Critical Crack Opening Displacement in Low Strength Steels

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Introduction The use of a critical value, δ_{crit}, of crack-tip opening displacement (COD), as a measure of a material's toughness, is feasible under conditions where the deformation field in the fracturing region immediately ahead of a crack-tip is a unique characteristic of the microscopic fracture mechanism operating in that region. Then, a value of δ_{crit} may be measured, in specimens which fracture either before or after general yield, and related to the critical value of potential-energy release rate, G_{crit} (in pieces which are sufficiently large to fail in a macroscopically brittle manner) through the expression: $G_{crit} = \bar{\sigma}\,\delta_{crit}$, where $\bar{\sigma}$ is the material's flow stress in the crack-tip region. The present work has been carried out to define relevant values of δ_{crit} and to establish conditions under which δ_{crit} is invariant in different testpiece geometries and loading configurations. The paper describes results obtained on the initiation of fibrous fracture at stress-concentrators in low-strength steel.

Tests have been made mainly at room temperature on a free-cutting mild steel, containing a large number of manganese sulphide inclusions. Testpieces were prepared to contain slots, notches or fatigue cracks and were all fully annealed before testing. Values of δ_{crit} quoted refer to displacement at the tip of the initial stress-concentrator. A full description of experimental techniques and previous results is given in ref. 1.

Effects of Testpiece Geometry Variables which have been examined include the width or root radius of the initial stress concentrator, testpiece thickness and loading configuration. Attention has been paid primarily to the displacement, δ_i, at which fibrous fracture initiates. The value of δ_i shows a linear increase with both slot width and root radius over a range from a sharp fatigue crack to 0.25mm (see fig. 1). These results can be explained simply by assuming that a constant strain, ε_f, is necessary to produce fracture at the tip of a stress concentrator. Then, δ_i is given by the product of ε_f and the effective gauge length at the tip. Substantially, this gauge length is given by the width of a slot or the root radius of a notch. For the steel tested, ε_f is calculated from the gradient of fig. 1 as approximately 80%. This result has been confirmed by micro-hardness measurements[1]. The same value of ε_f produces fracture ahead of a fully stress-relieved fatigue crack and the associated value of δ_i implies[1] that the crack has an effective gauge length of 0.046mm (point F, fig. 1). It is found that δ_i is independent of thickness in specimens 5mm, 10mm, 17mm and 64mm thick, but is increased by a factor of some 2.5 in a specimen 2mm thick[1]. The increase occurs when the through-thickness stress is no longer sufficient to constrain the plastic deformation preceding fracture.

Measurements of COD in 3- and 4- point bend and in CTS testpieces are shown in figs. 2 and 3 for different testpiece orientations. In each case, consistent values of δ_i are obtained, although the load-COD curves show distinct differences. The COD-crack growth curves are also markedly different for 3- and 4- point bend specimens. This can be shown to be due to the different macroscopic strain distributions in these specimens during crack growth.

Effects of Microstructure The effective gauge length of a fatigue crack was calculated above as 0.046mm. This value can be explained in terms of a mechanism of fibrous fracture initiation which involves the internal necking of the matrix between sulphide inclusions. The inclusion spacing is 0.042mm and each inclusion in the crack tip region can provide a site for void nucleation. In this steel, neither elongated grain-boundary carbides nor spheroidized carbides contributed significantly to the fracture process. In a low-alloy steel, containing manganese sulphide and alumina inclusions, voids were found to be produced around both sulphide and alumina particles, but, again, not around carbides. If a steel contains closely spaced, non-wetting inclusions, these will always control the fibrous fracture process. If the steel is very clean, high strains may be needed to promote internal necking between inclusions and carbide particles may be activated as void-initiating sites. The shape of a crack-tip at the initiation of fracture depends on the microstructure of the material.

Conclusions Consistent values of δ_i have been obtained for a wide range of testpiece geometries and loading conditions. In thick testpieces, the critical δ_i value can be explained in terms of a simple necking mechanism, dependent on inclusion spacing and the flow characteristics of the matrix. Values of COD at fracture throughout the fibrous/cleavage transition range increase with temperature as a result of two effects. Firstly, there is an increase in δ_i due to the decrease in yield stress. Secondly, the COD increases because there is an increase in the amount of fibrous crack growth preceding the final cleavage. (The manner of the increase of COD with crack growth is shown in fig. 2).

Further experiments have shown that slow crack growth can proceed under constant load at room temperature, once δ_i has been exceeded. Under constant displacement, the load is relaxed by an increment of growth, which then arrests.

The general conclusion is that, if the COD concept is to be applied to the assessment of material toughness, the only parameter for which a logical and consistent basis has been established is the value of COD at the initiation of fibrous fracture.

Reference 1. R.F. Smith & J.F. Knott, Practical Application of Fracture Mechanics to Pressure Vessel Technology Inst. Mech. Engrs. 1971, p65

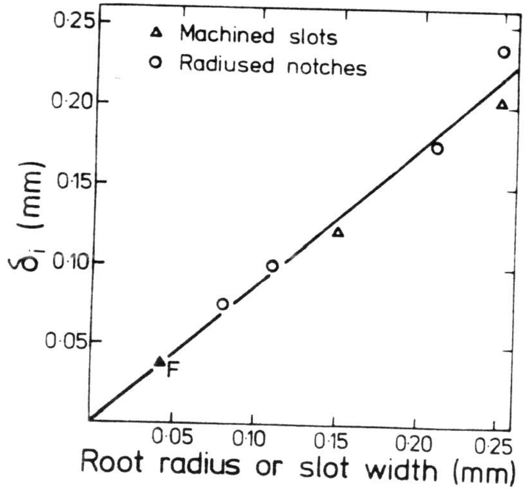

Fig. 1: Values of δ_i for a range of stress concentrators.

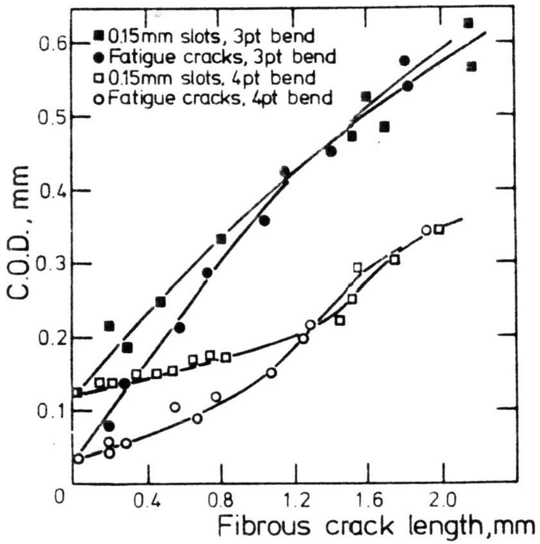

Fig. 2: C.O.D. versus fibrous crack length, 3- and 4- point bend compared.

Fig. 3: (below): C.O.D. versus fibrous crack length, 4- point bend and compact tension compared.