The Measurement of Elevated Temperature J Integral Fracture Toughness in Low Alloy Steels

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Abstract

A technique for measuring the fracture toughness of low alloy steels at elevated temperatures has been developed and proven. The technique adapts the standard J integral approach used for toughness measurement at ambient temperatures to elevated temperature measurements and includes significant modifications to the method used for measuring crack length during the tests.

The technique allows the determination of toughness at temperatures increasing from ambient to operational temperature, which will greatly improve the assessment of the integrity of pressure plant components known to contain cracks or other defects.

Introduction

A technique for measuring the fracture toughness of low alloy steels at elevated temperatures has been developed and proven. The technique adapts the standard J integral approach to toughness measurement and includes significant modifications to the method used for measuring crack length during the tests.

Stress levels from mechanical and thermal loading vary non-linearly with temperature when components are brought into service. The technique allows the determination of toughness from ambient to operational temperatures, which will greatly improve the assessment of the integrity of pressure plant components known to contain cracks or other defects over the full temperature range. This should lead to the safer operation of plant by reducing the risk of unpredicted failure and decrease the instances of unnecessary repair or replacement of components containing defects.

What is Fracture Toughness?

In an engineering sense, fracture toughness is a measure of a material's resistance to crack initiation and growth under load (generally from pre-existing defects). It is commonly expressed in terms of the energy required to propagate a crack within the material.

Its importance is demonstrated when a pressure vessel being considered is found to contain cracking at or near a weld, that can grow through the body of the vessel to cause a leak or burst. Under these conditions, a decision must be made as to whether it is safe to continue operation of the vessel or whether a repair or replacement must be conducted which is usually extremely costly.

In order to determine the safety of a vessel containing defects, several variables must be determined. These variables are the stress state at the site of cracking, the extent of cracking and the fracture toughness of the material containing the crack.

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Once these variables have been determined, an engineering assessment can be performed which will allow a decision to be made as to the integrity of the vessel and the likelihood of failure before either corrective action or further inspection can be undertaken.

Why Elevated Temperature?

It is most common to measure fracture toughness at room temperature or below and to assume the toughness increases as temperature increases. This assumption is based on the fact that much of the work on the effects of temperature on fracture toughness concentrated on the region below and around the transition temperature. Under these circumstances it is fair to say that the fracture toughness does in fact increase with temperature.

It is not clear, however, what effect temperature has on fracture toughness once this transition region is exceeded and operating temperatures are approached. Documents such as ASME Section XI and PD6493 [1,2] indicate that fracture toughness can be assumed to increase with temperature until plastic collapse is reached. However, work on tensile properties of carbon steels suggests that a phenomenon known as dynamic strain ageing may become active as the temperature is raised, and as this has a profound effect on the tensile properties of carbon steels, its effect on fracture toughness could be significant.

It was therefore decided to attempt to develop a technique which would allow the measurement of fracture toughness at temperatures ranging from room temperature to 500 °C.

Dynamic Strain Ageing

The strain ageing phenomenon in steels has been reported since the early 1960's and manifests itself chiefly by an increase in yield stress during or after straining; the increase after straining being static strain ageing and the increase during straining being dynamic strain ageing.

The strain ageing effect is the result of interstitial solutes diffusing to dislocations within the matrix and locking them, thereby preventing their movement through the matrix during straining.

Dynamic strain ageing can be seen in the tensile behaviour of susceptible materials by the presence of serrated yielding, elevated tensile properties and lower ductility. The dynamic response is determined by the temperature and the strain rate since it is controlled by the diffusion of carbon and nitrogen atoms within the matrix.

Some work has been performed on materials used in the nuclear industry with respect to the effect of dynamic strain ageing on fracture toughness; however, no work seems to have been performed on the more common low alloy steels.

Test Material and Sample Production

A carbon steel header material was chosen for the study. The material had been in service at approximately 400 °C for 132 000 hours and was removed from a pressure vessel in an area remote from any cracking previously found in the vessel. In this condition it was expected that most of the carbon and nitrogen would have been removed from solid solution by precipitation, and as such the effect of strain ageing on the mechanical properties should have been reduced.

In order to maximise the effect of the dynamic strain ageing, sections of the material were heat treated in order to put the carbon and nitrogen back into solid solution and to produce a material with approximately the original microstructure.

A number of heat treatment trials were performed with the final heat treatment chosen being a solution treatment at 855 °C followed by air cooling.

This heat treatment produced a material with a slightly finer grain size that the ex-service material.

Once heat treatment was completed, tensile and Compact Tension (CT) specimens were produced from both the heat treated and ex-service material. The CT specimens were modified to allow the measurement of load line displacement and the attachment of current input and voltage measurement leads.

The CT samples were then fatigue cracked in a fatigue resonance machine and side grooved by 20% in order to promote stable crack growth during the subsequent fracture toughness tests.

Measurement Techniques

The elevated temperature tensile tests were conducted at two strain rates to study the effect of strain rate on the properties of the material. The strain rates chosen were 2×10^{-4} and 4×10^{-5} per second. Due to the size of the large yield points encountered during these tests, the tests were conducted using displacement control rather than strain control in order to maintain control of the testing machine.

The tests were conducted according to the following pattern; two samples at each strain rate at room temperature and each 100 °C interval, one sample at each strain rate at 50 °C between these intervals above 100 °C.

In order to measure the J-integral fracture toughness of a material using a single specimen technique it is necessary to measure the crack length either continuously or at intervals during the loading of the specimen.

The normal approach is to use the change in stiffness of the sample (the compliance) as the crack grows to measure the crack length. This is done by performing periodic unloadings of the sample during the test in order to determine the crack length at intervals. This technique of crack length measurement requires the use of very stable and linear clip gauges. Many techniques were investigated to allow the measurement of crack length at elevated temperatures by this method. Eventually, it was decided that the equipment being used for this measurement (a capacitance clip gauge) could not be repeatably calibrated accurately enough to be used for unloading compliance measurements (although accurate enough for energy measurement) and another technique for crack length measurement was required. It was also felt that the effect of load holds on a diffusion controlled process could be difficult to separate from the dynamic strain ageing effect if present.

The potential drop (PD) technique was investigated as an alternative. The conventional PD technique impresses a constant current into the sample and measures the ensuing potential drop across the crack. As the crack grows, the potential drop changes and the crack length can be inferred. However, the potential drop calibration of a material is influenced by its electrical resistivity and therefore by temperature, and so a technique had to be developed which removed the effect of temperature from the calibration.

In order to achieve this it was necessary to formulate a technique for measuring crack length which was independent of resistivity and thermal emf. A programmable current source was used which allowed the stepping of the test current. This permitted a simple Ohm's law relationship to be used to remove the effect of emf as the stepping of the current allowed measurement of resistance as a function of crack length rather than potential. In order to remove the effect of resistivity, the resistance at the starting crack length of a test is normalised with the resistance of the same crack length at the calibration temperature and a resistance ratio used for subsequent crack length estimations.

To optimise the technique a finite element model of the sample geometry was produced which was then used to simulate current flow within the sample to allow the best locations for current input and potential measurement to be determined. From this procedure, two input and two measurement locations were chosen which were sensitive to crack growth but relatively insensitive to lead placement. To refine the geometry further, a 20:1 scale foil sample was produced which allowed potential measurements to be performed. From this simulation, one input location was eliminated. The two measurement locations were maintained as they allowed for simultaneous measurement from two independent sets of electrodes in case of lead failure during a test.

Final calibration curves were produced by placing several samples into an electric discharge cutting machine and progressively extending the crack in the testing machine while taking resistance measurements.

Once this crack length measurement technique was calibrated, the clip gauge was calibrated to perform the load line displacement measurements and the tests could commence.

Tensile Results

The tensile tests produced the results shown in Figure 1. As can be seen from this figure, the expected increase in tensile properties is apparent and is more pronounced in the heat treated material than in the ex-service material.

The presence of dynamic strain ageing can clearly be seen in the tensile load versus displacement traces, as demonstrated by the traces for the heat treated material (Figure 2). This behaviour was not as obvious for the ex-service material except in the yield plateau where small serrations were observed with both materials. It can also be seen from this figure that the serrations are greatest at 150 °C and reduced at higher temperatures. This would suggest that the highest tensile properties should be seen at approximately this temperature.

Due to the difficulty in removing the elevated temperature extensometers, the samples were not taken to failure in these tests and therefore elongation measurements were not available. Further tests were performed on similar header material removed from a sister unit with modified extensometers that allowed failure of the sample. The tensile results are similar to those reported above for the ex-service material with the elongation showing a strong minimum at approximately 250 °C.

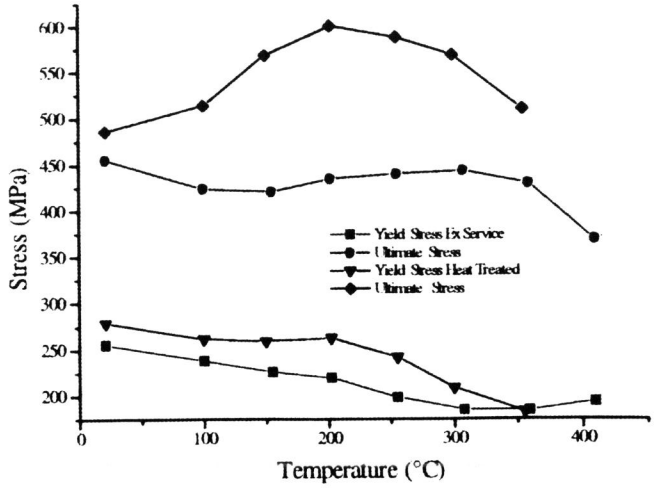

Figure 1 Tensile properties as a function of temperature for the ex service (lower curves) and heat treated materials (upper curves).

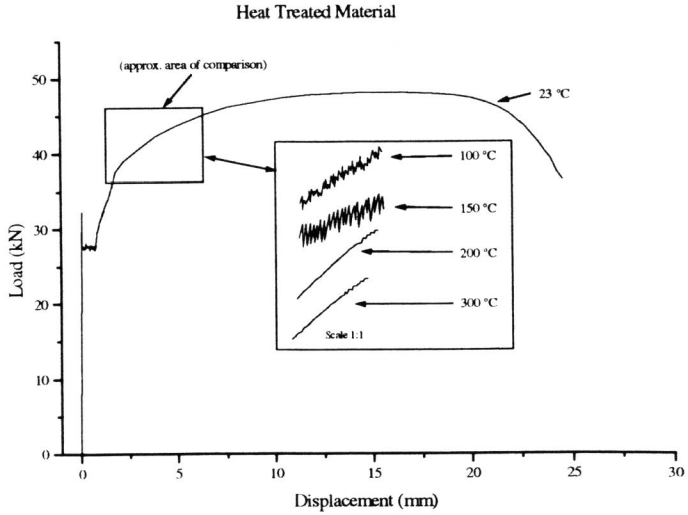

Figure 2 Tensile trace for heat treated material

Fracture Toughness Results

Potential drop crack length results

The potential drop technique produces predicted crack lengths during the test which can be checked against actual crack lengths after the test has been completed. In order to achieve this, the specimens were heat tinted (if tested under 300 °C) to delineate the extent of crack growth, and the initial and final crack lengths measured using the standard 9 point average method.

ASTM E1152 [3] dictates that the final and initial crack lengths measured on the opened sample must be predicted to within ±15% of the measured value. This is not a sufficient criterion as it is possible to have the predictions meet this criterion and report a negative crack growth.

To analyse the effectiveness of the current technique, the change in crack length was compared to the measured change, and the error histogram is shown in Figure 3.

As can be seen from this figure, the potential drop technique predicted the amount of slow crack growth quite accurately. The outlying results are either due to very small amounts of crack growth (therefore small errors produce large percentage errors) or to oxide build up under the input washers (a problem discovered early on in the testing programme and corrected in subsequent tests). It also needs to be remembered that the results are taken for tests spanning from room temperature to 400 °C.

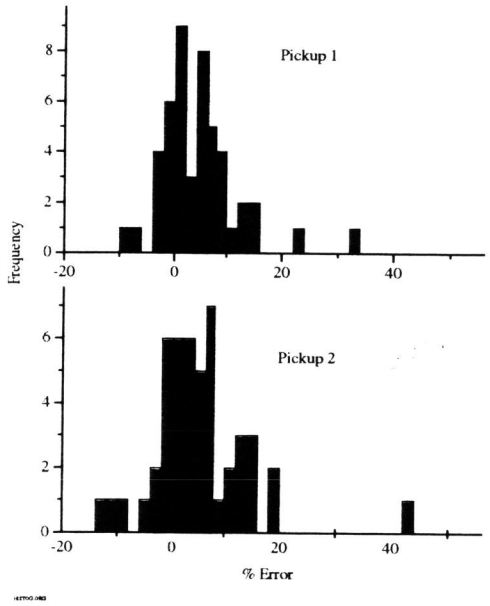

Figure 3 Error in crack length prediction for both input pickup locations as a percentage of crack growth.

J integral fracture toughness test results

The J integral tests produced test curves similar to the one shown in Figure 4

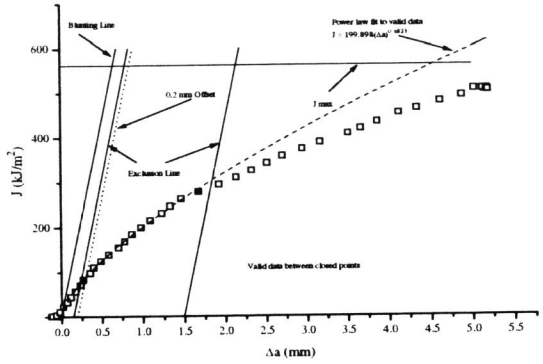

Figure 4 J resistance curve at 400 °C.

As can be seen from this curve, the crack length prediction method produces a curve of conventional shape and well spaced data points.

The results for the test program are presented in Figure 5 and Figure 6 which show the J_{IC} and tearing modulus values as a function of temperature.

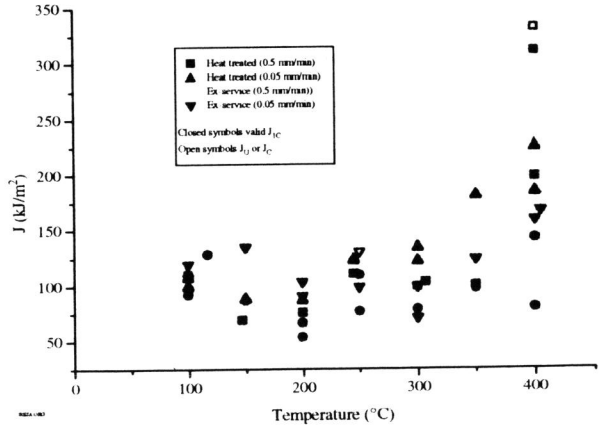

Figure 5 J_{IC} as a function of temperature at two strain rates and for both materials.

As can be seen from these figures, temperature has a significant effect on the fracture toughness of these steels, particularly the heat treated material. This effect is more clearly seen in the tearing modulus results than in the initiation results due to the scatter in the initiation results. The open symbols in Figure 5 are from samples which failed by fast

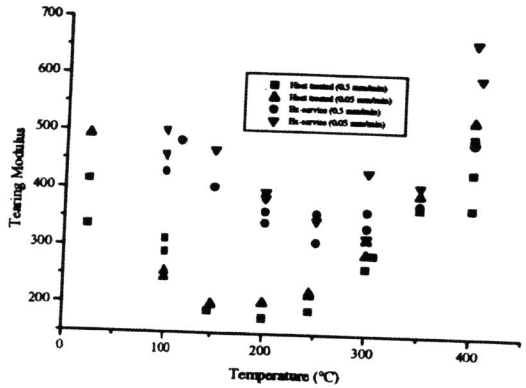

Figure 6 Tearing modulus as a function of temperature.

fracture during the test. It should be noted that fast fractures were experienced at 250 °C and 400 °C.

Conclusion

A method which allows the measurement of fracture toughness at elevated temperatures has been developed and proven.

Measurements conducted on low alloy carbon steel have demonstrated that dynamic strain ageing can affect the fracture toughness properties of these materials and that the assumption that fracture toughness is an increasing function of temperature is not correct.

As these materials are used widely in elevated temperature pressure plant, more work is needed to further quantify the effect on different samples of the material in an attempt to determine the effect on the integrity of pressure parts of dynamic strain ageing effects.

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