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Finite element analysis of warm pre-stressing of pressure vessel steel

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ABSTRACT

Finite Element (FE) predictions of pre-loading, unloading, cooling and reloading at a lower shelf temperature (warm pre-stressing) of ferritic steel are described. Results are described for different pre-load levels and different as-received fracture toughness. Predictions are made by matching maximum principal stresses with those given by the as-received toughness. The matching is made for large distances ahead of the crack tip. FE results are compared with earlier analytical models. The analytical models are found, in general, to predict a lower increase in toughness following warm-prestressing.

INTRODUCTION

Structural integrity assessments of ferritic pressure vessels, such as reactors and boilers, are based on maximum defects size following a successful proof test to a certain pressure. Warm prestressing effects on the fracture toughness of the steel are recognised consequences [1] of proof testing if the material properties change during service, and are generally manifested by an increase in the materials' apparent cleavage fracture toughness [2]. Several analytical models are currently available to predict warm pre-stress effects [3,4,5]. These models are based on small scale yielding behaviour and assuming superposition of stresses or displacements. A high degree of scatter in the cleavage fracture toughness of a ferritic steel also serves to reduce the degree of confidence with which these models can be applied. In order to obtain a more fundamental understanding of the mechanisms of the warm pre-stress effect, detailed finite element analyses were performed. Simulations of experimental studies were performed and the results used as a basis for predictions of cleavage toughness following proof loading.

FINITE ELEMENT ANALYSES

The commercial finite element analysis code ABAQUS [6] was used throughout the study. Initially, load cases were chosen from a prior experimental study into the warm prestressing effects on A533B ferritic steel single edge notch bend (SENB) specimens [2]. A half model of the SENB specimen was analysed in two dimensions using eight noded, plane strain, iso-parametric elements. Small strain elastic-plastic analyses were used throughout. Symmetry was exploited in the plane of the crack. A nominal crack length to width (a/W) ratio of 0.5 was used for all analyses, where the width (W) of the specimen was 100mm, the span (S) was

400mm and the thickness (B) was 50mm. J-Integral estimates were obtained from the analyses using the domain integral approach available within ABAQUS. Load based calculations of stress intensity factor, K, were also obtained. All experimental specimens investigated were notched in the L-T orientation subjected to a single overload at room temperature, unloaded and fractured at -120°C (a LUCF warm pre-stress cycle).

Simulation of Fracture Following Warm Prestressing

Two experimental load cases taken from Smith and Garwood [2] were simulated. For the FE analyses the elastic-plastic stress-strain curves for 20°C and -120°C, obtained by Smith and Garwood [2], were used. The first model investigated as-received fracture, that is, a specimen with no prior load history. Secondly, a specimen subjected to a pre-load of K_I= 153 MPa√m. The analyses follow the same load history as the experimental case, with the specimens loaded and unloaded at room temperature, and then reloaded to fracture at -120°C. Figure 1 illustrates the fracture stress distributions ahead of the crack tip for the two load cases. It is evident that following warm prestressing, the maximum principal stress at fracture corresponds to the as-received fracture stress distribution for distances well ahead of the crack tip. This indicates that following a warm pre-stress event, the subsequent cleavage fracture toughness is controlled by the magnitude of the maximum principal stress associated with the as-received toughness. Furthermore, for fracture to occur, agreement of the maximum principal stress was necessary well outside the regions of plastic deformation normally associated with final fracture.

Prediction of Fracture Following Warm Prestressing

Bearing in mind the above findings and the statistical nature of cleavage fracture toughness [7] of the steel, detailed finite element studies were performed to predict the warm pre-stressed fracture toughness for various as-received toughness levels. Four as-received toughness values, 47.4, 63.2, 69.6 and 82.2 MPa√m and five different pre-load stress intensity levels 63.2, 79.5, 94.8, 126.5 and 158 MPa√m were selected. Predictions of fracture were made by increasing the load to fracture incrementally, and examining the stress distributions with respect to the relevant as-received fracture distribution. Similar effects to those observed in Figure 1 were seen, namely that at relatively low loads, the near tip distributions were of similar magnitude to the as-received fracture case, but further away from the crack tip, no agreement between the stress distributions was observed. The load was increased to the point where the stress distribution agreed across as great a distance as possible without the near tip stress distribution exceeding the as-received fracture stress distribution. A summary of the results is given in Figure 2, where the predicted maximum load fracture toughness is shown as a function of the proof load stress intensity factor.

Comparison Between Isotropic and Kinematic Hardening Models.

The above results were obtained using an isotropic hardening material model. A previous experimental study [8] found the deformation properties of A533B steel to be close to kinematic hardening for low compressive stresses following pre-stress in tension, and close to isotropic hardening for high compressive stresses. To explore the influence of the reversed yielding model on the warm pre-stress predictions the kinematic model was examined for a single toughness, K_{Ic} = 47.4 MPa√m. Figure 3 compares the stress distributions at maximum pre-load, zero load following unloading and at fracture at -120°C. It is seen that the only significant difference between isotropic and kinematic hardening occurs in the near tip region following unloading. The fracture stress distributions were then found to be identical and consequently predictions of fracture following warm prestressing were identical to the isotropic case. This result suggests that the magnitude of the residual stress field is not the controlling factor in the warm pre-stress effect, rather that it is the extent of the compressive residual stress ahead of the crack tip.

DISCUSSION

The analytical models of Chell et al [3] and Curry [4] have been applied in several studies [2, 9] to predict the cleavage fracture toughness of ferritic steel following warm prestressing. In the above finite element studies, results were obtained by matching stresses for distances well ahead of the crack tip. This approach appears to be confirmed by comparing FE results directly with experimental data. These analyses did not use stress fields described using conventional fracture mechanics parameters such as K or J. Both Chell and Curry assume that the near crack tip continuum stress and strain fields can be described using fracture mechanics parameters. Chell and co-workers use a displacement superposition technique which is then related to a modified J integral. The final fracture criterion of the Chell model states that cleavage fracture occurs when the elastic displacements outside the final plastic zone equate to the critical value of J.

The Curry model uses the superposition of crack tip stresses at a critical distance. This model adopts the classical fracture criterion proposed by Ritchie, Knott and Rice [10], where a critical stress must be exceeded over a critical distance. The Curry model assumes that the critical stress and the critical distance are unchanged following the pre-load history. Wallin [7] and others [11, 12] used statistical methods to accurately describe the distribution of cleavage fracture toughness of ferritic steels. These statistical methods have been extended by Fowler et al [13] to describe the distribution of cleavage fracture toughness following warm prestressing, by combining the basic cleavage model with the Chell model of warm prestressing.

The predictions of the Chell and Curry models are compared in Figure 2 to the predictions from the finite element analyses. The Curry model underestimates the increase in toughness following proof loading. By using the methodology proposed by Curry and the results of the FE analysis it was found that the Curry approach matched stresses only very local to the crack tip and not at greater distances. This partly explains the conservatism of the Curry approach. The Chell model at low pre-load levels, however, is shown to be in good agreement with both the experimental results and the finite element predictions. At larger pre-load levels, relative to the as-received toughness, the FE analyses predict larger increases in toughness than predicted by the Chell model.

CONCLUSIONS

Finite element analyses have shown that fracture following a warm pre-stress event is predominantly controlled by the as-received cleavage fracture toughness of the material. The subsequent cleavage fracture toughness following warm prestressing can be predicted by matching the maximum principal stress ahead of the crack tip with the stress distribution in the as-received fracture condition. The distance over which the matching of the maximum principal stress takes place increases with increasing pre-load. The warm pre-stress effect is not dependant on the magnitude of the residual stresses but the extent of compressive residual stresses ahead of the crack tip. The analytical model proposed by Chell and co-workers agrees with the finite element predictions at low pre-loads. The model proposed by Curry based on superposition of stresses is shown to be conservative as a result of the assumption that the critical fracture stress and critical distance remain unchanged.

ACKNOWLEDGEMENTS

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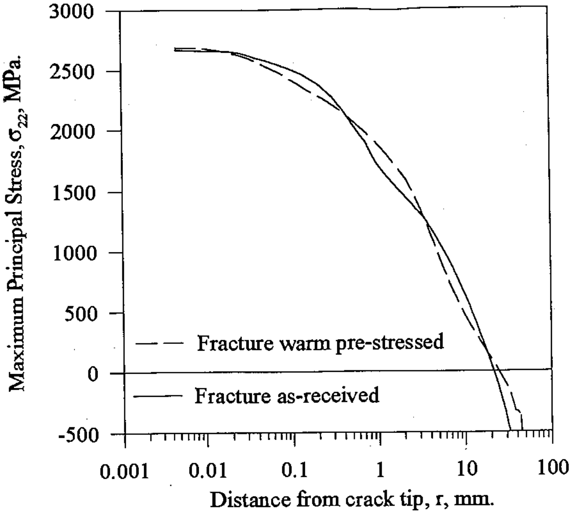

Figure 1. Comparison between fracture stress distributions at -120°C for as-received and warm prestressed conditions.

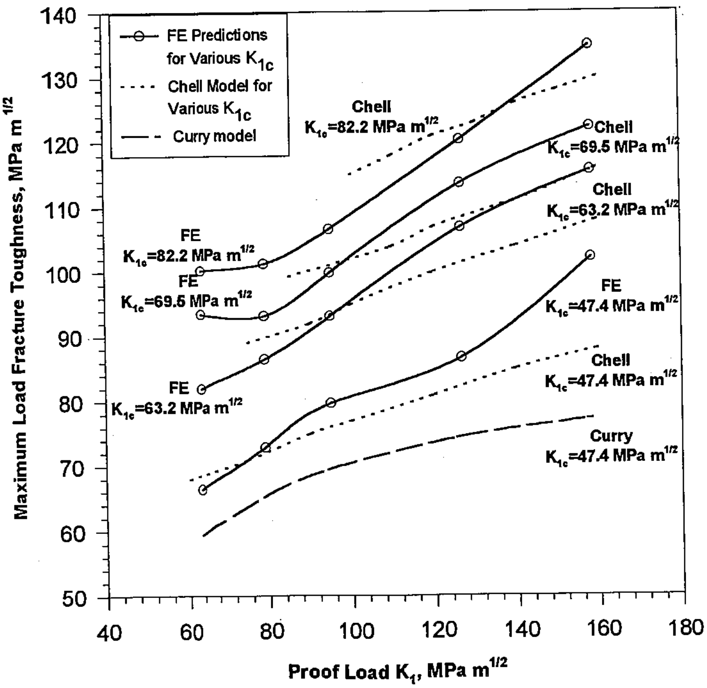

Figure 2 Comparison Between FE Predictions and Chell Model

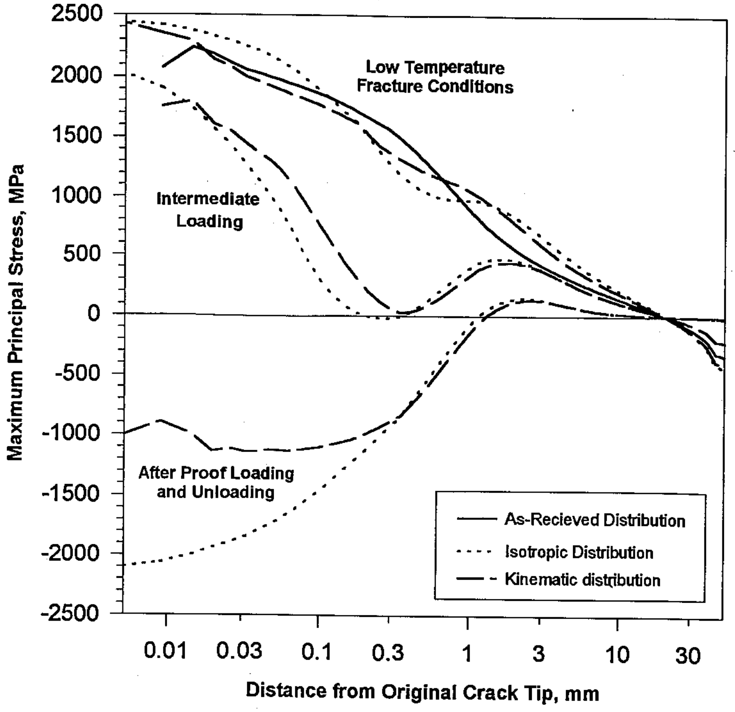

Fig. 3 Comparison of Isotropic and Kinematic Stress Distributions