THE EFFECT OF CYCLIC THERMAL STRESS ON CRACK PROPAGATION IN CYLINDRICAL STAINLESS STEEL COMPONENTS.

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Thick tubular components of a specific AISI 316L stainless steel, containing longitudinal defects, were subjected to thermal fatigue/creep loading. Two surface temperature shocks were imposed, from 80°C to 600°C and 80°C to 650°C, with hold times varying from zero to 2½ hours imposed at the maximum temperature during the cycle. The higher temperature shock promoted increased crack growth rates across the wall thickness. In addition, the longer hold times enhanced the crack propagation rates within a region at the component surface, defined by the specific stress and temperature distributions during the hold time. Furthermore, this enhancement was limited, in terms of hold time, due to the relaxation of the creep driving forces.

INTRODUCTION

Type 316L stainless steel is widely used in heat exchanger structures for a broad range of elevated temperature engineering applications. It has gained considerable importance in fast reactor service and as a candidate material for use in the European fusion reactor programme. Common to these applications are the transient thermal loads which develop due to plant start-up and shut-down, producing severe thermal shocks and stress gradients which vary with both distance from the shocked surface and time, as a function of the temperature distribution within the component. Superimposed on this behaviour is the time dependent material response occurring during normal plant operation. Thus, an understanding of the effect of different thermal shocks and the combined influence of hold times at maximum temperature is essential for the development of reliable structural integrity assessment procedures for components subjected to thermal loading, such as heat exchangers and turbine blades.

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EXPERIMENTAL METHODS

In order to understand and to predict crack growth in engineering components it is necessary to simulate the fluctuating thermal gradients consistent with their applications. In order to generate the thermal gradients, induction heating was used to externally heat the tubular components in conjunction with continuous internal water cooling. The experimental programme used surface temperature cycles of 80-600-80°C and 80-650-80°C, with hold times imposed at the maximum temperature during the cycle varying from zero, for the thermal fatigue case, to dwell periods of up to 2½ hours, for the thermal fatigue/creep case. Free expansion was allowed in the axial direction. Further details of the experimental set up, temperature control and the material characterisation are given in a previous publication, O'Donnell et al. (1).

To investigate the stress concentrations developed in real components, longitudinal defects were introduced in the component surface. The notches were electro-eroded (length = 15 mm, width = 0.5 mm and depth = 1.0 mm) and had rounded ends to avoid stress concentration from sharp corners. Continuous in situ monitoring of the crack growth rate from these artificial defects was achieved using a direct current/potential drop technique (d.c./p.d.), specially adapted for the component type test piece. One of the major advantages in the present study was the effectiveness of the d.c./p.d. in obtaining the necessary crack growth information. The calibration used was derived initially from 2-D foil calibration experiments and subsequently improved with interrupted test data.

ANALYSIS

Due to the thermal shock loading imposed the component was subjected to a transient fatigue cycle, where a temperature down-shock created a tensile stress at the shocked face and a corresponding compression at the opposite face to accord with the balance of forces across the wall thickness. The temperature up-shock, therefore, provided for a compressive stress at the external surface. During the subsequent hold time the residual stress field allowed for a tensile stress to develop in a region at the external (hot) surface. More importantly, this tensile residual stress relaxed with time imparting a creep loading within the region where there was sufficient tensile stress and temperature. However, once the residual stress was fully relaxed no further increase in the inelastic strain could occur (the influence of creep in this instance was to increase the inelastic strain during the hold period). The necessary stress/strain fields were calculated via finite elements, see O'Donnell et al. (2), where the influence of the notch, the variation of material properties with temperature and the fatigue hardening observed for this material were taken into account.

Based on the definition of an equivalent elastic stress distribution (2), i.e. the elasto-plastic stress plus the plastic strain augmented by the appropriate elastic modulus, an effective stress intensity factor was determined via the weight function method, Petroski and Achenbach (3). The application of an elastically calculated parameter may not at first seem reasonable for high temperature fatigue and creep behaviour. However, it is reported that the effective stress intensity factor better represents the crack driving force in a strain limited loading condition, such as pure thermal loading with no end constraint, Haigh and Skelton (4). The calculation of the effective stress intensity factor range was based on the finite element solutions over one complete thermal cycle, obtained after the mechanical steady state was attained, i.e. after shakedown. The development of the crack shape from the longitudinal defect into a semi-elliptical crack shape was accounted for in the shape functions necessary for the weight function calculation, given in (2), where an interpolation function between the two limiting stress intensity factor solutions was derived from the d.c./p.d. observations.

RESULTS AND DISCUSSION

A number of approaches to thermal fatigue analysis involve an assessment of the damage to cause crack initiation, whereas less attention has been paid to the crack propagation process. Most engineering components are not subjected to loading cycles as severe as those in the present work and crack initiation is therefore of most concern. However, if there are pre-existing cracks or if cracks initiate and can be detected, by non-destructive methods or otherwise, then it becomes increasingly important to understand how the cracked component will behave. Furthermore, under the imposed thermal loading the classical fatigue crack initiation stage was effectively by-passed, due to the interaction of elevated temperature, cyclic plasticity, creep and oxidation effects, and the component life was determined exclusively by the crack propagation behaviour, based on the effective stress intensity factor range.

The experimental observations of crack development, O'Donnell et al. (5), demonstrated that the various hold times imposed could be grouped together as a function of the length of the hold time into cycles with no hold time and cycles with intermediate (1.5 to 3.0 minutes) and long hold times (10 minutes to 2½ hours), where the experimental results for each grouping are presented in this paper.

To demonstrate the quality of the theoretical calculations, the experimental crack growth rates for both the thermal fatigue and thermal fatigue tests with hold times were plotted against the calculated stress intensity factor range, see Figures 1 and 2 for both of the temperature cycles investigated. The symbols represent the experimental values and the solid lines show the best fit through each set of data. Due to the gradient in the induced stress/strain field, reducing from a maximum at the component surface, both the experimental crack growth rates and the calculated range of stress intensity factor were initially large with both decreasing as the crack extended. The direction of increasing crack length is shown in Figure 2. More importantly, it is obvious from both these figures that all the experimental crack growth rates exhibit a linear dependence on the calculated range of the equivalent elastic stress intensity factor.

It is generally accepted that higher temperatures result in decreased fatigue lives, and although the maximum temperature was increased by only 50°C, from 600°C to 650°C, the magnitude of the crack growth rates observed for the higher temperature cycle were nearly twice that for each case at the lower temperature cycle. The enhancement of crack growth rate in 316L stainless steel with increasing temperature is not surprising due to the combination of slightly lower mechanical strength properties and the larger stress/strain fields induced for the higher temperature thermal shock, in particular the increase in the cyclic plastic strain range with temperature.

It was shown (5) that even a short hold time resulted in an increase in the thermal fatigue stress field, corresponding to higher crack growth rates for all tests with hold times across the component wall. In addition, both figures clearly illustrate the influence of increasing hold time on the crack growth rates. The longer hold time tests exhibit a further, small but significant, enhancement of the early crack growth rates over those observed for the intermediate hold times. The increased crack growth rates were accompanied by a change in the mode of cracking from transgranular to a mixed mode of intergranular and transgranular in the region supporting sufficient tensile stress and temperature, shown in Figure 3 for a test with a 1 hour hold period and a maximum temperature of 600°C. With further crack extension beyond this creep affected region, the crack path reverts to a purely transgranular mode of propagation and therefore the crack growth rates for the different hold time tests converge to similar values with increasing crack penetration. This latter point is illustrated in Figures 1 and 2 where the crack growth rates for long hold time data tended to converge to those of the intermediate hold times with increased crack depth, but always remained higher than the experimental crack growth rates with no hold time.

The extent of the enhancement of the thermal fatigue crack growth rates due to increased hold time is, however, limited due to the specific loading conditions imposed in the present study. In the absence of primary mechanical loads, the creep element is self reducing, i.e. the residual stress which drives the creep mechanisms relaxes and in turn reduces the creep rate. Therefore with longer hold times, no further increase in the crack growth rates would be expected.

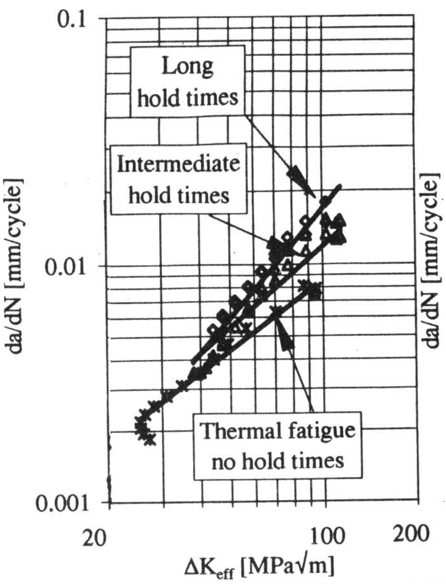

Figure 1 Experimental crack growth rates (80-600°C cycle).

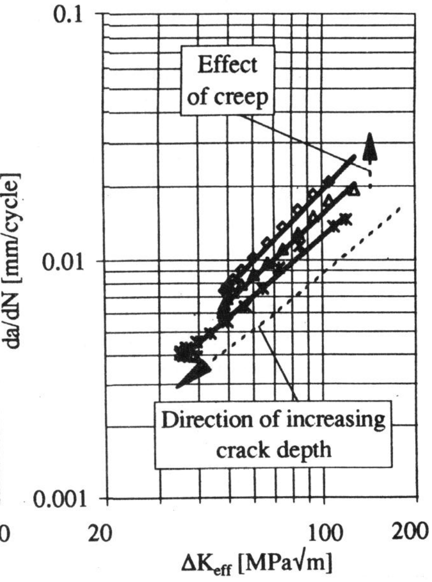

Figure 2 Experimental crack growth rates (80-650°C cycle)

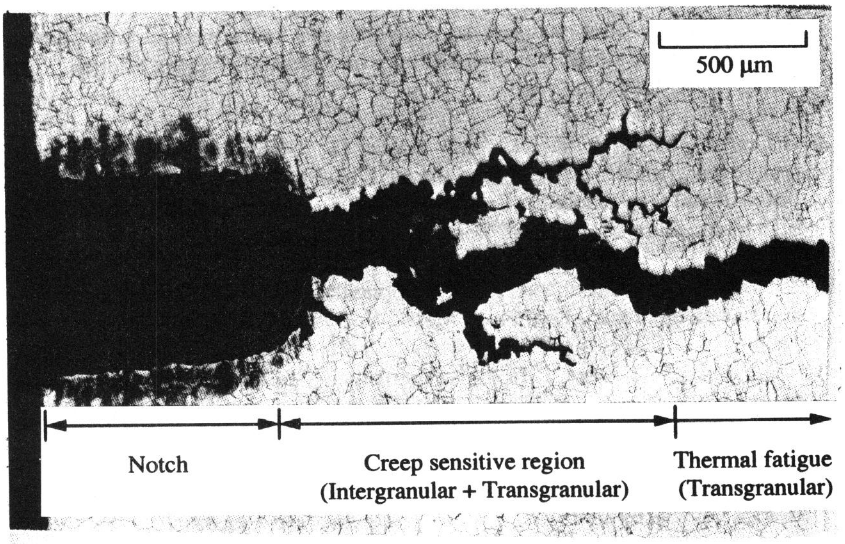

Figure 3 Metallographic observations of the crack path development.

CONCLUSIONS

1. Increasing the maximum temperature of the surface thermal shock from 600°C to 650°C, produced higher crack growth rates across the component wall.

2. With increasing hold time the crack growth rates within the creep sensitive region were enhanced and accompanied by a change in the mode of cracking. However, the increase in crack growth rate was limited due to the relaxation of the creep stresses.

3. At crack depths greater than the creep sensitive region the crack growth rates for all tests with hold times converged to those of a thermal fatigue cycle with a short hold time, for both temperature cycles examined.

SYMBOLS USED

ΔK_{eff}	Effective stress intensity factor range.
da/dN	Experimental crack growth rates.

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