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Fracture toughness variability of structural steel

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Abstract

The weakest-link model of brittle fracture initiation has had substantial success in describing the inherent variability (scatter) in fracture toughness values for steel samples failing by cleavage. The model predicts a Weibull distribution of fracture toughness with slope 4 when plotted in the conventional fashion [E 1921-02. Standard test method for determination of reference temperature, T_0, for ferritic steels in the transition range. Annual Book of ASTM Standards, vol. 3.01. PA, USA: American Society for Testing and Materials; 2002]. However, the Weibull slope for samples of a structural steel tested at CANMET has been found to be 1.86, significantly less than the expected value of 4. Possible reasons for the discrepancy are discussed.

Keywords: Brittle fracture; Cleavage; Steels; Weibull statistics; Weak link

1. Introduction

The weakest-link model for cleavage fracture [1] has proven highly successful in rationalizing the scatter in toughness and leading to an understanding of the effects of temperature and specimen size. It has been applied with particular success to ferritic steels [2], and is the basis of the ASTM standard E 1921 [3]. It has been suggested that the weakest-link model could be applied to any structural configuration to predict applied loads for cleavage fracture. In particular, the model should be applicable to simple test geometries such as Charpy samples. A validated model would make it possible to derive, for example, soundly based correlation between Charpy and fracture toughness data. To explore this idea, a project was launched at MTL/CANMET to test the transferability of model parameters between a variety of sample geometries (Charpy, SE(B), notched tensile). A steel was selected that would have a relatively high transition temperature to facilitate testing, and extensive tests were carried out over a range of temperatures. Some of the results were quite unexpected, and it is the purpose of this paper to present and discuss these results.

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2. Experiments

The steel used for this study was a CSA G40.21 50A (Canadian standard grade) structural steel, supplied as plate of 19 mm thickness in the as-rolled condition. The composition is given in Table 1. The microstructure was polygonal ferrite with slightly banded pearlite (volume fraction 19%) with average ferrite grain size 12 μm (surface) and 14.5 μm (centre). Typical micrographs are shown in Fig. 1; there was little difference between transverse and longitudinal sections. Samples for mechanical testing were taken from the center of a large (12.2 m × 2.4 m) 19 mm thick plate to keep the microstructure as uniform as possible.

Tensile tests were performed on standard cylindrical specimens machined with axes in the longitudinal direction. Fracture toughness tests were performed according to ASTM E 1921 [3]. Three-point-bend specimens of full plate thickness were machined in the L–T orientation (notch perpendicular to the rolling direction). Specimens were pre-cracked on a vibrophore machine to a nominal $a/W = 0.5$. Specimens were kept at the test temperature for 15 min and tested at a deflection rate of 0.5 mm/min with three unloadings in the elastic region for compliance measurement. Physical crack lengths were measured optically after testing using the nine-point-average method. The test temperature of −110 °C was chosen to give a median value in the range of 100 MPa$\sqrt{m}$ for the specimen size tested. It was estimated [3] using $T = T_{28J} + C$ with $C = -23$ °C and $T_{28J} = -90$ °C from Charpy tests. A total of 26 tests were done. J and K values were determined according to the standard [3].

3. Results

Tensile stress–strain curves showed yield-point elongations. Yield and ultimate strengths are shown in Fig. 2.

Results of fracture toughness tests are reported in Table 2, listed in order of increasing K_{Jc}. All results were valid according to E 1921, and no censoring of data was required. Crack-length measurements showed good agreement between optical and unloading compliance methods, the average difference being 0.8% and the maximum 2.1%.

The K_{Jc} results are shown in Weibull format according to E 1921 in Fig. 3, with $K_{min} = 20$ MPa$\sqrt{m}$. In this figure, lines are drawn according to the best fit to the data (dashed) and of slope 4 (solid) expected according to the standard [3]. There is a clear difference between the two; the best-fit line is of slope 1.86.

Extensive fractography was carried out on fractured samples. All samples showed classic cleavage, and a typical example is shown in Fig. 4. Although it was possible in many cases to identify initiation sites by tracing

Table 1
Steel composition

Element	C	Mn	S	P	Si	Cr	Ni	Cu	Mo
Weight %	0.09	1.16	0.008	0.008	0.41	0.55	0.30	0.29	0.01

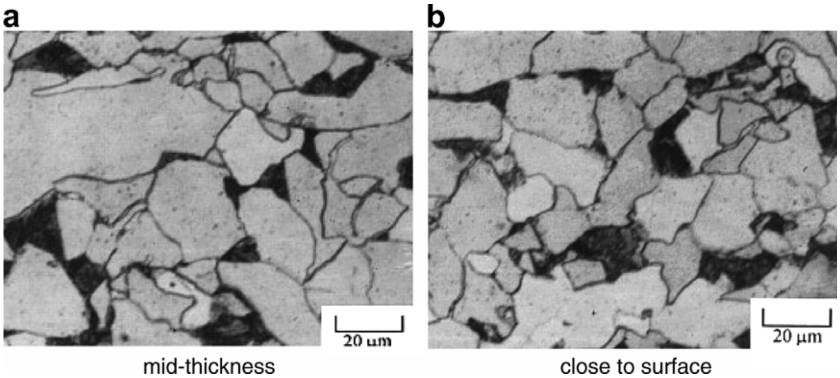

Fig. 1. Optical micrographs (a) mid-thickness; (b) close to surface.