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A study on spot heating induced fatigue crack growth retardation

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ABSTRACT The propagation of a growing fatigue crack can be effectively retarded by heating a spot near the crack tip (under zero stress condition). Spot heating to a subcritical temperature and at a precise location modifies the crack growth behaviour in a way, more or less, similar to specimens subjected to an overload spike. It is observed that the magnitude of spot heating induced crack growth retardation increases with increase in spot temperature. It is also observed that the crack growth behaviour is influenced by the position of the heating spot and there exists an optimum position of hot spot that produces maximum retardation in fatigue crack growth rate. The plastic zone length due to spot heating has been estimated using experimental data. It is found that the plastic zone length due to spot heating increases exponentially with increase in spot temperature. The Wheeler model for crack growth retardation has been modified by introducing a plastic zone correction factor λ. The values of λ and the shaping exponent, m, in the Wheeler model have been obtained for different spot heating temperatures.

Keywords fatigue crack growth retardation; plastic zone size; spot heating; Wheeler model.

NOMENCLATURE

a = crack length
a_0 = initial crack length at which spot heating is done
a_i = crack length at ith cycle (instantaneous crack length)
a_D = overload/spot-heating affected retarded crack length
C = constant used in the Paris equation
C_{p_i} = retardation factor
d = distance of the heating spot from the crack tip
da/dN = fatigue crack growth rate (FCGR)
D = button diameter
E = modulus of elasticity
m = shaping exponent in the Wheeler model
n = exponent used in the Paris equation
N = number of stress cycles
N_D = delay cycles
R = stress ratio = $\sigma_{min}/\sigma_{max}$
T = spot temperature
w = width of specimen
$z_m{}^{OL}$ = overload induced monotonic plastic zone length
z_{c_i} = cyclic plastic zone length corresponding to ith cycle
z_D = cyclic plastic zone length at the end of retardation
Z_{ST} = length of plastic zone due to spot heating
α = average coefficient of linear expansion

γ = retardation correction factor = λ^m
λ = cyclic plastic zone size correction factor
ΔK = stress intensity factor range = K_{max}–K_{min}
σ_{max} = maximum cyclic stress
σ_{min} = minimum cyclic stress
σ_y = yield stress
$\Delta\sigma$ = stress range = $\sigma_{max} - \sigma_{min}$

INTRODUCTION

Application of an overload spike or band overload during constant amplitude high cycle fatigue retards a propagating fatigue crack.[1–7] The overload introduces a large plastic zone and hence enhances the magnitude and size of compressive residual stress field in the vicinity of the crack tip. This enhanced compressive residual stress field reduces the available crack tip driving force, thus causing a reduction in fatigue crack growth rate (FCGR).[4–7] 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 retarded crack length, a_D.[5] These retardation parameters are shown in Fig. 1.

Another technique involves heating a zone ahead of the crack tip and then cooling to ambient temperature. During cooling, while the centre of the hot spot cools at a slower rate, the edges of the hot spot cools at a faster rate. Localized heating followed by non-uniform cooling introduces uneven distribution of inelastic strains which cause residual stress to develop.[8] It is reported[8,9] that the residual stress in the radial direction is tensile in nature and this zone of tensile residual stress is surrounded by a larger compressive residual stress field. Thus, the plastic zone ahead of the crack tip consists of a small residual tensile stress field surrounded by a larger compressive stress field. It is this residual compressive stress, which gives rise to retardation effect. Lam and Griffiths[10] suggested heating the whole cross-section when the component experiences maximum service load. This may be difficult to achieve and heating the whole cross-section may lead to general yielding because yield stress decreases with increase in temperature. Harrison[11] suggested direct heating at a precise location near the crack tip. However, direct heating may cause damage to the surface of the specimen/component. Chen *et al*.[12] suggested simultaneous localized heating over a large area near the crack tip and overload application to retard a growing fatigue crack. The method used in the present study involves indirect local heating at a precise position near the crack tip.[13–15] It is reported[13] that subcritical spot heating results no microstructural changes and the spot heating induced crack growth retardation is similar to the retardation caused by an overload spike. However, spot heating differs from overloading in that the compressive stress zone may extend into a region behind the crack tip, bringing about an increase in crack closure level. The present work attempts to locate the optimum position of the heating spot to effect maximum retardation of a growing fatigue crack. An attempt has also been made to estimate, based on experimental data, the plastic zone size (PZS) in a spot heated specimen. Finally, a cyclic plastic zone correction factor has been incorporated in the Wheeler model[16,17] for crack growth retardation, and the values of this correction factor and the shaping exponent in the Wheeler model have been worked out.

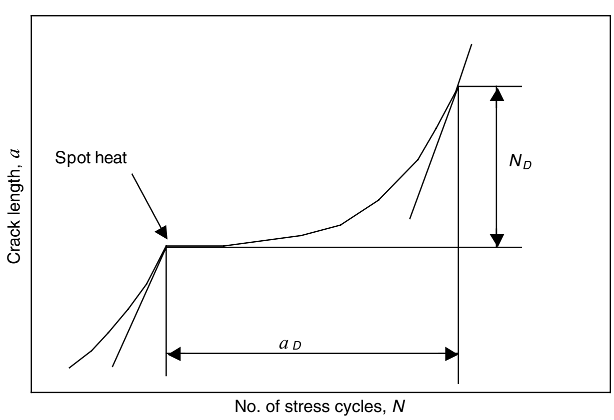

Fig. 1 Schematic representation of retardation parameters.

EXPERIMENTAL PROCEDURE

The material used in the present investigation was carbon steel (C—0.08, Mn—0.42, Si—0.05, S—0.03, P—0.04) in sheet form having a yield stress of 267 MPa. Single-edge notched (SEN) specimens of dimension 50 mm × 170 mm × 3.4 mm were prepared in the LT-direction. The notches were of flat type cut with jewellery saw up to a length of 6 mm. Before the fatigue test, the notched specimens were precracked up to a length of 8 mm (including the notch length of 6 mm, i.e. $a/w = 0.16$).

The fatigue tests were carried out in tension–tension constant stress amplitude mode using sinusoidal loading conditions in an Instron-1603 electromagnetic resonance (EMR) machine. The tests were performed at a stress ratio $R = 0.2$ and stress range $\Delta\sigma = 87$ MPa. The operating frequency was 150 Hz. Crack growth was monitored by a low-magnification microscope.

The precracked specimens were fatigue loaded under constant stress amplitude ($R = 0.2$, $\Delta\sigma = 87$ MPa) up to a crack length of 11 mm ($a/w = 0.22$), when the specimens were removed from the machine, spot heated and then again tested under fatigue at the same constant stress amplitude condition.

The indirect local heating was done using well-polished steel buttons, 7 mm thick and 12 mm in diameter. The hot ends of thermocouples were spot welded at the position to be spot heated (spot welded on both sides of the specimen). A well-polished steel button (with a narrow half slit to accommodate the hot end of thermocouple) was placed firmly over the top face of the specimen with the help of an adhesive (*M-seal*). Oxyacetylene gas flame was applied to the button and temperatures of both the surfaces of the specimen were monitored. However, the temperature of only the heating side of the specimen has been considered for analysis in the present study. As it was a sheet sample having a small thickness, heating was done on one side only and the temperature gradient across the thickness was ignored in this study.

The local heating temperature ranged from 300 to 700 °C. The oxyacetylene flame heating was done approximately at a rate of 9.5 °C per second. Figure 2 shows a typical heating and cooling curve (for specimen spot heated to 700 °C). The region surrounding the button was protected from direct flame of the gas torch and kept cool by covering it with cotton soaked in oil and pieces of asbestos sheet. The crack tip was used as the reference for locating the heating spot. The centres of hot spots were –3 (3.00 mm behind the crack tip), 0 (at the crack tip) and +3, +5, + 7 (3.00, 5.00, 7.00 mm ahead of the crack tip, respectively). The various heating positions are illustrated in Fig. 3.

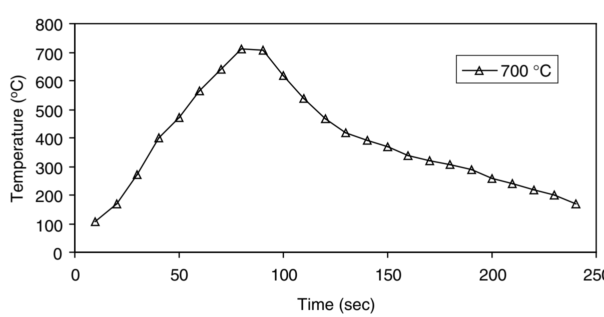

Fig. 2 Typical heating and cooling curves (spot temperature = 700 °C).

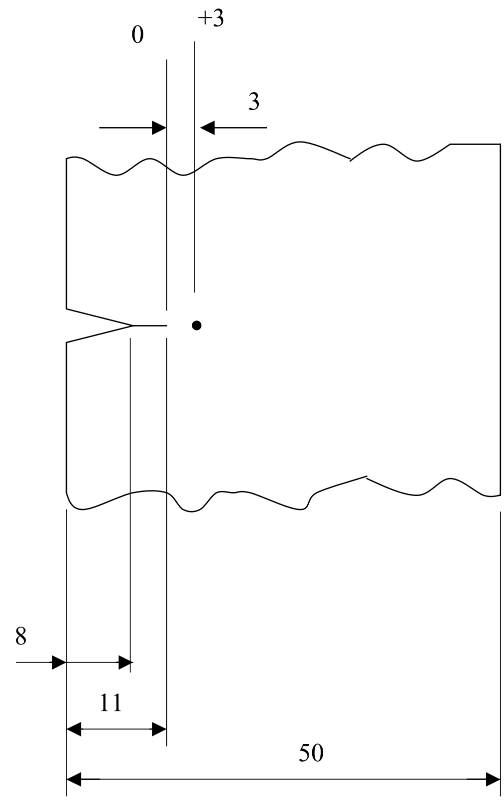

Fig. 3 Specimen dimensions and location of heating spots (position '0' and position '+3').

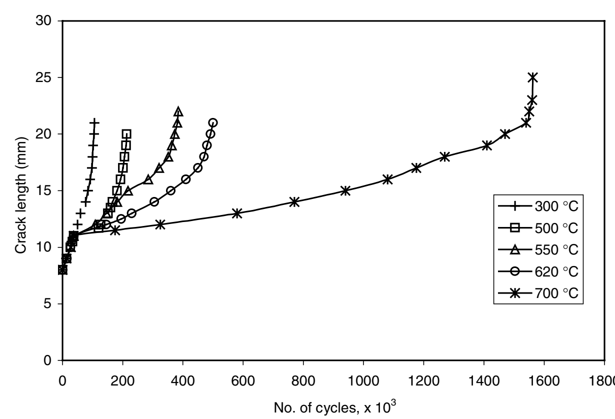

Fig. 4 Effect of spot heating temperature on crack growth (+5 heating position).[15]

RESULTS AND DISCUSSIONS

Effect of spot temperature on crack growth behaviour

The effect of spot heating to a subcritical temperature (at +5 position) on crack growth behaviour is presented in Fig. 4. It may be seen that the retardation effect increases with increase in spot temperature. The retardation effect is observed even at a temperature as low as 300 °C.

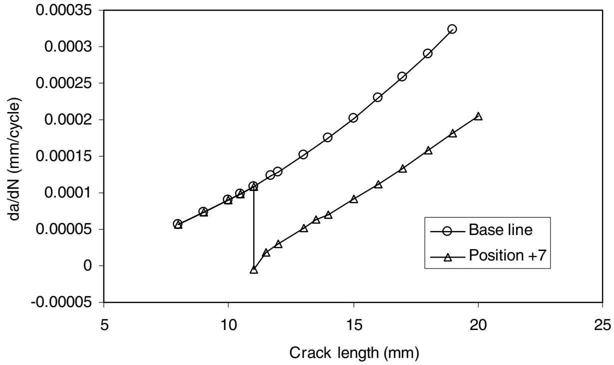

Fig. 5 Variation of FCGR with crack length (for specimens without spot heating and specimens spot heated to 500 °C at button position +7 mm).

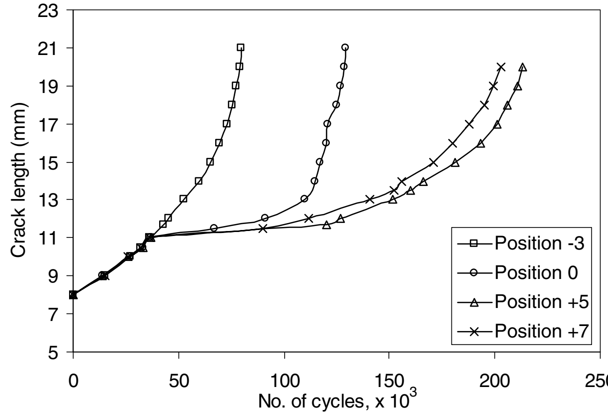

Fig. 6 Effect of spot heating positions on crack growth (spot temperature = 500 °C).[13,15]

However, the magnitude of delay cycle (N_D) is only 1.85 × 10^4 cycles at 300 °C compared to 1.34 × 10^6 cycles at 700 °C. The increase in retardation may be due to increased residual compressive stress field near the crack tip and/or enlargement of the stress field developed due to non-uniform heating.[13,15]

The variation of FCGR (da/dN) with crack length is shown in Fig. 5. The baseline data obtained from specimens without spot heating are superimposed on this plot for the purpose of comparison. The retardation zone is defined by the position where the retarded da/dN attains the value of baseline da/dN at $a = a_0$ (i.e. the crack length at which spot heating was carried out). It is seen from the figure that there is retardation in FCGR due to spot heating (spot heating done at crack length of 11 mm, button position = +7 mm, spot temperature = 500 °C) and it shows a sharp drop in FCGR followed by prolonged retardation. However, there is no immediate crack growth acceleration due to crack extension as is found in case of an overload application.[13] In contrast, the negative FCGR at 11 mm suggests increased crack closure effect due to the compressive residual stress field both ahead and behind the crack tip. The optical microphotographs presented by Verma and Ray[13] showed that spot heating had closed the crack with enhancement in crack closure level. These microphotographs also revealed the absence of crack-tip blunting/deflection which usually occur with overload application. This indicates that the crack closure effect is due to the compressive stress field only.

Effect of spot heating position on crack growth behaviour

The effect of the position of spot heating (spot temperature = 500 °C) on crack growth behaviour is presented in Fig. 6. The spot heating positions are measured (in mm) from the crack tip to the centre of hot spot (i.e. 0 position corresponds to crack tip), the positive direction being in the direction of in-plane crack propagation. It is observed from the figure that there is no appreciable retardation effect for specimens spot heated at –3 heating position. The retardation effect increases with increase in distance of heating spot from the crack tip up to +5 position. However, the retardation effect decreases at +7 spot position. Hence, it may be concluded that there exists an optimum spot heating position where the retardation effect is maximum.

Determination of optimum spot heating position

It is concluded from Figs 4 and 6 that the fatigue crack propagation at a particular stress level, crack length (a) is a function of spot distance (d) measured from the centre of the disc, number of cycles (N) and spot temperature (T), i.e.

$$a = \varphi(d, N, T). \quad (1)$$

At a given spot temperature the above relation reduces to

$$a = \varphi(d, N). \quad (2)$$

Analysing Fig. 6, the least square curve fitting technique gives the following equation of crack length for +3 mm $\leq d \leq$ +7 mm and 125 × 10^3 cycles $\leq N \leq$ 225 × 10^3 cycles.

$$a = A_3 N^3 + A_2 N^2 + A_1 N + A_0, \quad (3)$$

where $A_3 = 3.27 \times 10^{-6} d^2 - 3.846 \times 10^{-5} d + 1.1685 \times 10^{-4}$, $A_2 = 8.3352 \times 10^{-4} d^2 - 9.7562 \times 10^{-3} d + 3.0191 \times 10^{-2}$, $A_1 = 6.9252 \times 10^{-2} d^2 - 8.0487 \times 10^{-1} d + 2.5827$, $A_0 = 1.8171 d^2 - 21.03999 d + 61.14895$.

The analysis of Eq. (3) shows that under the present test condition (spot temperature = 500 °C), the retardation effect is maximum when the distance (d) of the heating spot is +5.853 mm measured from the crack tip. The effects of d and N on FCGR (da/dN) are shown in Fig. 7.

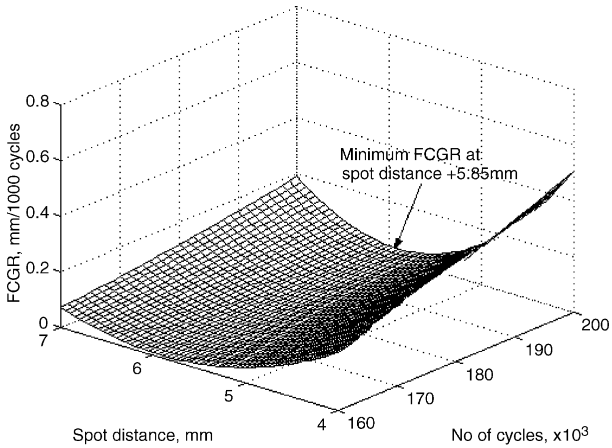

Fig. 7 Variation of FCGR with spot distance and number of cycles (spot temperature = 500 °C).

Estimation of plastic zone size due to spot heating

According to the Wheeler model,[16,17] the retardation effect ceases when the tip of the instantaneous cyclic plastic zone (z_{c_i}) reaches the end of the overload affected monotonic plastic zone (z_m^{OL}). Because of the similarity of crack growth behaviour due to an overload spike and spot heating,[13] it is reasonable to assume that the retardation effect ceases when the tip of the instantaneous cyclic plastic zone (z_{c_i}) reaches the end of the plastic zone due to spot heating (Z_{ST}). These are shown through Fig. 8a–c. Figure 8a shows the formation of plastic zone (Z_{ST}) due to spot heating. The progress of a crack through the plastic zone due to spot heating is shown in Fig. 8b. During this period, the crack growth gets retarded and there is an instantaneous cyclic plastic zone (z_{c_i}) at the tip of the crack. Retardation ceases when the crack advances and the instantaneous cyclic plastic zone reaches the end of the plastic zone due to spot heating (Fig. 8c). At this instance, z_{c_i} is denoted by z_D. Thus, the plastic zone length (Z_{ST}) due to spot heating may be written as

$$Z_{ST} = z_D + a_D, \quad (4)$$

where $z_{c_i} = z_D = (1/\pi)\,(\Delta K/\sigma_y)^2$

$\Delta K = f(g)\cdot\Delta\sigma\sqrt{(\pi a)}$

$f(g) = 1.12 - 0.231\,(a/w) + 10.55\,(a/w)^2 - 21.72\,(a/w)^3 + 30.39\,(a/w)^4$ [Ref. 16]

and $\ln a_D = 9.1 \times 10^{-3}\,T - 3.80$ [Ref. 13]

Figure 9 shows the variation of plastic zone length with hot-spot temperature. It is found that the plastic zone length increases exponentially with spot temperature. The relationship can be expressed as

$$Z_{ST} = 0.0714e^{0.00766T}, \quad (5)$$

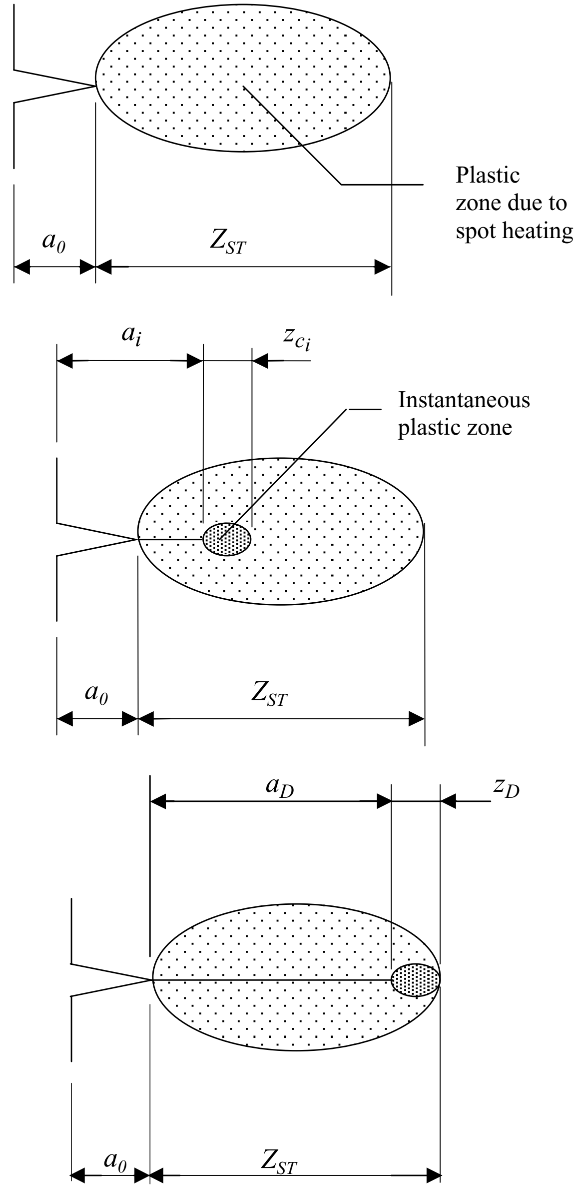

Fig. 8 (a) Plastic zone following spot heating. (b) Progress of crack due to cyclic loading after spot heating. (c) End of retardation. $Z_{ST} = a_D + z_D$.

where Z_{ST} is in millimetre and T is in degree C.

The plastic zone length (Z_{ST}) is a function of button diameter (D), average coefficient of linear expansion of specimen material (α), spot temperature (T), yield stress (σ_y) and modulus of elasticity (E) of the specimen material. In dimensionless terms, it may be written as

$$f\left(\frac{Z_{ST}}{D}, \alpha T, \frac{E}{\sigma_y}\right) = 0. \quad (6)$$

For a particular material, the above relation reduces to

$$f\left(\frac{Z_{ST}}{D}, \alpha T\right) = 0. \quad (7)$$

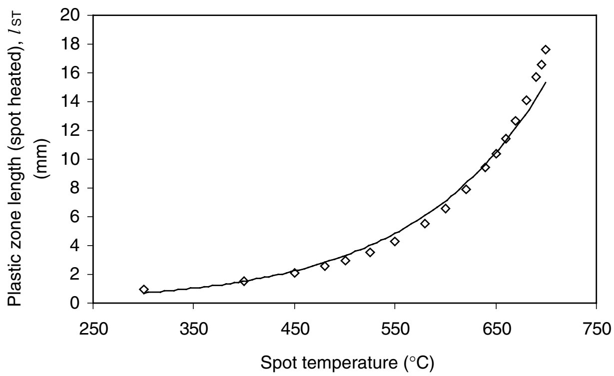

Fig. 9 Variation of plastic zone length (due to spot heating) with spot temperature.

The exact relationship of the dimensionless terms in the Eq. (7) can be obtained from Eq. (5). For the present steel material ($\alpha = 0.00011/^{\circ}\mathrm{C}$), the equation becomes

$$\frac{Z_{\mathrm{ST}}}{D} = 0.00593\mathrm{e}^{70\alpha T}. \tag{8}$$

Estimation of shaping exponent '*m*' in the Wheeler model

The stage-II FCGR under constant amplitude loading is represented by the Paris equation, which is

$$\mathrm{d}a/\mathrm{d}N = C(\Delta K)^n. \tag{9}$$

Wheeler proposed the following modified relation where crack growth is retarded due to a tensile overload spike or otherwise

$$\left(\frac{\mathrm{d}a}{\mathrm{d}N}\right)_{\mathrm{retard}} = C_{\mathrm{p_i}} \cdot C\,(\Delta K)^n\,, \tag{10}$$

where $C_{\mathrm{p_i}}$ is a retardation factor given by

$$C_{\mathrm{p_i}} = \left[\frac{z_{\mathrm{c_i}}}{a_0 + Z_{\mathrm{ST}} - a_{\mathrm{i}}}\right]^m, \tag{11}$$

Also from Eq. (10)

$$C_{\mathrm{p_i}} = \frac{(\mathrm{d}a/\mathrm{d}N)_{\mathrm{retard}}}{C\,(\Delta K)^n} = \frac{(\mathrm{d}a/\mathrm{d}N)_{\mathrm{retard}}}{(\mathrm{d}a/\mathrm{d}N)_{a=a_0}}. \tag{12}$$

Thus, the retardation factor $C_{\mathrm{p_i}}$ increases to unity when $(\mathrm{d}a/\mathrm{d}N)_{\mathrm{retard}} = (\mathrm{d}a/\mathrm{d}N)_{\mathrm{a=a_0}}$. This condition is reached when $a_{\mathrm{i}} + z_{\mathrm{c_i}} = a_0 + Z_{\mathrm{ST}} = a_{\mathrm{D}} + z_{\mathrm{D}}$. The minimum value of $C_{\mathrm{p_i}}$ is given by $(\mathrm{d}a/\mathrm{d}N)_{\mathrm{retard}_{a=a_0}}/(\mathrm{d}a/\mathrm{d}N)_{a=a_0}$.

In the present work, the values of $C_{\mathrm{p_i}}$ for different spot temperatures have been obtained with some modifications in Eq. (11). Because of the presence of a net compressive residual stress field around the crack tip in the plastic zone due to spot heating, it is assumed that the cyclic PZS in the compressive stress field is less than the usual size of the plastic zone for plane stress cyclic loading, and is therefore multiplied by a plastic zone correction factor λ. Thus, the size of the instantaneous cyclic plane stress plastic zone in a compressive stress field is given by

$$z_{\mathrm{c_i}} = \lambda(1/\pi)(\Delta K/2\sigma_{\mathrm{y}})^2. \tag{13}$$

Equation (11) is therefore modified as

$$C_{\mathrm{p_i}} = \left[\frac{\lambda z_{\mathrm{c_i}}}{a_0 + Z_{\mathrm{ST}} - a_{\mathrm{i}}}\right]^m = \gamma\left[\frac{z_{\mathrm{c_i}}}{a_0 + Z_{\mathrm{ST}} - a_{\mathrm{i}}}\right]^m, \tag{14}$$

where γ is a correction factor and is given by $\gamma = \lambda^m$.

The values of γ, m and λ have been computed from Eqs (12) and (14). The variation of λ and m with spot temperatures is shown in Figs 10 and 11, respectively. It is found that the values of λ and m increase with increase in spot temperature meaning an increase in the value of the retardation factor, $C_{\mathrm{p_i}}$. Finally, a comparison has been made in Fig. 12 in respect of the plastic zone length due to spot heating obtained from Eq. (5) and the Wheeler model.

CONCLUSIONS

It is observed that subcritical spot heating retards a growing fatigue crack and the retardation effect increases with the spot heating temperature. The magnitude of retardation is a function of the distance of the heating spot, and there is an optimum position of the heating spot where the retardation effect is a maximum. The plastic zone length due to spot heating is found to increase exponentially with increase in spot heating temperature. The values of retardation correction factor (γ), cyclic plastic zone correction factor (λ) and shaping exponent (m) increase with increase in spot temperature.

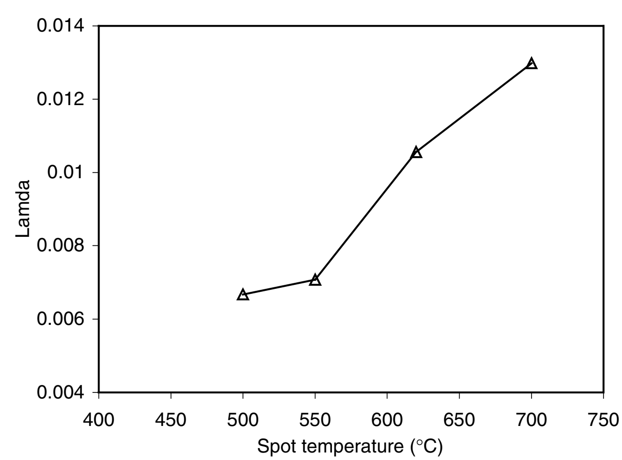

Fig. 10 Variation of plastic zone correction factor with spot temperature.

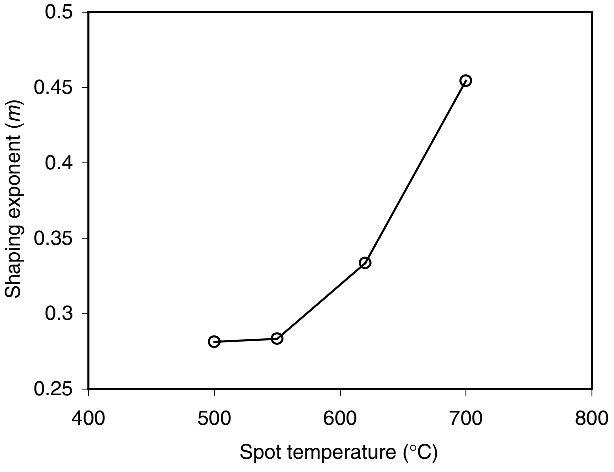

Fig. 11 Variation of shaping exponent with spot temperature.

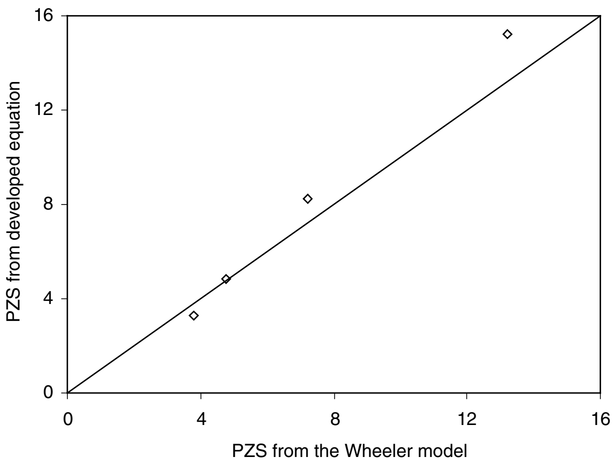

Fig. 12 Comparison plastic zone lengths obtained from the Wheeler model and developed equation.

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