SHOT PEENING EFFECT ON FATIGUE CRACK INITIATION OF SURFACE NOTCHES

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ABSTRACT:

This paper presents results of a fatigue crack initiation life investigation carried out in notched bend specimens. The material of the specimens was the A515 Grade 70 steel. The life initiation was predicted for a range of the notch size. The monotonic and cyclic mechanical properties were experimentally determined in this work. The stress concentration factors were obtained by the finite elements method. For one of these notch size the initiation life was obtained experimentally for the stress ratios (R) of 0 and 0.4 and for shot peening specimens. A good agreement was obtained between the predictions and experimentally results for the two stress ratios. An important improvement of the initiation life was observed for the shot peening specimens.

KEYWORDS

Shot peening; Fatigue; Crack initiation.

1 - INTRODUCTION

The A515 Grade 70 steel is currently used in pressure vessel construction. In this engineering applications geometrical discontinuities are frequently responsible for providing the origin of fatigue crack initiation. Recent methods based on the local strain approach provide to predict the crack initiation and the fracture mechanics approach is used to predict crack propagation. The use of fracture mechanics in fatigue life analytical predictions infers the presence of a pre-existing defect acting as a crack and an analysis is undertaken to estimate the number of cycles required to grow the defect to a value at which structural failure results.

Many of the defects observed in practice, are better considered as notches than as cracks, providing the introduction of a crack initiation stage, the calculation of which can be made by the application of an appropriate method.

At the root of the notch there is a local increase in strain as the notch root stress is limited by yielding. In most situations the local plastic strain will be sufficiently contained to limit the plastic zone to a small region and it is the behaviour of the material in this region that governs the crack initiation. Therefore, the methods employed in the prediction of fatigue crack initiation life are based in the assumption that only the notch root stresses and stains are responsible for the initiation stage. This is known as the "local strain approach". With this approach the fatigue life to crack initiation at notch root is related to the fatigue of strain-controlled unnotched laboratory specimens. Thus, the analysis reduces to i) the determination of the local stressed and strains and ii) the assessment of how those experimental local stresses and strains relate to the known strain-fatigue life curve of the analysed material, takin into account the mean stress effect (1) by application of Morrow's equation,

$$\frac{\Delta\varepsilon}{2} = \varepsilon'_f (2N_i)^c + \frac{\sigma'_f - \sigma_m}{E}(2N_i)^b \qquad (1)$$

Where ε'_f and σ'_f represent the fatigue ductility and fatigue strength coefficients respectively, σ_m is the local mean stress, c and b are the fatigue ductility and fatigue strength exponents respectively, E is the modulus of elasticity and N_i is the number of cycles to crack initiation.

Usually the maximum strain at the notch root is obtained by the application of the Neuber's rule (2), which was generalised lately by Seeger and Heuler (3). Topper et al (4) have extended Neuber's rule to cyclic loading situations. Neuber's rule postulates that during plastic deformation the geometric mean of the stress and strain concentration factors remain equal to theoretical concentration K_t. However, it was found (5,6) that Neuber's rule often overestimate the local inelastic strains and stress. The equivalent strain energy density method (7) is reported (6,8) to give better estimates of fatigue life than the Neuber's rule.

This paper assesses the applicability of the equivalent strain energy method to the analysis of the fatigue initiation life of notched bend specimens.

The crack initiation can be improved by surface treatments. In this paper the effect of shot peening on fatigue crack initiation is checked in notched bending specimens.

2 - MATERIAL AND EXPERIMENTAL DETAILS

The specimens used, single edge notch (SEN) cantilever beam, were machined from a plate with 12 mm thickness of A515 Grade 70 steel. Specimens details are shown in Fig.1. This figure shows also the geometry of the specimens used in the cyclic stress-strain and strain-life curves derivation. Chemical composition and mechanical property data are given in Table 1 and 2.

Table 1 - Chemical composition of A515 Grade 70 steel.

C	Mn	Si	P	S
0.30	1.30	0.30	0.03	0.04

Table 2 - Mechanical properties of A515 Grade 70 steel (tensile tests).

Tensile strength, σ_{UTS} [MPa]	512
Yield strength, σ_{YS} [MPa]	389
Elongation, ε_r [%]	21

The notch geometry used in the experimental work was in the semi-circular form of 3mm radii. The notches were prepared by drilling. After machining, the notches surfaces were mechanical polished, followed by a half hour stress relieving heat treatment at 550 °C of the whole specimen.

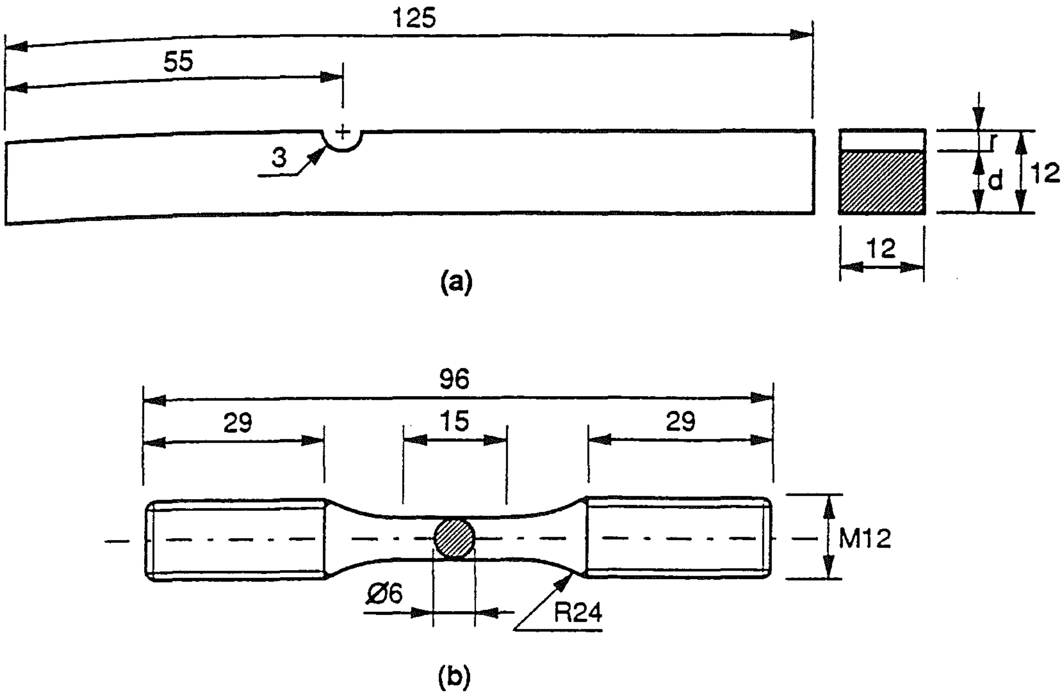

Fig.1 - Specimens geometry's: a)Notch cantilever beam; b)Low cyclic fatigue specimen.

One serie of specimens were treated by shot peening at the notch. The shot peening was made in the Portuguese Renault machine, using 2 minutes of peening and an incidence angle of 90 degrees.

The stress concentration factor (K_t) values were determined using a finite element program. The specimen was modelled using eight nodded isoparametric elements. The resultant K_t values for some of notch radii analysed are given in Table 3.

Table 3 - Stress concentration factor K_t.

Notche radii, r [mm]	0.9	1.2	1.5	2.0	3.0
r/d	0.081	0.111	0.143	0.200	0.333
K_t	2.476	2.331	2.219	1.982	1.726

The cyclic property data were obtained using a servohidraulic Instron machine, type 1341. The tests were undertaken in strain control with a strain ratio (R_ε) of -1. The strain rate $d\varepsilon/dt$ was kept constant in all specimens at the value 4×10^{-3} s^{-1}. The cyclic stress-strain curve was determined using one specimen for each strain level method, defining the stable hysteresis cycle as the cycle at which the specimen reached 50% of the fatigue life.

Fatigue testing of the notched specimens were carried out in a displacement controlled mechanical machine at a frequency of 25 Hz for the stress ratios (R) of 0 and 0.4. The load was monitored using a load cell and the crack length initiated at the notch surface was measured using a optical system with accuracy better than 10 μm. The initiation criteria was based on the size of the surface crack length grew at the notch, assumed 0.3 mm.

3 - LOW CYCLE FATIGUE RESULTS

The results obtained in the low cycle fatigue tests are shown in Fig. 2 as the variation of stress amplitude versus the number of strain cycles. For high strain amplitudes cyclic hardening followed by cyclic softening was observed whereas for low strain amplitudes the material showed cyclic softening. This is characteristic of this type of steel: it shows an initial yield point which disappears in the cyclic state. We found that most important changes of the hardening or softening was achieved during the early cycles of loading. We also observed a small cyclic hardening before final fracture at some strain amplitudes used in the tests.

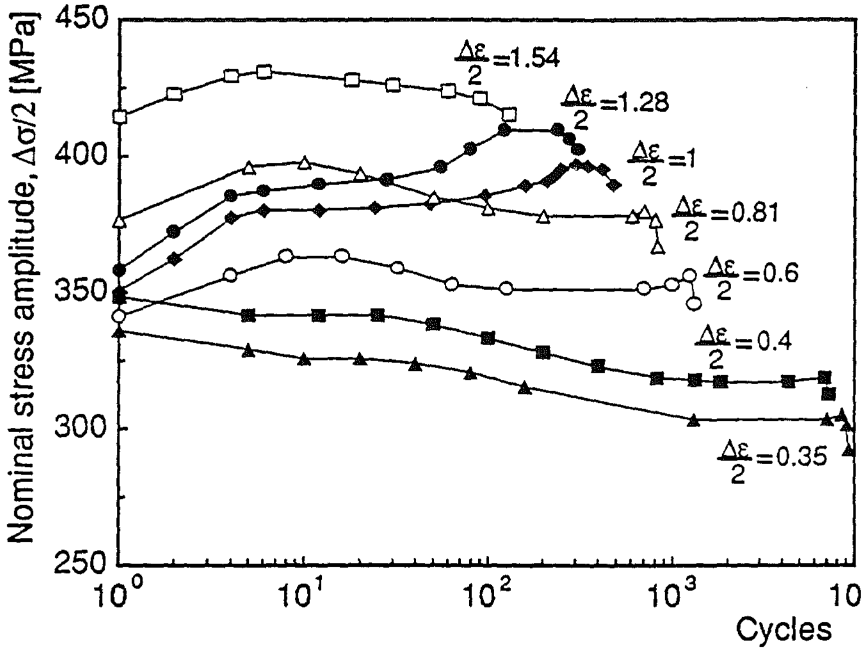

Fig. 2 - Variation of stress amplitude for strain cycling.

The cyclic and monotonic stress-strain curves are plotted in Fig. 3. A cyclic softening occur at low axial strain amplitudes of up to 0.57% which was caused by the gradual elimination of the yield drop phenomenon present in the monotonic curve. The elastic limit for the stress strain curve was reduced from de monotonic value of 389 MPa to 230 MPa. Cyclic hardening was observed at strain amplitudes higher than 0.57%. The strain hardening exponent and strength coefficient obtained are indicated in Table 4.

Table 4 - Cyclic stress-plastic strain curve parameters.

Cyclic hardening exponent, n'	0.165
Cyclic hardening coefficient, K' [MPa]	864

Results of low cycle fatigue tests are presented as a log-log plot of the total strain amplitude versus life in reversals ($2N_i$), as shown in Fig. 4. In addition to the total strain amplitude, the half-life values of elastic and plastic strain amplitudes were also recorded. The transition life of A515 Grade 70 steel was found to be about 36660 cycles. Therefore, for lives greater than 36660 cycles the fatigue resistance of this steel will be determined by its strength.

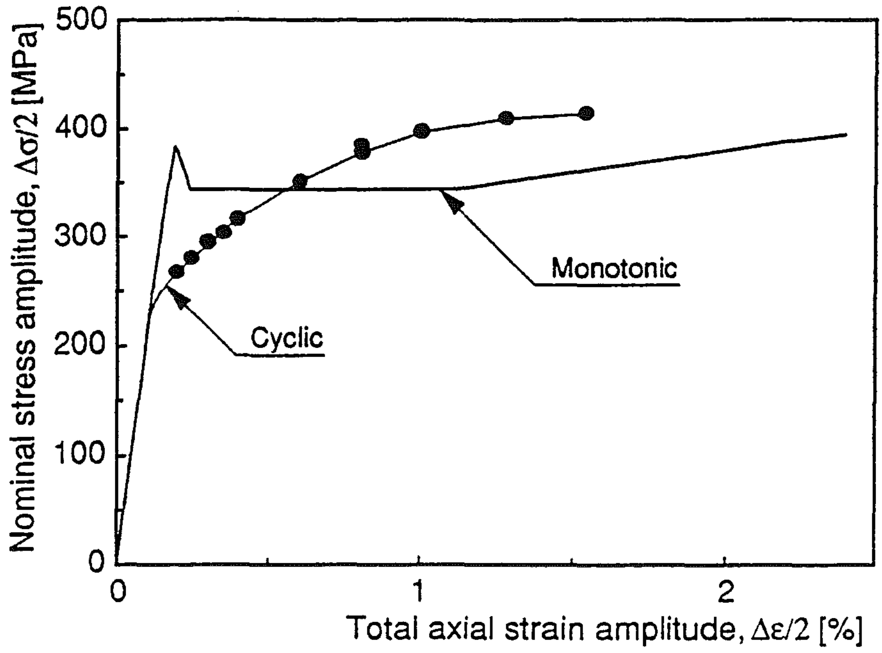

Fig. 3 - Monotonic and cyclic stress-strain curves for A515 Grade 70 steel.

The fatigue ductility and strength properties of the material were obtained from Fig. 4 and are given in Table 5.

Table 5 - Strength and ductility fatigue properties of A515 Grade 70 Steel.

Fatigue strength exponent, b	-0.0657
Fatigue strength coefficient, σ'_f [MPa]	610
Fatigue ductility exponent, c	-0.515
Fatigue ductility coefficient, ε'_f	0.328

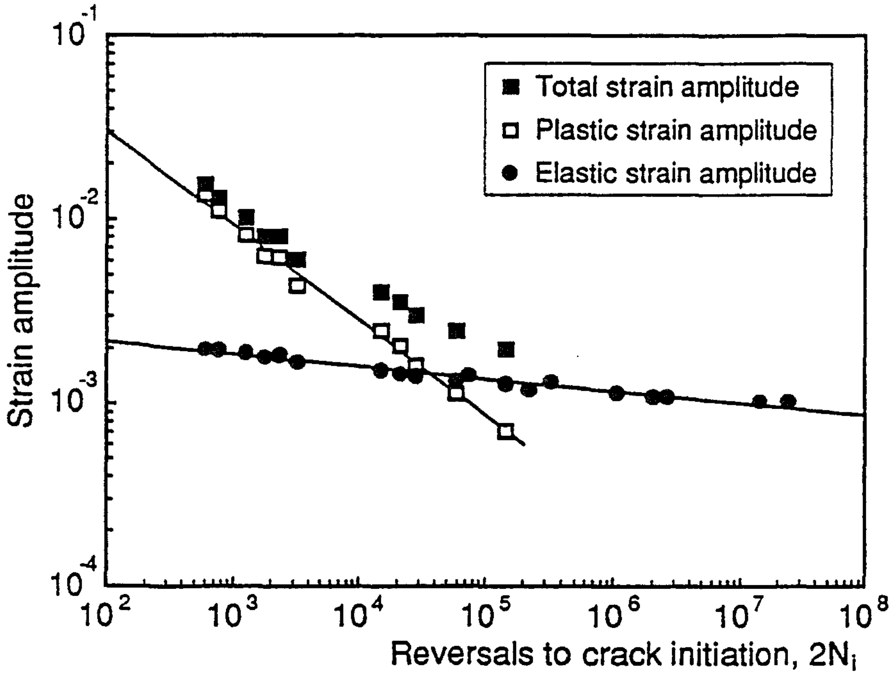

Fig. 4 - Elastic, plastic and total strains amplitudes versus life for A515 Grade 70 steel.

Therefore, eq. (1) can be expressed as:

$$\frac{\Delta\varepsilon}{2} = 0.328(2N_i)^{-0.515} + \frac{610-\sigma_m}{2.1\times10^5}(2N_i)^{-0.0657} \qquad (2)$$

4 - PREDICTIONS AND EXPERIMENTAL RESULTS

The number of cycles predicted from eq. (2) to the crack initiation for R=0 and R=0.4 are presented in Fig. 5 and Fig. 6. Experimental results of the crack initiation defined to a crack length of 0.3 mm are superimposed on the figures.

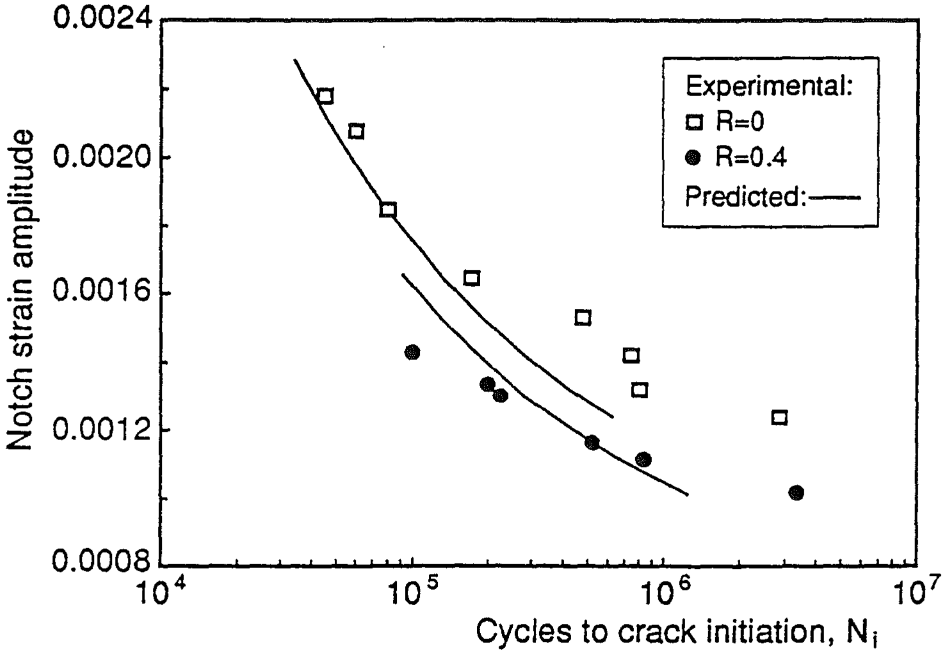

Fig. 5 - Notch strain amplitude versus cycles to crack initiation.

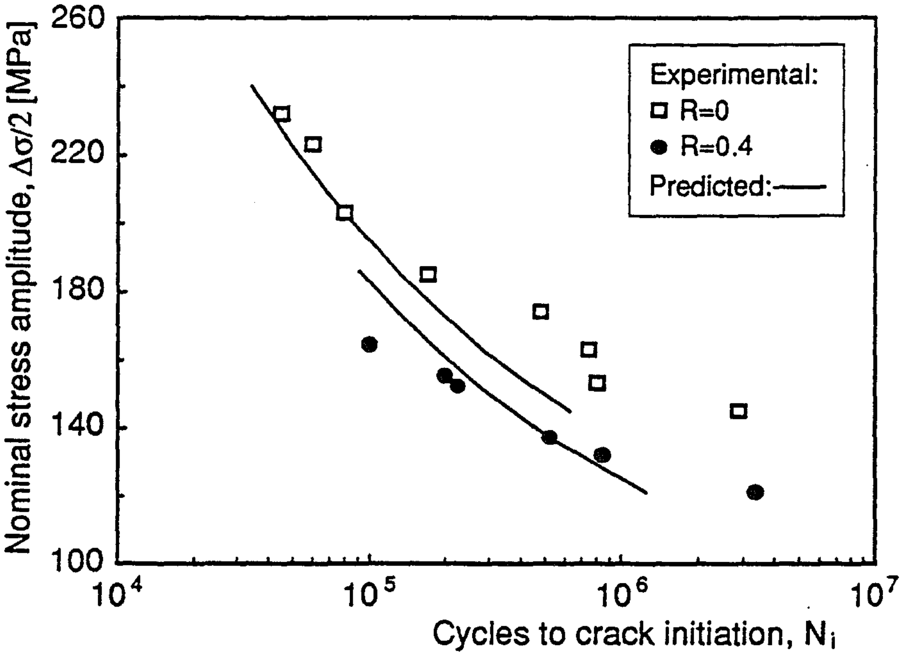

Fig. 6 - Nominal stress amplitude versus the cycles to crack initiation.

The Fig. 5 plots the notch strain amplitude versus the cycles to crack initiation. The Fig. 6 plots the nominal stress amplitude versus the cycles to crack initiation. As it was expected the crack initiation life is less to the stress ratio of 0.4 than for R=0. The predictions and the experimental results show a good agreement for the two stress ratios.

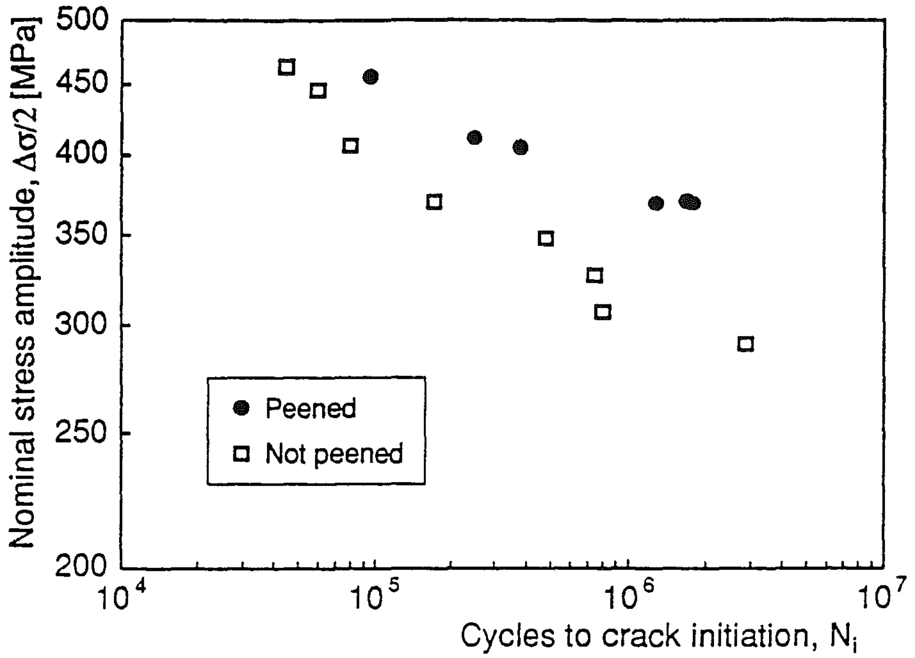

Fig. 7 - Effect of shot peening on the fatigue crack initiation. R=0.

The Fig. 7 presents the experimental results of crack initiation to shot peened specimens. The nominal stress amplitude is plotted versus the cycles to crack initiation. As is shown in the figure the fatigue crack initiation lives are higher for the shot peened specimens than for the specimens without treatment, specially in the low nominal stresses level. This improvement of the fatigue crack initiation life is a consequence of the residual stresses and of the hardness at the notch region. The residual stresses at the notch surface in the shot peened specimens obtained by x-ray fractografy were -356±60 MPa.

5 - CONCLUSIONS

1 - Low cyclic fatigue properties of A515 Grade 70 steel were experimentally determined. The transition fatigue life was found to be about 36660 cycles. Therefore, for lives greater than 36660 cycles the fatigue resistance of this steel is determined by its strength;

2 - The cyclic stress-strain curve shows cyclic softening at low axial strain amplitudes (up to 0.57%) and cyclic hardening at strain amplitudes higher than 0.57%;

3 - Fatigue crack initiation lives were predicted for this material and shown to be in good agreement with experimental results. The fatigue crack initiation lives obtained to R=0.4 are significantly less than the observed to R=0;

4 - An important improvement on the fatigue crack initiation was obtained by the shot peening surface treatment.

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