
Nelson Mandela Metropolitan University, Gardham Avenue, Port Elizabeth, South Africa

**ABSTRACT.** *Residual stresses have in the past been introduced to manipulate growth rates and shapes of cracks under cyclic loads. Previously, the effectiveness of shot peening in retarding the rate of fatigue crack growth was experimentally studied. It was shown that the compressive residual stresses arising from the shot peening process can affect the rate of crack growth. Laser Shock Peening can produce a deeper compressive stress field near the surface than shot peening. This advantage makes this technique desirable for the manipulation of crack growth rates. This paper describes an experimental program that was carried out to establish this effect in which steel specimens were partially laser peened and subsequently subjected to cyclic loading to grow fatigue cracks. The residual stress fields generated by the laser shock peening process were measured using the neutron diffraction technique. A state of compressive stress was found near the surface and tensile stresses were measured in the mid-thickness of the specimens. Growth rates of the cracks were observed to be more affected by the tensile core than by the compressive surface stresses.*

## INTRODUCTION

The compressive residual stresses arising from surface treatment techniques such as shot and laser peening are currently assumed to retard fatigue crack growth and delay the initiation of fatigue cracks [1]. The rationale behind this is that the compressive 'beneficial' stress which is locked in the component will, when the component is loaded externally, superimpose on the applied stress. In case of a tensile applied stress, this superposition results in a total stress which is lower than the externally applied stress and therefore leads to lower stress intensity factors at the crack tip.

Laser shock peening is a surface treatment technique where a solid-state laser beam is pulsed upon a metallic surface, producing a planar shockwave that travels through the material [2]. Here laser with a peak power greater that 1 GW is imaged to a spot size of about 5mm×5mm. Energy densities of 50 to 200 joules per $cm^2$ and pulse durations of

5 to 30 nanoseconds are typical [3]. As the laser beam irradiates the specimen, high pressure plasma from an ablative layer on the component is rapidly formed, sending a shock wave through the work piece which due to its high pressure travels some millimetres in the material and plastically deforms the material in its wake.

Compared to shot peening, laser peening generally has a much deeper effective penetration in the material, and compressive residual stresses can be generated much farther from the surface [4, 5].

In the past, shot peening has been used to demonstrate this effect on the fatigue crack initiation and growth rate in steel [6] and aluminium specimens [5] under cyclic loading. The success of these experiments, along with the fact that laser shock peening generates compressive stress fields much deeper than those produced by shot peening, is an important factor in expecting even better fatigue resistant results from laser shock peening [5, 7].

In order to assess the influence of laser shock peening on fatigue crack growth rate and evaluate its advantage over shot peening, a set of experiments was set up which will be explained in the next section.


**EXPERIMENTS**

A set of experiments was carried out where a total of four steel plates were partially laser peened (hereby called specimens 1, 2, A and B), and fatigue cracks were grown through the peened area in two of them (specimens A nad B). A starting notch was machined in these two specimens (A and B) and they were then precracked before being treated using laser beams. The residual stresses arising from the laser peening process were then measured using neutron diffraction strain measurement technique [8]. Figure 2 shows the overall dimensions of the specimens in which fatigue cracks were grown under cyclic loading. The thickness of all the specimens used was 10mm, and they were made of BS EN 10025 Grade S275JR steel [9].
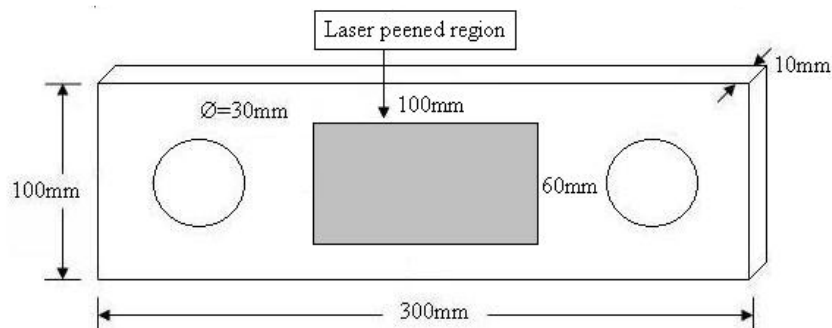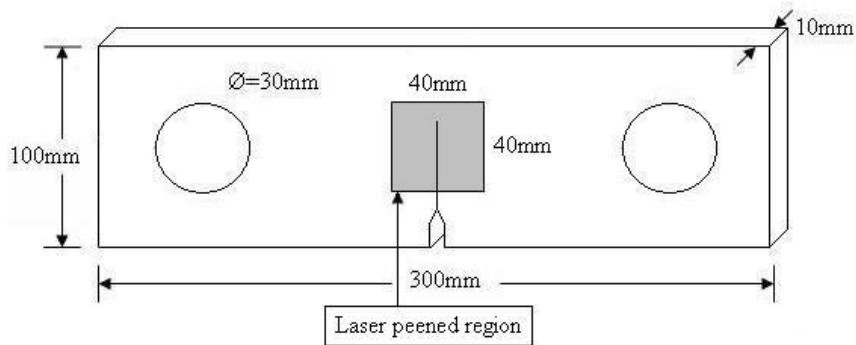


**Figure 1- Specimens 1 and 2**

**Figure 2- Specimens A and B**

The results of the neutron diffraction measurements were transformed from strains to stresses. The residual stress profiles through the thickness of specimens 1 and 2 in the peened region are shown in figures 3 and 4. In order to ensure the accuracy of the readings, strains at the required positions in each specimen was measured, and then the specimen was taken out of the set up and put back in, this time the reverse side facing the beam. Figures 4 and 5 show that a good agreement is observed between the two readings for each specimen.
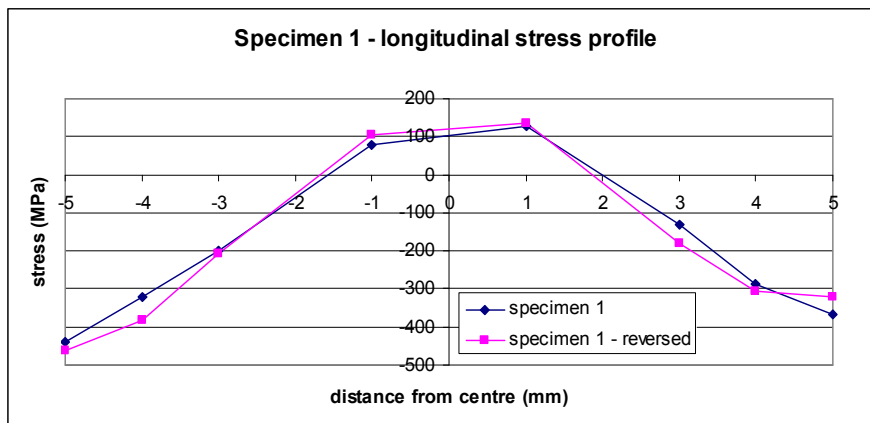


**Figure 3- Residual stress distribution profile in specimen 1 at the centre of the laser peened region.**
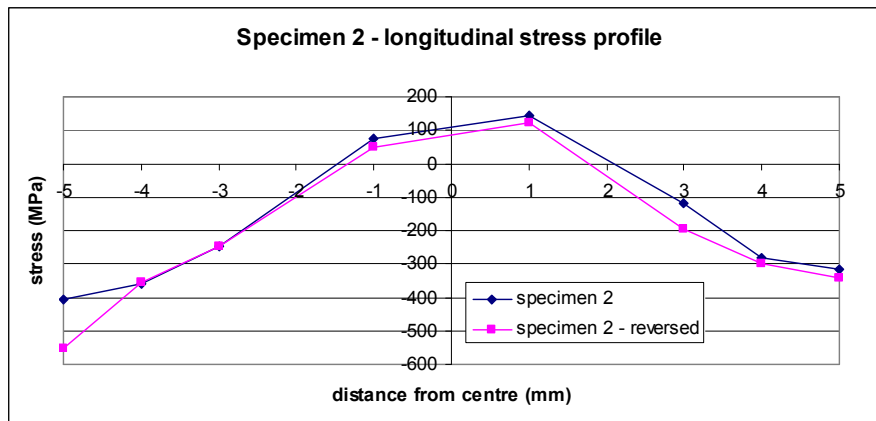
**Figure 4- Residual stress distribution profile in specimen 2 at the centre of the laser peened region.**

The effect of relaxation of the residual stresses under cyclic loads was also considered and experiments show that the relaxation of residual stresses arising from laser peening in the current test programme was negligible.

### Fatigue Crack Growth Tests

Two different load levels were used in these experiments. Two identical specimens were tested in which fatigue cracks initiating from a notch were grown into a laser peened region under cyclic tensile loads. Details of the laser peened region are shown in figure 6.
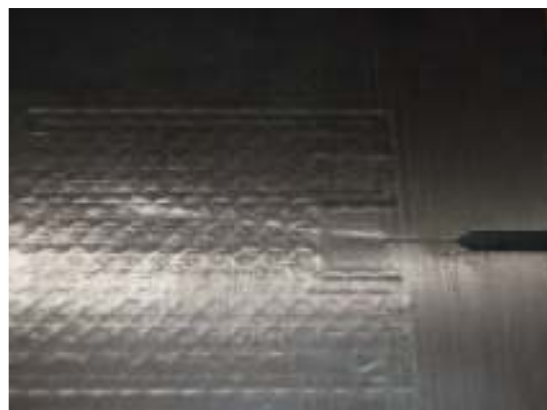


**Figure 6- showing the notch as starter crack. The textured area has been treated with laser.**

Two different load levels were used in these experiments. Specimen A was tested under cyclic tension between 5-55 kN and specimen B was tested under a cyclic tensile load of 5-95 kN. Given the cross section dimensions of these specimens as $10mm \times 100mm$, these loads respectively correspond to 5-55MPa and 5-95MPa of tensile stress. The crack length was measured using a travelling microscope.

*Test Results*

The a-N readings from the travelling microscope are shown in figures 7 and 8. The transition of the crack from the virgin material into the boundary of the peened region occurs at a crack length of 20*mm*.
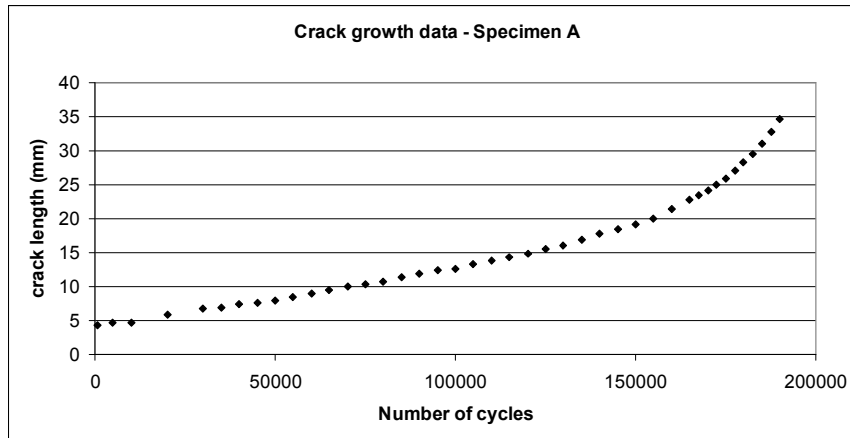


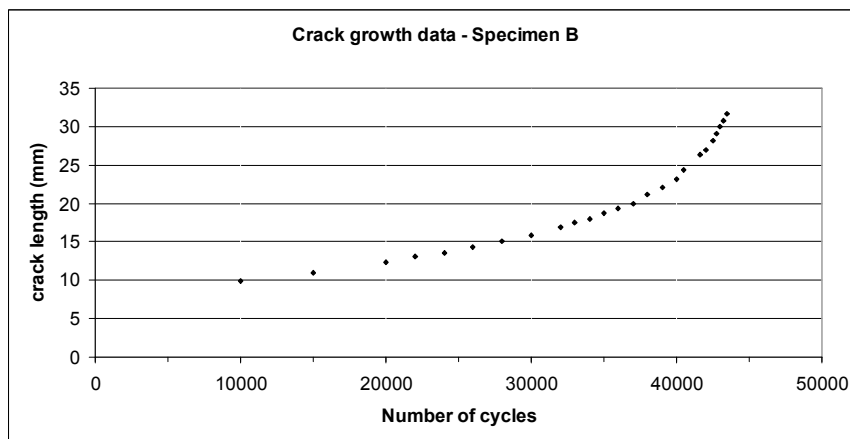**Figure 7- Fatigue crack growth data (a-N curve) for specimen A**



**Figure 8- Fatigue crack growth data (a-N curve) for specimen B**

## ANALYSIS

The results of the tests were not as expected. Based on the experience from shot peened specimens, a sudden halt in the growth of the crack was expected in the boundary of the treated region.

From the figures of stress distribution in the specimens (figures 4 and 5) it is evident that a tensile core of material exists in the midsection of the specimens. These tensile

stresses may jeopardise the beneficial effect of the superficial, compressive stresses that exist in the component.

Weight functions [10] can be used to evaluate the stress intensity factor values for arbitrary stress distributions in cracked components. An important decision at this stage is how to incorporate the residual stress values obtained from the neutron diffraction test in a one-dimensional analysis. *One fundamental problem of the numerical superposition of stresses is that when the magnitude of the average compressive residual stress value is larger than the externally applied load, the model predicts no crack growth.* However, in reality both cracks did grow. If the total stress is taken as the superposition of the applied and the residual stress, negative values of total stress may be encountered. This suggests that if an averaged value of the residual stress is to be used for each section, then no Paris law coefficients can be used to predict the outcome of these tests. The crack growth in specimen A, despite the fact that the average compressive residual stress is -120MPa and the externally applied stress was 50MPa, signifies that the average compressive residual stress does not superimpose on the externally applied load. The fact that the crack grew indicates that $K$ values are positive and non-zero. This will be discussed in detail in the next section.

To overcome this problem, the concept of 'effective fatigue stress' is introduced, which is the stress value that should be used for the evaluation of stress intensity factors in laser peened specimens when using one dimensional weight functions. This stress is here called the 'effective fatigue stress'.

In order to derive the effective fatigue stress, the following methodology is proposed. From the $\dfrac{da}{dN}$ values, experimental SIFs can be evaluated. These values depend on the coefficients obtained from the CT test. Now, to find out what stress distribution gives the resulted $K_{\exp}$, one can write:

$$K = \int_0^a \sigma f(x, a) dx$$

Where $f$ is the weight function and is known for each crack length for the current specimen geometry.

For the $n$ discrete points of crack length measurement

$$a = [a_1, a_2, ..., a_n]$$

$K_{exp}$ can be calculated as $K_{exp_i} = \sqrt[m]{\dfrac{1}{C} \times (\dfrac{da}{dN})_i}$ . Now, by assuming $\sigma = \sigma_{tensile}$ for $a = 0$ to $a = a_1$,

$$K_{exp1} = \int_0^{a_1} \sigma_{tensile} f(x, a_1) dx \tag{1}$$

and

$$K_{exp2} = \int_0^{a_1} \sigma_{tensile} f(x, a_2) dx + \int_{a_1}^{a_2} \sigma_{12} f(x, a_2) dx \tag{2}$$

Where $\sigma_{12}$ denotes the stress acting on the section from $a = a_1$ to $a = a_2$. Similarly,

$$K_{exp3} = \int_0^{a_1} \sigma_{tensile} f(x, a_3) dx + \int_{a_1}^{a_2} \sigma_{12} f(x, a_3) dx + \int_{a_2}^{a_3} \sigma_{23} f(x, a_3) dx \tag{3}$$

From these equations, the stress values can be evaluated as:

$$\sigma_{tensile} = \frac{K_{exp1}}{\int_0^{a_1} f(x, a_1) dx}$$

$$\sigma_{12} = \frac{K_{exp2} - \int_0^{a_1} \sigma_{tensile} f(x, a_2) dx}{\int_{a_1}^{a_2} f(x, a_2) dx}$$

$$\sigma_{23} = \frac{K_{exp3} - \int_0^{a_1} \sigma_{tensile} f(x, a_3) dx - \int_{a_1}^{a_2} \sigma_{12} f(x, a_3) dx}{\int_{a_2}^{a_3} f(x, a_3) dx}$$

And by induction:

$$\sigma_{i-1,i} = \frac{K_{exp_i} - \int_0^{a_1} \sigma_{tensile} f(x, a_i) dx - \sum_{k=1}^{i-3} \left[ \int_{a_k}^{a_{k+1}} \sigma_{k,k+1} f(x, a_i) dx \right]}{\int_{a_{i-1}}^{a_i} f(x, a_i) dx}$$

Where $f(x, a_i)$ is the weight function for a crack length of $a_i$.

Figure 9 shows the values of the effective fatigue stresses as obtained from the proposed technique. These values have been obtained by using the Paris law coefficients of $C = 6 \times 10^{-13}$ and $m = 4$ from the CT tests.
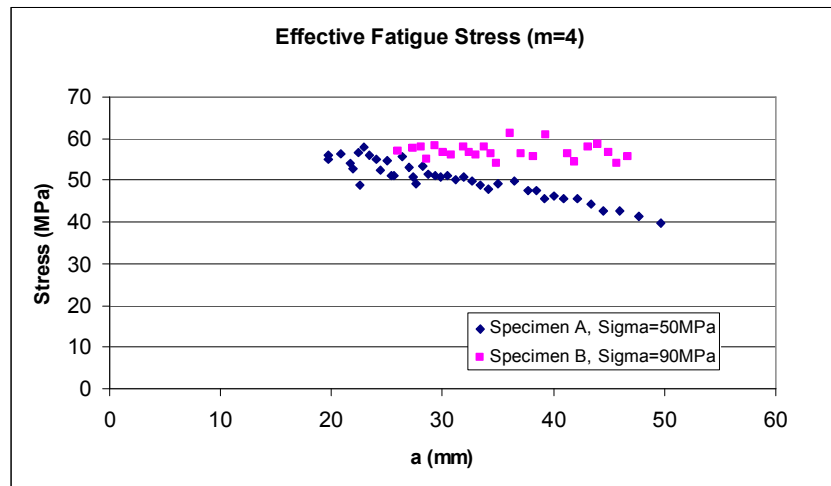


**Figure 9- Effective fatigue stress distribution for specimens A and B (*m*=4.00). Here 'Sigma' denotes the applied stress range.**

Here crack length 'a' is chosen such that the transition from the virgin material into the peened region occurs at a=30*mm*.

## CONCLUSIONS

The effect of laser shock peening on fatigue crack growth in steel specimens was studied. Specimens were partially laser peened and were then subjected to cyclic fatigue loading in order to grow fatigue cracks. Due to the high levels of compressive residual stresses at the surface of the specimen, and analogous to the effect of shot peening on crack growth, it was expected that the cracks should show considerable retardation upon reaching the treated region.

However, crack length vs. number of load cycle measurements did not show any considerable retardation of the fatigue cracks. This is believed to be due to the tensile core in the material that arises as a by-product of laser shock peening. This tensile region is essential for the internal balance of forces in the unloaded component.

The concept of effective fatigue stress was introduced and its evaluation was proposed. From the analysis of the test results it is evident that when dealing with laser shock peened specimens, traditional superposition of applied and residual stresses may lead to erroneous predictions.

152

**REFERENCES**

1. H Berns and L Weber (1984), Influence of Residual Stresses on Crack Growth, in Impact Surface Treatment, Edited by S A Meguid, Elsevier, pp. 33-44.

2. M R Hill, A T DeWald, A G Demma, L A Hackel, H L Chen, C B Dane, R C Specht, F B Harris (Aug 2003) Laser Peening Technology, *Advanced Materials and Processes*, Vol. 161, No. 8.

3. L A Hackel and H L Chen (Sept 2003), Laser Peenig – A Processing Tool to Strengthen Metals or Alloys to Imrprove Fatigue Lifetime and Retard Stress-Induced Corrosion Cracking, *Laser Science and Technology*.

4. R A Everett, W T Matthews, R Prabhakaran, J C Newman Jr., M J Dubberly (Dec 2001), The Effect of Shot and Laser Peening on Fatigue and Crack Growth in 2024 Aluminum Alloy and 4340 Steel, Langley Research Center Report, NASA /TM-2001-210843.

5. O Hatamleh, J Lyons and R Forman (Mar 2007), Laser and shot peening effect on fatigue crack growth in friction stir welded 7075-T7351 aluminium alloy joints, *International Journal of Fatigue*, Vol. 29 Issue 3, pp 421-434.

6. G H Farrahi, J L Lebrun and D Courtain (1995), Effect of Shot Peening on Residual Stress and Fatigue Life of a Spring Steel, *Fatigue and Fracture of Engineering Materials and Structures*, Vol. 18, No. 2, pp. 211-220.

7. Laser Shock Processing Increases the Fatigue Life of Metal Parts, *Materials and Processing*, Elsevier Science Publishing Co (Sept 1991).

8. T M Holden and G Roy (1996), The Application of Neutron Diffraction to the Measurement of Residual Stress and Strain, in Handbook of Measurement of Residual Stresses, Society for Experimental Mechanics, Edited by J Lu (1996), ISBN 08173229X.

9. British Standards Institute, "BS EN 10025:2004 – Hot Rolled Products of Non Alloy Structural Steels", British Standards Institute, 2004.

10. X R Wu (1990), Closed form weight function for edge crack problems, *Acta Mechanica Sinica*, Vol. 6, No. 2.