SCATTER IN CLEAVAGE FRACTURE TOUGHNESS FOLLOWING PROOF LOADING

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ABSTRACT

The inherent scatter in the cleavage fracture toughness of ferritic steels is well documented and statistical analysis techniques have been applied in the past to quantify the degree of scatter. In this paper it is shown that fracture toughness data retains its statistical nature following proof loading (or warm prestressing). The change in cleavage fracture toughness following proof loading can be quantified using several models. Scatter in fracture toughness data from a ferritic pressure vessel steel, A533B are analysed with and without warm prestressing. The experimental results are compared to theoretical predictions of the effect of warm prestressing on subsequent cleavage fracture. It is found that the theory predicts lower bound behaviour to the scatter distribution.

KEYWORDS

Warm prestressing, proof loading, ferritic steels, statistical behaviour.

INTRODUCTION

The statistical nature of cleavage fracture toughness data is well known and has been documented by various authors (Curry and Knott, 1976, Wallin *et al*, 1984, Slatcher 1986, Neville, 1987, Wallin, 1991). Many of these authors present models to describe the frequency distribution of the fracture toughness of the material. The majority of these models are based on the assumption that the cleavage fracture mechanism is controlled by a critical stress and failure is caused by the weakest link in the material matrix. The models then apply Weibull statistical methods (Weibull, 1951) to their data and provide expressions for the toughness distribution of the material in question.

Warm prestressing is a technique used to enhance the structural integrity of a component. The basic assumption during warm prestressing is that the component contains sharp defects, and when the structure is unloaded, compressive yielding occurs ahead of the crack tip. This compressive field needs to be overcome before fracture can occur, generally at a lower temperature. Warm prestressing thereby increases a structures' load bearing capacity. A typical load history used in warm prestressing is the load-unload-cool-fracture cycle (LUCF), illustrated in fig. 1. The component would normally operate at the fracture temperature for some time before fracture occurs. Warm prestressing effects may also be introduced via an accidental mechanism, such as a loss of coolant accident in a reactor.

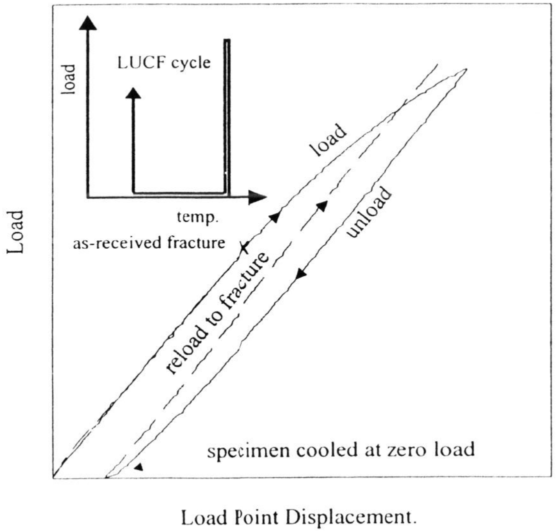

Fig. 1. Typical Load, Unload, Cool and Fracture cycle.

The effect of warm prestressing on a materials cleavage fracture toughness has been modelled by various authors (Chell, 1980, Curry, 1981, and Smith and Garwood, 1990a). The Chell model, has been shown to provide a good description of subsequent fracture following warm prestressing by Smith and Garwood (1990b) and Reed and Knott (1992).

In this paper scatter in cleavage fracture toughness in a pressure vessel ferritic steel before and after warm prestressing is examined using a model proposed by Wallin (1991). The change in toughness following proof loading is then compared with the predictions from the Chell model (Chell, 1980) with particular reference to the scatter in the change of toughness.

EXPERIMENTS.

The material examined was A533B Class 1 steel and was identical to that studied by Smith and Garwood (1990a). The specimens were taken from a 50mm thick quenched and tempered plate. The chemical composition is given in Table 1. The yield strength of the steel was 810, 637 and 500 MPa at -170°C, -100°C and room temperature respectively.

Table 1. Chemical Analysis of A533B Class 1 Steel.

C	S	P	Si	Mn	Ni	Cr	Mo	V
0.18	0.005	0.006	0.24	1.41	0.56	0.18	0.48	<0.002
Cu	Nb	Ti	Al	B	Sn	Co	CE	
0.12	<0.002	<0.002	0.018	<0.0003	0.01	0.01	0.59	

Tests were carried out on single edge notch bend (SENB) specimens of the following dimensions: W = 2B = 100mm; span, S = 400mm. Crack lengths were nominally 50mm. Fracture toughness tests were carried out at -170°C and -100°C using standard procedures (BS 5762, 1979). The tests at -170°C have been reported earlier by Smith and Garwood (1990a). The specimens fractured at -170°C were preloaded to approximately 60 % of the collapse load of the specimen based on the yield strength of the material at room temperature. Those fractured at -100°C were preloaded to approximately 110%. The specimens were then unloaded to zero load and cooled to the fracture test temperature at zero load. The loading and unloading was performed under strain control using a clip gauge across the crack mouth so that the loading rate could be carefully controlled.

Seventeen proof loaded tests were performed at -170°C and thirteen proof loaded tests at -100°C, in the as-received condition. The same number of tests were performed in the warm prestressed condition. All surfaces exhibited the features characteristic of cleavage failure. The fracture toughness was determined from measurements of maximum load and from a nine point average of crack lengths, where P is maximum load and a is crack length, using the following equation.

$$K = \frac{P}{B\sqrt{W}}\left\{\frac{3\frac{S}{W}\sqrt{\frac{a}{W}}}{2\left(1+2\frac{a}{W}\right)\left(1-\frac{a}{W}\right)^{3/2}}\left[1.99-\frac{a}{W}\left(1-\frac{a}{W}\right)\left\{2.15-3.93\frac{a}{W}+2.7\left(\frac{a}{W}\right)^{2}\right\}\right]\right\} \quad (1)$$

At -170°C, the as-received specimens provided valid K_{Ic}'s, satisfying the thickness requirements for K_{Ic} testing. However, at -100°C there was some plasticity and the as-received specimens did not meet thickness requirements given by:

$$B, a \geq 2.5\left(\frac{K_{Ic}}{\sigma_{ys}}\right)^{2} \quad (2)$$

The tests at -100°C provided toughness values given as K_Q.

Although proof loading involved extensive plasticity, equation (1) was used to determine the preload stress intensity factor K_I. For the tests subsequently fractured at -170°C and -100°C, K_I was 88.5 MPa√m, ± 8 MPa√m and 176.67 MPa√m ± 5 MPa√m respectively. As with the as-received fracture toughness at -170°C the fracture toughness following warm prestressing did meet the thickness criteria. For fracture testing following warm prestressing at -100°C the results again did not satisfy equation (2). At -170°C the increase in the mean fracture toughness was 63 % following proof loading, while at -100°C the increase in toughness was reduced to 21 %. The experimental results are presented in fig. 2 and fig. 3 in terms of the cumulative probability of failure, ΣP_f, and cleavage fracture toughness K_{Ic}, K_Q and K_f.

ANALYSIS

Wallin (1991) proposed that the probability of cleavage fracture can be described by

$$P_f = 1 - \exp\left[-\frac{B}{B_0}\left(\frac{K_{Ic} - K_{\min}}{K_0 - K_{\min}}\right)^n\right] \tag{3}$$

where B_0 and K_0 are normalisation constants. B_0 can be chosen as any desired reference thickness, and when $B = B_0$, the parameter K_0 is equal to the 63.2% failure probability value for K_{Ic}.

Equation (3) was fitted to the experimental results shown in fig. 2 and 3, assuming that K_{min} and K_0 are free variables and the slope is a constant with n=4 as proposed by the model. The fitted curves are shown in fig. 2 and 3 with K_{min} and K_0 = 8.91 and 64.2 MPa√m for the as-received material at -170°C, and 82.5 and 163.7 MPa√m for the as-received material at -100°C. K_{min} determined from curve fits was found to be within 1% and 5% of the experimental minimum values for the as-received material at -170°C and -100°C respectively.

Based on the good fit of equation (3) to the experimental results for fracture at -170°C and -100°C, the model is extended to predict the cleavage toughness following warm prestressing, by using the Chell model (Chell, 1980) . The form of the model is dependent on the yield properties of the material at the fracture condition and the applied proof load stress intensity factor. For the case where the final plastic zone at fracture is contained within both the proof load plastic zone and unloaded compressive plastic zone, the model is represented by the following equation:

$$K_f^2 = \left(\sigma_{y1} + \sigma_{y2}\right)^2 \times \left(\left(\frac{\left(\sigma_{y2}^2 - \sigma_{y1}^2\right)K_1^2}{2\left(2K_1^2\sigma_{y1}^3 - K_1^2\sigma_{y2}^2\right)}\right) \times \left[\left\{\sqrt{1 + \frac{7K_{Ic}^2\sigma_{y1}^3}{\sigma_{y2}\left(\sigma_{y2} - \sigma_{y1}\right)^2 K_1^4}}\right\}\right]\right) \tag{4}$$

where σ_{y1} and σ_{y2} are the yield strengths at the proof load temperature, T_1, and the fracture temperature, T_2, respectively. The predicted toughness following proof loading as a function of the proof load stress intensity factor K_I using equation (4) is shown in fig. 4, with T_I =20°C and T_2 = -170°C.

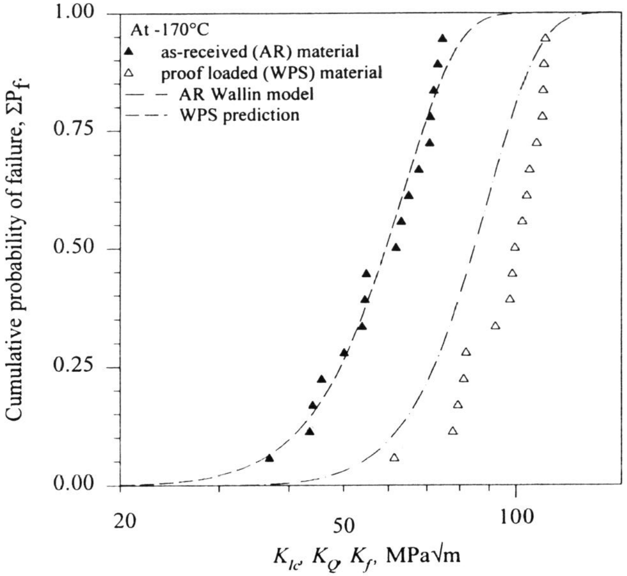

Fig. 2. Cleavage toughness distribution at-170°C for as-received and following proof loading.

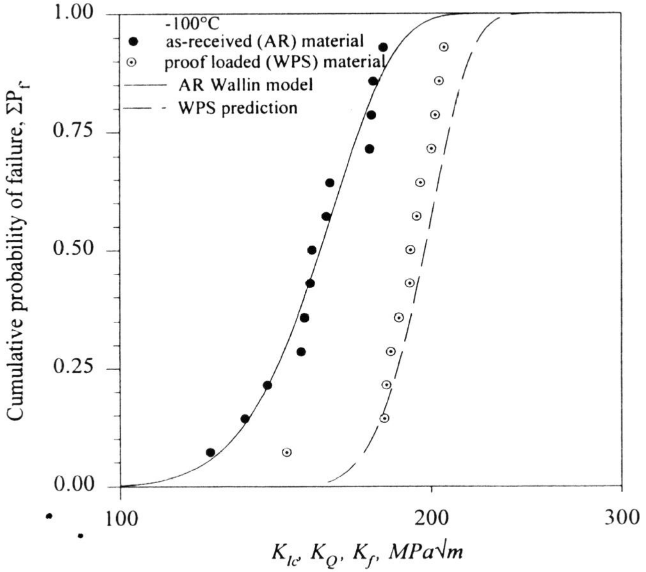

Fig. 3. Cleavage toughness distribution at-100°C for as-received and following proof loading.

The model is used to predict the change in K_{min} and K_0 following a prestressing event of average magnitude, in this case (-170°C, fig. 2) , K_I = 89 MPa$\sqrt{m}$. The corresponding ratios K_I/K_{min} and K_I/K_0 for fracture at -170°C are 9.93 and 1.39 respectively.

Using equation (4), (or fig. 4), values of K_0 and K_{min} are changed to K_{0f} = 90.8 and K_{minf} = 20.8 MPa$\sqrt{m}$. By selecting arbitrary values of K_f greater than K_{minf} the predicted failure probability is shown in fig. 2. It is evident that the predicted distribution of toughness following proof loading is less than that obtained experimentally. In particular the ratio of the experimental K_{0f} to the predicted K_{0f} is 1.36.

At -100°C, figure 3, the prediction is shown to be less conservative than at -170°C. The ratios K_I/K_{min} and K_I/K_0 for fracture at -100°C are 9.93 and 1.39 respectively. Modifying the values of K_0 and K_{min} using the Chell model provides values of K_{0f} = 202.8 and K_{minf} = 139.6 MPa$\sqrt{m}$. The ratio of the experimental K_{0f} to the predicted K_{0f} is 0.965. This indicates that the prediction is slighty non-conservative at this temperature, illustrated by the prediction curve lying to the right of the experimental data in the warm prestressed condition.

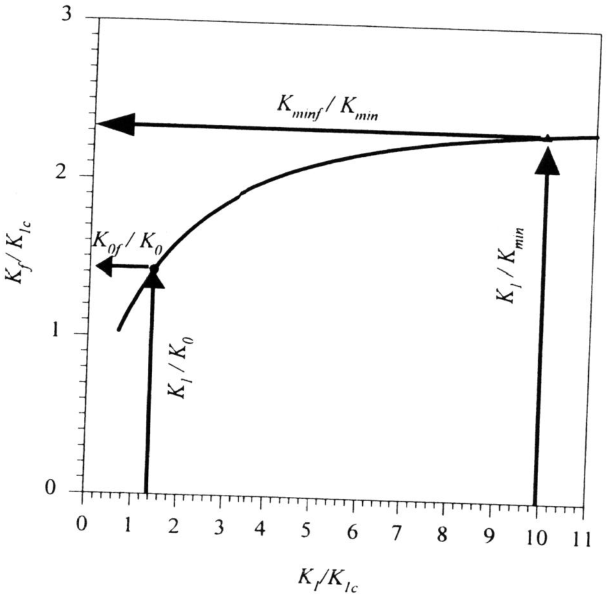

Fig. 4. Predicted fracture toughness at -170°C following proof loading at room temperature.

CONCLUSIONS

(i) The scatter in cleavage fracture toughness in A533B steel at -170°C and -100°C can be described by a model developed by Wallin.

(ii) Following proof loading (warm prestressing) it is found that there is an increase in toughness. The scatter in toughness following proof loading is found to be similar to the as-received material for fracture at -170°C. For tests at -100°C there are also similar trends.

(iii) A model developed by Chell to predict fracture toughness following proof loading was adopted to change parameters in the model for probability of failure. The predicted change in the statistical distribution at -170°C was found to be less than obtained experimentally.

(iv) At -100°C the proof loading model accurately predicts the shift in the cleavage toughness distribution. Experiments demonstrated a mean change in toughness of 23%.

REFERENCES

BS5762 (1979): Method for crack opening displacement (COD) testing. BSI, London, December 1979

Chell, G. G., (1980). Some Fracture Mechanics Applications of Warm Prestressing to Pressure Vessels. *C22/80*, IMechE

Curry, D.A., and Knott, J. F. (1976). The Relationship Between Fracture Toughness and Microstructure in the Cleavage Fracture of Mild Steel. *Metal Science*, **10**, 1.

Curry, D.A., (1981). A Micromechanistic Approach to the Warm Prestressing of Ferritic Steels. *Int. J. Fract.*, **17,** 335-343.

Neville, D. (1987). Statistical Analysis of Fracture Toughness Data. *Engineering Fracture Mechanics*, **27**, 143-151.

Reed, P.A.S., and Knott, J.F., (1992). An Investigation of the Warm Prestressing (WPS) Effect in A533B Weld Metal. *Fatigue. Fract. Engng Mater. Struct.* , **15**, 1251-1270.

Slatcher, S. (1986), A Probabilistic Model for Lower-Shelf Fracture Toughness-Theory and Application *Fatigue. Fract. Engng Mater. Struct.* , **9** , 275-289.

Smith D.J., and Garwood, S.J., (1990a). Application of Theoretical Methods to Predict Overload Effects on Fracture Toughness of A533B. *Int. J. Pre. Ves. & Piping,* **41,** 333-357.

Smith , D.J., and Garwood, S.J., (1990b). Experimental Study of Effects of Prior Overload on Fracture Toughness of A533B Steel. *Int. J. Pre. Ves. & Piping,* **41,** 297-331.

Weibull, W., (1951), A Statistical Distribution Function of Wide Applicability. *J. App. Mech.* **18,** 293-297.

Wallin, K., Saario, T., and Torronen, K., (1984). Statistical Model for Carbide Induced Brittle Fracture in Steel. *Metal Science*, **18**, 13-16.

Wallin, K., (1991). Statistical Modelling of Fracture in the Ductile-to-Brittle Transition Region. *Defect Assessment in Components-Fundamentals and Applications.* ESIS/EGF9 eds Blauel, J.G. and Schwalbe, K.H., 415-445.