BEHAVIOUR OF FATIGUE SHORT CRACKS IN LASER HARDENED MEDIUM CARBON STEEL SUBJECTED TO REVERSED TORSION

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Behaviour of short fatigue cracks in a laser hardened medium carbon steel subjected to reversed torsion was studied. Characteristic features of surface crack growth in the specimens with various surface laser track geometry were established on the basis of replication method and the observations made through the SEM and TEM. The relationship between crack growth rate and microstructural features was enhanced for two types of laser treated samples. The influence of laser treatment on surface crack extent in comparison to this one in non-treated specimens was analysed on the plots of crack population, crack growth rate in term of crack length or cycle ratio.

INTRODUCTION

Short fatigue cracks have been the object of numerous investigations developed since last one decade. The state of researches was widely presented in two books (1) (2) and in special issue of the journal (3) which contain about 80 papers performed on the conferences organized in Sheffield (UK) generally. The papers analyse an influence of various load conditions, material, geometrical and technological factors and aggressive environments on short crack growth behaviour.Continuously increasing number of publications in the problem in question can not be discussed here. Nevertheless it proves the importance of the problem.

The results of investigations of short crack behaviour in laser hardened 0.45% C steel samples under reversed torsion are reported here. The paper is connected with the previous papers of the authors concerning the research to long cracks in laser

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treated carbon steels under reversed bending.The results were reported in several papers.We shall mention here only one of them written by Kocańda and Natkaniec (4).

EXPERIMENTAL AND RESULTS

A medium carbon steel was used for fatigue test with a composition of (wt%): 0.48 C, 0.66 Mn, 0.24 Si, 0.02 P, 0.019 S, 0.25 Cu, 0.24 Cr, 0.20 Ni, 0.028 Al, 0.03 Mo, remainder ferrite. The mechanical properties of the steel were as follows: yield strength 425 MPa, ultimate tensile strength 690 MPa, elongation 18%, reduction of area 40%. The specimens of an hour glass shape (Fig.1) were hardened by an 1.5 kW power continuous wave CO_2 laser in nitrogen-oxygen atmosphere and at room temperature. Laser beam velocity was equal to 20 mm/s. The gauge specimen surface was covered by laser tracks of a 3.5 mm width in two different manners: circumferentially with a stroke of 3.5 mm - type A (Fig.1a) or by overlapping laser tracks - type B (Fig.1b). Depth of hardened zone of a semi-elliptical shape was about 1 mm. The structure of hardened zone created a narrow lath martensite in the surface layer of a 600 HV_{100} microhardness and martensitic-bainitic mixture at the bottom of laser track. Fatigue tests were conducted under reversed torsion at 5 Hz of frequency. Shear stress was calculated on the basis of the Nadai relationship relative to an applied torque for an elasto-plastic range. Surface short cracks were monitored using replication method and their growth measured with help of an optical microscope equiped with an image analysis system. Further micro-observations were made through the SEM and TEM microscopes.

The analysis of replicas taken from sample surface during whole fatigue test allowed to investigate the development of damage process in relation to surface crack nucleation, crack growth and crack density.Cracks were found to initiate in the specimens of type A mainly in slip bands in enlongated ferrite grains,favourably orientated to maximum shear stresses in non-hardened zone, between the laser tracks only. In hardened zones, in the laser tracks any nucleated cracks were not observed. Surface short cracks grew in directions parallel and perpendicular to sample axis creating a net of cracks. Short crack extention depended on microstructure, being temporary arrested at grain boundaries of ferrite and pearlite. In a transition zone - in a vicinity of laser track cracks branched at nearly a 45^{o} angle to sample axis and grew in direction of maximum normal stresses. Short and long cracks were completely arrested at the border of laser track and finally propagated along that border to failure. The structure of laser tracks and compressive residual stresses of value 600 MPa acted there, constituted a strong barrier for cracks.
In specimens of type B individual cracks were found to initiate in local melted spots and grew in direction of maximum normal stresses forming a few crossing systems on the sample surface.

Characteristic features of short crack behaviour are seen on the plots of crack length and crack growth rate against N_i/N_f (Fig.2, 3, 4). Crack growth rate was lower in laser treated samples of type A (symbols: L1,L2,L3) than in the case of non-treated samples signed on the figures as NL, tested at the same shear stress amplitude τ. In laser treated samples of type B (symbol: FL) crack growth rate was the lowest. Short crack growth rate successively decreases with an increase of crack length until 100-200 μm corresponding to a length of multigrained ferrite bands limited by pearlite grains. Analytical estimation of experimental data allows to describe crack growth rate in that stage by equation:

$$\frac{da}{dN} = C\,(d - a)^{\alpha} \qquad \alpha = 0.3 - 0.35 \quad \ldots\ldots(1)$$

where: d - size of ferrite grains or length of ferrite band in direction of crack growth.

In the next stage of crack extention the crack growth rate sharply increases and alters irregularly according to the equation:

$$\frac{da}{dN} = C\,a^{\alpha}\,(d_i - a)^{\beta} \qquad \alpha = 0.4 \qquad \beta = \alpha/2 \quad \ldots\ldots(2)$$

where: d_i - average distance between the pearlite colonies.

Crack growth rate of cracks extended in hardened matrix in the samples of type B can be expressed by relation:

$$\frac{da}{dN} = C\left(\frac{N_i}{N_f}\right)^{\alpha} \qquad \alpha = 1.8 - 2.0 \quad \ldots\ldots(3)$$

Experimental results revealed a great density of short cracks on an unitary surface nucleated in narrow bands between the laser tracks (Fig.5). Density of cracks of length less than 500 μm approaches to any saturation stage. Greater crack density is observed in the samples tested at lower stress and the saturation stage is achieved earlier than in the case of higher stress. Distribution of cracks length in the sample of type A shows diagram on Fig.6. Density of cracks of a 50-100 μm length gradually increases in the term relative to 0.6 N_i/N_f. Then cracks density decreases because of crack coalescence.

Microobservations made through the SEM and TEM microscopes revealed more details of short cracks initiation and mechanism of their propagation. Examination of fracture surfaces proved a cleavage or quasi-cleavage fracture in the surface layer of laser tracks in specimens with circumferential laser tracks. In martensitic-bainitic structure was found a quasi-cleavage fracture with certain sympthoms of plastic deformation. In specimens mentioned above a plastic fracture with local brittle fracture regions dominated exclusively only in non-hardened bands between the laser tracks. In specimens with overlapping laser tracks there was observed generally a brittle fracture along cleavage planes and rarely along grain boundaries. Final stage of specimen fracture developed in the laser tracks.

CONCLUSIONS

Short crack growth, their density and distribution in the bands between the laser tracks in the samples of 0.45% C steel tested under reversed torsion, are like with non-treated samples. But short cracks growth rate was much lower in laser treated material. Short and long cracks were strongly arrested at the border of laser tracks. Characteristic short crack behaviour was not observed in the samples with whole hardened gauge surface. Microcracks grew there almost continuously to a long cracks range and their growth rate was much lower in comparison with that one in the samples with circumferential laser tracks and in non-treated material.

SYMBOLS USED

a = surface crack length (μm)

d = average distance between the structural barriers (μm)

N_i = current number of cycles

N_f = number of cycles to failure

REFERENCES

(1) Miller, K.J. and de los Rios, E.R., (Editors) "The Behaviour of Short Fatigue Cracks",EGF1,Mechanical Engineering Publication Ltd,London,England,1986.

(2) International Conference on Short Fatigue Cracks, Sheffield, England, 1990. Fatigue Fract. Engng Mater. Struct., Special Issue, Vol.14, No2/3, 1991.

(3) Miller, K.J. and de los Rios, E.R., (Editors) "Short Fatigue Cracks", ESIS 13, Mechanical Engineering Publication Ltd, London, England, 1992.

(4) Kocańda, S. and Natkaniec, D., Fatigue Fract. Engng Mater. Struct.,Vol.15, No12,1992, pp.1237-1249.

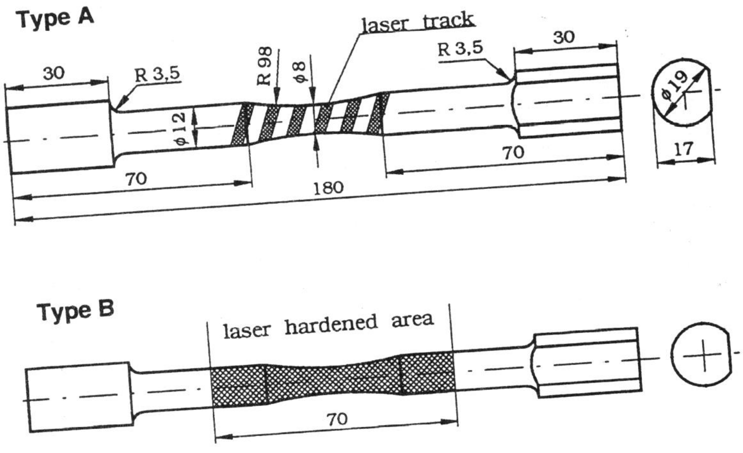

Figure 1. Geometry of specimens (dimensions in mm)

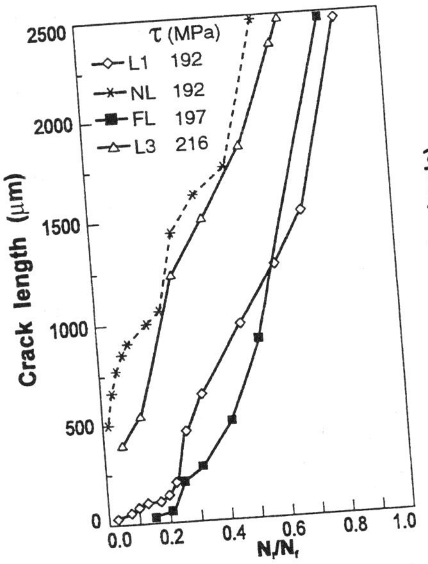

Figure 2. Crack length against cycle ratio

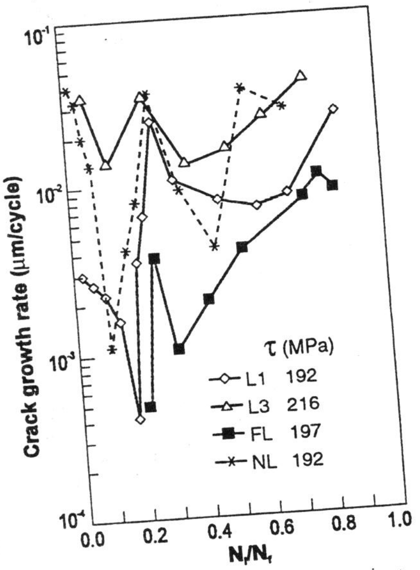

Figure 3. Crack growth rate against cycle ratio

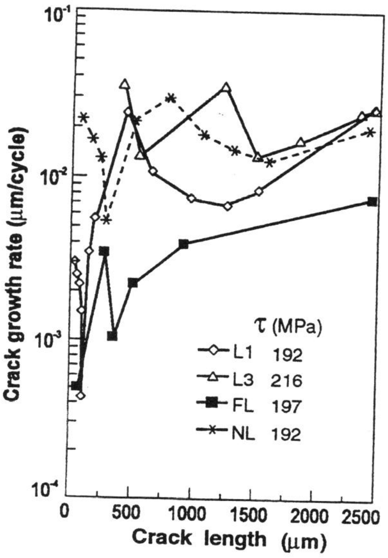

Figure 4. Crack growth rate against crack length

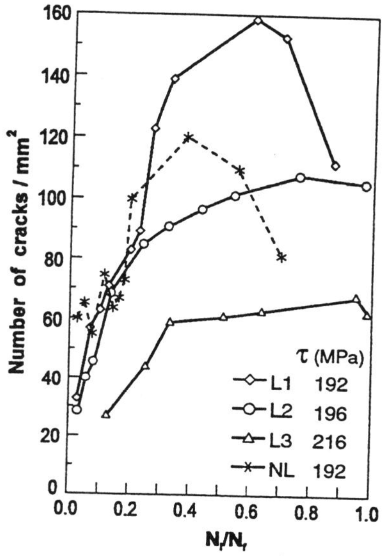

Figure 5. Short crack density against cycle ratio

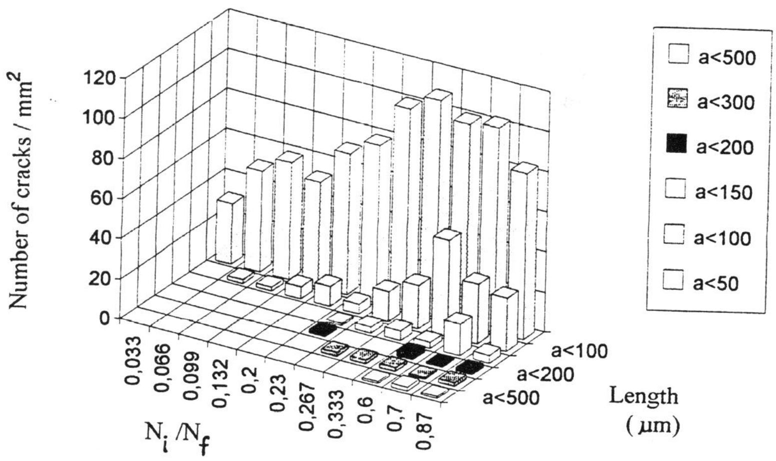

Figure 6. Short crack distribution in specimen with circumferential laser tracks (τ = 192 MPa)