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Grain size effects on notch sensitivity

P. Lorenzino, A. Navarro *

Departamento de Ingeniería Mecánica y de los Materiales, Escuela Superior de Ingenieros, Universidad de Sevilla, Camino de los Descubrimientos s/n, 41092 Sevilla, Spain

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ABSTRACT

This work presents experimental results on the fatigue behavior of cracks growing from circular notches under axial loading conditions for a very wide range of notch size to grain size ratios, including cases where the notch size is of the order of, or even smaller, than the grain size. Notch sensitivity is evaluated and the well-known dependence on grain size is clearly demonstrated. It was found that for the same specimen geometry and loading conditions, the influence of the stress concentration is directly dependent on the relationship between the notch size and the grain size.

1. Introduction

The problem of fatigue in notched components is of clear practical importance, since almost all mechanical components incorporate some form of stress concentration. Pioneering publications in this field date back to the early 30s of last century. Since then, many proposals have been made for calculating the fatigue limit of notched components. They range from the early formulas of Neuber [1] and Peterson [2–4] based on the idea of failure over a certain critical distance below the surface, until the recent and celebrated interpretation of Taylor [5,6] of this critical distance in terms of Linear Elastic Fracture Mechanics concepts. These techniques could be included within the classical methods of fatigue analysis, where the stress or strain in the area of the notch are used really as main indicators of fatigue damage and are thus correlated to the number of cycles to failure. Other recent methodologies will be described further down.

In the presence of a notch and if no plastic deformation occurs, the theoretical stress concentration factor determines the maximum stress at the notch. However it is well known that this parameter is not by itself sufficient to calculate the reduction in fatigue strength of a notched specimen as compared with an unnotched one of the same material. In fact, the distinction between the *fatigue notch factor* K_f and *theoretical stress concentration factor* K_t, is quite old [2,7,8]. They are defined as:

$$K_f = \frac{\text{Fatigue limit (unnotched component)}}{\text{Fatigue limit (notched component)}}$$

and

$$K_t = \frac{\text{Maximum stress at the notch}}{\text{Nominal stress}} \tag{1}$$

The difference between these two coefficients is traditionally displayed by means of the *notch sensitivity index* of the material:

$$q = \frac{K_f - 1}{K_t - 1} \tag{2}$$

As is well known, Neuber [1] and Peterson [3] considered that the fatigue strength of notched element could not depend only on the maximum stress at the root of the notch, which is reflected by K_t, but should also depend on the stress distribution in the region around the root of the notch. According to this idea, failure of the material would occur only if the overall stress level in a certain characteristic volume element of the material became high enough. Neuber suggested to compare the average value of the stresses calculated along a line of a certain length, measured inwards from root of the notch, with the plain fatigue limit of the material, obtained from the S–N diagram, developing an approximate formula for obtaining K_f,

$$K_f = 1 + \frac{K_t - 1}{1 + \sqrt{\frac{A}{r}}} \tag{3}$$

* Corresponding author. Tel.: +34 954487311; fax: +34 954487295.
E-mail address: navarro@us.es (A. Navarro).

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where r is the radius of the notch and A the length that characterizes the elementary structural volume of the material. The value of A depended on the material and the thermal and mechanical treatment to which it had been subjected. Kuhn and Hardrath [9] evaluated the value of this constant for a large number of steels, coming to the conclusion that A was a function of tensile strength of the material. Peterson simplified the procedure and proposed to simply evaluate the stress in only one point at a certain distance below the surface; this distance would also be a characteristic parameter of the material. Only if at that distance from the bottom of the notch into the plane of minimum cross-sectional area the stress was higher than the plain fatigue limit, there would be fatigue failure. From these considerations, and after several simplifications [3], Peterson developed the following relationship for K_f:

$$K_f = 1 + \frac{K_t - 1}{1 + \frac{\mathbf{a}}{r}} \tag{4}$$

where the parameter **a** is the characteristic distance from the notch, at which the stress is evaluated. Langer [10] after analyzing data from several steels proposed a relationship between the value of **a** and the ultimate strength of the material. The SAE and ASM Fatigue Handbooks [11,12] provide too a practical formula to obtain the length **a** from the ultimate tensile strength.

The applicability of Neuber's and Peterson's idea of a critical distance has been immensely increased by the recent proposal of Taylor in his point and line methods [5,6]. By applying the idea of failure over a distance below the surface not only to a notch but also directly to a sharp crack, and by invoking the Linear Elastic Fracture Mechanics condition for crack propagation, Taylor has been able to derive an extremely useful equation to calculate a characteristic critical distance L of the material in terms of the plain fatigue limit and the stress intensity threshold value,

$$L = \frac{1}{\pi}\left(\frac{\Delta K_{th}}{\Delta\sigma_{FL}}\right)^2 \tag{5}$$

All these methods thus relate failure to a certain measure of the stress level in the area of the notch, but they do not take into account, at least not explicitly, the fact that fatigue damage is really due to the propagation of a small crack. This further step, the explicit consideration of the existence of a small crack propagating from the notch has been attempted by the extension to notched geometries of a number of theories of short crack growth, which in essence try to extend fracture mechanics down to the regime where the cracks are of a size comparable to the size of the microstructure of the material [13–27]. At this level, the growth of the small cracks is strongly influenced by microstructural features, so that their behavior cannot be satisfactorily described by LEFM. These cracks begin to grow at a relatively high rate, but suffer strong decelerations when they approach barriers to plastic slip such as grain boundaries. Some of these cracks stop growing. Others suffer only a temporary delay, resuming their growth and accelerating once the plastic slip has spread beyond the barrier. In general, after an initial period, the growth of these cracks can be described by fracture mechanics, achieving convergence between the period of small crack and large crack. These studies about small crack growth can provide a satisfactory physical basis to understand the fatigue failure process in notched components.

A key factor here is the influence of the steep stress gradient through which the cracks must grow. The notch size to grain size relation must thus play an important role, for it will determine how many grains will see the enhanced notch stress field. This is clear when one reviews experimental results of tests where the notch size is varied. Consider a small hole in a plate subjected to tensile stress where the stress concentration factor K_t is approximately 3. This corresponds to a more or less blunt notch where

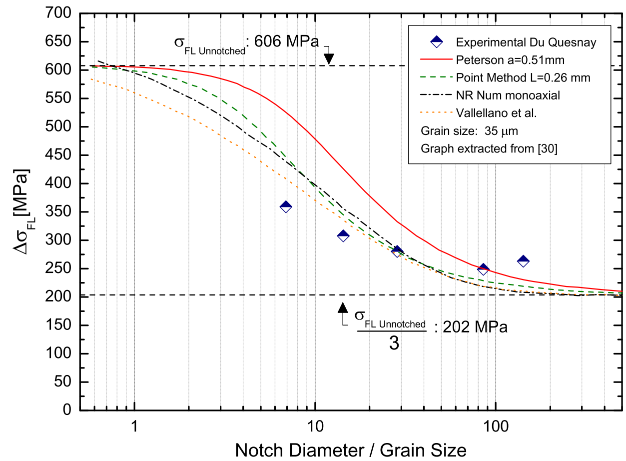

Fig. 1. Fatigue limit of SAE1045 steel specimens as a function of the notch size to grain size relationship. Predicted values of the different models reported in [29] and experimental data reported by Du Quesnay et al. [30].

normally (see [28]) non-propagating cracks are not observed. For these notches, the condition of crack initiation and crack propagation to failure are practically the same. In this case, in principle, the critical distance theories should work very well. And indeed they do, for the usual sizes of standard mechanical components, in which the size of the hole is very large compared to the microstructure of the material. For a normal steel used in typical machine elements such as a power transmission shaft, for example, the grain size can be about 50 microns or less, so that a hole about five or six millimeters in diameter is certainly very large compared with the microstructure. Applying to this situation the theories of Peterson or Taylor, and also some of the microstructural models mentioned above [24,29], we note that all theories predict very similar values for the fatigue limit of the notched specimen, see Fig. 1 which shows the predictions obtained with four different methods for holes of various sizes in SAE 1045 steel specimens tested by Du Quesnay et al. [30]. However, when the hole size decreases (maintaining the grain size), the differences between the predictions of the different models become clear [29].

In the literature one can find some experimental data, similar to those included in the figure, with hole diameters reaching down to about 150 microns. Obviously drilling holes so small in size is very difficult in practice. Smaller holes are a experimental big challenge. This means that going down to notch diameter to grain size ratios below between five to three in a graph such as the one in the previous figure is really difficult with conventional techniques. In the work reported here, we have used an experimental technique specially designed to allow us to obtain data for substantially smaller ratios. We present experimental results for specimens where the size of the hole is comparable and even smaller than the grain size of the material.

2. Material and experiments set-up

2.1. Microstructural aspects

One of the aims of this study is to determine as accurately as possible the influence of notch size to grain size relationship upon the fatigue notch factor (K_f). It is thus extremely important to control and measure the grain size of the material in a precise way. We have presented [31–33] a technique whereby "supersized" grains of commercially pure aluminum can be obtained by a combination of two heat treatments and an intermediate cold deformation