Spot heating induced fatigue crack growth retardation

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Abstract

Retardation in a growing fatigue crack can be achieved by heating (to a sub-critical temperature) a spot ahead of the crack. The retardation behaviour is comparable to that obtained in a specimen subjected to an overload spike. It is observed that the retardation increases with increase in spot heating temperature. The maximum retardation is obtained in specimens spot heated at a position 5 mm ahead of the crack tip.

Keywords: Spot heating; Overloading; Delay cycle; Fatigue crack growth retardation

1. Introduction

Despite advances in the understanding of fatigue failure and consequent improvements in design of structures and components, fatigue is still the most common cause of failures in service. Many investigators have shown that the imposition of an overload cycle during fatigue crack growth causes retardation of a propagating fatigue crack [1–3]. The application of an overload cycle introduces a plastic zone ahead of the crack tip [4]. The elastically deformed medium surrounding this plastic zone creates a compressive stress field around the crack tip. These compressive stresses reduce the available crack tip driving force, and cause a significant reduction in fatigue crack growth rate (FCGR) [5]. The extent of retardation is usually expressed in terms of the total number of cycles involved during retardation (called delay cycle, N_D) and the overload affected total crack length, a_D [2,4] (Fig. 1).

Several different techniques are known to retard a growing fatigue crack [6,8]. One method involves heating the whole cross-section of a component while the maximum load experienced in service is maintained [6]. This introduces a suitable compressive residual stress field around the fatigue crack. However, this can lead to general yielding in the heated region as the yield stress decreases with increase in temperature. A technique suggested by Harrison [7] involves direct heating near the crack tip. However, this requires heating at a precise location and such direct heating damages the surface. A more recently proposed method involves simultaneous localised heating over a large area around the crack tip and an overload application [8]. The state of hot spot while the overload is maintained introduces a plastic zone larger than that produced by an overload spike in a specimen at room temperature. This is due to the decrease in yield stress with increasing temperature. This technique and the simple overload application require controlled loading of the structure. It may be noted that in a complex structure, application of overload may require a special fixture.

2. Experimental method

The method proposed here involves the indirect local heating of the region around the crack tip under zero load. The non-uniform heating is intended to introduce a beneficial compressive residual stress field, which in turn is expected to retard a fatigue crack.

The material investigated was a 3.4 mm thick, 0.08% carbon steel sheet (yield stress = 267 MPa). The single edged notched (SEN) specimens of 170.0 mm × 50.0 mm × 3.4 mm dimensions in the LT orientation were used for fatigue testing. The notched specimens were fatigue precracked up to a length of 8.00 mm before the actual fatigue tests.

The fatigue tests were carried out in tension–tension constant stress amplitude sinusoidal loading conditions. The tests were performed at a frequency of 150 Hz, stress ratio $R = 0.20$, and stress range $\Delta\sigma = 87.0$ MPa. The

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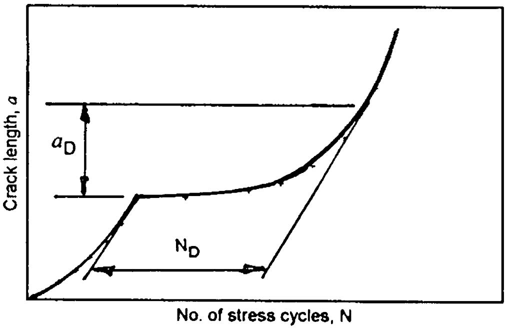

Fig. 1. Effect of an overload spike on fatigue crack growth (schematic).

fatigue crack growth was monitored with the help of a low magnification microscope.

The first few pre-cracked specimens were tested and data were used as reference for the subsequent set of experiments.

The second set of specimens was tested under constant amplitude fatigue loading up to a crack length of 11.00 mm (corresponding to $\Delta K = 23.02$ MPa m$^{1/2}$). Then each specimen was subjected to an overload spike. The subsequent crack growth was performed under constant stress amplitude loading condition. These data are used to compare the retardation in overloading with the spot heated specimens.

In the last set of experiments, specimens were fatigue loaded under constant amplitude up to a crack length of 11.00 mm. Afterwards, the specimens were withdrawn from the testing machine, spot heated, and subsequently tested under fatigue, maintaining the same constant amplitude loading conditions.

The indirect heating (i.e. through thermal conduction) of each specimen was done using a 7.0 mm thick and 12.0 mm diameter steel button. The spot heating zone was identified and the hot ends of the thermocouples were spot welded on either face of the specimen. A well-polished steel button was placed firmly over the top face of the specimen with the help of an adhesive (M-seal). An oxyacetylene gas flame was applied to the button and the temperatures of both surfaces of specimens were monitored. The top face temperature of the specimen is reported and analysed in the present study. The local heating temperature ranges from 300 to 700 °C. The final peak spot temperature of the specimen was achieved by heating approximately at a rate of 9.5 °C/s.

The region surrounding the button was protected from the direct flame of the gas torch and cooled by covering it with oil-wet cotton and asbestos sheet.

The fatigue pre-cracked tip was taken as the reference position for heating the specimens. The centre of the hot spot was varied from -3 (3.00 mm behind the crack tip) to $+7$ (7.00 mm ahead of the crack tip). The heating spots over the specimen are shown in Fig. 2.

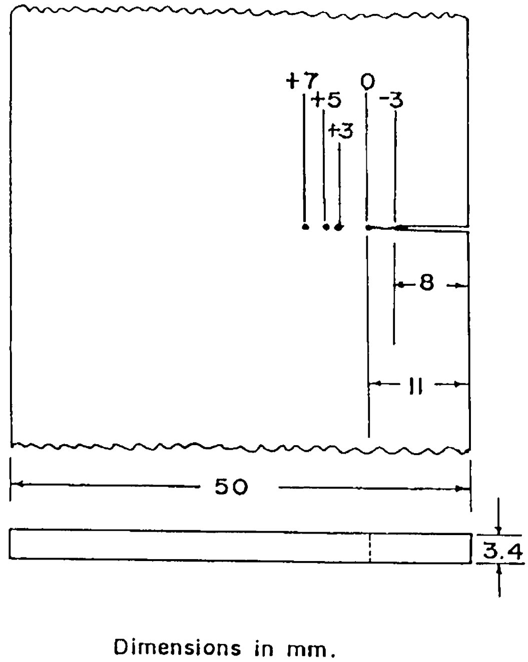

Fig. 2. Location of heating spots on specimen.

3. Results

The effects of an overload spike and spot heating on fatigue crack growth behaviour are typically presented in the form of crack length and number of stress cycles in Fig. 3. The figure shows that the fatigue crack is retarded by introduction of an overload spike as well as heating a spot ahead of the crack tip. It may also be seen that both the overloading and spot heating modify the crack growth behaviour in a similar way. Since the nature of retardation is the same in both the conditions, the conventional retardation parameter (used to represent the extent of retardation in overloaded specimen) can also be used to present the magnitude of retardation due to localised heating.

The results of spot heating specimens at different locations are presented in Fig. 4 in the form of crack length, a and a number of stress cycles, N. It may be seen from the figure that there is no retardation on heating specimens at

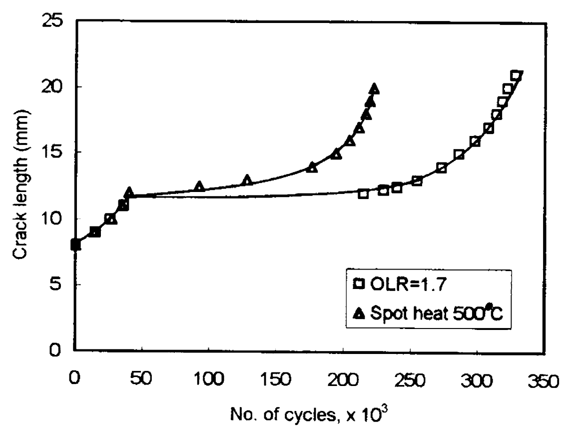

Fig. 3. Comparison of the effects of overloading and spot heating on crack extension.

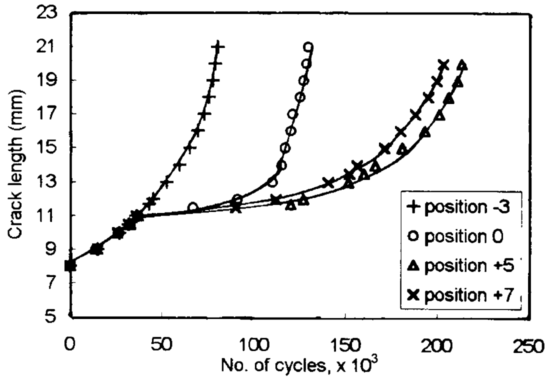

Fig. 4. Effect of heating positions on crack growth (at 500 °C).

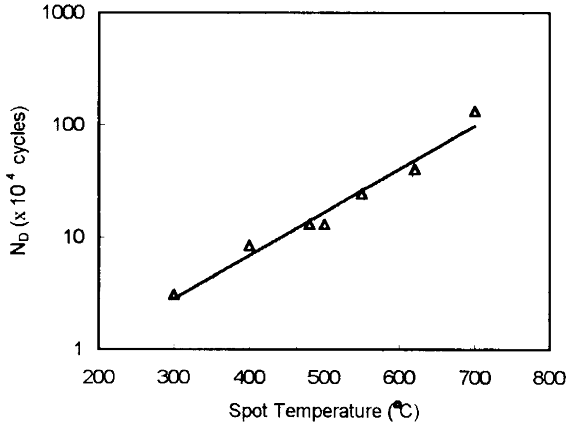

Fig. 6. Delay cycle (N_D) as a function of spot temperature (+5 position).

position −3. However, heating at positions 0, +5, and +7 produced significant retardation. It may also be seen that the optimum retardation is observed at heating position +5, i.e. 5 mm ahead of the crack tip. This position of heating also registered a much wider range of crack length over which retardation is experienced. This heating position also recorded the lowest value of the maximum crack growth rate, i.e. the slope of the curve subsequent to spot heating. This indicates that heating at the +5 position is most effective in retarding a growing fatigue crack. There is no appreciable reduction in retardation behaviour on shifting the location of heating to the +7 position. This shows that the location of heating is not very critical beyond a certain distance ahead of the crack tip. However, identification of the most suitable spot heating position requires further investigation.

The result of spot heating temperature on crack growth behaviour at the +5 position is presented in Fig. 5. It is evident that the magnitude of the retardation increases with increasing the spot heating temperature. The retardation effect occurs even on spot heating the specimen to 300 °C. However, the observed magnitude of the delay cycle is just 1.85×10^4 cycles whereas the delay cycle increases to a level of 1.34×10^6 cycles on increasing the heating temperature to 700 °C. The observed crack growth retardation may be due to the development of residual compressive stresses as a consequence of the non-uniform heating of the specimen. The increase in crack growth retardation with increasing spot temperature may be a result of enhanced residual compressive stresses around the crack tip.

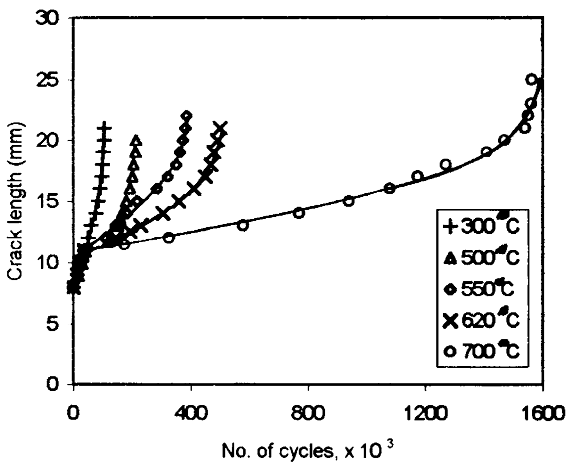

Fig. 5. Effect of spot heating temperature on crack growth (heating position +5).

The retardation parameter N_D is obtained from the plot of crack length vs. number of stress cycles (logarithmic scale) and is presented in Fig. 6 as a function of spot heating temperature. It may be seen that the delay cycle increases linearly with sub-critical spot heating temperature on a semi-logarithmic scale. It may also be noted that the spot heating temperature affects the delay cycles in a similar way to that of overloading [1].

4. Conclusions

On the basis of the above findings it is concluded that spot heating retards a growing fatigue crack in a similar way to overloading. In the present study the maximum extent of retardation is noticed on spot heating at a position 5 mm ahead of the crack. It is also concluded that the magnitude of retardation increases with the sub-critical spot heating temperature.

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