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The Notch Master Curve: A proposal of Master Curve for ferritic–pearlitic steels in notched conditions

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ABSTRACT

This paper presents a model for the prediction of the apparent fracture toughness of ferritic–pearlitic steels in notched conditions and operating at temperatures corresponding to their ductile-to-brittle transition zone. The model, here named the Notch-Master Curve, is based on the combination of the Master Curve of the material in cracked conditions and the notch corrections provided by the Theory of Critical Distances. In order to validate the model, the fracture resistance results obtained in 168 tests performed on CT specimens (84 for each material) are presented. These tests were carried out, for each material, in specimens with six different notch radii, from 0 mm up to 2.0 mm, and at three different temperatures within their corresponding ductile-to-brittle transition zone. It has been observed that the model provides good predictions of the fracture resistance in notched conditions for the two materials analysed.

1. Introduction

In many situations, the load-bearing capacity of a structural component is conditioned by the existence of stress risers. These may have very different natures: cracks, notches, holes, welded joints, corners, etc., all of them having different approaches when the corresponding structural integrity is being analysed. This paper is focused on notch-type defects, which may appear in structural components due to design details (e.g., holes), mechanical damage (e.g., gouges), corrosion defects or fabrication defects. If such defects are blunt, it is overly conservative to proceed on the assumption that the defects behave like sharp cracks, coupled with the use of ordinary Fracture Mechanics. Such assumption may lead to unnecessary repairs or replacements, or to oversizing. Components with non-sharp defects or notches exhibit an apparent fracture toughness that is greater than that obtained in cracked components because of the lower stresses acting at the notch tip and the evolution of fracture micromechanisms, as shown in [1–5]. This generally has direct consequences on the load-bearing capacity of the component and also on the corresponding structural integrity assessments.

In this sense, recent years have seen a great deal of research aimed at providing a notch theory capable of predicting the fracture behaviour of notched components, proposing two main failure criteria (e.g., [6,7]): the global fracture criteria and the local fracture criteria. Although both approaches are unquestionably significant from a scientific point of view, the local fracture criteria have more practical applications, especially those based on the Theory of Critical Distances (TCD) [8,9].

At the same time, it is known that the fracture resistance in cracked conditions of ferritic–pearlitic steels presents a clear dependence on the working temperature, with brittle behaviour at low temperatures (generally referred to as the lower

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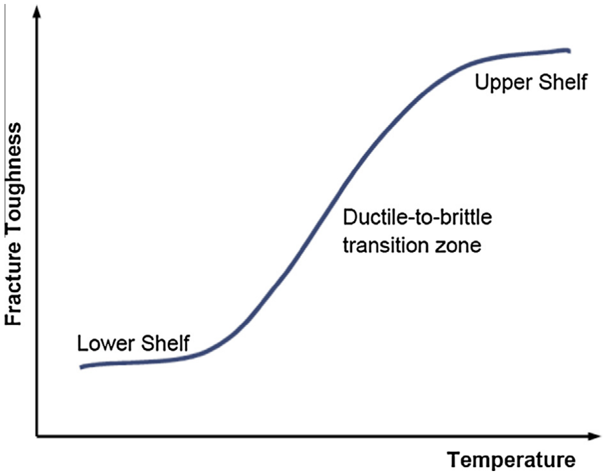

Fig. 1. Schematic showing the different regions of fracture behaviour in ferritic–pearlitic steels.

shelf, LS), ductile behaviour at high temperatures (upper shelf, US) and transition behaviour between the lower shelf and the upper shelf (ductile-to-brittle transition zone, DBTZ). Fig. 1 represents a schematic of this type of behaviour. The DBTZ of ferritic–pearlitic steels in cracked conditions has been successfully modelled through de Master Curve (MC) [10–14], which is nowadays a fundamental tool in the design and in-service assessment of critical structural components (e.g., nuclear pressure vessels). However, to the knowledge of the authors the analysis of this temperature dependence has not been previously reported in the literature when dealing with ferritic–pearlitic materials in notched conditions.

With all this, this paper presents a model for the fracture behaviour of ferritic–pearlitic steels in notched conditions and operating within the material DBTZ. The model is based on the above mentioned MC and the notch corrections provided by the TCD. With this purpose, Section 2 gathers some theoretical background on both the TCD and the MC and presents the proposed model, here named the Notch-Master Curve (NMC), Section 3 describes the experimental programme that is used here to validate the model, and Section 4 presents the corresponding validation, which is performed by comparison between the experimental results and the NMC predictions. Finally, Section 5 gathers the conclusions.

2. Theoretical background and the Notch-Master Curve

2.1. The Theory of Critical Distances

The Theory of Critical Distances (TCD) is in reality a group of methodologies with a common aspect: they all consider a characteristic material length parameter (the critical distance, L) when performing fracture assessments [8,9]. The critical distance is defined as follows:

$$L = \frac{1}{\pi}\left(\frac{K_c}{\sigma_0}\right)^2 \tag{1}$$

where K_c is the material fracture toughness and σ_0 is a strength parameter, named the inherent strength, which is usually larger than the ultimate tensile strength (σ_u) and must be calibrated. The inherent strength and the ultimate tensile strength are equal only in those situations where the fracture is brittle at both the macro and the micro scales (e.g., fracture of ceramics).

The origins of the TCD date from the middle of the twentieth century, with the works of Neuber [15] and Peterson [16], but it has been in this century that this theory has been comprehensively analysed, establishing its applicability to different types of materials (i.e., metals, ceramics, polymers and composites), processes (fracture and fatigue) and conditions (e.g., linear-elastic vs. elastoplastic) (e.g., [1,2,17–23]). A complete review, description and analysis of the fundamentals, the applications and the limitations of the TCD may be found in [8].

Here, suffice it to say that among the different methodologies composing the TCD two of them are particularly simple and interesting from an engineering point of view, the Point Method (PM) and the Line Method (LM) [8]:

- The PM establishes that fracture occurs when the stress reaches the inherent strength (σ_0) at a distance from the defect tip equal to $L/2$:

$$\sigma\left(\frac{L}{2}\right) = \sigma_0 \tag{2}$$