ASSESSMENT OF THE DUCTILE TO BRITTLE TRANSITION CURVE FOR C-MN FERRITIC STEELS BASED UPON A SMALL DATA SET

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Abstract

Fracture toughness tests were performed on compact tension specimens extracted from C-Mn plate and forging steels. Both steels were in a normalised and stress relieved condition. Tests were conducted on each material at each of three temperatures, -46˚C, 20˚C and 0˚C. Two forging and one plate specimen failed by cleavage instability at -46˚C after prior ductile crack growth of 0.2mm; a plate specimen failed by cleavage after 0.28mm of ductile growth. The remaining specimens were ductile up to ~0.8mm of growth. Since the data are sparse the outcome has been analysed by comparison with the predictions for cleavage and upper shelf fracture toughness determined from a statistical analysis of another silicon killed C-Mn plate steel database.

Introduction

Procedures such as the Master Curve address the cleavage fracture toughness behaviour in the ductile to brittle transition temperature region of carbon and low alloy ferritic steels [1 to 3]. However, this methodology does not accommodate cleavage instability after prior ductile crack growth. Moreover implicit in the Master Curve methodology is the assumption that the cleavage fracture toughness for all ferritic steels can be described by the same temperature, crack length and scatter dependencies [3]. This can be challenged since the amount of energy to initiate cleavage or ductile fracture depends upon the propensity of the steel to spread plasticity which is linked directly with both the yield strength and work hardening capacity [4]. These properties arise from the specific microstructure produced by the thermo-mechanical treatment of the particular steel. Therefore, alternative procedures based upon statistical considerations have been proposed to describe the fracture toughness behaviour in this region of the ductile to brittle transition curve [4]. In this paper, we describe the results of fracture toughness tests undertaken on C-Mn plate and forging steels manufactured to British Standard specification in the normalised and stress relieved heat treated conditions. However, the data obtained for these two steels are sparse. As a consequence these fracture toughness data are compared with the predicted probability of cleavage fracture based on a statistical analysis [5, 6] of silicon killed steel obtained from a well established database.

Experimental Procedure

Materials

A C-Mn steel plate and a forging manufactured to BS1501 part 1 223 490B and BS1503 224 430E respectively were selected for this investigation. The chemical concentration of the main alloying elements, in weight %, are given in Table 1. The room temperature tensile properties, obtained from the mill certificates, for the forging are: $R_{po.2}$ = 304MPa, R_m = 503MPa, elongation = 30% and reduction of area = 70.7% and those for the plate are: $R_{po.2}$ = 378MPa, R_m = 545MPa, and elongation = 31%. Both forging and plate were subjected to thermo-mechanical treatment that comprised:

a) Forging: Forged from 1230 ± 10˚C to a minimum temperature of 980˚C and air cooled (AC), normalised for 9h at 890-930˚C and AC, stress relieved for 3h at 610 ± 10˚C and cooled to 300˚C at a maximum rate of 100˚C/h.

b) Plate: Hot pressed in two operations, each after soaking at 870-900˚C for 40 minutes and AC, normalised for 40 minutes at 860-890˚C and AC, stress relieved for 3.6 h at 600-615˚C and cooled at a maximum rate of 200˚C/h.

The microstructure of both steels, shown in Figure 1, comprises a fine equiaxed grained ferrite and pearlite with very little evidence of non-metallic inclusions. The latter is to be as expected from the low sulphur content of these two steels, Table 1.

TABLE 1 Chemical Composition (wt.%) of Plate And Forging

Forging										
C	Si	Mn	P	S	Cr	Mo	Ni	Al	Cu	Fe
0.23	0.22	1.14	0.009	0.006	0.13	0.020	0.08	0.02	0.011	bal.
Plate										
0.18	0.35	1.13	0.013	0.002	0.14	0.025	0.044	0.052		bal.

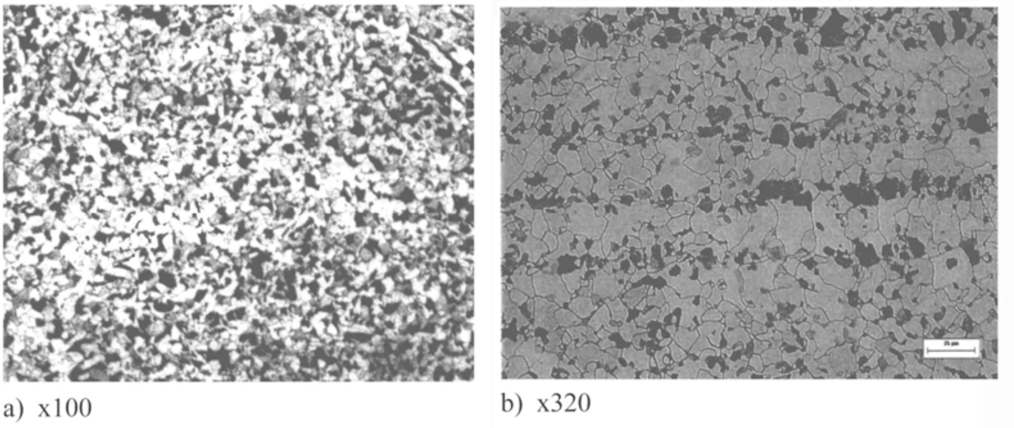
a) x100 b) x320

FIGURE 1 Optical Micrographs of C-Mn steel a) Forging and b) Plate Showing Ferrite and Pearlite (etched in Nital)

Fracture Toughness Testing

All fracture toughness tests were carried out on standard 25mm thick compact tension specimens. Forging and plate specimens were notched in CR and TL orientations, respectively. In the two letter code, the first letter indicates the direction perpendicular to the crack plane and the second the direction of crack front movement. The letters C and R represent the circumferential and radial directions in the forging, respectively and the letters T and L represent the transverse and longitudinal rolling directional in the plate, respectively.

Fracture toughness testing followed the guidance given in ESIS P2 procedure [7]. Specimens were instrumented with a LVDT gauge mounted on the loading rams and with a clip gauge mounted across the open mouth of the test piece between the knife edges. The test specimens and the loading shackles were enclosed in an environmental chamber in which the test temperature was controlled to within ±1˚C. Prior to testing, the specimen was held within ±2˚C of the test temperature to ensure a uniform temperature within the specimen. Loading of specimens was carried out under the displacement control at a rate of increase of stress intensity factor in the elastic regime of approximately 1 MPam$^{0.5}$/sec. Nine tests were performed on each material comprising three tests at each -46˚C, -20˚C and 0˚C test temperatures. Specimens which had not failed by a cleavage mechanism were interrupted after a certain amount of ductile crack growth and heat tinted for one hour at 300˚C before being reloaded to failure. The extent of ductile crack growth, in heat tinted specimens, was measured using a shadow-graph microscope. The prior ductile crack growth in the three specimens that failed by cleavage instability was measured at a higher magnification in a JEOL 840 scanning electron microscope using the secondary electron imaging mode. An average value of ductile crack extension was calculated from eight values comprising the mean of the two surface measurements and seven equally spaced measurements across the crack width.

Values of J_C appropriate to cleavage instability or values of J appropriate to the final load point for the interrupted tests were calculated from load vs displacement records using equations 1, 2 and 3 given by Neale et al [8].

$$J = \eta U/B(W\text{-}a_o) \tag{1}$$

where the value η is given by:

$$\eta = 1.97 + 0.815\ (1 - a_o/W) \tag{2}$$

a_0 is the initial crack length, U is the area under the load displacement curve appropriate to the final point, B is the specimen thickness and W is the specimen width. In the ductile to brittle transition temperature region, fracture toughness is analysed using stress intensity factor, K. The values of J obtained from equation 2 were used to calculate the equivalent K values from the relationship:

$$K = (EJ/(1 - v^2))^{1/2} \tag{3}$$

where E is the Young modulus of elasticity and v is the Poisson ratio. Values of E in GPa were taken from R51 materials data handbook [9] and the Poisson ratio was assumed to be equal to 0.3. Below a temperature of 20˚C, the values of the Young modulus were calculated from the relationship $E = 210 - 0.05T$(˚C) which gives the same values as the tabulated data in [7].

Results

An example of a force vs displacement curve, obtained by testing a forging specimen at -46°C, is presented in Figure 2 showing non-linear behaviour and a rising force as the displacement increases. This behaviour is characteristic of these modern steels. The results of fracture toughness tests are presented in Table 2. All but one plate specimen tested at -46°C showed a significant amount of plastic displacement. Except for two plate and two forging specimens tested at -46°C that failed by cleavage instability, the tests were terminated by unloading the specimens. Apart form one plate specimen, cleavage instability occurred prior to 0.2mm of ductile crack growth. Figure 3 shows a plot of the measured J values as a function of ductile crack growth and a mean line fitted by linear regression analysis using the method of least squares. Within the scatter of the data, the difference between the data for the forging and the plate was not discernible. Hence the data for the two materials were analysed together giving the relationship for the mean for $\Delta a \geq 0.2$mm:

$$J = 178.2 + 829.1\Delta a \quad (4)$$

where J is in N/mm and Δa, ductile crack growth, in millimetres.

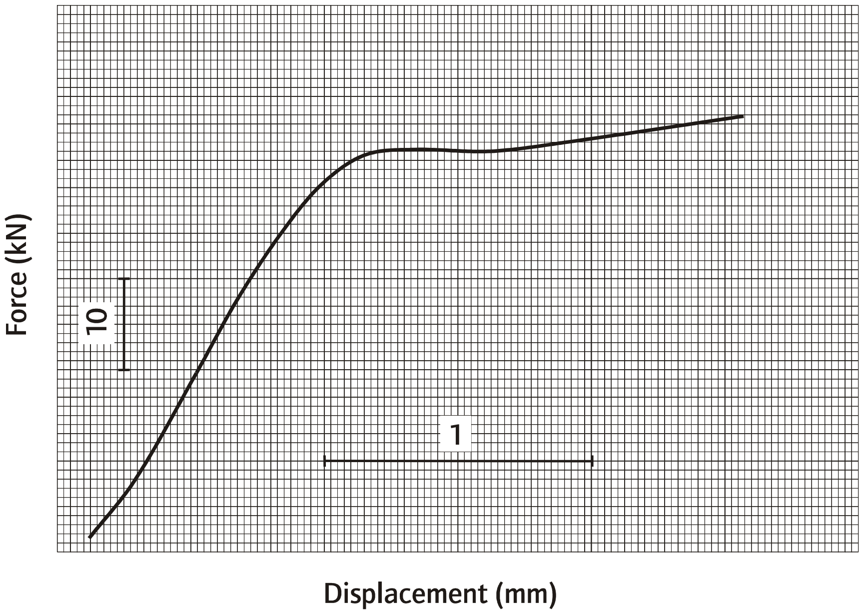

FIGURE 2 Example of a Force Displacement Curve Obtained on a Forging Specimen F4 at -46°C.

TABLE 2 Fracture Toughness Results Obtained for Plate and Forging

Spec	Test Temp. (˚C)	Crack Ext. (mm)	*J* (N/mm)	*K* (MPa√m)	Termin
Plate					
P1	0	0.34	458	325	Unload
P2	0	0.68	859	445	Unload
P3	0	0.41	549	356	Unload
P4	-20	0.29	401	305	Unload
P5	-20	0.31	400	305	Unload
P6	-20	0.62	857	446	Unload
P7	-46	0.36	452	325	Unload
P8	-46	0	60	118	Cleavage
P9	-46	0.28	571	365	Cleavage
Forging					
F1	0	0.30	302	263	Unload
F2	0	0.42	461	326	Unload
F3	0	0.86	867	447	Unload
F4	-20	0.39	457	326	Unload
F5	-20	0.79	815	435	Unload
F6	-20	0.89	862	447	Unload
F7	-46	0.18	265	249	Cleavage
F8	-46	0.77	754	419	Unload
F9	-46	0.16	265	249	Cleavage

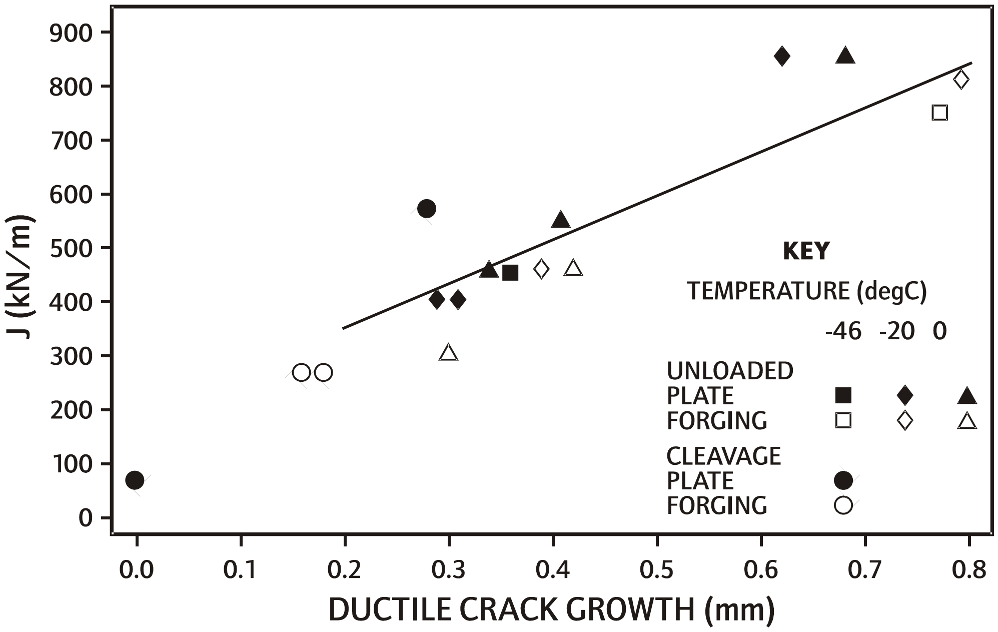

FIGURE 3 Fracture Toughness, *J* , of Plate and Forging as a Function of Ductile Crack Growth

Analysis of Test Data

A qualitative assessment of resistance to cleavage fracture can be made by inspection of the force-displacement records. These show that a significant amount of plastic deformation occurs prior to cleavage instability without giving rise to a large amount of prior ductile crack growth, due to the high ductile crack initiation and crack growth resistance of these steels. Clearly, these materials absorb a large amount of plastic deformation without bringing about a plastic collapse of the specimens. Despite the small amount of ductile crack growth observed in these tests the amount of plastic deformation observed in all but one plate specimen is typical of upper shelf fracture toughness behaviour.

Procedures such as the Master Curve [2, 3] seek to provide a common curve to describe the fracture toughness behaviour of a range of ferritic steels in the ductile to brittle transition region. However, the temperature dependence of the fracture toughness of ferritic steels within this region of the ductile to brittle transition curve depends upon the plasticity, work hardening rate and hardening capacity of the specific material. These parameters will depend upon the specific composition of the steel and the thermo-mechanical history [4]. As a consequence it is unrealistic to expect steels even within a broad specification range to necessarily obey a common trend curve. To accommodate these differences in behaviour, alternative procedures to describe data in the transition region including those based upon statistical analysis have been developed [1,10].

The test programme was intended to provide a sample of fracture toughness data for the ductile to brittle transition temperature region. Hence, for each material, there are nine test results of which two values at -46˚C for each material are for cleavage instability, Table 2. For these test results, it would be difficult to derive a relationship for cleavage fracture toughness as a function of temperature by statistical analysis. However, the information obtained from these tests can be used to make a judgement whether the cleavage fracture toughness of plate and forging is bounded by recommendations given for the silicon killed plate steels [5]. Fracture toughness values at cleavage instability or at a point when a specimen was unloaded are either within the scatter or in most cases above the 95% probability limit for cleavage fracture toughness of silicon killed plate steels in this database [5]. Indeed, equations in [5, 6] for fracture toughness properties have been used to predict the probability (percentage of cleavage), π, for silicon killed plate steels at -46˚C, -20˚C and 0˚C. The main analysis adopted takes into account the recognised competition between cleavage and ductile fracture modes in the ductile to brittle transition region. For this the well established competing risk statistical procedure can be adopted [11]. The respective values, derived using the standard computer program CUSURV [12] are: 58.7%, 17.4% and 5.9%, Table 3. These values can be used to calculate the probability, P, of getting the number of cleavage and ductile values that have been obtained for each material at each test temperature. The observed data can be classified as either ductile or brittle. The results were classified as brittle if cleavage instability occurred prior to 0.2mm of ductile cracking and ductile if 0.2mm of ductile growth was achieved. The probability of different outcomes can be modelled by the binomial distribution [13]:

$$P\left({}^{y}\!/_{\pi} \right) = \frac{n!}{x!\,y!}\pi^{x}(1-\pi)^{y} \tag{5}$$

where $P(y/\pi)$ is the probability of x number of cleavage failure and y number of ductile termination outcomes conditional on probability of cleavage failures, π, n is the total number of tests and ! denotes factorial. At temperatures of 0˚C and -20˚C all three outcomes are ductile terminations. The predicted probabilities of different types of outcomes are given in Table 3 and the experimental outcome in Table 4.

TABLE 3 Predicted Probabilistics of the Outcomes

Outcomes		3 Ductile	2 Ductile and 1 Cleavage	1 Ductile and 2 Cleavage	3 Cleavage
π, Probability (percentage) of cleavage	Test temp. (˚C)	P/π, Probability of outcome conditional on probability of cleavage			
58.7	-46	0.07	0.30	0.43	0.20
17.4	-20	0.56	0.35	0.075	0.005
5.9	0	0.83	0.16	0.01	0.0002

TABLE 4 The Experimentally Measured Outcomes at 0.2mm of Ductile Crack Growth (d = ductile, c = cleavage)

Test Temp ˚C	Forging	Plate
-46	1d + 2c	2d + 1c
-20	3d	3d
0	3d	3d

As shown in Table 3 the probability of outcome of a given contribution of fracture at the three testing temperatures conditional upon the probability of cleavage fracture gives a wide range of values. These values show that there is a high probability of three ductile failures at 0˚C whereas the probability of cleavage of three specimens is extremely low. However at a temperature of -46˚C the most probable outcome is one ductile and two cleavage failures with the next most probable being two ductile and one cleavage. These predictions are to be compared with the experimentally observed outcomes given in Table 4 where at –46˚C for 0.2mm of ductile crack growth there is one ductile outcome for forging steel and two for plate steel. The respective probabilities of having more ductile failures are 0.37 and 0.07. At temperatures -20˚C and 0˚C the outcome is three ductile values with respective values of having less than three ductile values of 0.43 and 0.17. Certainly in this case where the cleavage data are censored and there are cleavage fracture toughness values with prior ductile tearing, the Master Curve procedure could not be used.

Concluding Comment

Samples of nine fracture toughness values were obtained for both plate and forging at three different temperatures to assess whether the constants in the relationships for cleavage fracture toughness in [5] can be adjusted to derive cleavage fracture toughness for the plate and forging. Since most of the tests were terminated by unloading the specimens the associated values of fracture toughness are censored and cannot be used to modify the constants in [5]. To assess whether the relationships in [5, 6] predict conservative values of cleavage fracture toughness for the plate and forging, the probabilities of cleavage fracture for the reference curve were predicted by competing risks [11, 12]. Conditionally on these probabilities the probabilities of different test outcomes for plate and forging were computed based on a binomial distribution. This shows that the reference cleavage fracture toughness relationship in [5] provides a conservative description of cleavage fracture toughness behaviour of the plate and forging.

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