CRACK TIP OPENING ANGLE RELATED TO THE PARIS TEARING MODULUS IN A533B STEEL.

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Abstract.

Crack tip opening angles (CTOA) were measured on the side surfaces of three point bend test pieces of A533B steel. Measurement of the angle was facilitated by printing square grids with a spacing of 127 micrometres on the side surface through which crack propagation occurred. Sequential photographs of the grid during testing show the appearance of the surface crack and the subsequent development of the CTOA. The simultaneous determination of the J_R curve and the CTOA allowed a correlation between the CTOA and the Paris Tearing Modulus, T. The correlation is in agreement with the calculation of Ogasawara and Okamura (1983) for the plane stress CTOA which should be appropriate for surface measurements.

Introduction.

Rice Drugan and Sham (1) analysed growth of a crack under plane strain and small scale yielding conditions. The rate of crack face opening near to the crack tip was found to be dependent on J_{mat} and on other material properties. This result predicts crack tip shape to be a very flat ellipse for brittle materials but predicts a definite crack tip opening angle (CTOA) for materials with a sufficiently large tearing modulus and work hardening rate.

Experimental confirmation of this CTOA was obtained by Shih and co-workers (2). These workers used the silicone implant technique to obtain the shapes of crack tips in the central thickness region of the crack tip. Experimental casts showed CTOA's which agreed well with finite element calculations of the angles even though the ductile crack growth occurred under large scale yielding conditions.

Silicone implant techniques are rigorous but experimentally difficult. Further it is necessary to stop the crack in order to infiltrate the tip. We conceived of the possibility of measuring the crack tip angle in a virtually continuous fashion by taking a series of photographs of a surface grid imposed on the side surface of the material in the crack path. Since the side surface material ahead of the crack tip deforms under more nearly plane stress conditions we used the results of

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Ogasawara and Okamura (3) to relate the CTOA and the J value. These authors modified the Rice type of computation to allow for a plane stress plastic zone.

Experimental work.

The material we tested was an A533B steel in a very ductile ferrite/pearlite condition with the following composition (percentage):
C 0.2 Mn 0.99 Si 0.28 S(very low) P 0.11 Ni 0.15 Cr 0.09 Mo 0.015 Fe remainder. The standard mechanical properties were: Yield strength, σ_0, 233MPa; Yield strain, ε_0, 0.0011; Tensile strength 449mpa; elongation 60%; Reduction of area 42%. The stress strain relationship for the steel can be described by:

$$\sigma / \sigma_0 = 0.641\, (\varepsilon / \varepsilon_0)^{0.258}$$

or:

$$\varepsilon / \varepsilon_0 = \sigma / \sigma_0 + 1.303\, (\sigma / \sigma_0)^{5.77}$$

We tested three point bend specimens with a width, W, of 25mm, a thickness, B, of 17.5mm and a loading span of 100mm, which were fatigue cracked to a total crack length of between 0.33 and 0.50 of the width. Tests were carried out at a crosshead movement rate of 0.2mm/ minute at a temperature of approximately 20C. Cracking commenced after general yield in all cases.

The surfaces of these specimens were polished to a 6 micron diamond finish and a grid was deposited on the specimen surface using a photographic technique. The interline spacing of the grid was 127 micrometres. During tests this grid was photographed, as the crack propagated , using a camera looking through a lens giving a times fifteen magnification of the image. Photographs were correlated with the load/load point displacement records which were taken continuously. The tests were stopped at increasing values of crack growth in order to give a set of J_{mat} values for the particular crack lengths at which tests were stopped.

The amount of crack growth at the end of each test was measured by breaking open test samples at liquid nitrogen temperature. This allowed us to measure the fatigue crack length and the ductile crack growth using the ASTM recommended nine point method and an optical device capable of measuring length to +/- 0.001mm. The area under the load/load point displacement curves was measured using a digitised curve, the elastic (A_e) and plastic (A_p) components under the curve were measured separately.

Experimental Results.

The crack growth resistance curve from the series of tests is shown in figure 1. The J values for the material at the end of each crack growth test were evaluated from the sum of the elastic and plastic components:

$$J = Je + Jp$$

with η_e,the elastic eta factor, η_p , the plastic eta factor and a the initial crack length in:

$$J_e = \eta_e A_e / (B(W - a))$$

$$J_p = \eta_p A_p / (B(W - a))$$

Figure 1 shows a J_{IC}, at the intersection of the R curve and the blunting line, of 0.11MJ/m^2. The dJ/da from figure 1 is 198.9 MN/ m^2 and the T_{mat} is 356.8.

The plane stress CTOA according to Ogasawra is:

$$CTOA = 2\tan^{-1}\left[\left[\frac{\beta\sigma_f}{E}\right]\left\{\frac{\alpha E}{\beta\sigma_f^2}\frac{dJ}{da} + \ln\frac{eR}{r}\right\}\right] \quad \text{-----------------} \quad 1.$$

or:

$$CTOA = 2\tan^{-1}\left[\left[\frac{\beta\sigma_f}{E}\right]\left\{\frac{\alpha}{\beta}T_{mat} + \ln\frac{eR}{r}\right\}\right] \quad \text{-----------------} \quad 2.$$

where the constants α and β are $\alpha=0.5$ and $\beta=1.4$; σ_f is the flow stress, $(\sigma_0+\sigma_{uts})/2$, 341MPa for our material; E is the elastic modulus. R is (W-a)/4 for the fully yielded condition and r is the distance from the crack tip so that the logarithmic term is small which is why the CTOA is well defined.

Figure 2 shows a sequence of photographs from one test. We measured the CTOA by putting lines through four of the deformed grid points close to the crack tip. We chose points on a complete line closest to the crack face. The photographs show how clearly the grid demonstrates the definite CTOA.

As each test progressed the CTOA increased to a value of 35 degrees and then remained at that value as the crack propagated further. The CTOA estimated from Ogasawara's equation is 34 degrees.

At the point of maximum load on the load versus load-point-displacement curve the CTOA measured by the grid was about 24 dgrees. Break open tests showed that this corresponded to an interior crack with a maximum depth of about 0.5mm but no cracking was visible at the side surfaces. The surface grid showed an increasing CTOA, beyond maximum load, reaching a plateau level of 35 dgrees just as surface cracks appeared. The grid was then divided by the surface cracks running in shear bands. At this stage the interior crack was approximately 2mm in depth. The tips of the surface cracks each also showed a grid deformation corresponding to 35 degrees.

Discussion of the results.

The results show a good correlation between a CTOA, measured with the aid of fine surface grid, and the tearing modulus of the material. Given a J/T map for the material a local J_{mat} could also be derived for a crack tip location. This may be of practical use in the assessment of welded or composite structures of different steels or alloys where the local CTOA could be used to assess local toughness in the absence of any other effective method.

The term containing T_{mat} in equation 2 is about 120 which is large compared to the logarithmic term which has a value of around 5. This is the reason why the definite CTOA forms as was discovered by the Rice Drugan and Sham analysis of moving cracks. The finite CTOA thus forms only in tough materials and another corollary of this toughness is the formation of surface shear deformation and eventually shear lips to the crack. This surface deformation prevents the direct observation, except for the silicone rubber implant type of experiment (2), of the deformations which would reveal the plane strain CTOA. Our experiments show that this is no barrier to a technology based on measurements of CTOA to assess local toughness of regions as they are traversed by the crack since it is perfectly possible to use the plane stress CTOA on the metal surface to lead to the T_{mat} and J_{mat} values of the material local to the crack tip.

References.

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2. Shih C.F., DeLorenzi H.G. and Andrews W.R. (1979). ASTM STP 668 pp. 65-120.
3. Ogasawara M., and Okamura H.,(1983), Eng. Fract. Mechs., 18, No.4,pp 839-849.
4. Herman L. And Rice J.R., (1980) , Metal Science ,14, No. 8-9, pp 285-292.

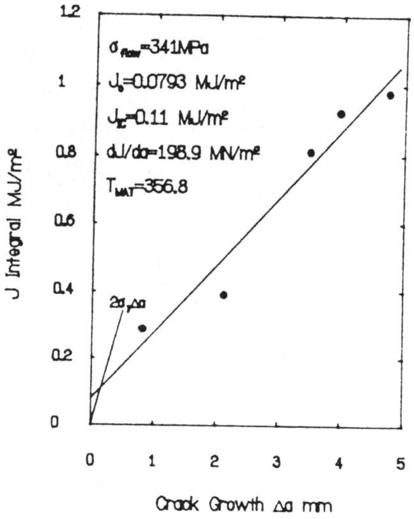


Figure 1.

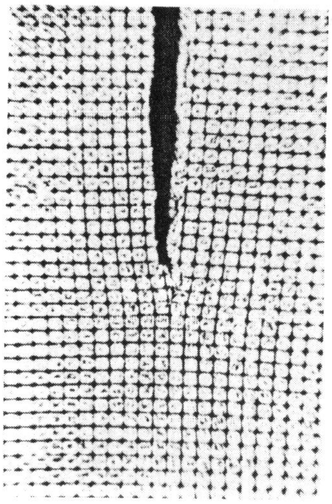
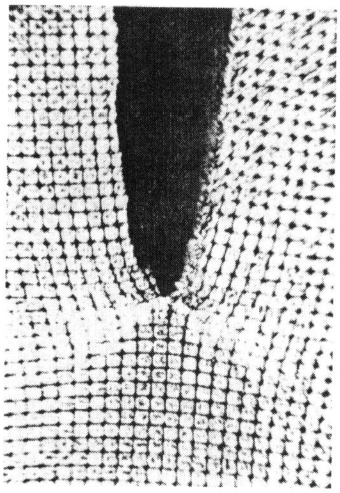


Figure 2.



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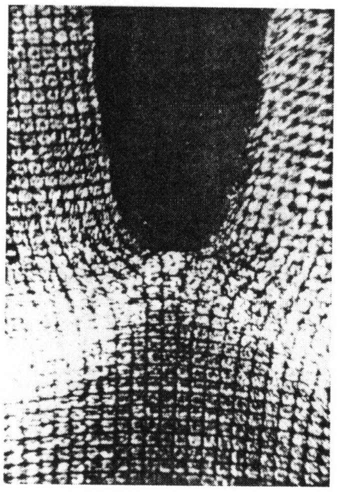

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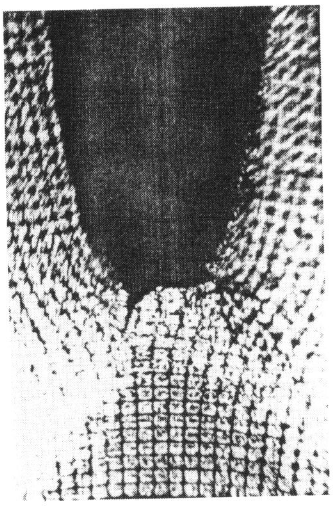

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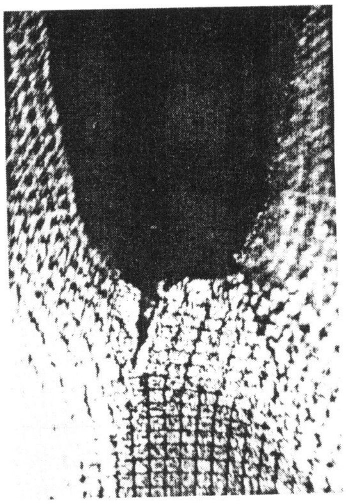

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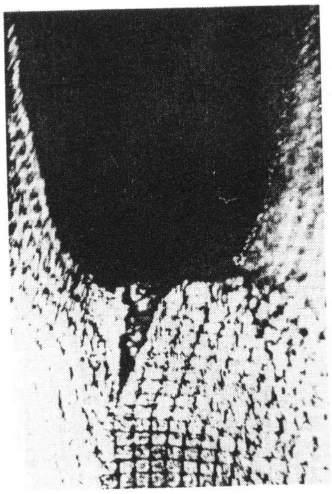

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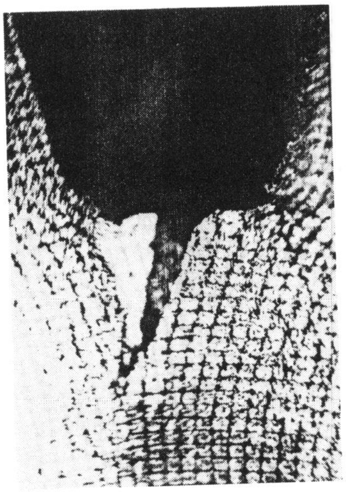

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