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Analysis of specimen size conversion in the ductile to brittle transition region of ferritic steels

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Abstract

The ASTM E 1921-15 standard covers the determination of the Master Curve, a function used to characterize the fracture toughness of ferritic steels that experience onset of cleavage fracture in the transition region. In the standard, the specimen size effect on fracture toughness at cleavage (K_{Jc}) in the transition range is explained by the weakest-link theory, using a three-parameter Weibull distribution with shape (b) and threshold (K_{min}) parameters fixed. When specimens from different sizes are tested, a K_{Jc} conversion is necessary. The effect of size conversion using either the equation given by the standard and a three parameter Weibull distribution with the parameters estimated from data sets are compared in this work. It was found that the distributions obtained from results converted to one-inch size did not adjust the data in the way the weakest link model would predict, meaning that the statistical effect due to the difference in the crack front volume would not be the only responsible for the difference in results for different specimen sizes. This was found using both the ASTM E1921 method and the three parameter Weibull distribution.

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Keywords: ductile-to-brittle; specimen size conversion; Weibull; Master Curve

1. Introduction

The characterization of fracture resistance of ferritic steels in the ductile-to-brittle transition region is problematic due to scatter in results, as well as size and temperature dependences.

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According to the weakest link theory, there are small areas of low toughness or weak links (possible sites initiators of cleavage) randomly distributed in the crack front, so that the brittle fracture would be a statistical event (Landes and Shaffer (1980), Landes and McCabe (1982)). The cleavage fracture is a stress controlled local fracture process, that takes place when the critical stress is reached in one of these weak links. The load required to produce the fracture will depend upon the location of the weak link and its critical stress.

In addition to the scatter that occurs in the transition region, the weakest link model also explains the effect of specimen size, since an increase in the length of the crack front enlarges the highly stressed volume of material at the tip of the crack, also increasing the likelihood to find a weak link.

Since 1997, after several decades of scientific researches that have included the implementation of some round robin projects, there is an ASTM standard that states the procedure for the determination of the Master Curve proposed by Wallin (1993). This standard has been modified over the time, with the latest version corresponding to the ASTM E1921-15a$^{\gamma 1}$ (2015). The Master Curve concept details, its origin and the methodology are explained in an excellent book written by Wallin (2011) that addresses wide aspects of fracture mechanics and focuses on the brittle to ductile transition region.

Prior to the Master Curve, the ASME Boiler and Pressure Vessel Code (ASME 1989) had already established the K_{IR} curve (a lower bound of K_{IC} and K_{Ia} results) for the characterization of ferritic pressure vessel steels. The reference temperature was RT_{NDT} instead of T_0 (McCabe et al. (2005)). The implementation of the Master Curve has been a huge advance in the need to have adequate tools for treating the complexities related to temperature, size and scatter in the ductile-to-brittle transition region for ferritic steels.

The Master Curve is fixed in the temperature axis when the temperature reference (T_0) is known. Its concept is based on a three parameter Weibull (*3P-W*) distribution with shape parameter equal to 4 and threshold value equal to 20 MPa.m$^{0.5}$, for compact specimens of 1-inch size. The standardized procedure includes a size conversion equation for those situations where different specimen sizes are used, and some instructions for censoring data for excessive ductile crack growth prior to fracture and for loss of constraint.

Some recent works pay attention to the influence of out of plane constraint in the effect of specimen size. Lu and Meshii (2014) state that the effect of thickness on the *Jc* values are related with T_{33} value (a measure of constraint), while Meshii et al. (2013) say that the effect of thickness is more a mechanical issue than a statistical phenomenon. Structure

1.1. Weakest link model size conversion

The Weakest link establishes that if the fracture toughness statistical distributions for thickness B_1 is known, the corresponding distribution for B_2 thickness would be derived, just taking into account the thicknesses ratio.

$$N = \frac{B_2}{B_1} \tag{1}$$

If the statistical distribution is the three parameter Weibull distribution, identifying the shape (b), the threshold (K_{min}) and the scale (K_0) parameters, with a sub index according to the specimen size, being P the probability of failure, it results

$$P_1 = 1 - \exp\left(-\left(\frac{K_{Jc(B_1)} - K_{\min(B_1)}}{K_{0(B_1)} - K_{\min(B_1)}} \right)^{b_{(B_1)}} \right) \tag{2}$$