COMPARISON BETWEEN NOTCH AND DEFECT IN MULTIAXIAL FATIGUE

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ABSTRACT

The fatigue of notched components is of main importance for industrial applications. In the case of casting materials, fatigue initiation is governed by micro defects with sizes ranging from the grain size to 100 times the grain size. In this paper, the comparison is done between a notch and a defect in order to evaluate the possibility to consider the defect as a notch. Furthermore, the problem of gradient and size effect under multiaxial loading is discussed.

A numerical analysis has been carried out with the commercial finite element program system ANSYS to estimate the stress fields around circumferential notches and spherical defects of different sizes. A relevant multiaxial endurance criterion based on the concept of elastic shakedown occurring at all the scales (from the mesoscopic to the macroscopic scale) was then used to define the fatigue strength conditions.

It is well known that components can show a large stress gradient at the notch tip. It becomes zero when going inside the material far from the notch. This gradient must be properly evaluated and taken into account because it is known to be benificial to the fatigue strength. More exactly, from the spatial stress component evolutions along the distance from the notch tip, one must define the real gradient effect.

It is shown in this work that the gradient acts mainly on the spherical part of the stress tensor through the hydrostatic stress. The multiaxial endurance criterion makes then appear a dependence on the spatial gradient of the maximum value of the hydrostatic stress over a loading period.

The gradient effect is experimentally estimated by tests carried out on a mild steel. Two different stress concentrator geometries are investigated: a circumferential notch of different radius in a smooth cylindrical specimen and a spherical defect of different size also introduced at the surface of a smooth cylindrical specimen. For the two cases, the fatigue limits and the related gradient effects have been estimated for different loading modes. The size effect related to these experiments is also discussed.

1 INTRODUCTION

The fatigue limit of notched components or defect containing materials is of importance in industrial applications and depends both on the notch or defect geometry and the loading mode. However, only a few methods have been proposed so far to account at the same time for the multiaxial state of stress and for the stress gradient occurring around the notch or defect. Moreover, a notch introduces most of the time cyclic plasticity at the notch tip that tends to an asymptotic level under fatigue loading mode. This remark holds true for the stress strain state around a defect. If this asymptotic state is related to plastic shakedown, then the initiation of a crack is likely to occur. On the contrary, if the material tends to recover a purely elastic response, the fatigue limit can be reached or in other words, under this threshold level no initiation is expected.

In some works, the fatigue limit of notched components is assumed to be due to some initiated cracks that stop to grow, the threshold stress intensity factor around a defect being reached. However, most of the time, the stopped cracks have been observed at the specimen surface. A recent study carried out in the bulk material showed that these cracks occuring below the fatigue limit are small corner cracks and never join each other to create a bigger crack around the defect (Nadot [1]). Furthermore, fatigue initiation mechanisms are not different between defect free and defective material (Billaudeau [2]).

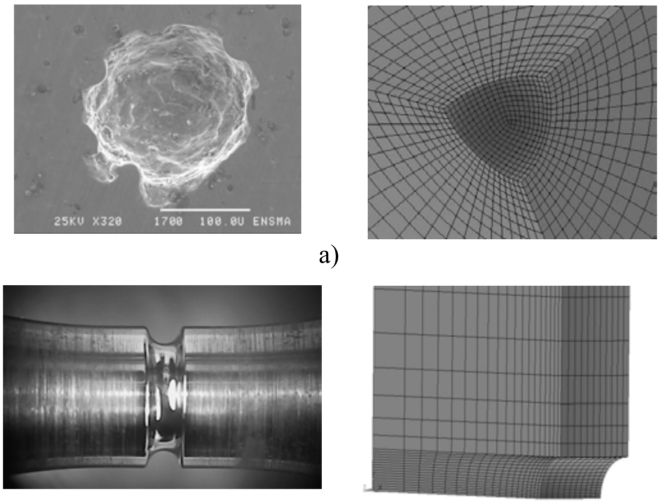
The influence of multi-axial loading conditions on the fatigue limit is usually described by means of a high cycle fatigue criterion. Many endurance criteria have been proposed so far and they all try, from the stress (or strain) history over a loading period, to estimate at least two relevant mechanical quantities. The combination (linear or not) of these parameters must not be greater than threshold that can be understood as an extension of the Von Mises or Tresca criterion.

In the last two decades, Dang Van criterion (Dang Van [3]) has been largely used in industry and is now well-known in the scientific community. This model accounts for the orientation distribution of grains, employing a micro-plasticity analysis to assess the intensity of local plastic strain within individual grains. Although the small fatigue crack growth behaviour is not described in this approach, the elastic shakedown of the cyclic micro-plasticity response is considered as another source of a fatigue limit. This is generally lower than that associated with the grain boundary blockage of micro-cracks. Within the same micro-plasticity framework, Papadopoulos proposed an other endurance criterion (Papadopoulos [4]) where it is assumed that each plastically deformed crystal within the elementary material volume follows a combined isotropic and kinematic hardening rule. Papadopoulos showed that a quadratic mean on the elementary volume V, denoted as $\sqrt{\langle T_a^2 \rangle}$, of the macroscopic resolved shear stress amplitude T_a is proportional to an upper bound estimation of the plastic meso-strain accumulated in some crystals of V so-oriented that their easy glide planes are parallel to a material plane. The operator <.> represents an integration carried out over all the possible glide systems of the elementary volume.

The multi-axial endurance criterion is defined as an inequality applied to a linear combination of $\sqrt{\langle T_a^2 \rangle}$ and the maximal hydrostatic stress $\Sigma_{H,max}$ reached during a loading period :

$$\sqrt{\langle T_a^2 \rangle} + \alpha \Sigma_{H,\max} \leq \kappa \qquad (1)$$

This approach represents a good evolution of Dang Van model when dealing with non-proportional loading conditions. Indeed, it has been proved (Morel [5]) that phase shift effects and the related micro-damage mechanisms are not properly taken into account by means of the Dang Van criterion. Better predictions are achieved with the Papadopoulos criterion.



a)

b)

Figure 1 : Finite element discretization of a) spherical defect introduced by electro-discharge on the specimen gauge length and b) circumferential notch

To account for the gradient effect occurring in smooth specimens loaded under different loading modes in the infinite fatigue life regime, Papadopoulos proposed an extension of any multiaxial endurance criterion by introducing a dependence on the spatial gradient of the maximum value of the hydrostatic stress reached during a loading cycle (Papadopoulos [6]). From the analysis of some torsion fatigue test results with or without mean levels, he showed that the gradient of the deviatoric part of the stress tensor seems not to influence the fatigue strength. This observation leads to the expression of a criterion where only a normalised value of the hydrostatic stress G occurs :

$$\sqrt{\left\langle T_a^2 \right\rangle} + p\left(1 - \beta\left\langle \frac{G}{\Sigma_{H,\max}} \right\rangle^n\right)\Sigma_{H,\max} < q \tag{2}$$

$$\text{with } G = \sqrt{\left(\frac{\partial \Sigma_{H,max}}{\partial x}\right)^2 + \left(\frac{\partial \Sigma_{H,max}}{\partial y}\right)^2 + \left(\frac{\partial \Sigma_{H,max}}{\partial z}\right)^2} \tag{3}$$

where (P;x,y,z) is a frame attached to the critical point P at the loaded sample surface.

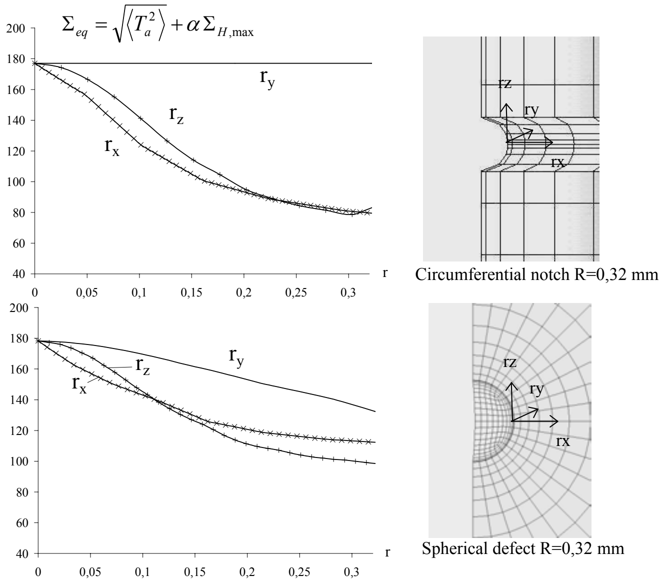
2 MULTIAXIAL GRADIENT AROUND NOTCH OR DEFECT

A numerical analysis has been carried out with the commercial finite element program system ANSYS to estimate the stress and strain fields around circumferential notches or spherical defects of different size (figure 1). To reduce the computational expenditure, a partial discretization of a circular segment instead of a full discretization of the notched structure is applied in the FE analysis. The partial discretization of a circular segment with an angle θ=15°

uses the axisymmetry of the notched shaft, and it requires additionnal boundary conditions (displacement constraints). It has been shown that the full discretization of the notched structure results in a large computational time and brings no essential improvements of the numerical results.

For the defect, the discretization is performed on one quarter of a cylindrical specimen (figure 1).

Under tension, the two stress concentrators lead to a multiaxial stress state at the critical point on the surface. Moreover, the stress components show a gradient in three orthogonal directions from the critical points (figure 2). From these evolutions and the relation eqn (3), one can deduce the G value corresponding to the normalised hydrostatic stress gradient.



Circumferential notch R=0,32 mm

Spherical defect R=0,32 mm

Figure 2 : Equivalent stress distributions in three orthogonal directions for a notch and a defect

3 EXPERIMENTAL PROCEDURE

The fatigue tests have been conducted under different load conditions (tension, torsion, rotating bending) on a mild steel C36. All the specimens were machined out from a rolled bar in the longitudinal direction and were carefully polished using 6 µm diamond.

The circumferential notch were introduced on the specimen surface by machining and the spherical defect by using an electro-discharge machine. The notch radii were identical for the notched specimen and the artificial defect specimen : 320 µm and 730 µm. A tempering at 500 °C for 1 h under vacuum is carried out to remove any residual stress induced by the machining of the specimens. It leads to a 0.2 % yield stress of 350 MPa and an ultimate tensile stress of 580 MPa for the smooth specimens.

All the tests were conducted in laboratory air and at room temperature either with a resonance machine at the frequency of 100 Hz or with a servo-hydraulic fatigue machine, operating under load control at the frequency 10 Hz.

In this work, the fatigue limit is estimated using a step by step loading procedure : a sample is loaded at a given stress level until 10^7 cycles, if the failure does not occur, the stress is then increased by 10 or 20 MPa and the procedure is repeated until failure (see [2] for more details).

The aim of this experimental investigation is to find if the defect can be considered as equivalent to a circumferential notch from the fatigue strength point of view. This equivalence is not that easy to state because one has to use the proper stress parameter to represent the fatigue limit level. Indeed, the nominal stress could seem appropriate when dealing with defect but a net stress defined from the minimum section is more convenient in the case of circumferential notch. In this work, all the numerical calculations were carried out by applying a nominal stress equal to the experimental fatigue limit. Then, at the critical point, the stress values and the stress distributions were computed.

4 ENDURANCE CRITERION PREDICTIONS COMPARED TO FATIGUE DATA

The hydrostatic stress gradient effect is now introduced into the multiaxial endurance criterion and all the fatigue tests performed on smooth and notched specimens or on samples with defects are gathered on figure 3. The notch specimens have been subjected to tension with a load ratio of -1, the smooth specimens were loaded in tension, torsion and rotating bending (R=-1) and the samples containing defects were submitted to tension and torsion (R=-1).

Figure 3 shows clearly that the torsion loading mode is not influenced by the gradient. This observation explains the choice of the criterion formulation eqn (2) where only the hydrostatic part is affected by the gradient. Moreover, the predictions lie within an error band of +/- 10 % around the endurance line drawn from the tension and torsion fatigue limits estimated on smooth specimens.

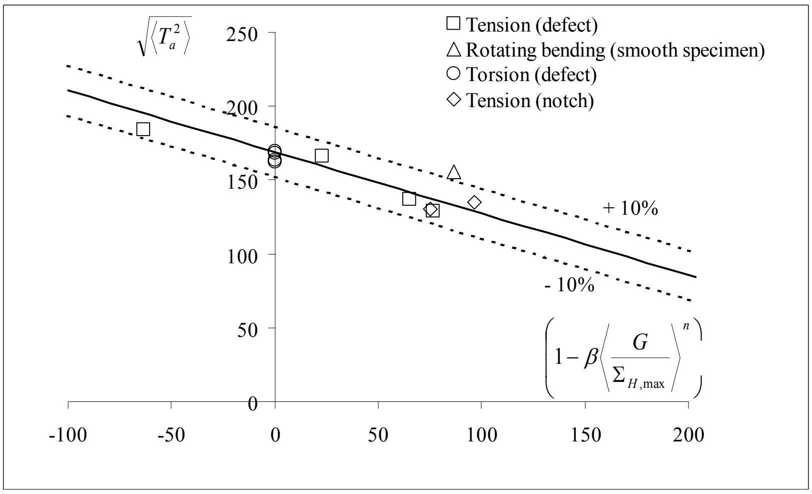


Figure 3 : Experimental results (mild steel C36) in the plane of the multiaxial endurance criterion including the stress gradient effect

5 CONCLUSIONS AND DISCUSSIONS

According to the present experimental results, the gradient effect seems to be predominant compared to the size efect. Let us recall that the difference between rotating pure bending and plane pure bending can not be explained by the only influence of the gradient whereas tension and rotating bending can be discriminated from this point of view. Indeed, the plane bending fatigue limit is very often higher than the rotating bending fatigue limit. This indicates that the loaded surface can influence the fatigue strength. For rotating bending all the points at the surface are subjected to the same stress level and the same stress state. The tension loading mode leads to the same feature but does not introduce any stress gradient. For plane bending that exhibits a gradient, all the points of the surface are not equally stressed. The probability to find a defect that leads to the specimen failure is then lower. The endurance criterion employed in the previous part can not account for the size effect.

A probabilistic approach based on the weakest link concept can be introduced. However, if a Weibull law is defined at the specimen surface (where the cracks generally initiate in high cycle fatigue), it is not able to account for the gradient effect that occurs for all the experimental results discussed in this paper. One must define an equivalent stress that makes appear this stress gradient dependence as in eqn (4):

$$\Sigma_{eq} = \sqrt{\left\langle T_a^2 \right\rangle} + p \left(1 - \beta \left\langle \frac{G}{\Sigma_{H,\max}} \right\rangle^n \right) \Sigma_{H,\max} \tag{4}$$

This equivalent stress is then used in a Weibull approach and leads to a cumulated failure probability expressed as

$$P_F(\Sigma_{eq}) = 1 - \exp\left[-\frac{1}{S_0} \int_S f(\Sigma_{eq}) dS \right] \tag{5}$$

where the stress function f can present several expressions whether a threshold stress is introduced or not. The identification of three or two coeffcients is then required.

By taking into account the size effect from this surface Weibull approach, one can explain the higher fatigue strength in plane bending compared to rotating bending.

The size effect that could occur when comparing notch and defect leading approximately to the same maximum stress levels and the same gradient is not significant and for this reason the notches and defects of the same size lead to very close fatigue limit levels.

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