TWO PARAMETER APPROACHES IN THE PROBABILISTIC FAILURE ASSESSMENT OF FERRITIC STEELS

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ABSTRACT

The present study is concerned with an assessment of constraint effects in the probabilistic assessment of cleavage fracture in ferritic steels. For this purpose, a variety of fracture mechanics specimens with different geometries, overall sizes and crack depths is tested and assessed according to the master curve concept. It is observed that the choice of the specimen has a distinct effect on the reference temperature T_0. The crack front constraint situation of the different specimen types is quantified in terms of different two parameter concepts including the K-T_{stress}, J-Q, J-A_2 and J-h approaches. The inclusion of higher order terms enables an improved description of the mechanical fields in the vicinity of the cleavage origin ahead of the crack front. Their effect on the fracture toughness K_{Jc} for brittle failure within the master curve concept can be included by an appropriate shift of the reference temperature.

1 INTRODUCTION

The brittle failure of ferritic steels by intergranular or transgranular cleavage is a stochastic phenomenon since cleavage failure emanates from weak spots such as grain boundaries and inclusions which are stochastically distributed within the material. For an appropriate assessment accounting for the stochastic nature of the cleavage process, a number of probabilistic fracture models has been developed which can be grouped into local and global approaches.

Local models such as the well known Beremin [2] model and its variants or the more recent model proposed by Faleskog et al. [4] are based on effective field parameters computed from the local mechanical fields in the vicinity of the crack front such as the Weibull stress σ_W or similar quantities. Advantage of the local approaches is that they are based on the mechanical situation in the entire cleavage process zone and thus might include the effects of stress variations within the highly stressed volume in a natural manner.

On the other hand, macroscopic probabilistic models based on a global fracture parameter might be numerically more efficient. The most important macroscopic probabilistic fracture model is the master curve concept according to Wallin [8] which is also incorporated into ASTM Standard E1921 [1]. This approach uses the stress intensity factor K_J computed from the J-integral as a fracture parameter. For the corresponding fracture toughness K_{Jc}, a three parameter Weibull distribution is assumed in order to account for the stochastic nature of cleavage fracture. Temperature effects are included by the assumption that the median fracture toughness can be described by a “master curve” with a similar shape for all types of ferritic steels where a reference temperature T_0 is the only material dependent parameter.

The adoption of the stress intensity factor K or the J-integral as a fracture parameter is motivated by the fact that these parameters govern the first (dominant) term of the expansion of the elastic crack tip field or the elastic plastic HRR field. Thus, they quantify the mechanical fields directly ahead of the crack front in a unique manner. On the other hand, it is experimentally observed that cleavage fracture originates not from the crack front itself but from a point in the ligament ahead of the crack front. At this point, the singular parts of the respective crack tip fields are not necessarily dominant and the higher order terms in the expansion of the mechanical field might have a distinct effect on the stress state at the cleavage origin. To include this effect into the master curve approach, Wallin [9] has suggested a T_{stress} controlled linear shift of the master curve reference temperature.

In the present study, the effect of the intensities T_{stress} and A_2 of the second terms in the Williams expansion and the corresponding expansion of the HRR field on the master curve

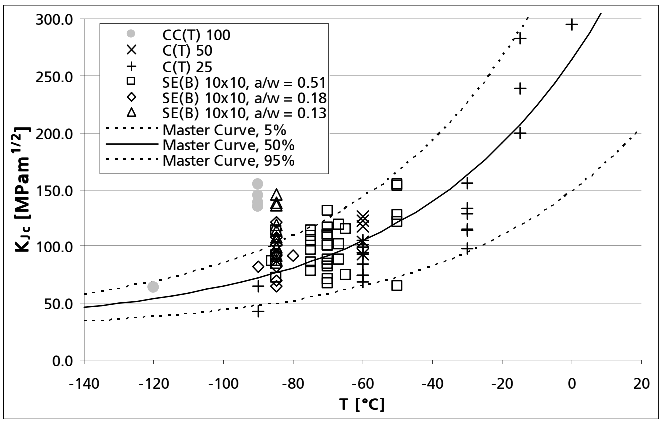

Figure 1: Experimental results.

reference temperature T_0 are investigated. As an alternative, the Q parameter and the stress triaxiality coefficient h are considered to quantify the crack front constraint situation.

2 EXPERIMENTAL INVESTIGATION

For the investigation of the effect of the higher order terms in the expansion of the mechanical fields on the reference temperature T_0 in the master curve concept, an experimental program is performed. The material investigated is a non irradiated German 22NiMoCr3-7 rector pressure vessel steel. The basic mechanical characterization of the material in terms of its elastic constants and its yield curves is performed using round tensile bars tested at different temperatures.

Subsequently, the fracture toughness of the material is determined using a variety of fracture mechanics specimens including Charpy size SE(B) 10x10 specimens with three different crack depths ($a/w \approx 0.51$, $a/w \approx 0.18$ and $a/w \approx 0.13$), C(T) specimens with different sizes (C(T) 25 and C(T) 50, both with $a/w \approx 0.51$) as well as center cracked CC(T) 100 specimens with $2a/w \approx 0.51$. All specimens are tested displacement controlled under quasi static loading conditions. The test temperatures are varied over the range from $T = -120°C$ to $T = 0°C$. The fracture toughness is determined according to ASTM Standard E1921 [1]. For the shallow cracked SE(B) 10x10 specimens, the plastic correction factor in the approximate formulae given in ASTM E1921 [1] is adjusted such that the obtained approximation for the average J-integral matches with the value obtained from a finite element analysis of the test (see Section 3) using its definition as a path independent integral around the crack front. The fracture toughness for the CC(T) specimens is obtained in a similar manner. All experimental results are corrected to a crack front length of $B = 25$ mm as required in ASTM E1921 [1].

The experimental results are presented in Fig 1. The master curve reference temperature obtained from the high constraint specimen permitted in ASTM E1921 [1] is determined to be $T_0 = -63.7°C$. It is observed that although the 5% and 95% curves cover most of the experimental results, a significant amount of data points is not covered. Especially, fracture toughness values K_{Jc} obtained from the CC(T) 100 specimens tested at $T = -90°C$ as well as the fracture toughness values obtained from the shallow crack SE(B) 10x10 specimens with $a/w \approx 0.13$ exceed the prediction of a failure probability of $P_f = 95\%$ as predicted by the master curve concept.

3 TWO PARAMETER CONCEPTS

A possible explanation for the outlying data points in Fig. 1, especially in case of the CC(T) 100 specimens and the shallow crack SE(B) 10x10 specimens, is the different stress state in the vicinity of the crack front of these specimen types compared to the deep crack bend bars and the compact tension specimens. In order to quantify this effect, a detailed three dimensional elastic plastic finite element analysis of all tests is performed. From the results of the simulation, the secondary fracture parameters for a variety of two parameter concepts are determined.

The most important two parameter concept is the elastic K-T_{stress} concept (see e.g. Du and Hancock [3]), where the asymptotic crack tip stress field is assumed to be given by

$$\sigma_{ij}(r,\varphi) = \frac{K}{\sqrt{2\pi}} r^{-\frac{1}{2}} f_{ij}(\varphi) + T\, r^{0}\, g_{ij}(\varphi) \tag{1}$$

where the fracture toughness K together with the T_{stress} form the two parameter fracture toughness locus. Advantage of this concept compared to the corresponding one parameter concept in terms of K only is that the area of dominance for the asymptotic crack tip field is extended. Within the present study, T_{stress} at fracture is determined from an elastic finite element analysis with the same external load level as the critical load level measured in the experiment.

The elastic plastic equivalent to the elastic K-T_{stress} concept is the J-A_2 concept (see e.g. Yang et al. [10]). Within this concept, the expansion of the HRR field is extended up to the third term so that the plane strain crack front stress field is approximated by

$$\frac{\sigma_{ij}}{\sigma_0} = A_1\left(\left(\frac{r}{l}\right)^{s} f_{ij}(\varphi) + A_2\left(\frac{r}{l}\right)^{s_2} g_{ij}(\varphi) + \left(A_2\right)^2\left(\frac{r}{l}\right)^{s_3} h_{ij}(\varphi)\right) \tag{2}$$

where A_1 is related to the J-integral and s_1 is the HRR singularity exponent. The secondary fracture parameter A_2 is determined by a comparison of the elastic plastic stress fields obtained in the ligament with the fields predicted by Eq. (2) using the method presented by Nikishkov [6].

Whereas both the K-T_{stress} and the J-A_2 concepts use rigorous mathematical formulations, the J-Q concept (see e.g. O'Dowd [7]) simply employs the difference

$$Q = \frac{\sigma_{\varphi\varphi} - \sigma_{\varphi\varphi}^{ref}}{\sigma_0} \tag{3}$$

of the crack front stress field $\sigma_{\varphi\varphi}$ obtained in a finite element simulation and a reference stress field $\sigma_{\varphi\varphi}^{\mathrm{ref}}$. Throughout the present study, the stress differences are evaluated in the ligament at a distance of $r = 2J/\sigma_0$ ahead of the crack front. The reference stress field is a plane strain field for the problem of a semi infinite crack in an infinite medium with the same material properties as for the material used in the experiments. The reference stress field is determined numerically in a boundary layer analysis under prescribed displacements according to the critical J-integral obtained in the corresponding fracture experiment. Advantage of the J-Q concept is that it can address both, the in-plane constraint due to a cleavage origin at a finite distance ahead of the crack tip as well as the effect of constrained transverse deformation along the crack front. Disadvantage of this concept is its lack of a rigorous mathematical foundation.

Alternatively to the concepts mentioned previously, the stress triaxiality coefficient

$$h = \frac{\sigma_{kk}}{3\sigma_e} \tag{4}$$

is often employed to quantify the deviation of the crack front stress field for the considered crack two or three dimensional crack configuration from a corresponding plane strain reference stress field governed by the stress intensity factor K or the J-integral. The stress triaxiality coefficient is evaluated at the same position as used in the determination of Q.

4 RESULTS

The different two parameter fracture concepts introduced in Section 3 are now applied to the experimental database from Section 2. In Fig 2, the secondary fracture parameters T_{stress}, A_2, Q and h for all fracture mechanics specimens tested are presented as a function of the respective test temperature T. In all cases, a distinct separation of the different specimen geometries is observed, where the C(T) 25 and C(T) 50 specimens feature the largest values of all secondary fracture parameters followed by the deep cracked SE(B) 10x10 specimens. The lowest values of T_{stress}, A_2,

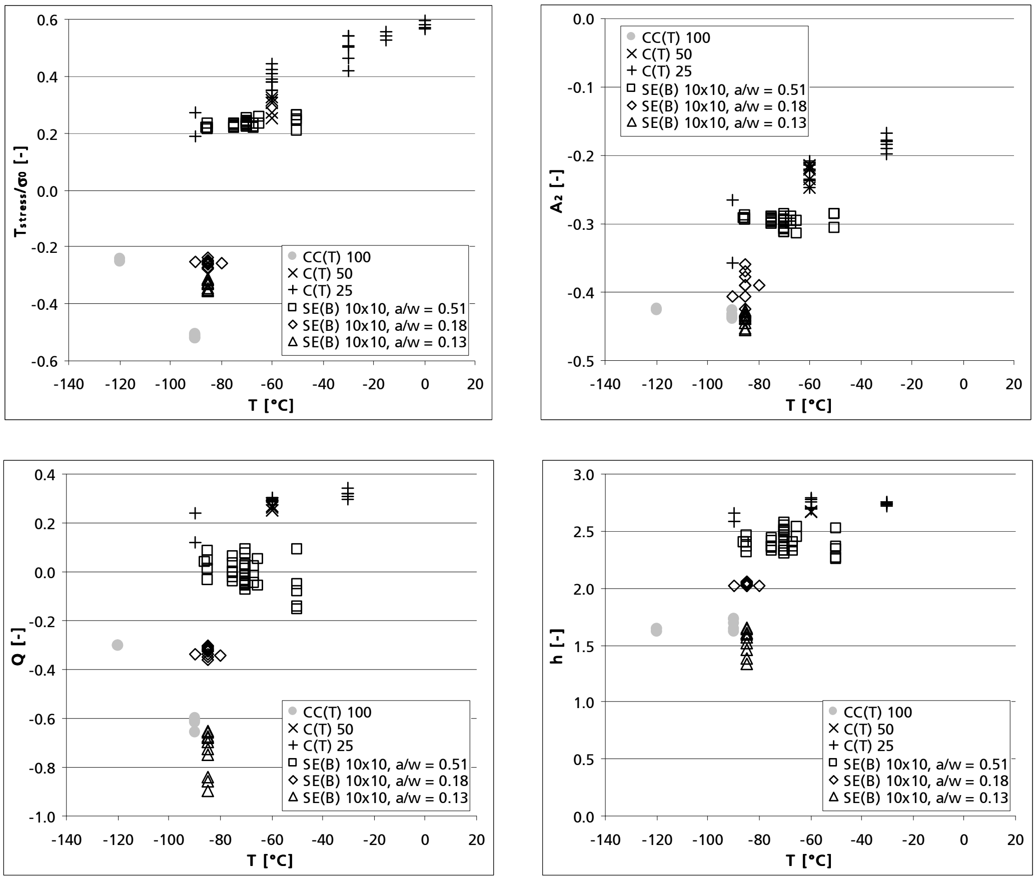

Figure 2: Secondary fracture parameter in dependence on temperature.

Q and h are obtained with the CC(T) 100 and the shallow crack SE(B) 10x10 specimens respectively. Thus, the secondary fracture parameters can be used to quantify the differences in the crack front fields corresponding to the different specimen geometries at equivalent load levels. In case of the C(T) and CC(T) specimens, a distinct temperature dependence of T_{stress} is observed where the level increases with increasing test temperature. Since T_{stress} is proportional to K, this effect is actually a load level effect due to the increasing load levels reached in tests at increasing temperatures. Similar effects are observed in terms of the Q parameter. As in terms of the fracture toughness K_{Jc}, no difference between the results based on the C(T) 25 specimens and the results based on the C(T) 50 specimens is observed.

In order to investigate the effect of the secondary fracture parameters T_{stress}, A_2, Q and h on the master curve reference temperature T_0, an individual reference temperature is computed for all tests performed. In Fig 3, the results are presented, plotted versus the secondary fracture parameters. For all four secondary fracture parameters, a similar effect is observed where the master curve reference temperature T_0 decreases with decreasing values of the secondary fracture parameter and thus with decreasing constraint level of the respective specimen geometry. Due to the stochastic nature of cleavage fracture, a distinct scatter of the results is obtained. Nevertheless, the trend is clearly visible in all cases. For $T_{\mathrm{stress}} < 0$, Wallin [9] has suggested a linear function $T_0 = 0.1°\mathrm{C}\ T_{\mathrm{stress}}/\mathrm{MPa}$ to describe the dependence of the master curve reference temperature T_0 on T_{stress}. It is observed in Fig 3 that this approximation is close to a linear regression of the results

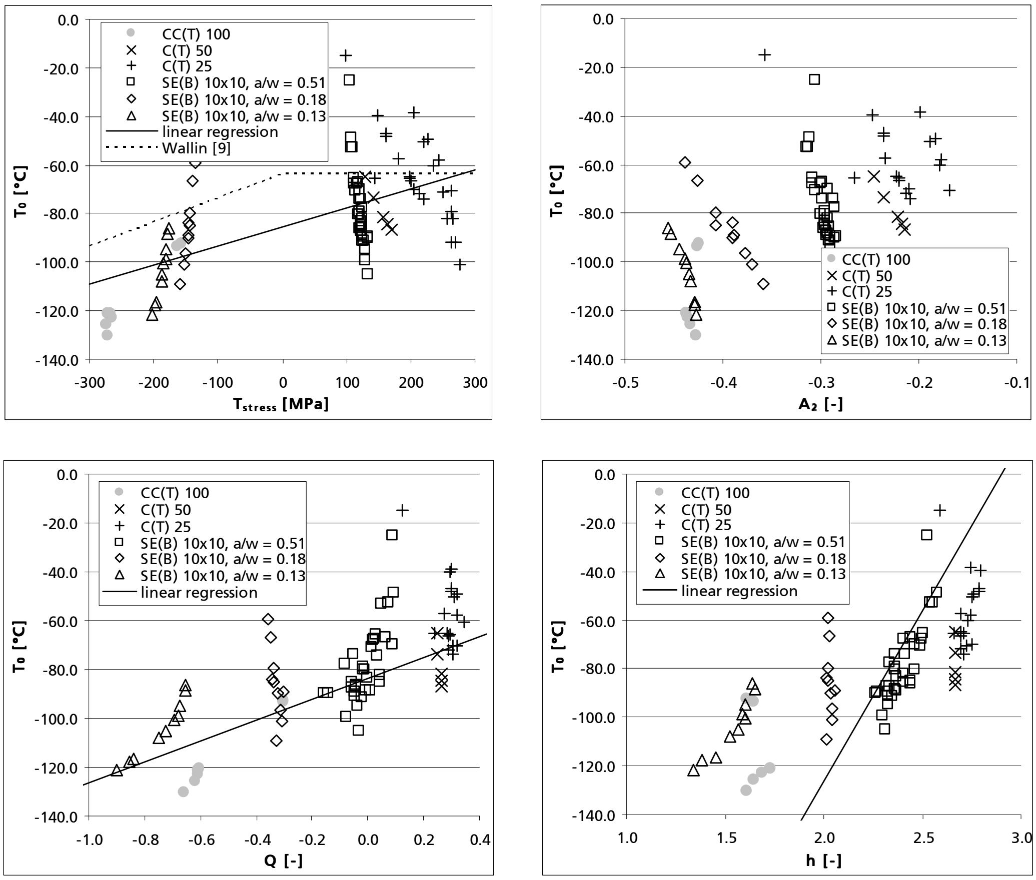

Figure 3: Constraint effect on master curve reference temperature T_0.

although the slope of the linear regression function is less steep than the slope of Wallin's [9] approximation since the experimental data in the positive T_{stress} range is found mostly below this function. A similar regression analysis by means of a least square minimization can be performed for the other two parameter concepts. In case of A_2, the scatter of the results is too large for a proper linear regression analysis. Therefore, no curve is presented in this case.

The effect of the secondary fracture parameters on the reference temperature suggests a constraint correction of the test data where the actual test temperature T is replaced by a constraint corrected temperature $T^* = T - (\partial T_0/\partial X)\, X$ where X can be any of the secondary fracture parameters. In Fig 4, the temperatures of all experimental data points have been adapted in this sense, using Q as a constraint parameter. The master curve reference temperature is determined as T_0 = -65.8°C. In the Q-corrected representation, nearly all experimental data points are found in between the 5% and 95% fractiles. The only exceptions are six points which are found rather close to this range. Since 10% of the total data has to be expected below or beyond the 5% and 95% fractiles, the correction approach can be regarded as clearly justified by the test data.

5 CONCLUSION

The present study is concerned with the effect of the secondary fracture parameters in different two parameter fracture concepts on the master curve reference temperature. It is observed that

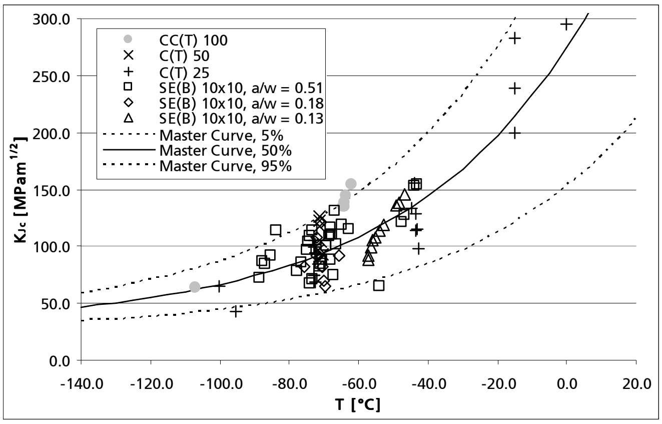

Figure 4: *Q*-corrected experimental results.

differences in the fracture toughness obtained from fracture mechanics specimens with different geometries can be explained in terms of the secondary fracture parameters. To include the effect into the master curve concept, a constraint correction shift of the actual test or service temperatures is proposed. Nevertheless, a deeper investigation using additional specimen geometries and sizes is required for a further verification of this approach in engineering application.

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