The Application of Fracture Mechanics to the Problem of Reheat Cracking in Low Alloy Steels during Postweld Heat Treatment

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INTRODUCTION

The problem of reheat cracking* is most commonly encountered in low alloy ferritic steels during postweld heat treatment, but also occurs during service at high temperatures and is found in austenitic steels and nickel-based alloys. The type of reheat cracking which forms the subject of this paper, occurs during the postweld heat treatment of low alloy steels containing secondary hardening elements such as molybdenum and vanadium. Cracking usually occurs at the prior austenite grain boundaries of the heat affected zone (HAZ) adjacent to the fusion boundary of the weld, and exhibits the morphology of creep failure. Reheat cracks often initiate from pre-existing defects such as liquation cracks or hydrogen induced cracks, usually at points of geometric stress concentration such as the weld toes of nozzles.

Many of the previous attempts to assess the susceptibility of steels to reheat cracking have suffered from various shortcomings such as the use of blunt notched specimens and higher strain rates than occur in practice.

The present work was undertaken in order to obtain data under experimental conditions more closely simulating practical situations than previous investigators and the experimental approach required the use of specimens containing sharp defects (fatigue cracks) sited in thermally simulated HAZ structures. Time to failure under constant load was measured at typical stress relief temperatures, and it was anticipated that the results could be analysed using fracture mechanics.

EXPERIMENTAL TECHNIQUE

Blocks of the steels to be investigated were programmed through a simulated weld thermal cycle to 1350°C using The Welding Institute's Weld Thermal Cycle Simulator, and were machined, notched and fatigue cracked on the centreline of the simulated HAZ region as shown in Fig. 1. Two sizes of specimen have been used. Type A ($a = 5$ mm, $W = 12.5$ mm, $B = 5$ mm) were tested in three point bend and type B ($a = 10$ mm, $W = 20$ mm, $B = 10$ mm) were tested in tension, both under constant load, after heating quickly to the temperature of interest.

Three test temperatures (550, 600 and 675°C) were chosen, spanning the temperature range for stress relief heat treatments of the steels investigated, and the stress intensity at the end of the fatigue crack was calculated from the compliance of the specimen and the applied load. A range of stress intensities was used, since cracks of different size in nominally the same residual stress field would experience different stress intensities. Because the residual stresses which cause reheat cracking are dependent on the yield stress of the region in which they lie, it was considered necessary to measure the yield

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*Also known as 'stress relief cracking', 'strain-age cracking' and 'postweld heat treatment cracking'.

stresses of the simulated HAZ structures at the three temperatures used, and at different times after reaching temperature, in order that the results of the fracture tests might be analysed more realistically.

EXPERIMENTAL RESULTS

The initial data obtained from three point bend specimens of type A were plotted as time to failure versus initial applied stress intensity, and a typical set of points for $2\frac{1}{4}$Cr Mo steel is presented in Fig. 2. Short times to failure and small applied stress intensities both indicate greater susceptibility to reheat cracking than high values. Increasing either the applied stress intensity or the temperature reduces the time to failure. This latter observation is contrary to practical behaviour, where progressive increase in the temperature of stress relief beyond a certain level, reduces the risk of cracking in the majority of situations. The reason for this apparent contradiction, is that measurement of stress intensity alone fails to take account of the decrease in acting residual stress as temperature is increased.

In this work the criterion a, B, W-a $>2.5\left(\frac{K}{\sigma_y}\right)^2$ was used to assess whether or not linear elastic stress intensities were measured. Although this criterion is based on fracture toughness tests at ambient temperatures or below for the assessment of brittle fracture susceptibility, in the absence of any other it was considered best to use this criterion as a basis for the present tests and modify it if experience showed it to be unsatisfactory. It was observed that all tests which satisfied this criterion initiated intergranularly over the complete width of the notch, without evidence of shear lips on the sides, indicating initiation under plane strain conditions. Those tests which did not satisfy the criterion were often found to have shear lips intervening on the fracture surface soon after initiation, and this was found to correspond to a change in fracture mode from intergranular to transgranular shear fracture. Whether or not measurements outside the linear elastic regime are relevant to this problem is not certain at this stage, but no transgranular failures of this kind have been reported. Typical fracture surfaces are shown in Fig. 4. Specimens that failed in short times (<10 hr) showed typical Zener type fracture (Fig. 4a) but at much longer times (>20 hr), evidence of grain boundary cavitation was observed (Fig. 4b), similar to that found in actual heat treatment failures (Fig. 4c).

Analysis of the results using fracture mechanics

If it is assumed that the acting level of residual stress in a weld HAZ is proportional to the yield stress of the HAZ at any given time and temperautre, then to a first approximation, the elastic stress intensity at the ends of a defect in the HAZ of length 2a would be $K \alpha \sigma_y \sqrt{\pi a}$ which may be rearranged to $a \alpha \frac{1}{\pi}\left(\frac{K}{\sigma_y}\right)^2$. If K represents the critical value for cracking to occur in a certain time at a given temperature, then 'a' is proportional to the size of defect necessary to cause cracking, and can thus be regarded as a defect tolerance parameter capable of indicating comparative susceptibility to reheat cracking. Accordingly, measurements of HAZ yield stress at the three temperatures of interest after different times were made, and the plots of calculated 'a' values are presented in Fig. 3 for the three steels investigated.

The results indicate that there is a worst temperature for each steel at which cracking occurs most rapidly for a given defect tolerance parameter value. This bears out practical experience as well as previous experimental findings. The data also bears out the observation in practice that $\frac{1}{2}$Cr $\frac{1}{2}$Mo $\frac{1}{4}$V steel is more susceptible to reheat cracking than $2\frac{1}{4}$Cr Mo steel and $\frac{1}{2}$MoB steel, which suggests that the technique is capable of distinguishing between materials.

The effect of specimen size and loading

During the later stages of this programme, single edge-notched tensile specimens were used in place of the bend specimens. Figure 5 presents data obtained using both types of specimen on $\frac{1}{2}$Cr $\frac{1}{2}$Mo $\frac{1}{4}$V steel. It will be noted that the data from both specimen types fall on the same curve, indicating that the change of specimen type and loading did not significantly affect the results.

DISCUSSION

The encouraging results obtained using the experimental technique described in this paper, lead to the conclusion that the method used has considerable potential as a means of assessing reheat cracking susceptibility in a more quantitative manner than has hitherto been possible. Although the comparisons between different steels made in this paper using a defect tolerance parameter can only be considered as qualitative, the quantitive basis of that parameter renders the present qualitative assessments more meaningful, by quantifying the relative susceptibilities, even though actual susceptibilities cannot be determined. In particular the lack of deformation at the ends of the fatigue crack on the surface of the specimen, together with the fact that changing specimen size, type and loading did not alter the results, suggests that a true linear elastic stress intensity was being measured in each test, thus confirming the validity of applying linear elastic fracture mechanics to this problem. Nevertheless, the technique in its present form does have certain limitations in relating to practical situations. The most significant of these is that during postweld heat treatment, residual stresses relax and the applied stress intensity at the end of a defect would thus be expected to decrease with time, and not remain constant up to the point of initiation of cracking as in the present tests. It is proposed therefore that future development of the technique should incorporate stress relaxation, preferably with temperature compensation to allow heating to be carried out at typical heating rates while specimens are loaded.

CONCLUSIONS

1. The results of this investigation have demonstrated that the susceptibility of steels to reheat cracking may be assessed using the techniques of fracture mechanics.
2. It is concluded that linear elastic fracture mechanics is more relevant to the problem of reheat cracking than general yield fracture mechanics.
3. The use of a defect tolerance parameter 'a' $\alpha \frac{1}{\pi}\left(\frac{K}{\sigma_y}\right)^2$ promises to be the best means of assessing the comparative susceptibility of different materials.
4. The limitations of the technique as presented in this paper, can be overcome by designing equipment to simulate the conditions of stress relaxation that occur in practice, by applying weld heat treatment cycles to specimens loaded at room temperature.

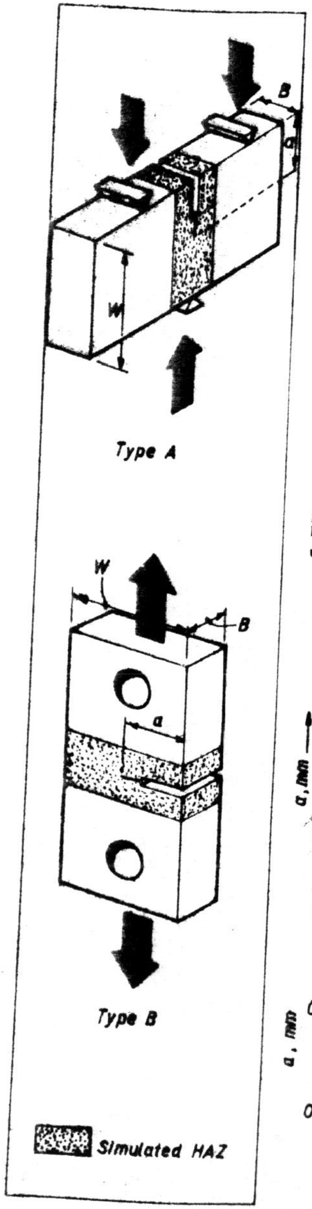

Fig. 1. Fracture toughness specimens used in the investigation.

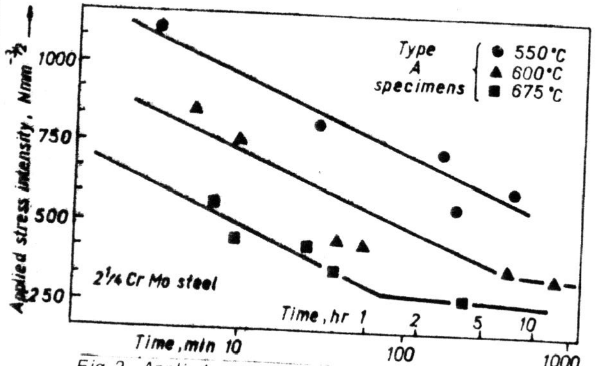

Fig. 2. Applied stress intensity versus time to failure.

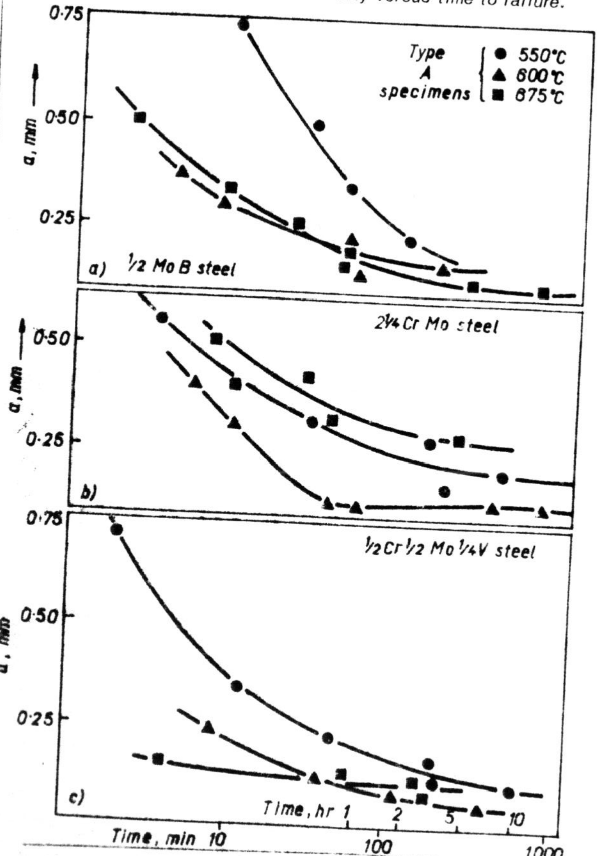

Fig. 3. Variation of defect tolerance parameter $a = \frac{1}{\pi}\left(\frac{K}{\sigma_y}\right)^2$ with time to failure for three steels investigated.

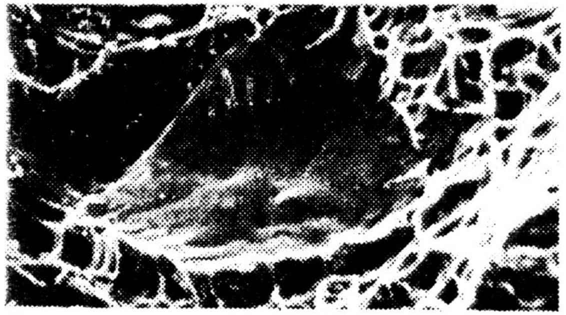

Fig. 4a. Zener type fracture. Scanning electron micrograph, x 500.

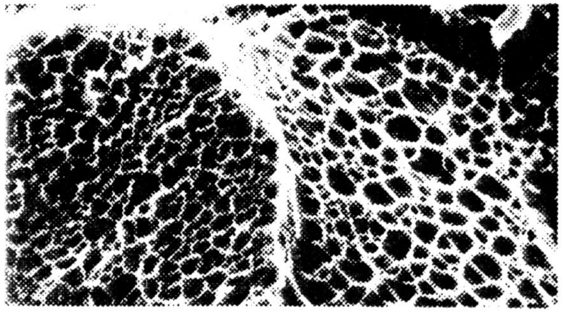

Fig. 4b. Grain boundary cavitation. Scanning electron micrograph, x 1000.

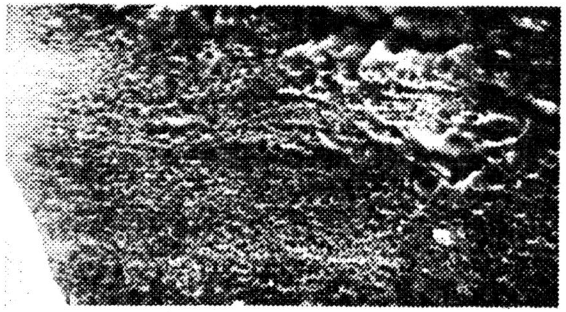

Fig. 4c. Surface of reheat cracks formed in the HAZ during heat treatment for 48 hr at 640°C, of a structure in a steel containing Mo and V. Scanning electron micrograph, x 1000.

Fig. 4. Fracture surfaces of reheat cracks showing evidence of creep failure.

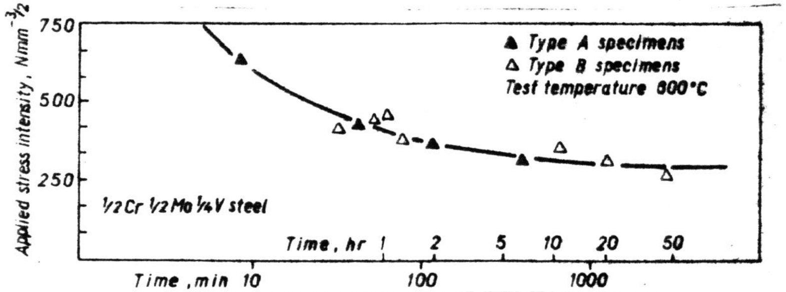

Fig. 5. Data from three point bend and tension specimens.