DERIVING A DESIGN FATIGUE RESISTANCE CURVE FOR ANALYSING CRACK INITIATION

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SUMMARY

In previous publications, a criterion for determining the number of cycles for initiating fatigue cracking and the initial orientation of crack propagation at acute notches and geometrical singularities had been introduced theoretically then verified experimentally. This criterion is based on the calculation of the value of the maximum range $\Delta\sigma_{\theta\theta}(d)$ of the normal stress at the distance d of the notch tip. This paper presents the program performed to obtain the curve relating the number of cycles for crack initiation to the value of $\Delta\sigma_{\theta\theta}(d)$, for different stainless steels.

INTRODUCTION

Classical methods of fatigue evaluation are often inadequate to analyse singular geometries which have stresses and strains very high at the notch tip and which are submitted to very steep gradients. Indeed, one is faced with unresolved questions as :

- What value of stress intensity is to be taken ?
- In what particular orientation at the notch tip ?
- If using a theoretical elastic stress intensity factor K_t, to what "nominal stress" must it be applied ?

Thus, there is an industrial need for a new criterion enabling one to compute the number of cycles to initiate a crack, at geometrical configurations bearing high stress gradients, applicable in the frame of finite element analysis.

In previous publications (Devaux, 1979 ; Bosser, 1979 ; d'Escatha, 1980), we have presented the theoretical basis and experimental verification of a criterion by which the number of cycles Na for crack initiation is related to the variation $\Delta\sigma_{\theta\theta}(d)$ of the normal stress at the distance d of the notch tip.

Its pratical application requires to establish the $\Delta\sigma_{\theta\theta}(d)$ - Na relation for the materials of interest, taking into account their manufacturing variations. In particular, attention must be given to the influence of the properties of the materials on the value of the critical distance d, and to the consequences that this may have for the application of the method.

BASIS OF THE CRITERION

The basis is that the damaging process which leads to the initiation of cracking at the geometrical singularity necessarily affects a zone of finite size the length of which should be a characteristic dimension of the microstructure of the material.

This idea has been advanced as soon as in 1943 by PETERSON who showed that the results of stair-case measurements of the endurance limit of sharply grooved specimens could be rationalized by assuming that the endurance limit measured on standard specimens had to be reached at a characteristic distance of the notch tip. He found distances of the order of 0.02", (0.05 mm) for a SAE 1020 low carbon steel. This distance was the order of the grain size.

Resting on the work of ERDOGAN and SIH (1963) and WILLIAMS and EWING (1971) on brittle fracture, we propose for any notch root geometry, any root radius ρ , and any loading :

- Firstly, to determine the number of cycles to initiate cracking Na from the maximum value reached by the variation during one loading cycle, $\Delta\sigma_{\theta\theta}(d)$, of the stress $\sigma_{\theta\theta}$ normal to the radial plane of orientation θ at the distance d from the notch tip (d being a characteristic value of the material)(Figure 1).
  The distance is to be found experimentally ; and, in this model, initiation is predicted from a unique characteristic curve of the material, $\Delta\sigma_{\theta\theta}(d)$ versus N_a (Figure 4).

- Secondly, to determine the initial direction of crack propagation at the notch tip as the orientation θ_0 which maximizes $\Delta\sigma_{\theta\theta}(d)$ or $\sigma_{\theta\theta}(d)$ during the loading cycle.

This criterion ought to be used as well for high cycle and low cycle fatigue when small scale yielding occurs at the notch tip, that is, when the bulk of the section remains elastic. Indeed, in such cases, the plastic strain field governing the damaging process is governed by the elastic surrounding field of the elastic solution. This small-scale yielding classical argument accounts for the possibility of describing the fatigue damage process, which is basically plastic, through an elastic expression.

CALCULATION OF $\Delta\sigma_{\theta\theta}(d)$, FOR MODE I LOADED NOTCHES

Using the expression of CREAGER (1966) for the stress distribution around the tip of deeply notched specimen loaded in mode I :

$$\Delta\sigma_{\theta\theta}(d) = \frac{K_I}{\sqrt{2\pi x'}}\left(1 + \frac{\rho}{2x'}\right) \quad (1)$$

$$x' = x + \frac{\rho}{2}$$

(where ρ is the notch root radius, and ΔK_I is the stress intensity factor which the notch would bear if it was a crack with $\rho = 0$ (Figure 1) ; x' is defined at Figure 1.

The following expression is obtained for $\Delta\sigma_{\theta\theta}(d)$ in mode I :

$$\Delta\sigma_{\theta\theta}(d) = \frac{2}{\sqrt{\pi}}\,\frac{\Delta K_I}{\sqrt{2d+\rho}}\,\frac{d+\rho}{2d+\rho} \quad (2)$$

which tends to the two limits :

$$\text{For large } \frac{\rho}{2d} \text{ ratios : } \Delta\sigma_{\theta\theta}(d) = \frac{2}{\sqrt{\pi}}\,\frac{\Delta K_I}{\sqrt{\rho}} \quad (3)$$

$$\text{For small } \frac{\rho}{2d} \text{ ratios : } \Delta\sigma_{\theta\theta}(d) = \frac{\Delta K_I}{\sqrt{2\pi d}} \quad (4)$$

In keeping with the preceding paragraph, it is worth to recall, as DEVAUX and coworkers (1979) that those expressions explain and account for the main features which have been established experimentally on the influence of the root radius on the number of cycle to initiation in deeply notched specimens (Jack and Price, 1970 ; Rabbe and Amzallag, 1974), and we used them to find for d an order of 0.04 to 0.05 mm for a forged Z 3 CND 17-12 steel (A 316 type) from a number of experimental results covering the various features of the phenomenon.

EXPERIMENTAL PROGRAM

It has been conducted on different varieties of stainless steels used in the fabrication of thermal sleeves and penetrations for Pressurized Water Nuclear Reactor primary circuits :

- A forged steel Z 3 CND 17-12 (similar to A 316)
- A cast Z 4 CND 19-10 (similar to a CF 8 M)
- A 309 L first layer cladding deposited on ferritic vessels (.020 C - 24 Cr - 12 Ni)
- A 308 L weld (.020 C - 20 Cr - 10 Ni).

The determination of the characteristic distance d and of the characteristic curve $\Delta\sigma_{\theta\theta}$ (d) - Na has been made using fracture mechanics compact tension specimens having a width of 20 mm or 25 mm and root radii ranging from 0.05 to 4 mm. For the measurements on the claddings and welds, the CT specimens have been cut in a composite test piece, made by cladding a ferritic plate then by welding it to an austenitic plate, and have been provided with 0.05 mm notch root radii. The notch root have been machined, then grounded, into the shapes shown at Figure 2.

The number of cycles to initiation Na is derived conventionally from a plot of the variation of the range of mouth opening of the specimen versus the number of cycles, as shown in Figure 2. With this definition, initiation occurs on the CT specimen before any cracking appears on the surfaces. Metallographic examination of specimens after interrupting the test has shown that Na corresponds to the formation of a crack of one to two tenth of millimeters deep in the center portion of the front of the notch.

The tests have been performed in nearly repeated loading with a R ratio of 0.05.

INTERPRETATION OF THE EXPERIMENTAL RESULTS

For a given set of experiments on CT specimens, and for different selected values of d, $\Delta\sigma_{\theta\theta}(d)$ is calculated according to (2) from the knowledge of ρ and of ΔK_I. For any chosen value of d, the $\Delta\sigma_{\theta\theta}(d)$ - Na data can be fitted to an expression of the form :

$$\Delta\sigma_{\theta\theta}(d) = \sigma_o(d)\,Na^{n(d)} \qquad (6)$$

by a least square best fit, taking log $\Delta\sigma_{\theta\theta}(d)$ and log Na as coordinates.

The characteristic value of d can then be determined as the one which minimizes the standard deviation of log $\Delta\sigma_{\theta\theta}(d)$ from the best fit curve, as shown in Figure 3, respectively :

a. For the measurements made on the forged steel at ambiant temperature.

b. For the measurements made on the cast steel and the welds at ambiant temperature.

c. For the gathering of all measurements made on all qualities of steels at room temperature and 320° C.

In the three cases, distinct minima are obtained for different values of d, respectively of a : 0.050 mm, b : 0.072 mm, c : 0.059 mm. The corresponding values of σ_o, n, and the standard deviations in Log $\Delta\sigma_{\theta\theta}(d)$ unit are given at Table I. The exponents n are nearly alike, but the values of σ_o differ, as was expected from the relations (2) and (4). However it can be seen from Figure 3 that the variation of S remains small in this range of variation of d, and therefore a set of data can be interpreted with a value of d somewhat different from the one giving the minimum of S without a significant loss of accuracy.

Analysing the data of the three sets of experiments with d = 0.59 gives the values of σ_o, n and S shown at Table II. The whole set of experimental values is presented on Figure 4 with the 3 S band of the least square best fit data reduction of case c.

APPLICATION FOR STRUCTURAL ANALYSIS

It may be seen at Figure 3 that, despite the marked minima on the S-d curves, the value of the standard deviation S varies slowly when d departs from its value at the minimum. Therefore, for a particular quality of steel, the choice of a value of d somewhat different from the value at the minimum should not increase significantly the scatter of the $\Delta\sigma_{\theta\theta}(d)$ - Na plot. Then, it should have little influence on the precision of the drawing of the $\Delta\sigma_{\theta\theta}(d)$ - Na resistance curve. For instance, the use of d = 0.059 mm, coming from the case c (gathering of all data), to reduce the data of cases a and b, increases the standard deviation S, by a factor of 1.015 and 1.12 respectively.

For application to structural analysis, it is therefore possible to conceive a unique design fatigue resistance curve, applicable to a vide variety of stainless steel products.

In the present state of data gathering, we would choose a value of d = 0.059 mm (or 0.060 mm to simplify).

The design resistance curve should be derived from the mean curve established for case c, by including a proper safety margin.

The safety margin should account not only for the scatter in material properties, but also for the possible effect of the environment and for the creation of geometrical or metallurgical defects that could take place during the operation of the industrial manufacturing process.

CONCLUSION

The physical concept of a critical material distance parameter d, which formed the basis of the proposed criterion is substantiated by the statistical analysis showing a minimum in the scatter of the $\Delta\sigma_{\theta\theta}(d)$ - Na experimental data for a particular value of d.

The figures thus obtained for the value of d agree very well with those obtained previously (Devaux and co-workers, 1979), from theoretical arguments.

The analysis of the data obtained on a wide variety of stainless steel qualities shows the possibility to derive a unique design resistance curve $\Delta\sigma_{\theta\theta}(d)$ - Na based on a value of d close to 0.060 mm.

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TABLE 1 Parameters of the best fit relations between $\Delta\sigma_{\theta\theta}(d)$, and Na for the optimum value of d

Index	Material and Temperature	d (mm)	$\sigma_0'(d)$ (MPa)	n (d)	S
a	Z 3 CND 17 12 20° C	0.050	9444	- 0.228	0.1484
b	CF 8 M, 308 L, 309 L 20° C	0.072	8259	- 0.238	0.0658
c	all materials 20° and 320° C	0.059	9464	- 0.246	0.1772

TABLE 2 Parameters of the best fit relations for d = 0.059 mm

Index	Material and Temperature	d	σ_0'	n	S
a	Z 3 CND 17 12 20° C	0.059	8999	- 0.227	0.1507
b	CF 8 M, 308 L, 309 L 20° C	0.059	8672	- 0.235	0.0737
c	all materials 320° C	0.059	9464	- 0.246	0.1772

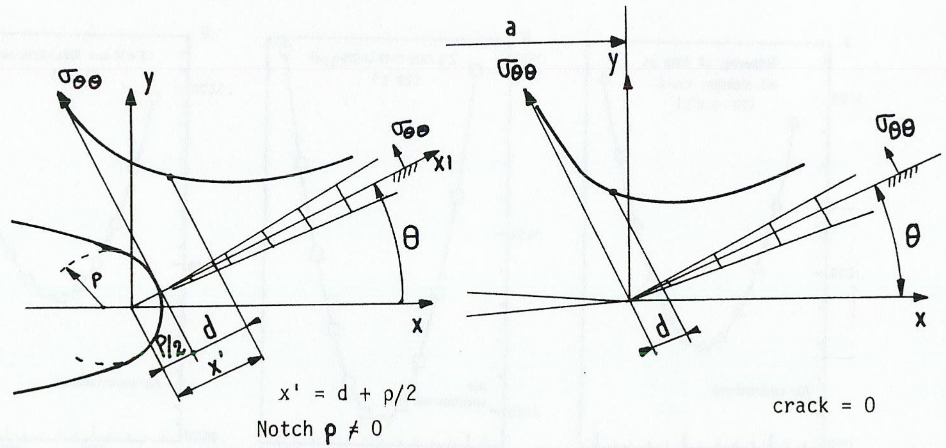

Fig.1 - DEFINITION OF THE CRITERION $\Delta\sigma_{\theta\theta}$ (d)

$$K_I = \sigma_\infty \sqrt{\pi a} \quad \begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} \cos\frac{\theta}{2}\left(1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) - \frac{\rho}{2x'}\cos\frac{3\theta}{2} \\ \cos\frac{\theta}{2}\left(1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right) + \frac{\rho}{2x'}\cos\frac{3\theta}{2} \\ \sin\frac{\theta}{2}\cos\frac{\theta}{2}\sin\frac{3\theta}{2} - \frac{\rho}{2x'}\sin\frac{3\theta}{2} \end{bmatrix} \frac{K_I}{\sqrt{2\pi x'}}$$

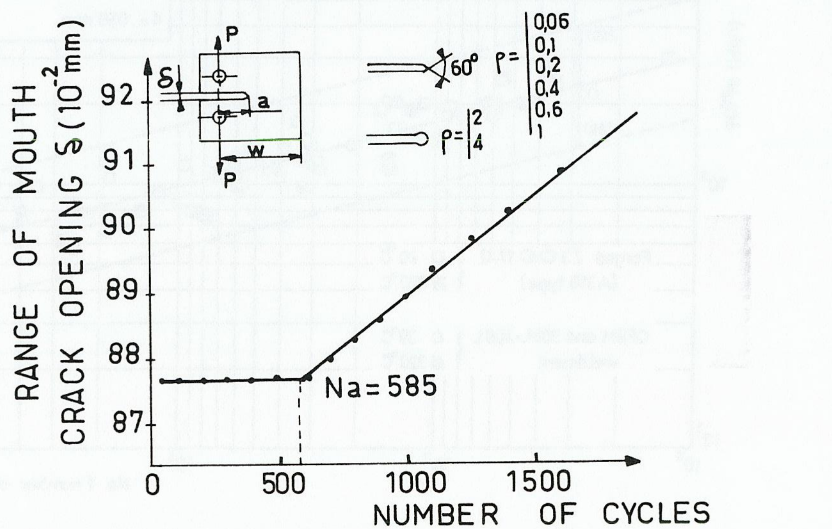

Fig.2 - MEASUREMENT OF THE NUMBER OF CYCLE TO INITIATION AND NOTCH CONFIGURATIONS

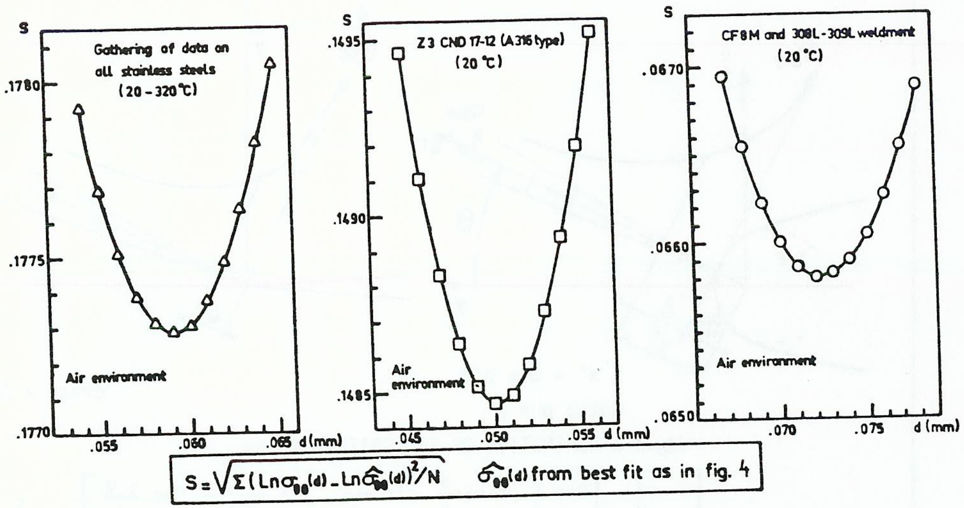

Fig. 3 - Definition of d as the value which minimizes the standard deviation from the best fit curve of the $\Delta\sigma_{\theta\theta}(d)$-Na representation

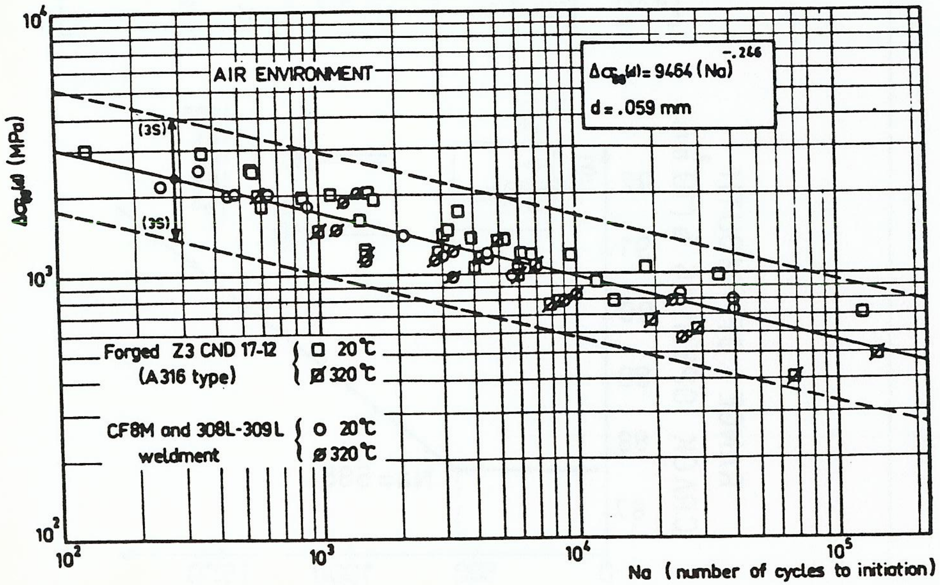

Fig. 4 - Plot and reduction of all measurements on CT specimens