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Application of the Master Curve to ferritic steels in notched conditions

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ABSTRACT

This paper evaluates the application of the Master Curve methodology for the prediction of the apparent fracture toughness of ferritic-pearlitic steels in notched conditions. With this purpose, a new parameter is defined named the notch reference temperature (T_0^N), which is different from the reference temperature (T_0) obtained in cracked specimens and varies with the notch radius. In order to validate this application, the fracture resistance results obtained in 240 CT specimens have been used. The tests cover two different structural steels (S275JR and S355J2) and five different notch radii, from 0.15 mm up to 2.0 mm. The predictions provided by the Master Curve have also been compared to those provided by the Notch-Master Curve, revealing the temperature ranges where each prediction tool provides the best results.

1. Introduction

The structural integrity of real components is conditioned by the presence of defects, which can appear in any stage of the component's life. There are many situations where such defects or stress risers are not necessarily sharp. Some examples are defects such as notches, holes, corners and welded joints. This paper focuses on notch-type defects, which can be due to fabrication errors, frictions and impacts suffered during transportation and in-service, structural details (i.e. holes), or corrosion processes. The presence of a notch in a component creates conditions which are intermediate between those of a plain component (i.e. without any stress riser) and those of a sharp crack. On some occasions, notched components behave in a similar way to plain components, once the stress-concentration factor has been considered; in other cases, (sharp) notches behave like cracks of the same length. However, in many cases, notches do not conform to either of these extreme cases. Therefore, if notches are considered as cracks when performing fracture assessments, the corresponding results may be overconservative, increasing the costs due to premature replacements and repairs, or oversizing the structures. The notch effect has been widely studied in different types of materials (i.e. [1–7]), showing that notched components develop a fracture resistance greater than that developed by cracked components. In the last two decades, the scientific community has made a significant effort to provide a notch theory capable of predicting the fracture behaviour of notched components. Among all of these approaches, this research focuses on a group of methodologies belonging to the Theory of Critical Distances (TCD), which can easily generate predictions of the apparent fracture toughness exhibited by notched components. Further details on the TCD and its different proposals for notch effect predictions are described in Section 2.

At the same time, it is known that the fracture resistance in cracked conditions of ferritic steels presents a clear dependence on the working temperature. Fig. 1 represents a schematic of the three different existing regions depending on the temperature. The lowest temperatures are within the so-called lower shelf (LS), at which the material behaviour is totally brittle and the probability of cleavage initiation in the case of cracks becomes the unit, given that all possible initiation sites are activated [8]. The upper shelf (US) covers the highest temperatures, at which the fracture surface only shows stable crack extension. The transition region between both of them is

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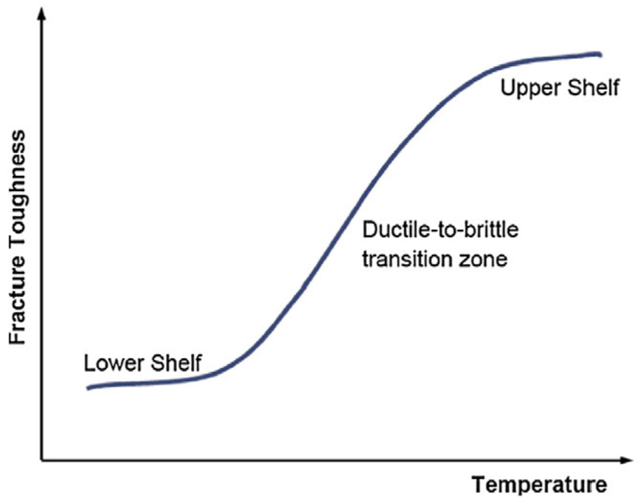

Fig. 1. Schematic showing the different regions of fracture behaviour in ferritic-pearlitic steels.

named ductile-to-brittle transition zone (DBTZ), wherein one or few initiation sites are seen on the fracture surface [8,9]. The DBTZ of ferritic steels in cracked conditions has been successfully modelled through the Master Curve (MC), which provides a description of the fracture toughness scatter, size effect and temperature dependence [8].

Concerning the apparent fracture toughness dependence on temperature, [10] proposed an engineering tool named Notch-Master Curve (NMC) which extends the MC application in notched conditions. The NMC combines the MC and a notch effect correction factor provided by the TCD, assuming that both effects are independent. A detailed explanation of the NMC is included in Section 2.

Apart from the research carried out on notched ferritic steels working within the DBTZ [10], further research has been completed on the LS of these steels [11], also in notched conditions. This research has shown that, even in the LS (as defined for cracked conditions), ductile fracture micromechanisms may appear around the initial notch front when the notch radius increases.

In spite of the capacity of the NMC for the analysis of the apparent fracture toughness within the DBTZ in notched ferritic steels, this paper intends to verify the applicability of the proper MC methodology in notched components. With this aim, the corresponding transition temperature (here named the notch transition temperature) is determined for each notch radius.

With all this, Section 2 gathers some theoretical background on the MC, the notch effect and the evolution of the fracture micromechanisms. Next, Section 3 describes the experimental programme that has been used here to validate the MC application in notched ferritic steels, and Section 4 presents the corresponding validation by comparison between the experimental results and the MC application. Finally, Section 5 presents the conclusions.

2. Theoretical background: Master Curve, notch effect and Master Curve application in notched conditions

2.1. Master curve

The Master Curve (MC) [12–15] constitutes a fracture characterisation tool for a wide variety of steels, mainly those of a ferritic nature, within their ductile-to-brittle transition zone (DBTZ). It is based on statistical considerations, related to the distribution of cleavage promoting particles around the crack tip. In the end, fracture is controlled by weakest link statistics and follows a three-parameter Weibull distribution. Thus, within the scope of small-scale yielding conditions, the cumulative failure probability (P_f) on which the MC is based follows Eq. (1):

$$P_f = 1 - \exp\left\{-\frac{B}{B_0}\left(\frac{K_{Jc}-K_{min}}{K_0-K_{min}}\right)^b\right\} \quad (1)$$

where K_{Jc} is the fracture toughness for the selected failure probability (P_f), K_0 is a scale parameter located at the 63.2% cumulative failure probability level, B is the specimen thickness and B_0 is the reference specimen thickness assumed in this methodology ($B_0 = 25$ mm). K_{min} and b take the same values for all ferrritic steels and have been experimentally fitted, providing 20 MPa·m$^{1/2}$ and 4 respectively. In any case, it can be observed that the fracture characterisation within the DBTZ is performed by using K_{Jc}, which is an elastic–plastic equivalent stress intensity factor derived from the J integral at the point of onset of cleavage fracture, J_c.

The dependence of K_0 on temperature under cleavage fracture conditions follows Eq. (2) [12–14,16]:

$$K_0 = 31 + 77 \cdot \exp\{0.019 \cdot (T - T_0)\} \quad (2)$$

where T_0 is the reference temperature, which corresponds to the temperature where the median fracture toughness for a 25 mm thick specimen is 100 MPa·m$^{1/2}$. Therefore, the only parameter required to determine the temperature dependence of K_{Jc} is the material