THE EFFECT OF SECTION SIZE ON THE TRANSITION FRACTURE TOUGHNESS OF A SILICON-KILLED CMn PLATE STEEL

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Well founded, statistically-based equations are available for describing the transition fracture toughness of C-Mn steel in the size range 25-100mm thick. The statistical description accommodates the amount of any ductile tearing prior to cleavage and specimen size effects. In order to examine the extrapolation of these equations to smaller section sizes, fracture toughness tests have been performed on 10mm thick pre-cracked Charpy specimens and 13mm thick compact tension specimens. The influence of sidegrooving on the fracture toughness values obtained from the compact tension specimens was also investigated. The results showed that extrapolating the large specimen equation to smaller section sizes yielded conservative estimates of fracture toughness. This was due, in part, to the broad range of compositions, heat treatments, etc. covered by the large specimen data. Sidegrooving was found to have a measurable reduction on the fracture toughnesses of the compact tension specimens.

INTRODUCTION

During structural integrity assessments, there is often a need to quantify the fracture toughness of component materials. In many instances, relevant fracture toughnesses are those within the ductile to brittle transition regime. Within this regime, fracture response varies from linear elastic cleavage instability in the lower transition regime to increasing amounts of ductile tearing prior to the onset of cleavage instability as temperatures are increased up to the onset of the upper shelf of fracture toughness.

In recent years novel statistical techniques have been developed and used to describe the fracture toughness response of ferritic steels throughout the transition temperature range. These techniques accommodate not only the differing fracture response throughout the transition regime, but also specimen thickness effects. Indeed, for the assessment of CMn steels used in the nuclear power industry, well established equations exist which relate fracture toughness to temperature for component thicknesses of 25 to 100mm.

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Increasingly, there is a need to assess the toughness of smaller section components and the current paper describes experiments conducted to obtain fracture toughness data within the ductile to brittle transition temperature range on 10mm thick pre-cracked Charpy specimens and 13mm thick standard compact tension specimens. Additionally, a preliminary investigation of constraint effects is made by examining the influence of sidegrooving on the response of the compact tension specimens. A competing risks statistical assessment of the resulting toughness data is presented and the extrapolation of the existing transition toughness equation derived for thicker section components down to 10mm considered.

MATERIAL AND EXPERIMENTAL PROCEDURE

The material used for the fracture toughness test programme was a ferritic-pearlitic cross rolled plate steel. The main chemical constituents were (wt%): 0.14C, 1.31Mn, 0.11Si, 0.029S and 0.012P. The steel had been subject to a stress relief heat treatment of 6 hours at 600°C, cooled at 10°Ch^{-1} to 250°C and then air cooled.

Fracture toughness tests were performed over the temperature range -140°C to -40°C. Plane-sided 10mm thick pre-cracked Charpy specimens, tested in three point bending, and 13mm thick standard compact tension (CT) specimens were used for the bulk of the test work. However, a small number of sidegrooved (vee profile, 10% each side) CT specimens were also tested. All specimens had initial crack length to specimen width ratios of ~0.5. Testing conformed to the ESIS P1/92 and P2/92 procedures (1, 2).

Unloading compliance was used during the toughness tests, where this was practicable. In all cases, specimens were examined fractographically after testing to measure the extent of any ductile crack growth prior to the onset of cleavage. This usually required scanning electron microscopy to ensure accurate crack growth measurements.

The test programme was designed with the following specific aims:

Pre-cracked Charpy. To evaluate cleavage fracture toughness as a function of temperature, a number of specimens were tested at temperatures which yielded;

a) linear elastic cleavage fractures
b) elasto-plastic deformation followed by the initiation of cleavage fracture, and
c) cleavage instability after prior ductile crack growth.

CT Specimens. To evaluate the effect of sidegrooving on fracture toughness.

RESULTS

Figure 1 shows the fracture toughness data obtained in the current work plotted as a function of test temperature. It can be seen that toughnesses were, in general, bounded by the plane-sided CT specimens result; on mean properties, CT specimen toughnesses were higher than either the pre-cracked Charpy specimens or the sidegrooved CT specimens. To rationalise the variability in cleavage fracture toughness with temperature, pre-cleavage ductile crack growth was also analysed as a function of test temperature, Figure 2. The data indicated that more ductile crack growth occurred prior to cleavage in the CT specimens than in the pre-cracked Charpy specimens. In this case, however, there was no obvious effect of side grooving.

STATISTICAL ANALYSIS

Existing relationships for the cleavage fracture toughness of CMn steel are based on a statistical method known as competing risks and have been derived using data for section thicknesses in the range from 25 to 100mm, Moskovic and Crowder (3) and Moskovic (4). In order to use the new data to support the extrapolation of these equations to smaller section thicknesses, the dependence of cleavage fracture toughness for Charpy sized and 13mm thick test pieces as a function of test temperature and ductile crack growth must be determined. The method of maximum likelihood estimation was employed to derive a model based on competing risks.

Statistically, the outcomes of a fracture toughness test are threefold; observed values of K, observed values of Δa and the cause of failure, either cleavage or ductile fracture. The observed values of both cleavage fracture toughness and pre-cleavage ductile crack growth are random variables and form a joint probability distribution. Indeed, cleavage fracture toughness is dependent on prior ductile crack growth and their relationship is prescribed by a crack growth resistance curve. For the purpose of evaluating cleavage fracture toughness, this can be considered in terms of a relationship between K and Δa.

The distributions of cleavage fracture toughness and pre-cleavage ductile crack growth, Δa_c, can be described using loglinear regression models. The test results can be classified as ductile or cleavage. Ductile tests are those which have not experienced cleavage instability and have been stopped by unloading the specimens after different amounts of ductile crack growth. The possibility of fracture by cleavage instability can not be ruled out in these tests if they had been continued to a higher amount of tearing. Statistically, this can be accommodated by treating all the ductile data as censored values. The appropriate statistical methods for analysing these data are discussed in (3, 4). It should be noted that for the current analyses, data at temperatures of >100°C only were used. This avoided the biasing effect of the linear elastic cleavage fracture results at temperatures below -100°C which exhibited on different temperature dependence to those at temperatures of > -100°C. This restriction eased specimen size comparisons. The results of the statistical analyses are summarised below:

a) Estimation of the probability, P_a, that $\Delta a_c = 0.09$mm.

$P_a = 1/(1 + \exp(16.10 + 0.203))$, for the pre-cracked Charpy and side-grooved CT specimens, and (1)

$P_a = 1/(1 + \exp(12.57 + 0.203T))$, for the plane-sided CT specimens (2)

b) Estimation of the relationship for pre-cleavage ductile crack growth, Δa_c.

$\Delta a_c = 9.967 \exp(0.06T + 0.577Up)$, for the pre-cracked Charpy specimens (3)

$\Delta a_c = 10.105 \exp(0.06T + 0.577\,Up)$, for the CT specimens (4)

c) Estimation of the relationships for cleavage fracture toughness, K_c.

$$K_c = 418.6 \exp(-0.0075T_2 + 0.0115T + 0.214 \ln \Delta a_c)(-\ln(1-p))^{0.112} \quad (5)$$
$$K_c = 470.1 \exp(-0.0061T_2 + 0.0115T + 0.214 \ln \Delta a_c)(-\ln(1-p))^{0.112} \quad (6)$$
$$K_c = 352.8 \exp(-0.0092T_2 + 0.0115T + 0.214 \ln \Delta a_c)(-\ln(1-p))^{0.112} \quad (7)$$

where T is the test temperature, p is a random variable between 0 and 1 and U_p is the standard normal deviate. In equations (5) to (7), T_2 is the temperature at which Δa_c is just greater than 0mm (actually 0.09mm). Equations (5), (6) and (7) relate to pre-cracked Charpy, CT and side-grooved CT specimen, respectively. The applicability of the relationships derived are a direct result of the statistical analyses.

Equations (3) to (7) can be re-arranged and expressed as the marginal, $f_{c,a}(\Delta a_c)$, and conditional probability densities, $f_{c,K}(K_c \mid \Delta a_c)$, of Δa_c and K_c, respectively. However, in order to estimate the probability of cleavage and the cleavage fracture toughness values for use in the structural integrity assessments, it is necessary to consider the joint failure probability distribution of K_c and Δa_c, $F_{c,j}(K_c, \Delta a_c)$: This is given by:

$$F_{c,j}(K, \Delta a) = P_a \int_o^k f_{c,K}(K_c \mid O)dK_c + (1-P_a)\int_o^{\Delta a}\int_o^{K} f_{c,K}(K_c \mid \Delta a_c) f_{c,a}(\Delta a_c)dK_c da_c \quad (8)$$

Equation (8) was used to estimate the values of K_c associated with the 0.05, 0.5 and 0.95 quantiles of $F_{c,j}$ using a Monte Carlo integration technique. Fracture toughness values for these quantities are conventionally used in structural integrity assessments as the lower bound, best and upper bound property estimates. The best estimates of cleavage fracture toughness obtained from Equation (8) are shown in Figure 3 compared with the predicted response from the extrapolated 25mm to 100mm equations (5).

DISCUSSION

The best fit equations to the current data are shown in Figure 3. Also shown in Fig 3 is the predicted response of 10mm thick samples using the extrapolated large specimen equation. It can be seen that a conservative prediction of the small specimen data would have been obtained from the extrapolated curve fit. At first sight, this appears surprising until it is recognised that the fit to the large specimen database encompassed data from a wider compositional/heat treatment range than represented by the small specimen test data.

An interesting result from the current work is the observation that plane-sided CT specimens apparently yielded higher toughnesses than the pre-cracked Charpy specimens. However, the effect is small, and may simply be the result of too few test data. Although this is also true of the number of results of the plane-sided CT specimen tests is more significant, indicating a possible effect.

CONCLUSIONS

1 Small specimen fracture toughness data in the ductile to brittle transition region have been successfully modelled using competing risk analysis.

2 Comparison with extrapolated equations derived from a large data set on 25-100mm thick specimens have been shown to conservatively estimate the toughnesses measured on smaller specimens.

3 Although relatively few tests were performed, sidegrooved CT specimen data gave measurably lower fracture toughness values compared with plane-sided specimen results.

REFERENCES

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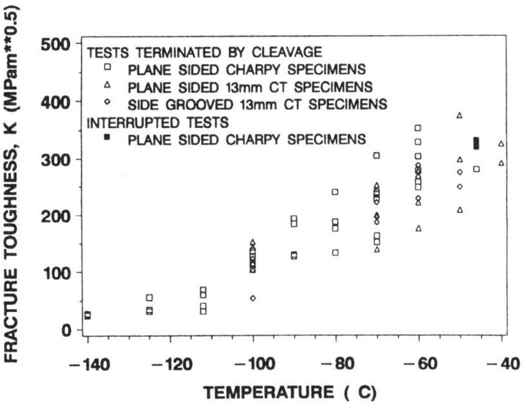

Figure 1 Fracture Toughness Data

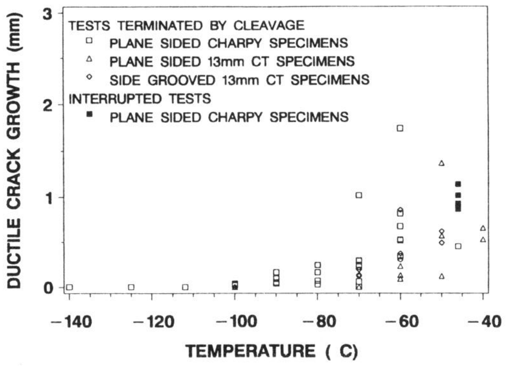

Figure 2 Ductile Crack Growth

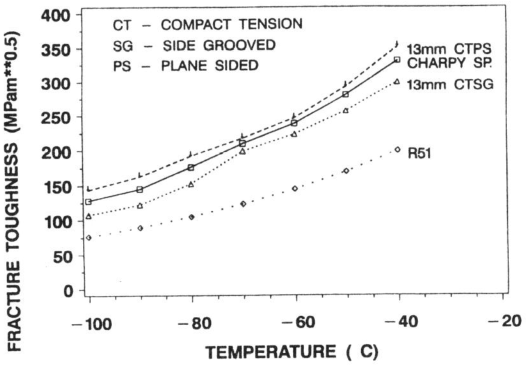

Figure 3 Predicted Best Estimate Toughnesses