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Prediction of cleavage fracture for a low-alloy steel in the ductile-to-brittle transition temperature range

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Abstract

This paper attempts to predict the cleavage fracture probability for a low-alloy bainitic steel. Fractographic analysis of broken compact tension (CT) and Charpy V-notch (CVN) specimens was performed. An evolution of physical mechanisms of cleavage initiation was found: cracked-particle-induced cleavage was observed at low temperature, whereas a plasticity-induced mechanism was assumed as temperature increases. To take into account these observations, temperature-dependent Weibull parameters were used in the Beremin model. The introduction of a threshold cleavage stress was necessary to account for the skewness of the fracture probability distribution. With these parameters identified on the instrumented Charpy data set, the fracture toughness J_c was successfully predicted in the DBTT range.

Keywords: Ductile-to-brittle transition; Fracture toughness; Instrumented Charpy test; Fractography; Electron backscattering diffraction; Finite element analysis

1. Introduction

The ductile-to-brittle transition in steels remains one of the important issues of materials science, although it has been subjected to extensive research. The integrity assessment of key safety components made of steel, such as reactor pressure vessels, depends on the material's resistance to brittle fracture.

A model relating the fracture toughness of mild and/or low-alloy steel to its yield and fracture stresses through a microstructurally determined characteristic distance has been proposed by Ritchie, Knott and Rice (RKR) [1]. The fracture criterion is given by the condition that the stress must exceed the critical stress over some critical distance ahead of the crack tip. In general, the characteristic distance has to be determined empirically since no simple relationship exists between this distance and microstructural parameters, e.g., grain size [2]. The probability of sampling the particles of critical size to fulfil the Griffith criterion of crack propagation was taken into account by Curry and Knott [3]. Nevertheless, these models, which take into account only the lowering of yield stress with increasing temperature, cannot explain the sharp upturn of fracture toughness in the ductile-to-brittle transition temperature (DBTT) region.

Beremin [4] proposed a model based on weakest link theory (Weibull statistics [5]), which allowed for the prediction of the probability of failure induced by cleavage in the lower shelf, provided that the stress–strain field in the structure is known. Using this statistical local approach to fracture, e.g., Rossoll et al. [6] determined the fracture toughness of a low-alloy steel from instrumented Charpy tests in the lower shelf.

In the DBTT range, the prediction of fracture is complicated, since two fracture mechanisms are in competition. Final cleavage fracture is frequently preceded by ductile tearing. Ductile crack growth preceding the unstable fracture, changes the stress–strain field ahead of the crack tip (stress, strain and constraint). This was treated, for example, in Refs. [6,7], using the model of Gurson, Tvergaard and Needleman (GTN) [8–10], prescribing the material softening linked

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to the nucleation, growth and coalescence of voids. However, even with the stress–strain field modified by the ductile crack growth, the Weibull parameters identified at low temperature lead to a far too pessimistic prediction of cleavage fracture probability in the DBTT range [6]. This was confirmed with different modelling of the mechanical material behaviour, including temperature-dependent viscoplasticity, adiabatic heating and ductile crack growth (e.g., [7,11]).

Different modifications of the Beremin model have been proposed: In his original paper [4], Beremin suggested a strain-correction of the Weibull stress, applied to specimens that had been pre-strained assuming an increase of the cleavage stress with increasing strain. Xia and Shih [12] proposed to correct the Weibull stress with a term depending on the void volume fraction, assuming that both cleavage and ductile damage originate from the same population of carbides. However, these modifications yielded no significant improvement in the prediction of the sharp increase of the fracture toughness in the DBTT range.

The firmly held original assumption of temperature-independent Weibull parameters has also been questioned. Rossoll et al. [6] and Bernauer et al. [7] suggested the necessity of modifying this assumption because their results showed that a single set of Weibull parameters does not allow an adequate description of the ductile-to-brittle transition. In fact, a single mechanism of cleavage is assumed in the Beremin model. However, it was shown that cleavage in pressure vessel steel can be triggered by several mechanisms in the DBTT range [13,14].

In this paper, a fractographic study focussing on the change of the cleavage initiation mechanism in the DBTT region was carried out on A508 Cl.3 steel. In addition to classical scanning electron microscopy, the electron backscattering diffraction (EBSD) technique was used in order to determine the crystallographic orientations of initiation cleavage facets at different temperatures. The main purpose of the study is to extend the validity domain of the probabilistic cleavage fracture model towards DBTT. Some modifications of the Beremin model based on fractographic results are proposed. An estimate of the cleavage fracture probability in the DBTT region as a function of the fracture toughness is performed from instrumented impact Charpy tests data.

2. Experimental details

The material chosen for this study was the French 16MND5 tempered bainitic pressure vessel steel, which is considered as an equivalent to the American standard A508 Cl.3. The chemical composition is given in Table 1. The

Table 1
Chemical composition of 16MND5 (A508 Cl.3) steel (wt.%)

C	S	P	Mn	Si	Ni	Cr	Mo	Cu	Al
0.159	0.008	0.005	1.37	0.24	0.70	0.17	0.50	0.06	0.023

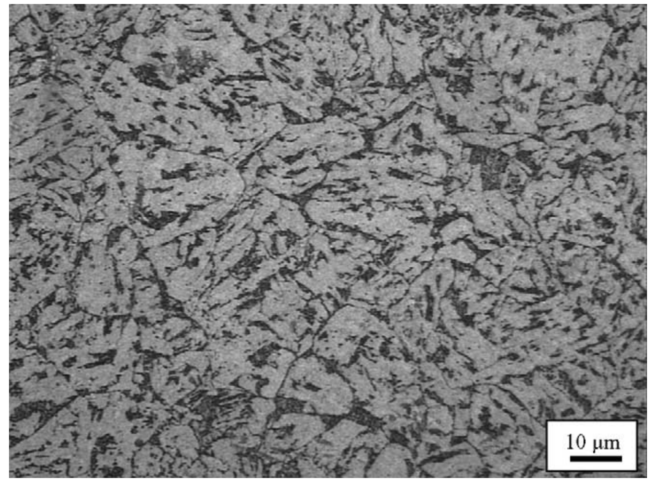

Fig. 1. Microstructure of tempered bainitic A508 Cl.3 steel (5% picric acid etching).

material was subjected to a thermal treatment consisting of two austenitisations at 880 °C/4 h 40 min followed by water quenching, tempering at 640 °C/7 h 30 min, and final stress relief annealing at 610 °C/8 h. The resulting microstructure is shown in Fig. 1.

The standard CT 25 (1 T) and CVN specimens (with a 10 mm × 10 mm section, a central 45° V-notch of 2 mm depth and a 0.25-mm root radius) were taken from a nozzle cut-out of a pressure vessel at a distance 3/4 from the edge of the inner wall. The specimens were sampled in the T–S (long transverse–short transverse) orientation.

The mechanical tests were carried out on a Charpy-instrumented impact pendulum device and an INSTRON hydraulic testing machine at various temperatures ranging from −196 °C to room temperature. The upper shelf impact energy reaches 160 J. The $TK_{28\,J}$ transition temperature is −60 °C (more results are reported in [15]). About 30 CVN specimens were tested at −90, −60 and −30 °C in order to assess the statistical probability of the cleavage fracture. In order to compare the Weibull parameters with those identified on CVN specimens, 24 CT specimens were tested at −90 °C, and 10 at 0 °C. The majority of these experimental results were obtained from previous studies [6,16].

Fractured specimens were carefully examined in the field emission gun scanning electron microscope (SEM) LEO Gemini equipped with a TSL™ EBSD analyser. SEM observations were performed at 25 kV. The micrographs were recorded at normal incidence. For EBSD analysis, the samples were inspected at a tilt angle of 70°. Acquired data were evaluated by the OIM™ software.

3. Fractography

The fracture surfaces of all the specimens examined exhibit transgranular cleavage facets. The cleavage crack path deflection leaves unbroken ligaments fractured by ductile