Stress Concentration Effects on Low Cycle Fatigue Crack Initiation

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ABSTRACT

A crack initiation study on specimens of a 1CrMoV rotor steel subjected to low cycle fatigue damage is in progress at CISE laboratories, in the frame of an ENEL-DSR (Italian Electricity Board, R&D Division) research program aimed at a complete characterization of the component. Crack formation is monitored by compliance and DC potential drop techniques. Tests are carried out at room temperature and at 540 °C, on specimens with different geometrical stress concentrator, Kt = 1 - 4.5, cycled in different loading conditions: uniaxial, plane stress - uniform tension, plane strain - predominantly bending. Data are analyzed with the main emphasis on the capability of methods widely used in the literature to correlate notch effects.

KEYWORDS

Low Cycle Fatigue, notches, crack initiation, Neuber's rule.

INTRODUCTION

Notches are a common feature in a large number of components. They act as stress raisers; even when the component is loaded under predominantly elastic conditions, the material at the notch root may be fully yielded. A proper understanding of elastic-plastic behaviour of notch root material is essential for optimum design and for purposes of damage evaluation and life prediction of components. The evaluation of the intensities of the cyclic stresses and strains in notch regions can be done by f.e. analyses. As this solution is often impractical, Neuber's (1961a) rule is mostly used,

$$\frac{\Delta\sigma}{\Delta S} \cdot \frac{\Delta\varepsilon_t}{\Delta e} = K_t^2 \qquad (1)$$

due to its simplicity as well as to its theoretical background. Here $\Delta\sigma$ and $\Delta\varepsilon_t$ represent maximum values of stress and strain fields at notch root, ΔS and Δe are nominal values, i.e. neglecting the stress and strain concentrations produced by the notch geometry, and Kt is the elastic stress concentration factor. Eq.1 was rigorously derived for a plane stress condition in shear.

A large amount of experimental work has been done in order to analyze the validity of Neuber's rule under various conditions of loading. Quite commonly in the oldest analyses the numbers of cycles to failure Nf from conventional low cycle fatigue (LCF) tests on smooth cylindrical specimens were compared with numbers of cycles to failure from tests on notched specimens with different amounts of Kt. Consistently longer lives were always found for notched specimens than for smooth specimens. Therefore Neuber's rule has become increasingly used in engineering analysis of notched components, for which the fatigue endurances are conservatively predicted on the basis of conventional LCF test data. However a number of difficulties are often inherent in the experimental verifications of Neuber's rule:

1. A valid assessment of Neuber's rule cannot be done on the basis of data of total lives to failure, Nf. Once a crack is formed in a specimen, the remnant life is a matter of crack propagation down the decreasing stress and strain fields away from the notch root. Neuber's rule has nothing to do with such fields, as only maximum (surface) quantities are considered; therefore its application should be restricted to crack initiation data, N < Ni. In practice the concept of a crack initiating from a zero length has no physical meanining, and it is more reliable to consider an "initial crack length" ai > 0. Practical considerations dictate the best choice of ai. In terms of Neuber's rule, stress and strain fields up to a certain distance ahead of a notch remain close to surface values. In addition, while a crack is growing within this distance the notch stresses and strains are not altered by the presence of the crack itself. If this critical distance is taken as the definition of ai, eq.1 can then be used to correlate situations of damage involving cracks with $a \leq a_i$. According to Dowling (1979), for most geometries a reasonable value of ai is of the order of r/10 (r = notch root radius). In view of the typical notch root radii in technology, of the resolution limits of modern NDI techniques and of the limit of applicability of crack growth models based on fracture mechanics parameters, it is convenient to put ai=0.1mm. Consequently, the initiation life Ni is definided as the number of cycles needed to form a crack with this length. In order to obtain reliable Ni data in fatigue tests, techniques capable of accurately detecting the presence of cracks as small as 0.1mm are required. As these techniques were not available in most experimental studies on Neuber's rule conducted in the past, only total lives to failure Nf had to be considered.
2. The behaviour of stress and strain fields in the notch material is complicated. In conventional tests on blunt notched specimens with constant ΔS under small scale yielding conditions, it is generally recognized (Stadnick and Morrow, 1972) that stresses and strains follow cyclic patterns bounded by two hyperbolae, fixed by the value of $(Kt \cdot \Delta S)^2/E$. During this portion of the life the "local" R-ratio in the notch material ($R = \varepsilon_{min}/\varepsilon_{max}$) is a variable quantity; subsequently a steady-state condition is reached, with a constant R-ratio. The situation in a conventional ε-controlled LCF test on a smooth specimen is different: here R is a constant throughout the test. For consistent comparisons between notched and unnotched data, the so called "Neuber's control" is sometimes adopted in LCF tests, which however requires a particular software. In lack of this facility, analysis of notch effects in different types of tests may not be truly meaningful.
3. It was previously observed that Neuber's rule was derived for shear loading under plane stress conditions, whereas it is extensively used for predictions involving complicated loading modes of notched components. Due to their large dimentions, a plain strain situation is generally verified. On the other hand the LCF data used for predictions result from laboratory tests on small unnotched specimens, under a uniaxial straining condition. Similar differences were present in several experimental studies carried out to check the validity of Neuber's rule. It may be expected that the state of constraint and the loading conditions are important factors for the significance of the analysis.

In the frame of an ENEL (Italian Electricity Board) project aimed at a complete mechanical and microstructural characterization of a 320 MW rotor steel, an experimental LCF study on damage accumulation and crack initiation resistance in regions with geometrical stress concentrations has recently been started at CISE laboratories. Scopes of the study are to set up techniques appropriate for detecting the instant of crack formation (Ni) during fatigue tests, to compare data for Ni, on the basis of Neuber's correlation, for different types of specimen and loading modes, and to examine the possible improvements to Neuber's correlation provided by other methods in literature.

EXPERIMENTAL

The rotor material is a 1CrMoV steel, ASTM A470 Cl8. The microstructure is tempered upper bainite, resulting from air quenching after austenitization. Chemical composition and basic mechanical properties are given in Table 1. Salient features of the microstructural characterization as well as a review of LCF results were given previously (Bicego et al., 1987).

The crack initiation study consisted of two series of tests, one at room temperature and the other at 540°C, this latter being the nominal inlet steam temperature, i.e. the maximum expected temperature of HP rotor material. Different types of specimens were considered, Fig. 1.

- Smooth specimens were cycled under strain controlled conditions with R=0, $R = \varepsilon_{min}/\varepsilon_{max}$. Longitudinal strains were obtained from measurements of transverse deformations according to ASTM E606 standard practice. The tests were intended to represent fatigue resistance under uniaxial straining, with no concentration factor present (Kt=1).

- Blunt notched 1TCT-type specimens were used in fatigue tests with costant load amplitudes at R = 0.05, R=Pmin/Pmax (i.e a slightly positive value, to avoid machine backlash). The nominal concentration factors Kt were 3.0 and 4.4, estimated from formulae reported by Neuber (1961b). These tests were representative of a predominantly bending condition of the notch root material, under plane strain.
- Center Notched specimens in uniform Tension (CNT specimens) were cycled at constant load amplitudes, again with R = 0.05. Two notch geometries were considered: circular holes with Kt = 2.7, and ellipses with Kt = 4.5, with the estimates of Kt values derived from Heywood (1952). The tests on the CNT specimens were intended to represent a plane stress condition.

Crack formation was analyzed by two methods, namely a technique based on Compliance (C) measurements and a technique based on electric Potential Drop (PD) measurements. Values of C were measured during the unloading portions of the fatigue cycles, with the values of the load line displacements measured by clip on gages (CT and CNT specimens) and by extensometers (smooth specimens). An automatic data acquisition system was used. This allowed a large number of C-data to be stored and analyzed; the instant of first deviation of C values beyond 1% the stationary value was assumed representative of crack initiation, N=Ni (preliminary observations from an interrupted test showed that at this stage crack length was about 0.1mm). The PD measurements were taken using a Reversing Direct Current Electrical Potential Drop method (Catlin et al., 1985). Here again Ni values were defined from firstly observed 1% increase of measured potentials over stationary values. When used in conjunction with the C method, consistancy of Ni data obtained from C and from PD measurements was demonstrated, Fig. 2. The PD technique was used to overcome difficulties which were present in the C method. In general the experimental conditions which make critical the obtainment of accurate C values are:
- poor elastic responses of specimens, due to anelastic and/or creep effects;
- critical working conditions for the clip on gages (corrosive media, high temperature);
- stiff specimen geometries, with small displacements to be measured.

The data shown in Fig. 2 were derived from a test on a CNT specimen, the stiffest geometry considered.

Table 1. Chemical composition and tensile properties of the 1CrMoV steel.

Element, weight percent

C	Si	Mn	P	S	Cr	Mo	Ni	V	Cu	As	Sn
0.33	0.22	0.77	0.009	0.006	1.25	1.18	0.06	0.27	0.05	0.01	0.005

Tensile properties

Temperature C	Rotor zone	Orientation	$\sigma_{0.2}$ MPa	σ_{uts} MPa	Elongation %	Red. of Area %
500	HPR	axial	506	563	22	79
500	HPB	transverse	504	553	19	69
500	IPB	transverse	472	564	12	45

HPR = High Pressure Rim; HPB = High Pressure Bore; IPB = Intermediate Pressure Bore.

Heat treatment: austenitizing 970 C + air cool + tempering + furnace cool.

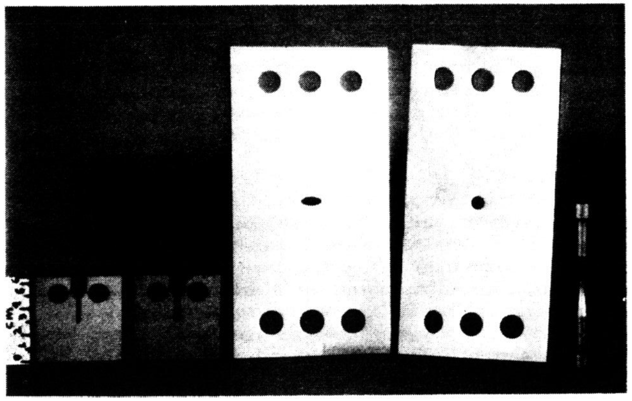

Fig. 1. The different types of specimens used in the tests.

ANALYSIS OF RESULTS

In Table 2 the results from all the tests on smooth, CT and CNT specimens are presented. Smooth and notch data were correlated according to:

$$\left(\Delta\sigma \cdot \Delta\varepsilon_t\right)^{1/2} = \frac{K_t \cdot \Delta S}{E^{1/2}} \qquad (2)$$

Eq.2 is equivalent to Neuber's rule, eq.1, if a small scale yielding condition is satisfied in the notched specimens. As no universally agreed standard exists to define this condition, the problem is often left undetermined in literature. Perhaps the simplest solution is to consider applicable, at least to deep notches, a LEFM relationship:

$$R_y < \frac{1}{15}(W-l) \qquad (3)$$

with Ry = radius of the plastic zone at notch root, W = specimen length, l = notch depth. In this equation Ry may be evaluated in terms of the applied stress intensity factor K, using formulae valid for cracks (i.e. treating notches as if they were cracks). However the procedure is accurate only for sharp notch-

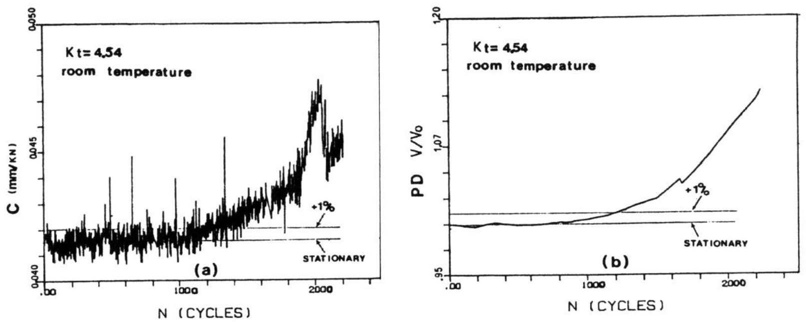

Fig. 2. Compliance (a) and PD (b) measurements during a fatigue test on a CNT specimen.

es. It appears more appropriate to use a formula from Kreager and Paris (1967):

$$R = \left[\left(\frac{Kt\cdot\Delta S}{\sigma_y}\right)^{2/3} - 1\right]\cdot r \qquad (4)$$

where r = notch root radius. Eq.4 was used in the analyses of present data, with the results given in Table 2. It is observed that the condition in (3) was reasonably fulfilled in all the tests on notched specimens; it can be concluded that the use of eq.2 was correct.

Values of plastic zone radius vs. specimen thickness, Ry/B, were also calculated and reported in Table 2. Again in analogy with LEFM theories, it was assumed that a value Ry/B < 1/15 should be indicative of a predominant plane strain condition, and Ry/B > 1/2 of a plane stress condition. It is seen from Table 2 that CT specimens were indeed in plane strain, and CNT in plane stress, as previously anticipated.

Table 2. Results of the crack initiation study and notch yield analysis.

Specimen geometry	Temperature C	K_t	K_t S MPa	$\Delta\varepsilon_t$ %	N_i cycles	N_f cycles	$\frac{W-a}{R_y}$	$\frac{B}{R_y}$
CT	25	4.42	234		1900		19.6	19.6
CT	25	4.42	158		7900		32.9	32.9
CT	25	4.42	140		16800		40.4	40.4
CT	25	3.03	185		3850		11.2	11.2
CT	25	3.03	140		13700		17.2	17.2
CNT	25	2.75	155		4000		13.5	1.11
CNT	25	2.75	135		8500		25.6	1.95
CNT	25	4.54	212		1220		23.1	1.86
Smooth	25	1		1.92	970	1065		
Smooth	25	1		1.00	2340	3628		
Smooth	540	1		0.60	38600	39816		
Smooth	540	1		0.97	1250	1536		
Smooth	540	1		0.58.	3500	4423		
Smooth	540	1		0.50	9500	10380		

R-ratio

It was pointed out that in tests on blunt notched specimens with a constant ΔS and a nominal R-ratio equal to 0.05, the "local" value of the R-ratio (i.e. at notch root) is different, and even not constant at the beginning of the test. As this is in contrast with the conventional LCF tests on smooth specimens, with fixed R-ratio (R=0 in present tests), the analysis of correlation methods might therefore suffer the potential risk of an R-ratio effect, impairing the significance of the comparisons to be considered.

It is often recognized that under strain-controlled conditions the R-ratio has a negligeable effect on fatigue resistance of ductile materials when large deformation levels are involved. As an example in Fig. 3 results of the present experiment, from the tests on smooth specimens with R=0, are compared with the Coffin-Manson curve determined from a large number of data with R=-1, which were available from the main LCF characterization of the 1CrMoV rotor material. Despite the large difference in R the numbers of cycles to failure are similar. It is believed that even in the case of present analysis of smooth specimen data (R-ratio equal to 0) and notched specimens data ("local" R sligthly varying above 0), the effect of R on LCF lives is likely to remain a small one. Analysis of correlation methods based on data from such tests should be therefore meaningful. (Incidentally, it is remembered that the situation here is different from the familiar idea of a consistent life shortening effect by increasing R, typical of high cycle fatigue (HCF) tests. The R-ratio effect in HCF is related to the high amount of damage caused by large positive loads on elastically stressed specimens. Under LCF conditions the plastic strains are the main damaging feature. One should consider that in addition the definition of R is also different, being R = Pmin/Pmax in HCF

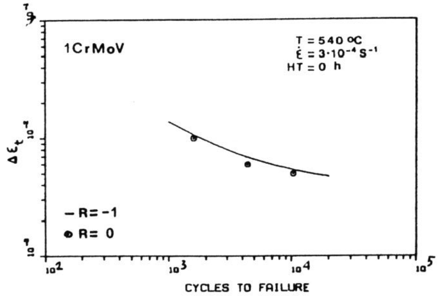

Fig. 3. Comparisons of LCF data from tests with different R-ratio.

and R = $\varepsilon_{min}/\varepsilon_{max}$ in LCF: a positive R in HCF means tension-tension loading, whereas in LCF the minimum load is compressive anyway. For fatigue softening materials like the one of the present experiment the steady-state amounts of tension and compression loads are scarsely affected by the R value.)

Initiation vs. failure

The tests on smooth specimens were continued up to failure, N=Nf, whereas the tests on notched specimens were interrupted shortly after having reached the instant N=Ni. From the data on the smooth specimens reported in Table 2 it can be inferred that the life fractions spent in the crack initiation phase were 0.91, 0.64 and 0.97 at room temperature, and 0.81, 0.79 and 0.92 at 540°C. Differences in these values may be due to scatter as well as to real physical trends. Scatter would be related to:

- the stochastic event of crack formation, N=Ni;
- the limited precision of the technique used to detect Ni;
- the stochastic event of failure, N=Nf.

Due to the limited number of data, a definite trend in life fractions as a function of deformation levels cannot be definitively confirmed from the present analysis (increased periods of crack formation with respect to crack growth at low strain ranges are frequently reported in literature). It only seems possible to conclude that more than 2/3 of the total lives of smooth specimens in conventional LCF tests were spent in nucleating and propagating cracks up to a length of about 0.1mm, and less than 1/3 in the crack propagation phase. It should be desirable to have information of this type as a standard outcome of conventional LCF tests. It might be useful for engineers in planning NDI activities, and allow assessment of LCF life prediction methods based on distinct models for the crack initiation phase and for the crack propagation phase.

NOTCH CORRELATION METHODS

Crack initiation data were analyzed in terms of three correlation criteria:

- Neuber's rule, in the form of eq.2;
- the modification of Neuber's rule according to Peterson's (1959) parameter Kf,

$$Kf = 1 + \frac{Kt - 1}{1 + A/r} \qquad (5)$$

  with A=an empiric constant of the material, defined for example in SAE Handbook (1968);
- the energy-based criterion due to Glinka (1985):

$$\oint_0^{\Delta\varepsilon_t} \sigma \cdot d\varepsilon = \frac{(Kt \cdot \Delta S)^2}{2\,E} \qquad (6)$$

The analyses considered room temperature data, as the experiment at 540°C is still in progress.

The capability of the three methods to correlate notch effects for the different types of test is shown in Fig. 4.

The amount of conservatism in using Neuber's correlation for predicting the lives of notched specimens from smooth specimens data is a moderate one, Fig. 4a. This confirms that Neuber's rule is substantially valid in fatigue analysis of notches, if the life data are correctly referred to the instant of formation of small cracks, and not to the final event of failure. Closer examination of results reveal systematic differences among the data of different types of tests. Results indicate largest Ni values for CT specimens, intermediate for CNT and lowest for smooth specimens. These results seem to be due to the different constraint conditions in the different types of specimens. The best degree of correlation by Neuber's rule should be expected between CNT (plane stress) and smooth specimen (uniaxial) data, whereas deviations are more likely between smooth and CT (plane strain) data, this latter representing a condition far from the theoretical limits under which Neuber's rule should be applied (it is remembered that Neuber's rule was rigorously derived for a plane stress situation, in shear). Therefore the closer correlations found for the CNT data than for the CT data appear reasonable.

No substantial improvement was provided by the adoption of the empirical parameter Kf due to Peterson, Fig. 4b. Probably this was due to the low acuities of the notches considered: the

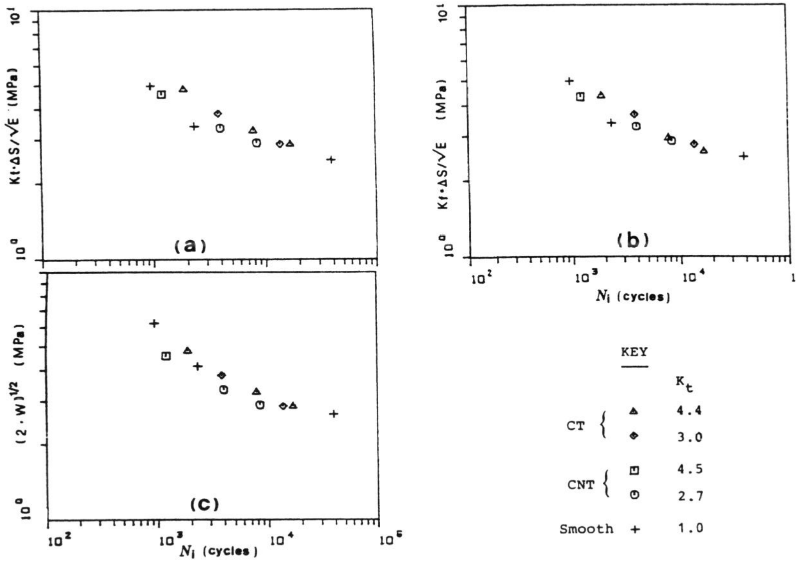

Fig. 4. Results of the analysis of correlation methods: (a) Neuber's rule (b) Peterson's parameter and (c) Glinka's criterion.

effect of the Kf-correction would have become significant for higher stress concentrations.

Application of Glinka's method, Fig. 4c, was uneffective in removing the plane stress - plane strain discrepancies. This method, in a sense similar to the Equivalent Energy method used in fracture mechanics studies (ASTM E992), provided conservative predictions for the CT data, but it was unconservative for the CNT data.

In view of the satisfying degree of correlation capability, present results therefore substantially support the use of Neuber's rule for engineering purposes of notch analysis. It is believed that the well recognized conservatism of Neuber's rule in engineering treatment of notch effects is mainly related to the different constraint conditions of the material in large notched components with respect to the small LCF laboratory specimens.

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