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An experimental investigation of the effect of biaxial loading on the master curve transition temperature in RPV steels

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Abstract

During the 1990s considerable work was conducted to characterize the effect of biaxial loading on the ductile to brittle transition temperature. The work centered on a series of tests using large cruciform bend specimens from an experimental A533B test plate denoted as HSST Plate 14 (Heavy Section Steel Technology Plate 14). Recently a series of similar biaxial cruciform tests has been conducted on the steel used for an extensive European Round Robin that investigated the ductile-to-brittle transition master curve and associated T_0 reference temperature. The results of these tests have been used to promote the concept of a "Biaxial Effect" which corresponds to a shift in the shallow crack transition master curve of +20 °C or more when biaxial stresses are present, in comparison with the master curve for uniaxially loaded shallow crack specimens. A comprehensive analysis of the all of the available HSST Plate 14 data and data from two other structural steels was performed to investigate the extent of a biaxial effect on the reference temperature, T_0. The analysis included many additional biaxial cruciform test results on three different materials. The results of all three materials discussed in this paper fail to clearly demonstrate that biaxial loading, imposed through the use of a cruciform specimen geometry, has an effect on the fracture toughness, characterized using a master curve approach and reference temperature T_0. The analysis utilized in this paper assumes that the toughness distribution and temperature dependence of shallow cracked specimens can be modeled by using the master curve approach. This assumption has not been rigorously validated and would benefit from further study. Additional detailed stress analysis of the constraint evolution in the cruciform specimens may better define the precise conditions under which a biaxial effect on the fracture toughness could be realized.

Keywords: Ductile-to-brittle transition; Biaxial loading; Shallow crack; Structural assessment; Master curve; Reference temperature; T_0

1. Background

It has been well established that cleavage fracture toughness in the ductile–brittle transition region of ferritic steels is strongly influenced by specimen geometry, mode of loading, and specimen size. In general any

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deviation of the crack tip field from a high constraint condition characterized by small-scale yielding results in an increase in the measured fracture toughness and a corresponding decrease in the transition temperature. Several parameters such as the T stress, Q and the Weibull stress have been proposed to characterize the degree of crack tip constraint and engineering approaches have been developed to predict the appropriate fracture toughness value to use in structural assessments for applications where low constraint conditions are frequently encountered.

Some general trends about the effect of constraint on fracture toughness in the ductile–brittle transition region have been well-documented through experimental observations.

- There is a size effect on the measured fracture toughness where larger specimens tend to produce lower median values of fracture toughness [1].
- The mode of loading has an influence on the fracture toughness with bending loads generally producing lower median fracture toughness than tensile loads [2].
- The crack size can have a dramatic effect on the median fracture toughness with shallow crack specimens exhibiting significantly higher fracture toughness compared to deeply cracked specimens [3].
- When fracture toughness is characterized by the master curve approach, the shallow crack effect can lead to a decrease in the reference temperature, T_0, of 30 °C or more compared to the reference temperature for a standard deep crack bend specimen [4].

During the 1990s considerable work was conducted at Oak Ridge National Laboratory (ORNL) to characterize the effect of biaxial loading on fracture toughness in the ductile to brittle transition region. It was postulated that a tensile biaxial stress field, like that experienced on the inner wall of a reactor pressure vessel during a pressurized thermal shock transient, could increase the constraint at the crack tip and thereby lead to a lower fracture toughness than would be expected from a shallow crack in the vessel. The major part of this work involved a series of tests of large (100×100 mm cross-section) 4T cruciform bend specimens [5–8] removed from an experimental A533B test plate denoted as HSST Plate 14 (Heavy Section Steel Technology Plate 14).

ORNL observed a "biaxial effect" wherein biaxial loading of the cruciform specimen led to a reduction of the fracture toughness in the lower transition region for the A533B steel. The data supporting this conclusion is shown in Fig. 1 where the fracture toughness is plotted as a function of the biaxiality ratio. The biaxiality

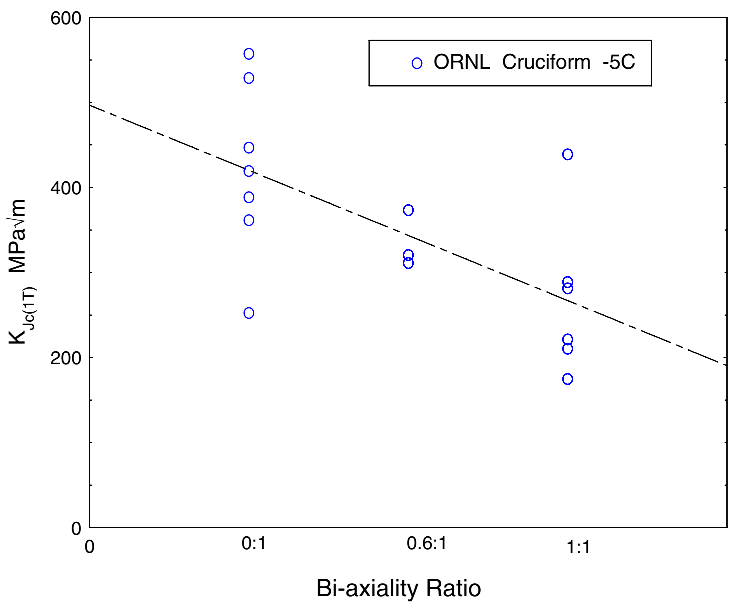

Fig. 1. Biaxial effect as reported by ORNL for A533B steel (HSST Plate 14).