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An investigation of the loading rate dependence of the Weibull stress parameters

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Abstract

This paper examines the dependence of the Weibull stress parameters on loading rate for a 22NiMoCr37 pressure vessel steel. Extensive fracture tests, including both quasi-static and dynamic tests, are conducted using deep- and shallow-cracked SE(B) specimens. The fracture specimens are carefully prepared to ensure the crack fronts are placed at the location where the material is homogeneous. Three dynamic loading rates (in terms of the stress intensity factor rate, $\dot{K}_J$) in the low-to-moderate range are considered. The load-line velocities for the dynamic tests are chosen so that the resulted $\dot{K}_J$ values for the deep- and shallow-cracked specimens are the same. Independent calibrations performed at each loading rate (quasi-static and the three dynamic loading rates) using deep- and shallow-cracked fracture toughness data show that the Weibull modulus, m, is invariant of loading rate. The calibrated m-value is 7.1 for this material. Rate dependencies of the scale parameter (σ_u) and the threshold parameter ($\sigma_{\text{w-min}}$) are computed using the calibrated m and the results indicate that σ_u decreases and $\sigma_{\text{w-min}}$ increases with higher loading rates. The demonstrated loading rate invariant of m, when combined with the master curve for dynamic loading, can provide a practical approach which simplifies the process to estimate σ_u as a function of loading rate.

Keywords: Cleavage fracture; Fracture toughness; Failure probability; Weibull stress; Loading rate; Pressure vessel

1. Introduction

Transgranular cleavage fracture in the ductile-to-brittle transition (DBT) region of ferritic steels often leads to spectacular and catastrophic failures of engineering structures. But two significant obstacles arise in applications of fracture mechanics to assess the integrity of these structures in the DBT region: the scatter of measured fracture toughness data and the transferability of toughness values between crack configurations with different levels of constraints [1,2]. These are results of the strongly stochastic effects of metallurgical scale

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inhomogeneities and the nonlinear mechanical response from plastic deformation. The significance of cleavage fracture behavior has stimulated an increasing amount of research in the past two decades. These research efforts have led to a quantitative understanding of the scatter and temperature dependence of macroscopic fracture toughness (in terms of J_c or K_{Jc}) under the high constraint, small scale yielding (SSY) conditions. Scatter of the SSY toughness data can be described by a three-parameter Weibull distribution, where the Weibull modulus for the K_{Jc} distribution is 4 and the minimum fracture toughness for common ferritic steels is $K_{\min} \approx 20\ \text{MPa}\sqrt{\text{m}}$ [1,3]. This three-parameter Weibull distribution has been adopted in ASTM standard E1921 [4]. E1921 also adopts a so-called "master curve", empirically derived by Wallin and co-workers [5,6], to describe the dependence of the median fracture toughness on temperature for ferritic steels in the DBT region. E1921 and the master curve approach have gained widespread acceptance to describe the transition fracture toughness and the scatter of toughness values in recent years.

The master curve defines the median fracture toughness under the high constraint, SSY conditions while in engineering applications the crack front often experiences constraint loss. This motivates the development of micromechanics-based models to address the transferability of cleavage fracture toughness across varying levels of crack-front constraint. The Weibull stress model, originally proposed by the Beremin group [7], provides a framework for quantifying the relationship between macro-scale and microscale driving forces for cleavage fracture. The introduction of the so-called Weibull stress (σ_{w}), calculated by integrating a weighted value of the maximum principal stress over the fracture process zone, provides the basis for generalizing the concept of a probabilistic fracture parameter and supports the development of procedures that adjust toughness values across different crack configurations and loading modes (tension vs. bending). The Beremin model has two material parameters, the Weibull modulus (m) and the scale parameter (σ_u). Gao et al. [8] introduced a threshold parameter ($\sigma_{\text{w-min}}$) into the Weibull stress model and proposed a procedure to calibrate the model parameters using fracture toughness data obtained from two sets of fracture specimens that exhibit different constraint levels at failure. Using the three-parameter Weibull stress model with parameters calibrated according to the proposed procedure, Gao et al. [9] predicted the distributions of measured fracture toughness values in various specimens of an A515-70 pressure vessel steel, including surface crack specimens subject to different combinations of bending and tension.

Cleavage fracture involves a complex metallurgical and mechanical process and the cleavage fracture behavior can be affected by temperature, loading rate, irradiation, pre-straining, and many other parameters. Kroon and Faleskog [10,11] and Gao et al. [12,13] included the effects of plastic strain in the framework of Weibull stress and studied the effects of temperature and constraint on fracture toughness. These modifications are inspired by the observations that the number of microcracks in the material increases with the plastic strain level. However, other observations have shown that microcracks arrested at grain boundaries are blunted with further straining, making them unlikely to propagate again. This was the basis of the strain correction introduced in the original Beremin model [7]. Petti and Dodds [14] argued that the Weibull modulus (m) is independent of temperature and the scale parameter (σ_u) increases with temperature to reflect the increase of microscale toughness of ferritic steels. They proposed a procedure to calibrate the variation of σ_u with temperature using the master curve. More recently, Wasiluk et al. [15] calibrated the Weibull stress parameters for a 22NiMoCr37 pressure vessel steel at different temperatures using the fracture toughness data generated in a fracture research project sponsored by the European Union [16], and demonstrated the temperature invariance of m. Gao and Dodds [17,18] studied the effects of loading rate on the Weibull stress model for the A515-70 steel and found a loading rate-independent m can be employed in the range of low-to-moderate loading rates. However, due to limited experimental data, Gao and Dodds [17,18] were only able to calibrate m at the quasi-static loading rate and one slow dynamic loading rate. They made the assumption of m invariant of loading rate based on micromechanics arguments. But if their conclusion can be verified, it would permit a similar approach to Petti and Dodds [14] to estimate σ_u as a function of loading rate. This will significantly reduce the amount of fracture tests required for defect assessment at dynamic loading rates. To verify the conclusion of Gao and Dodds [17,18], the Weibull modulus should be calibrated independently at several different loading rates, which motivates the present work.

In this study, extensive fracture tests are conducted on a 22NiMoCr37 pressure vessel steel obtained from Framatome (through Oak Ridge National Laboratory). Deep- and shallow-cracked SE(B) specimens were tested at quasi-static as well as three low-to-moderate dynamic loading rates and the Weibull stress parameters