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Brief Notes

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A Note on the Use of High-Speed Infrared Detectors for the Measurement of Temperature Fields at the Vicinity of Dynamically Growing Cracks in 4340 Steel

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Introduction

The dissipation of energy, due to plastic deformation, near the tip of a dynamically propagating crack may result in large temperature increases of the material near the crack tip. It is suspected that such temperature increases will strongly affect the nature of the near-tip deformation field and may result in changes of the dynamic fracture toughness of the material. To investigate these effects experimental measurements of the crack-tip temperature distribution were performed using a noncontact system of eight high-speed infrared (IR) detectors focused on eight discrete points perpendicular to the prospective crack path.

Experimental Arrangement

The experiments were performed on wedge loaded, double cantilever beam specimens of 4340 steel with heat treatment and material properties identical to those used by Zehnder and Rosakis (1983). The in-plane specimen dimensions were 15.14 cm × 6.09 cm, the thickness was 1 cm, and the specimen contained an initially blunted notch which was 3.81 cm long. The specimen geometry is shown in Fig. 1.

The temperature field near the tip of the dynamically propagating crack was recorded using a high-speed infrared detector system. This system is similar to the one used by Hartly, Duffy, and Hawley (1987), who studied heat generation during adiabatic shear band formation. This noncontact measurement uses an eight element, linear array of InSb IR detectors to record the time history of temperature increase at eight discrete points on the specimen surface. The points are aligned perpendicularly to the prospective crack path.

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Using the system of spherical mirrors, shown in Fig. 2, radiation from the eight points on the specimen is focussed onto the eight IR detector elements with a magnification of one. As shown in Fig. 2, the areas of measurements, both on the specimen and on the IR detector, are eight squares (0.16 mm × 0.16 mm) and the spacing between them is 0.2 mm. The high spatial resolution of the system allows for the measurement of temperature well within the crack-tip plastic zone.

The voltage output of each of the infrared detector elements was separately amplified and recorded on high-speed digital oscilloscopes. The recorded signals were then converted into temperature increase through an experimentally obtained calibration. The rise time of the IR detectors and their amplifiers is 0.75μs, which is safely below the minimum experimentally observed rise time of 2.5μs.

The crack-tip velocity history was simultaneously recorded in the back of the specimen by means of a grid of conductive paint placed perpendicular to the crack path. As the crack runs, the conductive strips are broken and the resistance of the whole grid is increased, providing the time history of the crack motion.

Experimental Results

Figure 3 shows the time record of the temperature measured by each of the eight detector elements as the crack tip approaches and passes through the detection points. Time $t=0$ corresponds to the triggering of the oscilloscopes. For this

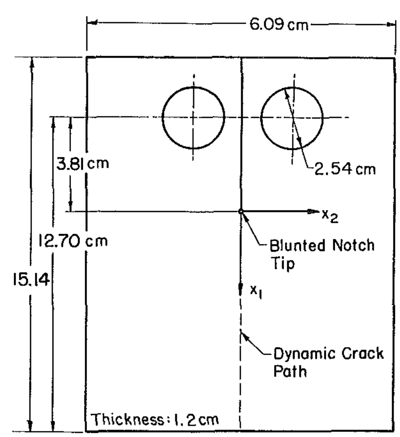

Fig. 1 Specimen geometry

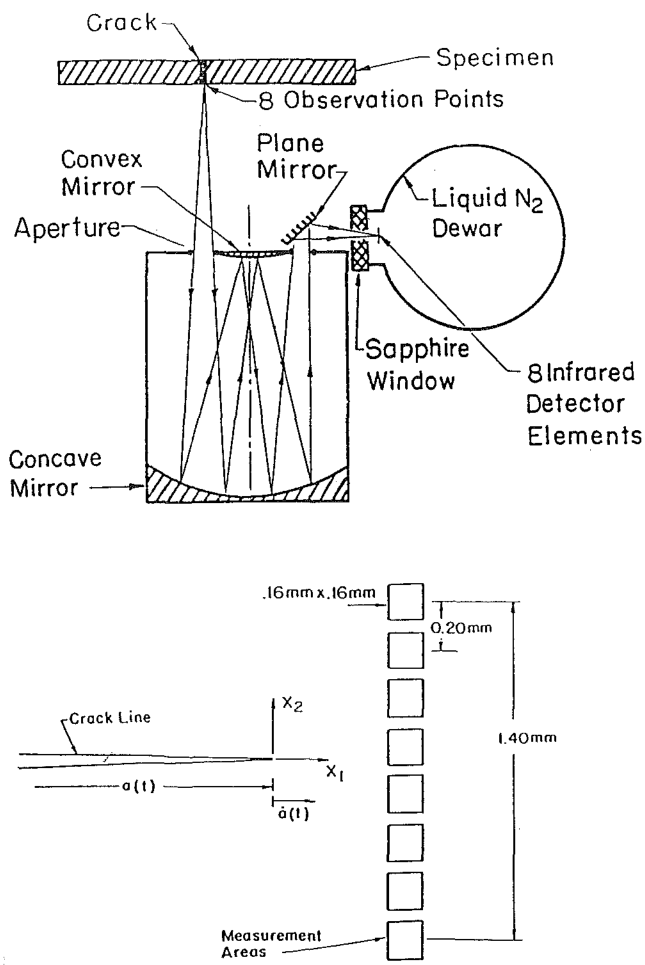

Fig. 2 Schematic of the experimental set-up. The top shows the focusing of radiation onto the infrared detectors. The bottom shows the location of measurement areas relative to crack line.

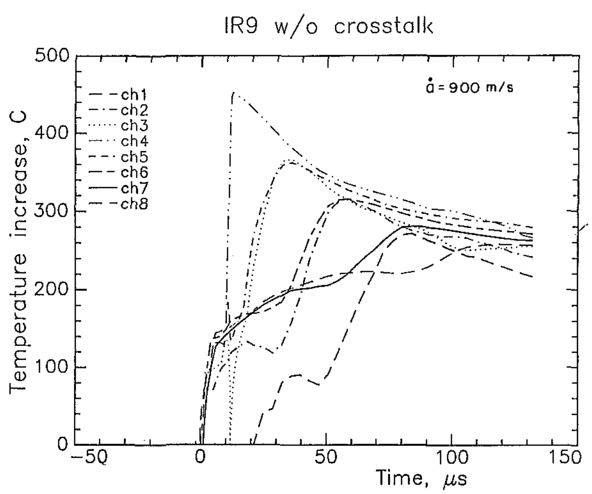

Fig. 3 Temperature rise versus time for each detector element

particular experiment, the crack propagation speed was constant through most of the specimen and equal to approximately 900 m/s. The maximum temperature increase of 450°C was recorded by element 4 (Ch4 in the figure). The minimum rise time of 2.5μs was also recorded by this element. In this experiment, the crack tip traversed the array of detection points slightly off center, but through the region focused on element

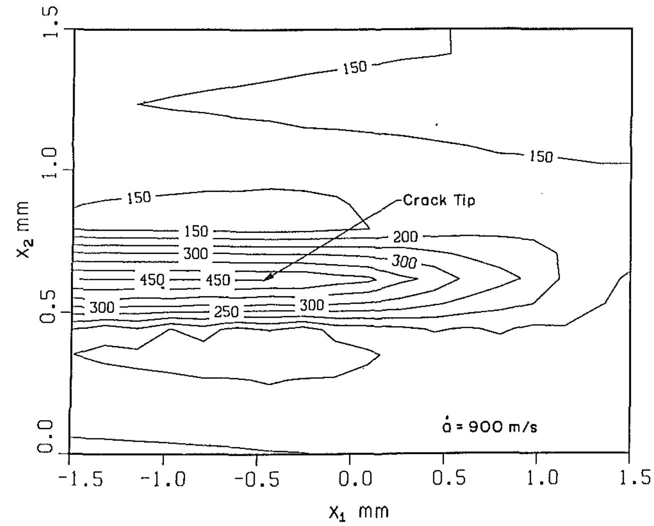

Fig. 4 Contours of equal temperature rise at the vicinity of the propagating crack. Temperature increase is in °C.

4. Thus, as may be expected by symmetry, the elements to the left and right of element 4 (channels 3 and 5) recorded temperatures very similar but not exactly equal to each other. These points also had markedly slower rise times than element 4.

An alternative means of viewing these results is shown in Fig. 4. This figure shows contours of equal temperature in the vicinity of the propagating crack. These were obtained from the temperature versus time results of Fig. 3, by converting the time axis into distance parallel to the direction of crack growth, using the measured crack-tip speed of 900 m/s. Each detector element corresponds to a fixed distance from the crack on a line perpendicular to the direction of crack growth. In this figure, the estimated crack-tip position is $x_1 = -0.5$ mm.

The isotherms of Fig. 4 clearly show that the region of intense heating (temperatures ranging from 450°C–150°C) extends approximately 0.5 mm ahead of the crack tip while the half-width of the resulting wake of temperatures is approximately 0.25 mm. It should be observed that the isotherms in the wake region behind the crack tip remain almost parallel to the crack line for at least 1.5 mm, suggesting that at least *locally*, the deformation remains essentially adiabatic.

An estimate of the size of the region of intense heating relative to the plastic zone size can be obtained by an elementary calculation. The maximum extent of the plane-stress plastic zone radius, is $r_p \approx 0.25\ (K_I^d/\sigma_o)^2$, where K_I^d is the dynamic stress intensity factor and σ_o is the yield stress in uniaxial tension. During crack growth, K_I^d is often assumed to be equal to the dynamic fracture toughness, K_{IC}^d, of the material. For this particular heat treatment of 4340 steel, K_{IC}^d can be inferred from the experimental results of Zehnder and Rosakis (1989) who give its dependence on crack-tip speed. For a speed of 900 m/s, $K_{IC}^d = 130$ MPa $\sqrt{m}$ which corresponds to $r_p \approx 2$ mm for $\sigma_o = 1450$ MPa. The results show that the region of intense heating is limited to distances roughly equal to $r_p/4$ from the crack tip.

The results presented in this technical note are preliminary. We are now conducting an extensive set of experiments covering a wide range of crack-tip velocities and materials including a variety of ductilities of 4340 steel as well as several titanium alloys.

Acknowledgments

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A Note on the Interface Crack Problem

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Introduction

The use of a complex dislocation density to formulate the governing equations for interface crack problems has provided a convenient encompassing method to obtain stress intensity factors and energy release rates (see Rice (1968), Thouless et al. (1987), Hutchinson et al. (1987), Suo and Hutchinson (1989a, 1989b, 1990), He and Hutchinson (1989), Suo (1989), and Hutchinson and Suo (1991)). The governing equation for the dislocation density is a singular integral equation of the second kind, the solution to which can be obtained numerically, e.g., see Gerasoulis and Vichnevetsky (1984). Jacobi polynomials can be used since they appear as the fundamental solution to the integral equations (Erdogan (1969), Erdogan and Gupta (1971, 1972), and Erdogan et al. (1972)). However, these polynomials are not convenient because the coefficients in the polynomials depend on the material constants; instead Chebyshev polynomials are more suited for numerical work as demonstrated in the works cited previously.

The purpose of this Brief Note is to consider the classical interface crack problem (England (1965) and Rice and Sih (1965))—a crack on a bimaterial interface—with a view to obtaining a number of interesting results for the stress intensity factor when the traction on the crack is expanded in a series of Chebyshev polynomials. We also obtain an interesting result for the stress intensity factor for a crack in a homogeneous material. The basic equations can be found in the references cited.

Formulation

The interface crack is modeled by a dislocation density function along the crack and the equation for the dislocation density following the formulations in the references cited above takes the form

$$\beta i A(u)+\frac{1}{\pi}\int_{-1}^{1}\frac{A(t)}{t-u}\,dt=\frac{\bar{p}(u)}{2\pi},\quad |u|<1 \tag{1}$$

$$\int_{-1}^{1}A(t)dt=0 \tag{2}$$

where $A(t)$ is the dislocation density. Equation (1) is of the second kind arising from the concentrated load in the expression for the traction induced by the dislocations on the interface (see, e.g., Dundurs and Markenscoff (1989) and Hui and Lagoudas (1990)).

The stress intensity factor is related to the dislocation density in the form

$$\bar{K}=(2\pi)^{3/2}\sqrt{1-\beta^2}\lim_{t\to 1-}A(t)(1-t)^{1/2+i\epsilon}. \tag{3}$$

In the usual approach to the numerical solution of (1) and (2), we assume that the approximate solution can be written in a finite series of N Chebyshev polynomials of the first kind in the form

$$A(t)=\left(\frac{1+t}{1-t}\right)^{i\epsilon}\frac{1}{\sqrt{1-t^2}}\sum_{k=0}^{N}A_kT_k(t)=W(t)\sum_{k=0}^{N}A_kT_k(t). \tag{4}$$

Upon substitution of (4) into (1) and use of the result

$$\int_{-1}^{1}\frac{W(t)T_k(t)}{t-u}\,dt=-\pi\beta iW(u)T_k(u)+\frac{\pi}{\cosh\pi\epsilon}Q_k(u) \tag{5}$$

where $Q_k(t)$ is the principal part of $T_k(t)(t+1)^{-1/2+i\epsilon}(t-1)^{-1/2-i\epsilon}$ at infinity, we find

$$\sum_{k=0}^{N}A_kQ_k(u)=\frac{\cosh\pi\epsilon}{2\pi}\bar{p}(u). \tag{6}$$

The functions $Q_k(u)$ are expressible as linear combinations of Chebyshev polynomials of the second kind U_k and are given in the appendix.

Equation (2), upon integration and upon use of the expressions for Q_k together with a recurrence relation for U_k, leads to

$$A_0+\frac{1}{2}\left\{A_1(4i\epsilon)+A_2(-8\epsilon^2)+A_3\frac{4}{3}i\epsilon(1-8\epsilon^2)+\cdots\right\}=0. \tag{7}$$

The expression for $\bar{K}$ follows from (3) and (4):

$$\bar{K}=\pi^{3/2}2^{1+i\epsilon}\sqrt{1-\beta^2}\sum_{k=0}^{N}A_k. \tag{8}$$

We see that when $\epsilon=0$, $A_0=0$, and (6) becomes

$$\sum_{k=1}^{N}A_kU_{k-1}(u)=\frac{\bar{p}(u)}{2\pi}. \tag{9}$$

Orthogonality of the $U_k(u)$ then gives

$$A_k=\frac{1}{\pi^2}\int_{-1}^{1}\bar{p}(u)\sqrt{1-u^2}U_{k-1}(u)du,\quad k\ge 1 \tag{10}$$

for the coefficients in the solution (4). The expressions for A_k can also be written in the form

$$A_k=\frac{1}{2\pi^2}\int_{-1}^{1}\frac{\bar{p}(u)}{\sqrt{1-u^2}}[T_{k-1}(u)-T_{k+1}(u)]du,\quad k\ge 1 \tag{11}$$

upon use of relations between U_k and T_k.

If the load is expanded in a series of T_k,

$$\bar{p}(u)=\sum_{k=0}^{N-1}a_kT_k(u) \tag{12}$$

where

$$a_0=\frac{1}{\pi}\int_{-1}^{1}\frac{\bar{p}(t)dt}{\sqrt{1-t^2}};\ a_k=\frac{2}{\pi}\int_{-1}^{1}\frac{\bar{p}(t)T_k(t)dt}{\sqrt{1-t^2}},\quad k\ge 1 \tag{13}$$

then the coefficients A_k become

$$A_1=\frac{1}{4\pi}\{2a_0-a_2\}$$

$$A_k=\frac{1}{4\pi}\{a_{k-1}-a_{k+1}\},\quad k=2,\ldots N. \tag{14}$$

It follows therefore that

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