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Some thoughts about the application of the Master Curve methodology to ferritic steels containing notches

Sergio Cicero[a]*, Sergio Arrieta[a]

[a]LADICIM (Laboratory of Materials Science and Engineering), University of Cantabria, E.T.S. de Ingenieros de Caminos, Canales y Puertos, Av/Los Castros 44, Santander 39005, Spain

Abstract

The Master Curve (MC) is an engineering tool that allows the fracture toughness of ferritic steels operating within their ductile-to-brittle transition zone to be estimated. It is based on statistical considerations, related to the distribution of cleavage-promoting particles around the crack tip, and assumes that: a) fracture is controlled by weakest link statistics; b) it follows a three parameter Weibull distribution. The authors have previously provided two different approaches for applying the MC in notched conditions. The first one consists of determining the reference temperature (T_0) in cracked conditions and applying a subsequent notch correction to estimate the fracture toughness at a given temperature; the second one proposes obtaining directly a notch reference temperature (T_0^N) for a given notch radius by testing notched specimens. This second approach assumes that both the Weibull parameters (K_{min}=20 MPam$^{1/2}$ and b=4) and the censoring criteria used in cracked conditions are applicable in notched conditions. This paper provides some thoughts about these assumptions with the aim of analysing the applicability of the MC in ferritic steels containing notches, and includes specific validation on steels S460M and S690Q.

Keywords: fracture; fracture toughness; Master Curve; notch

1. Introduction

There are numerous situations where the defects or stress risers that limit the load-bearing capacity of a given structural component are not necessarily sharp (i.e. crack-like defects). Some examples are defects such as notches, corners or holes. Notches, in particular, can be originated by fabrication imperfections, by corrosion processes, or may be structural details (i.e. holes). The presence of a notch in a structural component generates conditions that are somehow between those existing in a plain component, without any stress riser, and those caused by a sharp crack. The analysis of notches is not straightforward, as there are occasions where notched components behave in a similar way to plain components with the same net section, and there are other cases where notches behave like cracks of the same length. Moreover, in most cases, notches do not respond to either of these extreme cases, as they do affect final failure acting as stress risers, but its severity is lower than that caused by a crack.

The notch effect has been widely studied in different types of materials and failure modes (e.g., Taylor (2007), Cicero et al. (2012), Berto and Lazzarin (2014), Cicero et al. (2015a), González et al. (2019)). In the last two decades, the scientific

* Corresponding author. Tel.: 34-942-200-017
E-mail address: ciceros@unican.es

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community has made a significant effort to provide a notch theory capable of predicting the fracture behaviour of notched components.

At the same time, the fracture behaviour of ferritic steels in cracked conditions strongly depends on the operating temperature. At low temperatures, the material operates in the so-called lower shelf (LS), at which the material behaviour is totally brittle. The upper shelf (US) covers the highest temperatures, at which the fracture surface only shows ductile mechanisms. The terms low and high temperatures are relative, and depend on the material being analysed. Nevertheless, the transition region between both of them is named ductile-to-brittle transition zone (DBTZ), wherein one or few initiation sites are seen on the fracture surface (Merkle et al. (1998), Wallin (2002). In cracked conditions, the DBTZ of ferritic steels has been successfully modelled through the Master Curve, which provides a description of the fracture toughness scatter, size effect and temperature dependence (Wallin (1984), Wallin et al. (1984), Wallin (1985), ASTM E1921 (2020)).

This paper analyses the basis for a direct application of the Master Curve to ferritic steels containing notches, deriving the corresponding notch (or apparent) Reference Temperature (T_0^N). This parameter depends on the material being analysed and the notch radius being considered. The validity of the different hypotheses sustaining the Master Curve in cracked conditions are scrutinised for notched conditions, including some validation supporting its use in the presence of this kind of defects.

With all this, Section 2 provides a brief overview of the Master Curve, and Section 3 provides thoughts and discussion about the use of this tool in notched conditions, together with some experimental validation on steels S460M and S690Q. Finally, Section 4 summarises the main conclusions.

2. The Master Curve

The Master Curve (MC) (Wallin (1984), Wallin et al. (1984), Wallin (1985), ASTM E1921 (2020)) is a fracture characterisation tool for ferritic steels operating within their ductile-to-brittle transition zone (DBTZ). It is built on statistical considerations, associated with the distribution of cleavage promoting particles around the crack tip. Fracture is then assumed to be controlled by weakest link statistics, following a three parameter Weibull distribution. Within the scope of small-scale yielding conditions, the cumulative failure probability (P_f) on which the MC is based follows equation (1):

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

where K_{Jc} is the fracture toughness for the selected failure probability (P_f) (in stress intensity factor units), B is the specimen thickness and B_0 is the reference specimen thickness assumed in this methodology (B_0 = 1T = 25 mm). K_0, K_{min} and b are the three parameters of the Weibull distribution, with K_0 being a scale parameter (located at the 63.2 % cumulative failure probability level), K_{min} being the location parameter and b being the shape parameter. The MC methodology assumes the same values of K_{min} and b for all ferritic steels, 20 $MPam^{1/2}$ and 4 respectively. The dependence of K_0 on temperature within the DBTZ follows equation (2) (Wallin (1993)):

$$K_0 = 31 + 77e^{0.019(T-T_0)} \tag{2}$$

where T_0 is the reference temperature, which corresponds to the temperature where the median fracture toughness for a 25 mm (1T) thick specimen is 100 $MPam^{1/2}$. Consequently, T_0 is the only parameter required to determine the temperature dependence of K_{Jc}. Besides, once the material T_0 is known, it is possible to define the MC for any probability of failure (P_f):

$$K_{Jc,P_f} = 20 + \left(-\ln\left(1-P_f\right)\right)^{0.25}\left(11 + 77e^{0.019(T-T_0)}\right) \tag{3}$$

Accordingly, the curves associated to probabilities of failure of 95%, 50% and 5% are those gathered in equations (4), (5) and (6) respectively,:

$$K_{Jc,0.95} = 34.5 + 101.3e^{0.019(T-T_0)} \tag{4}$$

$$K_{Jc,0.50} = 30 + 70e^{0.019(T-T_0)} \tag{5}$$

$$K_{Jc,0.05} = 25.2 + 36.6e^{0.019(T-T_0)} \tag{6}$$

When the thickness of the component being analysed is not 25 mm, ASTM1921 provides equation (7) to derive the fracture toughness value for a given thickness (B_x) from the fracture toughness value for a 25 mm thick specimen:

$$K_{Jc(x)} = 20 + \left(K_{Jc(0)} - 20\right)\left(\frac{B_0}{B_x}\right)^{0.25} \tag{7}$$

where $K_{Jc(x)}$ is the fracture toughness for a component size B_x, and $K_{Jc(0)}$ is the fracture toughness for the reference thickness (B_0=1T=25 mm).

3. The use of the Master Curve in notched conditions

The authors have previously provided two different approaches for applying the MC in notched conditions. The first one consists of determining the reference temperature (T_0) in cracked conditions and applying a subsequent notch correction (e.g., Theory of Critical Distances, Taylor (2007) to estimate the fracture toughness at a given temperature (see Cicero et al. 2015b). The second one, analysed here, proposes obtaining directly a notch reference temperature (T_0^N) for a given notch radius by testing notched specimens. This direct application of the Master Curve in notched conditions implies the use of the following formulation:

$$K_{Jc,P_f}^N = 20 + \left(-\ln\left(1-P_f\right)\right)^{0.25}\left(11 + 77e^{0.019\left(T-T_0^N\right)}\right) \quad (8)$$

$$K_{Jc,0.95}^N = 34.5 + 101.3e^{0.019\left(T-T_0^N\right)} \quad (9)$$

$$K_{Jc,050}^N = 30 + 70e^{0.019\left(T-T_0^N\right)} \quad (10)$$

$$K_{Jc,0.05}^N = 25.2 + 36.6e^{0.019\left(T-T_0^N\right)} \quad (11)$$

where K^N_{Jc} is the apparent fracture toughness for the notch radius analysed and T_0^N is the apparent reference temperature. However, the generalised use of these formulae entails justifying that the different hypotheses supporting the use of the MC in cracked conditions are also valid in notched conditions. These hypotheses are the following (see Cicero and Arrieta (2021) for further details):

- Weibull distribution: when dealing with notched steel within the corresponding DBTZ, fracture is caused by cleavage and, therefore, the fracture process obeys weakest-link statistics. This kind of processes are appropriately described by a three-parameter Weibull distribution. Consequently, provided that the fracture processes in cracked and notched conditions follow the same fracture micromechanisms, they both obey analogous cumulative failure probability equations.
- K_0: the equation followed by the scale parameter in cracked conditions (equation (2)) was empirically fitted from an extensive set of experimental results (Wallin (1993)). The authors have proven that the same equation may also be used in notched conditions, given that it describes adequately the K_0 dependence of a number of experimental results obtained in notched ferritic steels (Cicero and Arrieta (2021), see Figure 1 for results in steels S460M and S690Q). Thus, the scale parameter in notch analysis (K^N_0) follows equation (12):

$$K_0^N = 31 + 77e^{0.019\left(T-T_0^N\right)} \quad (12)$$

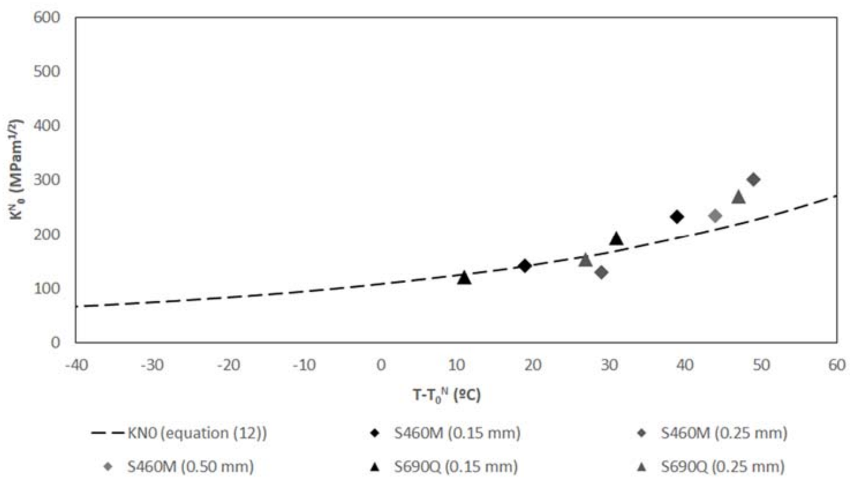

Fig. 1. K_0^N results in S460M and S690Q steels containing notches, and comparison with the fracture toughness transition curve (equation (12)) assumed by the Master Curve.

- K_{min}: provided that cleavage requires a minimum stress intensity factor to occur, the location parameter of the Weibull distribution is also necessary in notched conditions (K^N_{min}). Here, it is proposed to use the same value used for cracks, (20 MPam$^{1/2}$), given that fracture is caused by the same micromechanisms. However, K^N_{min} would not be achieved at the same temperature as K_{min}, given that the DBTZ curve in notched conditions is shifted to lower temperatures. Additionally, not considering any notch effect in K^N_{min} is, in any case, a conservative practice.

- b: the Weibull slope is assumed to be 4 in the MC, and statistical analyses (Wallin (1998)) confirm that this value is adequate in cracked ferritic steels. Following the same reasoning, Figure 2 shows the different b values (slopes) obtained in a several datasets developed by the authors on steels S460M and S690Q (Cicero et al. (2015b)), for different notch radii, together with the corresponding confidence bands (90% limits). It can be observed how the values fit well within the confidence bands, proving that it is reasonable to use this value for notched conditions (b^N=b=4). Details on the procedure followed to obtain the different points may be found in Cicero and Arrieta (2021):

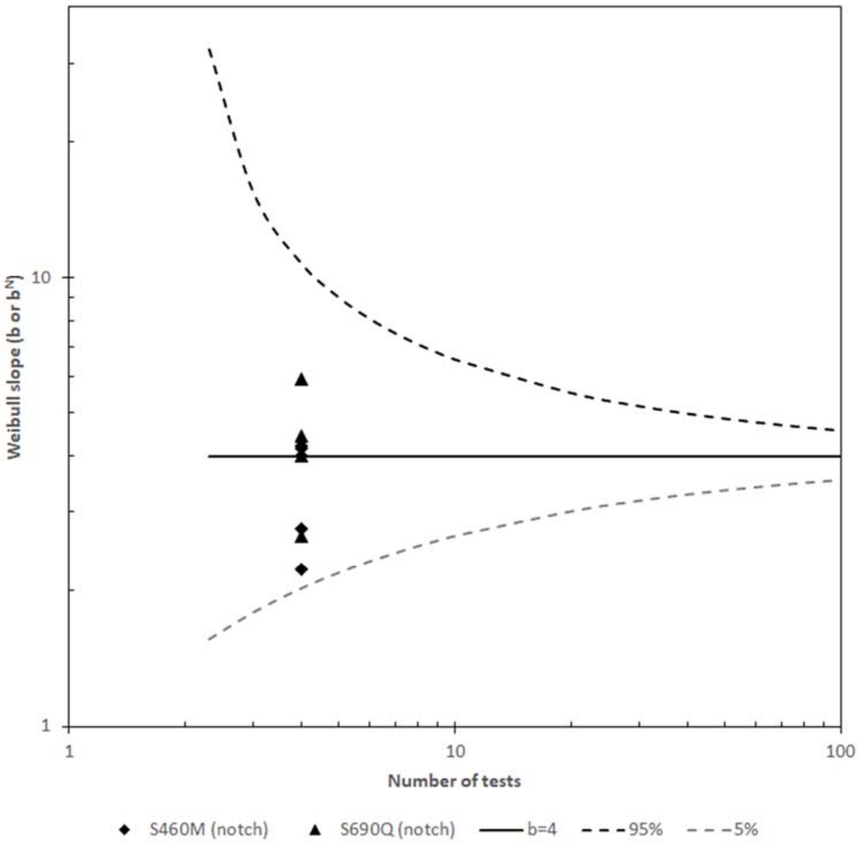

Fig. 2. 90% confidence limits for estimates of the Weibull slope in steels S460M and S690Q.

Other methodological aspects, such as the censoring criterion are also justified in Cicero and Arrieta (2021). With all this, the different hypotheses assumed in cracked conditions are sufficiently justified in notched conditions, and can now be applied to experimental results obtained by the authors in steels S460M and S690Q (see Cicero et al. (2015b)). The results, obtained in 16 mm thick specimens and subsequently converted to 1T through equation (7), are shown in Figure 3, where it can be observed how the MC provides a very good fitting of the experimental values, the validation (in this case) being limited to 0°C < ($T-T_0^N$) < 50°C.

4. Conclusions

This paper analyses the application of the Master Curve (MC) for the apparent fracture toughness characterisation of ferritic steels operating within the Ductile-to-Brittle Transition Zone (DBTZ) and containing notches.

With this aim, the different hypotheses sustaining the use of the MC in cracked conditions are reviewed, and their possible use in notched conditions is critically analysed. Then, some experimental results in two structural steels (S460M and S690Q) containing notch radii between 0.15 mm to 0.50 mm are compared with the MC predictions. The results show that the application of the MC in notched conditions provides very good estimations of the apparent fracture toughness within the DBTZ.

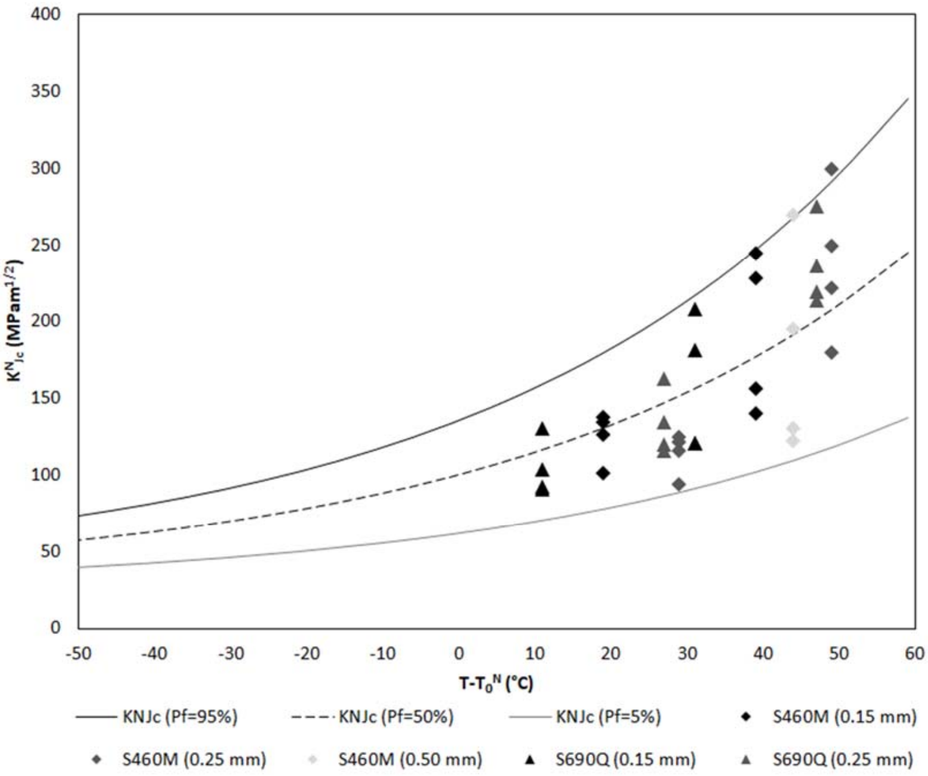

Fig. 3. Comparison between apparent fracture toughness (K^N_{Jc}) experimental results obtained in notched structural steels (S460M and S690Q) and MC predictions.

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