Comparison of Global and Local Approaches to Predicting Warm Pre-stress effect on Cleavage Fracture of Ferritic steels

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ABSTRACT

Potentially both global and local approaches may be used to predicting the effect of loading history on cleavage fracture toughness distribution of ferritic steels. In this paper the dramatic increase in the apparent lower shelf fracture toughness of A533B steel following warm pre-stressing (WPS) has been predicted using these approaches. Extensive experimental evidence suggesting significant enhancement in fracture toughness of ferritic steels within the lower shelf temperatures following WPS are used to verify and compare the applicability and the extent of validity of the models. The global approach is based on the distribution of toughness data described by Wallin statistical model in conjunction with the Chell model for WPS effect. The local approach on the other hand is a Beremin type model that uses the Weibull stress to predict the WPS effect. Weibull stresses would essentially reflect the WPS effect on redistribution of stress-state around the crack tip. Predictions for apparent toughness using the two approaches are discussed in the light of the suggestion that residual stresses are the main cause of the enhancement, at least for the material and geometry used in this study.

1. INTRODUCTION

Cost effectiveness and safety are among the most crucial factors in design, fabrication and application of mechanical components. One especially important example is the reliability and structural integrity assessment of ferritic steel components used in pressure vessel industry. The fracture resistance of ferritic structures containing cracks dramatically decreases below a certain transition temperature. There exists extensive experimental evidence [1,2] that pre-stressing at upper shelf temperatures results in enhancement in cleavage fracture toughness of pressure vessel steels when subsequently loaded to fracture at lower shelf temperatures (known as the warm pre-stress effect). Figure 1 provides a schematic illustration of temperature dependence of fracture behaviour of ferritic steels and the effect of WPS on toughness. Quantification of WPS effect has received great interest in light of its significance in the integrity assessment of ferritic pressure vessel steels.

Experimental observations on the other hand indicate considerable uncertainty (wide scatter) in the cleavage fracture toughness of ferritic steels both before and after warm pre-stressing [3,4]. Statistical models, based on weakest link theory, are usually used to describe the scatter in fracture data.

Theoretical models have been used to predict the WPS effect using near crack tip stress and strain fields. For example the model developed by Chell [5], combined with a local fracture criterion developed by Ritchie, Knott and Rice (RKR) [6], was used by Fowler et al [4] to predict the WPS effect on cleavage fracture. To explore the scatter in fracture data, they used a three-parameter expression proposed by Wallin [7]. Fowler et al [4] demonstrated that the failure probability following WPS can be given by:

$$P_f\left[K_f\right] = 1 - \exp\left[-\frac{B}{B_0}\left(\frac{K_{Ic} - K_{\min f}}{K_{0f} - K_{\min f}}\right)^{\beta}\right] \tag{1}$$

where K_{IC} is the as-received fracture toughness, and the distribution parameters K_{minf} and K_{0f} were calibrated for the as-received (AR) conditions and then modified, using the Chell model [5,8] to predict the WPS effect. The shape parameter β was chosen by Fowler et al [4] as a constant equal to 4. The general expression for the theoretical models for WPS effect is given by:

$$K_f = g\left(K_{Ic}, K_1, \sigma_{Y1}, \sigma_{Y2}\right) \tag{2}$$

where σ_{Y1} and σ_{Y2} are the yield stresses at pre-load and fracture temperatures respectively, and K_1 refers to the pre-load level. Fracture toughness following WPS, K_f, is related to the as-received fracture toughness, K_{IC}, through Eq. 2.

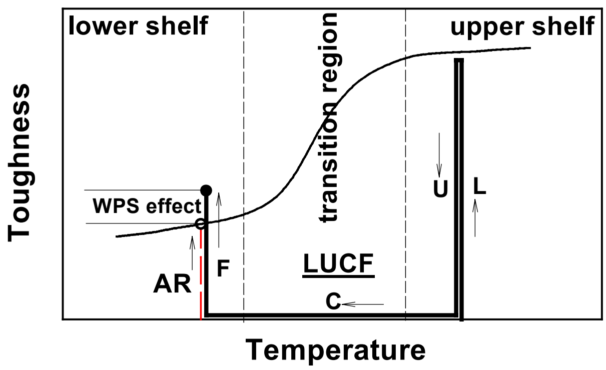

Fig. 1. Schematic description of WPS effect on cleavage fracture toughness
AR = as-received, LUCF = Load - Unload - Cool and Fracture

This global approach to predicting cleavage fracture was also supported by finite element simulations. Fowler et al [9] showed that the fracture following WPS was predominantly controlled by the as-received toughness together with the residual stresses generated by WPS. They used the maximum principal stress distributions ahead of the crack tip for the AR condition and following WPS and predicted fracture by matching the stresses ahead of the crack tip. Using this stress matching technique they obtained results consistent with those predicted using the combined Chell-Wallin approach.

An alternative approach to predicting cleavage fracture is to use a local approach that adopts a stress based Weibull distribution and the assumptions of the weakest link theory. In the model developed by Beremin [10,11], the Weibull probability parameters, fitted to fracture test results from round notched bar (RNB) specimens, were used to predict the scatter in fracture data for the pre-cracked specimens. In their round robin studies on micro-mechanical models, the European Structural Integrity Society (ESIS) suggest using the parameters fitted to the RNB test results to predict cleavage fracture in pre-cracked C(T) specimens [12]. The failure probability is given by:

$$P_f\left[\sigma_f\right]=1-\exp\left[-\left(\frac{\sigma_w}{\sigma_u}\right)^m\right] \tag{3}$$

where the Weibull stress, σ_w, is representative of failure conditions and is determined from the following integral.

$$\sigma_w=\left[\frac{1}{V_0}\int_{V_p}\sigma_1^m dV\right]^{1/m} \tag{4}$$

The reference stress, σ_u, is a characteristic stress corresponding to a failure probability of 63.2%, and is referred to as the mean reference stress. The Weibull exponent, m, characterises the scatter bond of fracture data. The integration is performed over the plastic zone, V_p, [13] that is a pre-requirement for the activation of the weakest link and V_0 is a reference volume. Equation 3 is further modified by introducing σ_{min}, a threshold stress, as:

$$P_f\left[\sigma_f\right]=1-\exp\left[-\left(\frac{\sigma_w-\sigma_{\min}}{\sigma_u-\sigma_{\min}}\right)^m\right] \tag{5}$$

where for $\sigma_w < \sigma_{min}$, failure is assumed impossible. The Weibull parameters are determined from experimental results. It should be noted that in both the Beremin [10,11] and the ESIS [12] studies the analyses were conducted assuming no threshold stress ($\sigma_{min}=0$).

The main objective of the present work is to compare the predictions of the enhancement in "plane strain" cleavage fracture toughness of A533B steel obtained using both the global and the local approaches to cleavage fracture. A very low temperature of –170°C is used in all analyses to ensure that fracture occurs by cleavage. First the stress distributions normal to the crack plane and ahead of the crack are explored for the AR and WPS conditions using the results of finite element simulations. A load – unload – cool – fracture, LUCF, loading cycle is used to simulate the fracture following WPS. Using the results of FE analyses the global and local approaches are then used to predict the WPS effect. Finally the predictions are contrasted and the strength and weaknesses of various techniques are highlighted.

2. STRESS DISTRIBUTIONS

All models used here are directly or indirectly using a stress distribution ahead of the crack tip. The maximum principal stress (or the stress normal to the crack plane), the residual stress field due to WPS and the redistributed stresses on reloading to fracture all contribute to determining the condition of fracture. It is therefore essential to study the stress distribution throughout the AR and LUCF loading cycles.

The stress data were obtained from finite element simulations of these loading cycles using the specified material and geometry as used in the reference experimental studies. A summary of distribution of normal stresses from FE analysis for A533B steel is shown in Fig. 2.

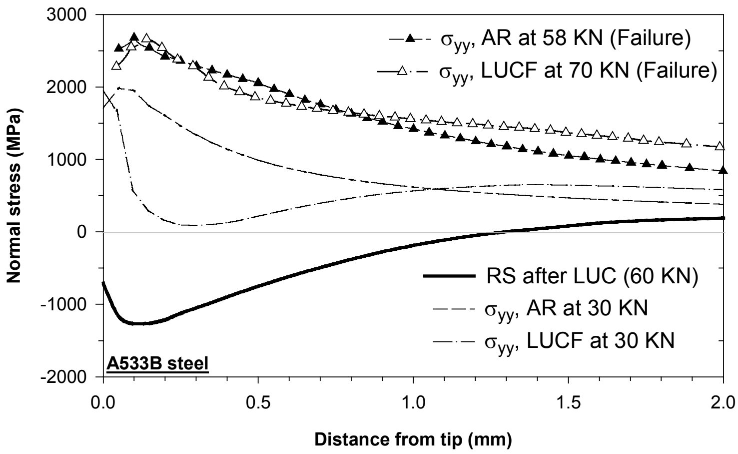

Fig. 2. Normal stress distribution for the as-received and warm pre-stressed conditions for A533B steel at -170°C

3. PREDICTION OF WPS EFFECT

Two global approaches, the theoretical Wallin-Chell approach and the stress matching technique [3] using the results of finite element analysis for the stress distributions, were examined to predict the cleavage fracture toughness distribution following WPS. In addition the potential of a local approach proposed earlier by the authors [13] has been also assessed. These are explained in further detail in this section.

3.1. The Global Approaches

The Chell [5] model was used to predict the improvement in toughness following WPS for A533B steel at –170C. The predicted improvement in toughness is shown in the curve in Fig. 3. The fracture toughness following WPS, K_f, depends on the pre-load level, K_1, based on Eq. 2, written in terms of yield stresses at the pre-load and fracture temperatures. The analysis is based for the case

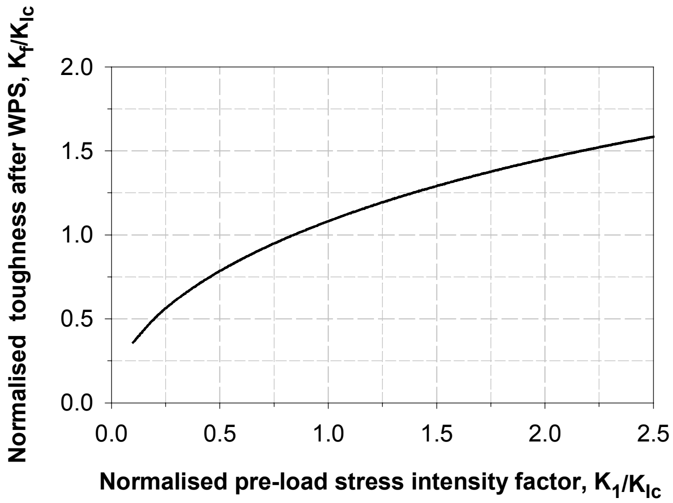

Fig. 3. Enhancement in toughness for A533B steel warm pre-stress at 20°C, fractured at -170°C

where the plastic zone representing reloading to fracture at low temperature is contained in both the pre-load plastic zone and the plastic zone on unloading. The curve was used to modify the as-received calibrated parameters by simply replacing K_1 by K_{min} or K_0 and correcting based on the ratio obtained from the K_f / K_{IC} axis (i.e. $K_{f\text{-}min}$ and $K_{f\text{-}0}$). The predictions based on Wallin-Chell model are shown in Fig. 4.

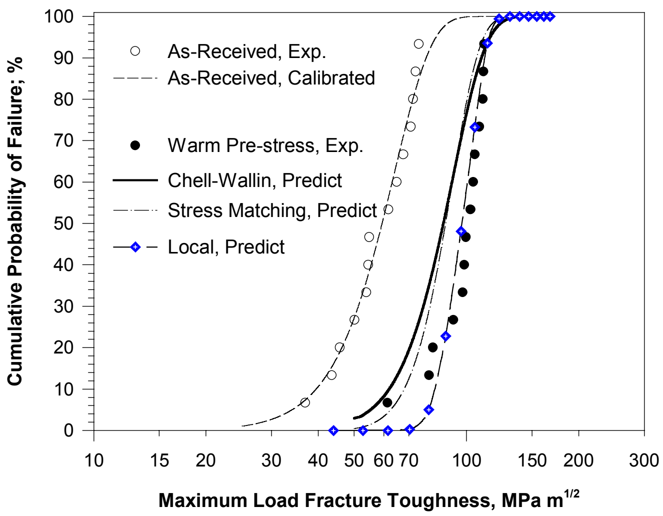

Fig. 4. Comparison of predictions of probability distribution following WPS based on "Global" and "Local" approaches for A533B steel at -170°C

An alternative global approach is based on matching the corresponding stress fields for the AR and WPS conditions. This approach uses the stress results of FE analysis for the AR, as well as the WPS conditions and predicts the condition of failure. The load cases used to provide input to the FE analyses following unloading were developed from the experimental studies of Smith and Garwood [2] and Fowler [3]. Finite element simulations for these experiments were carried out for A533B steel at –170°C. Here attention is confined to the SEN(B) specimen with *a/W=0.5* and *(W-a)=50mm*. Finite element simulations of fracture were performed for two experimental load histories, the as-received (AR) and load – unload – cool and fracture (LUCF) conditions.

The stress distributions for the AR and LUCF simulations are shown in Fig. 2. It was found that the stress distribution after WPS matched the as-received case for distances as far as possible ahead of the crack tip, corresponded to a fracture load that was close to the experimental conditions. These results suggest that when complete stress matching is made for the maximum principal stresses between the AR and WPS conditions, the resulting fracture load following WPS is well defined. Predictions of the critical stress intensity factor at maximum load were made using the load achieved at the increment where the stress distributions were in best agreement with the stress field for the as-received toughness.

The results of these FE predictions are summarised in Fig. 4. The results correspond to the fracture behaviour of A533B steel at –170°C. The FE predictions based on stress matching generally agree with the Chell model predictions at low levels of pre-load. At higher pre-loads in the LUCF cycle the FE analysis provides a slightly larger increase in maximum load toughness compared with the analytical model.

3.2. Local Approaches

Beremin type model, that included a threshold stress, was used to predict failure probability following WPS. The adopted model used the same Weibull parameters calibrated based on the as-received fracture data to predict the influence of WPS. This model assumed that the maximum principal stresses integrated over the elements within the crack tip plastic zone, characterise the conditions of failure. The effect of WPS on subsequent fracture is therefore automatically considered. The application of this approach was later extended to predict the probability of failure for the situations where an initial residual stress field was present prior to loading to fracture, regardless of the source of the residual stress [14]. Results of finite element analyses were then used to calculate the Weibull stress and hence the failure probability. A user routine was developed based on Eq. 4 and Eq. 5. The routine extracted incremental stress data from FE analysis, performed using ABAQUS and subsequently calculated the corresponding values of probability of failure. The model took into account only the maximum principal stress at the integration points that had undergone plastic deformation (or plastically reactivated after the pre-loading step). Predictions obtained from application of this approach to A533B steel high constraint 50mm thick SEN(B) and 25mm thick C(T) specimens are presented in Fig. 4.

4. DISSUSSION AND CONCLUDING REMARKS

The Two main approaches examined in this study to predict the effect of WPS on cleavage fracture toughness are based on the stress state, either locally around the tip area or the far field stress away from the tip. The experimental data used to assess these approaches were taken from previous studies [2] using highly constrained fracture test specimens.

The local approach used the maximum principal stresses within the plastic zone where the effect of WPS is accounted for through the redistributed stresses with the applied stresses interacting with the crack tip residual stress field. The method did not take into account the stresses in the material that remained elastic throughout the fracture event. The stress matching method on the other hand matched the stresses for large distances from the crack tip. The distance over which the stress matching takes place increased with increasing pre-load. According to this approach the WPS effect is not only dependent on the magnitude of residual stress but on the extent of the interaction of the applied and residual stresses some distance ahead of the crack tip. Finally the Chell-Wallin model does not directly include stresses in the assessment of failure conditions. It simply uses the pre-load level together with the material's yield strength at the pre-load and fracture temperatures to predict the WPS effect. Despite the differences between all three models, each provide reasonable predictions for the test configuration examined here. This suggests that fracture is dominantly controlled by the stress state.

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