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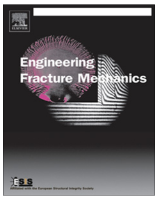

Analysis of size and temperature effects in the ductile to brittle transition region of ferritic steels

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ABSTRACT

This paper presents an analysis of ferritic steels in the ductile-to-brittle transition region that includes the determination of the temperature reference of the Master Curve, which assumes a Weibull distribution with fixed threshold and shape parameters for compact specimens of one inch thickness. Some differences arise between the scale parameter and the median of the distribution calculated from these specimens and those converted from other sizes. The dependence with size and temperature of the parameters of a non-fixed three parameter Weibull distribution were also analyzed. The estimated threshold and shape parameters resulted clearly temperature dependent, and different from those stated in the 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.

Ferritic steels are, as defined in ASTM E1921-13 [1], “*typically carbon, low-alloy, and higher alloy grades. Typical microstructures are bainite, tempered bainite, tempered martensite, and ferrite and pearlite. All ferritic steels have body centered cubic crystal structures that display ductile-to-cleavage transition temperature fracture toughness characteristics*.”

The statistical treatment is mainly based on Weibull statistics, which has been used with two (2P-W) (Eq. (1)) or three parameter (3P-W) (Eq. (2)). The parameters to be determined in the 2P-W distribution are the shape parameter, also known as Weibull slope (b_K or b_J), and the scale parameter (K_0 or J_0). For a 3P-W distribution, the threshold parameter (K_{min} or J_{min}) is added.

$$P = 1 - \exp\left[-\left(\frac{Jc}{J_0}\right)^{b_J}\right] \quad P = 1 - \exp\left[-\left(\frac{K_{Jc}}{K_0}\right)^{b_K}\right] \tag{1}$$

$$P = 1 - \exp\left[-\left(\frac{Jc - J_{min}}{J_0 - J_{min}}\right)^{b_J}\right] \quad P = 1 - \exp\left[-\left(\frac{K_{Jc} - K_{min}}{K_0 - K_{min}}\right)^{b_K}\right] \tag{2}$$

Data expressed in terms of K are derived from J_C (K_{JC}) using Eq. (3).

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Nomenclature

a_0	initial crack length
b_0	initial specimen remaining ligament
b_J	Weibull shape parameter estimated from J_C data
b_K	Weibull shape parameter estimated from K_{JC} data
$b_{k\text{-}1T}$	b_k for 1T-C(T) size (original and converted)
b_{Kj}	Weibull shape parameter derived from estimated b_J
r	number of non-censored tests
B	specimen thickness
B_{1T}	equivalent 1T-C(T) thickness
C(T)	compact tension specimen
E	elastic modulus
J_C	experimental J-integral at the onset of cleavage fracture
J_{max}	maximum allowed J_C value
J_{min}	Weibull threshold parameter estimated from J_C data
J_0	Weibull scale parameter estimated from J_C data
K_{J_c}	elastic–plastic equivalent stress intensity factor derived from the J_C value
$K_{Jc\text{-}1T}$	equivalent 1T-C(T) value of K_{J_c}
$K_{Jc(i)}$	*i-th* value of K_{J_c}
K_{Jmax}	maximum allowed K_{J_c} value
K_{med}	median of K_{J_c} distribution
K_{min}	Weibull threshold parameter
$K_{min\text{-}exp}$	minimum experimental K_{J_c}
$K_{min}(J)$	K_{min} derived from estimated J_{min}
$K_{min}(K)$	K_{min} estimated from K_{J_c} data
$K_{min\text{-}1T}$	K_{min} for 1T-C(T) size (original and converted)
K_0	Weibull scale parameter
$K_{0\text{-}1T}$	K_0 for 1T-C(T) size (original and converted)
$K_0(J)$	K_0 derived from estimated J_0
$K_0(K)$	K_0 estimated from K_{J_c} data
MC	Master Curve
N	total number of tests
T	test temperature
T_0	reference temperature
W	specimen width
ξ	factor relating b_J and b_{Kj}
ν	Poisson's ratio

$$K_{Jc} = \sqrt{\frac{EJ_c}{(1-\nu^2)}} \tag{3}$$

where E is the elastic modulus and ν is the Poisson's ratio.

For instance, Landes and Shaffer [2], Iwadate et al. [3], Anderson et al. [4], Landes et al. [5], and Heerens et al. [6,7] made use of a 2P-W distribution based on J_C values, while Landes and McCabe [8], Neville and Knott [9], and Perez Ipiña et al. [10] based their analysis on the 3P-W distribution using J_C data. The use of such distributions based on K values was promoted by Wallin, with a 2P-W distribution [11], and later with a 3P-W distribution [12].

Besides the possibility of working with two or three parameters, and also with J or K data, some authors have proposed a fixed shape parameter with a given value: 2 when working with J_C [4–6,13] and 4 when working with K_{JC} [1,12,14].

Although the 2P-Weibull slopes in terms of J and K are related by $b_K/b_J = 2$, this relationship does not apply when the third parameter (threshold parameter) is introduced. It was shown in previous papers [15,16] that the slopes ratio is not 2, and it is given by the factor $\xi = \frac{2K_0}{K_0+K_{min}}$. The slope b_{Kj}, converted from b_J using the factor ▹, and the b_K estimated from K_{Jc} values are not equals, but they are similar.

ASTM [1] has adopted the Master Curve method for the analysis of fracture toughness in this region. The temperature dependence of the 1T-C(T) median fracture toughness is based on an empirical equation calibrated at the T_0 temperature that corresponds to a $K_{med} = 100\ \text{MPa m}^{0.5}$ for this size, and it is determined assuming a Weibull distribution with $K_{min} = 20\ \text{MPa m}^{0.5}$ and slope $b_K = 4$ for the scatter treatment.