COMBINED EFFECT OF RESIDUAL STRESS AND LOADING HISTORY ON BRITTLE FRACTURE

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ABSTRACT
The aim of this paper is to examine the influence of residual stress (RS) and loading history on the subsequent low-temperature cleavage fracture resistance of ferritic steel structures such as pressure vessels. Three dimensional finite element analyses of compact tension, C(T), specimen are carried out for various RS fields (i.e. local, global, combined. A Beremin type local approach [1] has been shown to predict the apparent fracture toughness for various situations and the predictions are evaluated using the data obtained from a test programme and through comparison with the as-received fracture data. The dominating role of warm pre-stressing in enhancement of cleavage fracture toughness depending on the significance of global RS field is also discussed. Finally the strengths and weaknesses of the adopted predictive model are discussed and suggestions to further generalisation of the model are provided.

Keywords: residual stress, WPS, cleavage fracture, local approach, FE, failure probability

1. INTRODUCTION

There exists significant evidence in the literature, supported by extensive experimental data, that the presence of residual stresses in cracked components affects their subsequent fracture response [2-4]. Welded structures, where the residual stresses are not relaxed, exhibit lower levels of load carrying capacity [5] whereas warm pre-stressing (WPS) for example enhances the subsequent cleavage fracture toughness [6]. Residual stresses are widely believed to be responsible for these effects [7,8]. However, “global” residual stress fields such as those in welded components and “local” residual stresses like those resulted from WPS in the crack tip region in cleavage fracture are studied separately. Less attention has been paid to the interactions of residual stresses originating from various loading history and the combined effect of RS and loading history on cleavage fracture [9].

To study the interaction between various residual stress states and the applied loading we use a “weakest link” theory to predict onset of cleavage fracture. The basic assumptions of “weakest link” theory are considered valid for the materials that fail by cleavage and thus Weibull distribution functions [10] are extensively used to describe the scatter in cleavage fracture toughness of such materials. Ferritic steels for example fracture by cleavage at lower shelf temperatures and are modelled using these assumptions [11]. A range of “modified” Beremin models [12, 13] are used to predict the scatter in cleavage fracture toughness where failure probability is given by:

$$P_f\left[\sigma_f\right] = 1 - \exp\left[-\left(\frac{\sigma_w}{\sigma_u}\right)^m\right]; \qquad \sigma_w = \left[\frac{1}{V_0}\int_{V_p} \sigma_1^m dV\right]^{1/m} \tag{1}$$

where σ_u, V_0 and m are reference stress, reference volume and the Weibull exponent respectively. The maximum principal stress, σ_I integrated over the plastic volume, V_p, determines the Weibull stress, σ_w. One modification to the Beremin model is to introduce a threshold minimum stress, σ_{min} where:

$$P_f\left[\sigma_f\right] = 1 - \exp\left[-\left(\frac{\sigma_w - \sigma_{\min}}{\sigma_u - \sigma_{\min}}\right)^m\right] \tag{2}$$

In using these approaches it is assumed that only the weak links within the plastic region at the vicinity of the crack tip can initiate failure and the maximum principal stress is usually used to estimate the Weibull stresses, a characteristic of failure conditions. Due to the importance and sensitivity of distribution to the Weibull parameters, calibrating these parameters has been studied in detail. For example Gao and co-workers [14] suggested that an estimation of the parameters would be attained from two data sets corresponding to two different levels of constraint. Other research work includes Milella and Bonora [15], Ruggieri et al [16] and Kozak et al [17, 18].

The local approach to cleavage fracture is also used to predict fracture toughness distribution following warm pre-stressing. Stockl et al [19] proposed that quantifying WPS effect using both the maximum principal stress and the equivalent plastic strain predicted higher, more realistic, fracture load compared with the simple Beremin model. Kordisch et al [20] suggested that a modified Beremin model with temperature dependent parameters can be used to quantify the WPS effect. Recently Hadidi-moud et al [1] used the modified Beremin model, equation (2) to predict failure probability for the as-received and WPS conditions using the same Weibull parameters. In present work, the use of this model is extended to more general situations for the interaction of residual stresses and a-plied loading.

This work attempts to present a unified local approach to predict cleavage fracture toughness and the corresponding failure probability, regardless of presence or lack of residual stress and whether the source of residual stress is local, global or combined. First we present the fracture data obtained in previous and current experimental programme that is used to assess the model predictions. Finite element simulations of C(T) specimens are used to predict and compare the distribution of residual stresses with various sources together with redistribution of the stress-state in presence of residual stress. The local approach [1] to cleavage fracture is applied to the cases where global and combined stress fields influence the cleavage fracture response. Results of application of the local approach are evaluated using experimental data. Finally possible modifications to further generalisation of the model are discussed.

2. EXPERIMENTAL FRACTURE TESTS

2.1. Description of experiments

To fully assess the model predictions, experimental data were generated for residual stress fields as well as the as-received condition. In a previous test programme [21] A533B steel 50mm thick SEN(B) and 25mm thick C(T) specimens were tested in both the as-received and after warm pre-stressing (WPS) conditions. For WPS, pre-loading was performed at room temperature and the fracture test temperature was –170°C. warm pre-stressing introduce residual stresses local to the crack tip. these tests are termed load, unload, cool and fracture, LUCF, conditions. The results of those experiments are used in assessment of model predictions described later in section 4. A global residual stress field was introduced by applying local compression (or coining) on both sides of A508 steel 25mm thick C(T) specimen using 25mm diameter hardened EN24 steel punches. The compressive load was adjusted such that the remaining indentation was measured around 2% of the specimen thickness. Fracture tests were carried out for the as-received (AR) specimens, the warm pre-stressed and the coined specimens. These specimens are termed punch, unload, cool and fracture, PUCF, conditions. For all fracture tests initial mechanical loading of specimens (i.e. mode-I pre-stressing and or side compressing) were performed at room temperature and the specimens were fractured at –170°C. All specimens failed by cleavage.

2.2 Details of A508 steel experiments

Twenty four C(T) specimens obtained from a block of A508 steel were tested - as three sets of eight specimens each - under three load cycles, the as-received, PUCF and LUCF. Electro-discharge machining (EDM) technique was used to introduce cracks into the specimens. Using a 0.1mm diameter wire, the resulting notch width was approximately 0.16mm. The punching tools were hardened before being used for coining. Heating to 600ºC followed by cooling in water increased the hardness by around 200 Rockwell-C. This significantly decreased surface deformation of the punching tools during the coining process. An LVDT was directly attached to the punching tools to accurately measure the displacement during punching. Local compression process was performed on eight specimens in the room temperature. The size and positioning of the punching tool was decided based on the results of earlier parametric studies [22] to obtain the greatest extent of a tensile residual stress field ahead of the crack tip. A compressive load between 335-360kN left approximately 2% indentation after unloading. The pre-loading level for the LUCF tests was equivalent 108MPa√m.

2.3 Summary of results

The experimental fracture toughness test results for all cases were distributed against failure probability P_f using equation (3) [24].

$$P_f = \frac{i - 0.5}{N} \tag{3}$$

where N is the total number of specimens, and i the order number.

Probability of failure as a function of stress intensity factor, determined at failure loads, are shown in figures 1 and 2. Figure 1 shows the experimental results for A533B in the as-received state and after WPS. There was a considerable improvement in toughness after WPS compared to the as-received condition. Presented in figure 2 are the experimental results for A508 for three conditions, PUCF, AR and LUCF. Again subjecting the steel to LUCF cycles considerably improves the fracture toughness. In contrast for the PUCF cycle the toughness was reduced.

3. FINITE ELEMENT SIMULATIONS

3.1. Description of FE models

Finite element models of 25mm thick A508 and A533B steel C(T) specimens were created using ABAQUS/CAE [23]. Due to symmetry only one quarter of the specimens were modelled so that the smallest element size in the planes normal to the crack plane was no more than 0.05mm in each direction. The models had 16 layers of elements in their thickness direction. Also included in the FE models were the punching tool and the loading pin. For the analyses where no coining was involved, the punching tools were moved away from the specimen surface in an initial analysis step.

3.2. Results of FE analyses

To understand the importance and the role of the residual stress (RS) field on cleavage fracture it is important to study their distribution prior to final loading to fracture. It is specially important to note how residual stresses are distributed at the crack tip region within the plastic zone as the initiation of plasticity is the additional mechanism that is assumed as an essential ingredient to activate a potential "weak link". First the distribution of the RS field along the crack line, normal to the crack plane, and through the thickness of the specimen were determined for each analysis. Stress distributions on reloading to fracture were also compared for typical fracture loads corresponding to the LUCF and PUCF load histories.

A local residual stress field was introduced by warm pre-stressing the C(T) specimen at room temperature. A typical RS field for the normal stress, s22 is shown in figure 3 a and b for A533B and A508 respectively. For both materials the WPS cycle at room temperature introduced compressive residual stresses directly ahead of the crack tip up to about 1.0 mm. An initial FE analysis provided estimations of the required pre-load levels that resulted in sufficiently high level of residual stresses after unloading. Both pre-loading and reloading were performed under displacement control. The pre-load applied in the experiments, as well as the FE analyses, was 60KN and 62KN for A533B and

A508 steel C(T) specimens respectively. Also shown in figure 3 are the distributions of the stresses on reloading at low temperature.

Introduction of a global RS field into the C(T) specimen was achieved by coining, i.e. applying local compression on both sides of the specimens. The compressive load was sufficiently high to result in certain level of indentation. On releasing the specimen from compression a residual stress field remained throughout the specimen. Figure 4 shows typical residual stresses ahead of the crack after local compression for both A533B (figure 4a) and A508 (figure 4b). In contrast to the WPS cycle, local compression introduced tensile residual stresses directly ahead of the crack tip up to about 5 mm from the crack tip. Also shown in figure 4 are the predicted stress distributions for reloading at low temperature until fracture. At an intermediate load prior to fracture it can be seen that the stress distributions for the AR and PUCF conditions are very different. The residual stress field was the result of an average indentation of 1.5% – 2.0% of the specimen thickness.

4. FAILURE PROBABILITY PREDICTIONS

4.1. The local approach

Recently the authors [1] used a Beremin type model that included a threshold stress to predict failure probability following WPS. They used the same Weibull parameters calibrated based on the as-received fracture data to predict the influence of WPS. This model assumes that the maximum principal stresses integrated over the elements within the crack tip plastic zone, characterises the conditions of failure. The effect of WPS on subsequent fracture is therefore automatically considered. It is suggested that this approach can be applied also to predict the probability of failure regardless of the source of RS field such as WPS or local compression. The finite element results described earlier were then used to calculate failure probability using the Weibull model.

To predict the distribution of fracture toughness, a user routine was developed using a modified Beremin type model, equations (1) and (2). The model uses the incremental stress-state during the final loading step of the analysis. It takes into account only the maximum principal stress at the integration points that have undergone plastic deformation (or plastically reactivated- in case they became plastic during the pre-loading step). The routine also includes the calculation of fracture toughness values corresponding to the incremental stress states for the C(T) specimen. The stress-state at each increment was used to calculate the probability of failure using calibrated Weibull parameters from the as-received data. The calibrated parameters where then used to predict the fracture toughness for various test configurations. Details are described in this section and the predictions are presented.

4.2. Calibrating the distribution parameters

The Weibull parameters were calibrated to provide a fit to the results from the as-received tests. Milella and Bonora [15] showed that the shape parameter m in equation (1) is a function of the notch tip geometry, >20 for blunt notches and decreases to 4 for sharp tip cracks. Here we use m=4, and calibrate the remaining parameters using the fracture toughness results for the as-received tests. V_0 is a scaling parameter for the Weibull stress values and may also be pre-selected [1]. The Weibull stress (σ_w) is a function of V_0 and m and for a given value of V_0 the remaining parameters (σ_u and σ_{min}) were determined by obtaining failure probabilities from the FE analysis that best matched the experimental as-received data for each steel. For V_0=0.01mm^3, the calibrated values of σ_u and σ_{min} for A533B steel were 8.0 and 2.0 GPa respectively. As an evidence of non-uniqueness it was found that with V_0=0.1mm^3 (ten times bigger), σ_{min} =1.0 GPa and σ_u =4.5 GPa also provided a close estimate of failure probability. The calibrated parameters for A508 steel are σ_{min} =3.0GPa and σ_u =9.0GPa. The calibrated parameters were then used to provide failure probabilities for the AR stateand also after WPS (LUCF) and local compression (PUCF).

4.3. Prediction of the effects of various RS fields

Toughness distributions were predicted using the results of FE analysis in conjunction with the user routine. The information required for the user routine are extracted from the incremental results of the FE analysis and include the incremental applied load and maximum principal stresses, plastic zone identifiers and the volume of the plastic elements. For A533B steel two different sets of parameters provided very similar distributions for AR failure probabilities. Subsequently, both sets of parameters resulted in virtually identical predictions for the LUCF cycle. Predictions are in good agreement with the experimental data. Although no experiments for the PUCF load cycle were performed for A533B steel, FE simulations were performed and predicted failure probabilities obtained. The results are shown in figure 5.

Figure 6 shows the predictions of WPS effect as well as the effect of local compression (PUCF cycle) for A508 steel. To predict the effect of local compression the same parameters that predicted the WPS effect were used. The predicted decrease in toughness shown here is greater than the decrease suggested by the experiments. In contrast, the predicted increase in toughness from the local approach was lower than obtained from the experiments. This will be discussed in section 5.

5. DISCUSSION

This work has focused on the issue of correlating the fracture resistance of cracked structures to the stress-state only. Cleavage fracture is also associated with Uncertainty in the fracture toughness. Here the local approach is shown to provide reasonably good predictions for the reduction after local compression and the enhancement after WPS in fracture toughness for a specific geometry, constraint level and under mode-I loading at a lower shelf temperature.

There is a lot of discussion related to the estimation and calibration of distribution parameters such as interdependence, non-uniqueness, transferability and dependence on other parameters (e.g. temperature, constraint, triaxiality). The predicted improve in toughness following WPS for A508 steel was considerably less that observed in the experiments while for A533B the model predictions were in good agreement with the experimental data. Further study of the FE models revealed strong dependence of the predictions on the degree of mesh refinement on the boundary of the plastic zone and the integration volume for calculation of Weibull stress. For both the LUCF and PUCF load cycles the inclusion or exclusion of the initial plastic zone (due to warm pre-stressing or local compression respectively) also changed the predictions. To validate the local approach as a general design tool, further investigation is required to link the characterising stress, the Weibull stress, to the fore mentioned parameters.

Consistently, where the predictions are good the corresponding normal stress distributions for the AR and LUCF and /or the AR and PUCF at failure are also fairly similar, where as they differ significantly where the predictions are not as promising.

6. CONCLUDING REMARKS

Using finite element simulations of LUCF and PUCF load cycles, distribution of RS fields and subsequent stress-state on reloading to fracture has been studied and compared with the as-received stress-state for similar load levels. Results are used to explain the role of residual stress on subsequent cleavage fracture response for different situations.

Application of a local approach to cleavage fracture toughness distribution, previously used to predict the WPS effect is extended to also predict the effect of LUCF and PUCF load cycles on apparent cleavage fracture toughness. It is shown that residual stresses, depending on their direction may either reduce (e.g. the case of PUCF) or increase (e.g. the case of LUCF) the apparent cleavage fracture toughness of the structures.

The model predictions are based on maximum principal stresses within the plastic zone only. Predictions for LUCF and PUCF, demonstrating opposite RS fields at the crack tip region, suggest that failure is controlled by redistributed stresses during reloading to fracture regardless of the source of the RS field.

This work among others supports the suggestions that residual stresses are a major cause for change in fracture resistance of structures containing defects and highlights the importance of residual stresses in the integrity assessment of such structures.

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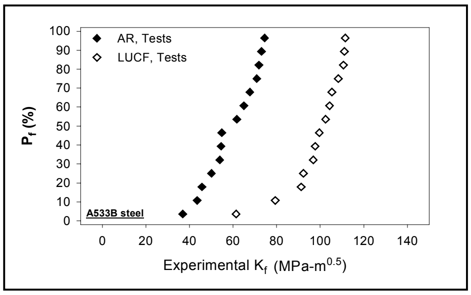


Figure 1. Experimental cleavage fracture data for A533B steel at –170°C

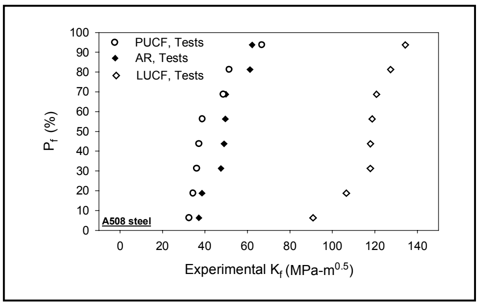


Figure 2. Experimental cleavage fracture data for A508 steel at –170°C

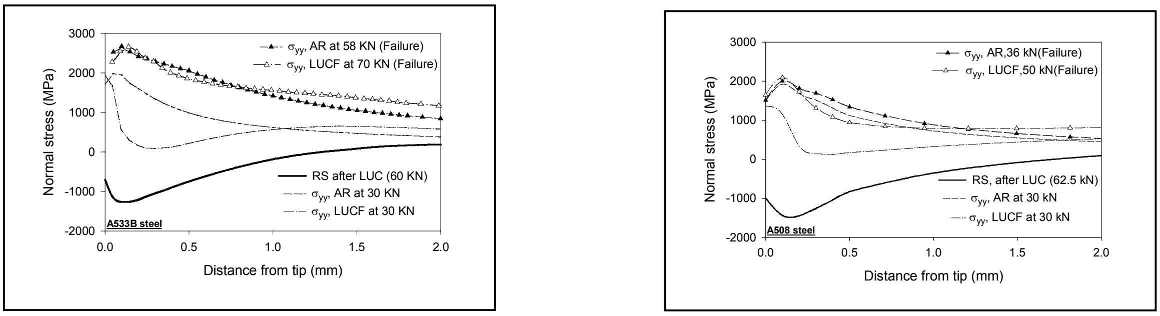


Figure 3. Normal stress distributions for a) A533B, b) A508 steels for the AR and LUCF conditions

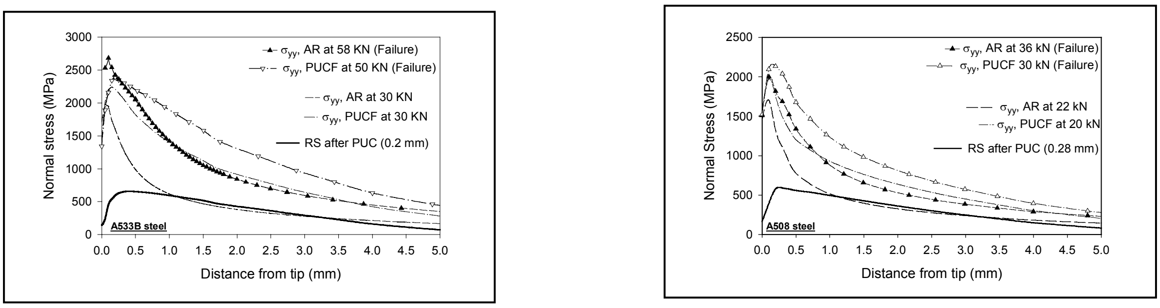


Figure 4. Normal stress distributions for a) A533B, b) A508 steels for the AR and PUCF conditions

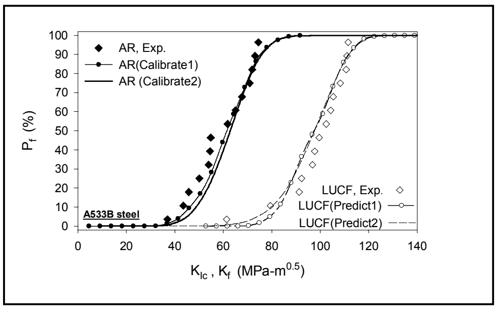
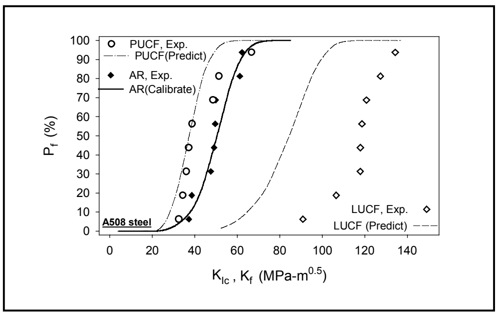


Figure 5. Predictions of fracture toughness after LUCF and PUCF for A533B steel at –170°C



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