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Calibration of the Weibull stress scale parameter, σ_u, using the Master Curve

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Abstract

This work proposes that the Weibull stress scale parameter, σ_u, increases with temperature to reflect the increasing microscale toughness of ferritic steels caused by local events that include plastic shielding of microcracks, microcrack blunting, and microcrack arrest. The Weibull modulus, m, then characterizes the temperature invariant, random distribution of microcrack sizes in the material. Direct calibration of σ_u values at temperatures over the DBT region requires extensive sets of fracture toughness values. A more practical approach developed here utilizes the so-called Master Curve standardized in ASTM Test Method E1921-02 to provide the needed temperature vs. toughness dependence for a material using a minimum number of fracture tests conducted at one temperature. The calibration procedure then selects σ_u values that force the Weibull stress model to predict the Master Curve temperature dependence of K_{J_c} values for the material. At temperatures in mid-to-upper transition, the process becomes more complex as fracture test specimens undergo gradual constraint loss and the idealized conditions of high-constraint, small-scale yielding assumed in E1921-02 gradually degenerate. The paper develops the σ_u calibration process to incorporate these effects in addition to consideration of threshold toughness effects and the testing of fracture specimens with varying crack-front lengths. Initial illustrations of the calibration process for simpler conditions, i.e. 1T crack-front lengths, use the temperature dependent flow properties and a range of toughness levels for an A533B pressure vessel steel. Then using the extensive fracture toughness data sets for an A508 pressure vessel steel generated recently by Faleskog et al. [Engng. Fract. Mech., in press], the paper concludes with calibrations of both m and σ_u over the DBT region and assessments of the Master Curve calibration approach developed here.

Keywords: Ferritic steels; Cleavage fracture; Constraint loss; Local approach; Weibull stress; Transition region; Master Curve; Finite element modeling

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Nomenclature

B	thickness
$B_{x\mathrm{T}}$	thickness for an xT size specimen ($B = x$ in.)
$B_{1\mathrm{T}}$	thickness for an 1T size specimen ($B = 1$ in., 25.4 mm)
$\mathscr{C}$	material constant relating Weibull stress to J-integral
$\overline{\mathscr{C}}$	material constant relating Weibull stress to K_J
E	elastic modulus
E_T	hardening modulus
H	height of compact tension specimen
J	value of J-integral
J_avg	through-thickness average of J-integral
J_c	value of J-integral at cleavage fracture
$J_{\mathrm{c(limit)}}$	limiting value of J_c
K_c	microcrack toughness
K_I	mode I stress intensity factor
K_J	plane-strain conversion of J
K_{J_c}	plane-strain conversion of J_c
$K_{J_\mathrm{c}}^{(x\mathrm{T})}$	plane-strain conversion of J_c for an xT size specimen
$K_{J_\mathrm{c}}^{\mathrm{SSY(1T)}}$	plane-strain conversion of J_c for small-scale yielding conditions at 1T thickness
$K_{J_\mathrm{c}(\mathrm{med})}$	median value ($P_\mathrm{f} = 0.5$) of K_{J_c}
K_min	threshold or minimum fracture toughness
K_0	toughness scale parameter ($P_\mathrm{f} = 0.632$)
$K_0^{(1\mathrm{T})}$	toughness scale parameter ($P_\mathrm{f} = 0.632$) for a 1T size specimen
M	non-dimensional deformation, $M = b\sigma_0/J$
$M^{(x\mathrm{T})}$	non-dimensional deformation for an xT size specimen
M_min	non-dimensional deformation based on K_min
$M_\mathrm{min}^{(x\mathrm{T})}$	non-dimensional deformation for an xT size specimen based on K_min
N	total number of fracture specimens in a given data set
$\mathscr{L}$	length-scale parameter
P_f	cumulative probability of failure
R	outer radius of boundary layer model
R_p	radius of plastic zone
θ	temperature
$\bar{\theta}$	specific test temperature
T_0	reference temperature
T_σ	magnitude of T-stress
V	volume of the fracture process zone
V_0	reference volume
$\overline{V}_0$	alternate reference volume
W	width of fracture specimen
Y	microcrack geometry factor
(x, y, z)	Cartesian coordinate system with origin at initial crack-front location
(u, v, w)	displacement components in (x, y, z)
a	crack length