APPLICABILITY OF C^*- INTEGRAL FOR STRESS CORROSION CRACK GROWTH BEHAVIOUR IN A LOW STRENGTH STEEL

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ABSTRACT- A path independent energy rate line integral C^* was used to correlate with the stress corrosion crack growth rate. The constant displacement rate tests were conducted on a low strength steel of compact tension geometry. The test solution was 2N $(NH_4)CO_3$ at 75°C. The C*integral was calculated from the test data by the multiple specimen graphical technique and the results were compared with values obtained from the analytical solutions proposed in the literature for the crack propagation under creep conditions.

INTRODUCTION

The fracture mechanics approach has hitherto been used for crack propagation under stress corrosion conditions for components that remain within the limits of linear elastic fracture mechanics. In this approach, stress corrosion crack propagation rates were correlated with the stress intensity factor, K_I. The range of applicability of this parameter is limited to small scale yielding at the crack tip. In low strength materials considerable plastic strain will occur before fracture at the crack tip and the stress intensity factor K_I, looses significance. Then, the elastic-plastic fracture mechanics parameters are expected to describe the crack tip conditions more accurately.

More recently, the comparison of various fracture mechanics parameters to describe the stress corrosion crack growth rate were represented in work done by the authors [1]. In that study $C^*$was found to correlate stress corrosion crack propagation rate data.

In this paper, experimental C* values obtained in the manner proposed by Landes and Begley [2] are compared with C* calculated from equations given in the literature [3,4].

Saxena [5] has conducted an experimental program on 304 stainless steel where creep crack growth rates, da/dt, were correlated by the C^* integral. He compared the results with the C^* values obtained from the analytical solutions using an analogy to the fully plastic J-integral solutions. He found discrepancies between the C^* values obtained from the two techniques to be in the order of 8 to 40 percent. In this study other expressions to calculate C^* for the compact tension geometry were used.

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C^* LINE INTEGRAL

The C^* parameter is a path independent energy rate line integral defined by analogy to J-integral [2]. For the two dimensional case it is defined as:

$$C^* = \int_\Gamma W^* dy - T_i \left(\frac{\partial \dot{u}_i}{\partial x} \right) ds \qquad (1)$$

where

$$W^* = \int_0^{\dot{\varepsilon}_{mn}} \sigma_{ij} \, d\dot{\varepsilon}_{ij}$$

Γ is a contour taken from the lower crack surface in a counterclockwise direction to the upper crack surface (Fig. 1). W^* is the strain energy rate density, and T_i is the traction vector defined as $T_i = \sigma_{ij} n_j$ where n_j is the outward normal along Γ, $\dot{u}_i$ is the displacement rate vector and ds is the element along Γ.

The energy rate interpretation of C^* was given by Landes and Begley also by analogy to J-integral. They defined C^* as the power rate difference between two identically loaded bodies with incrementally differing crack lengths and is given by:

$$C^* = - \frac{1}{B} \frac{dU^*}{da} \qquad (2)$$

where B is the specimen thickness and dU^*/da is the change in strain energy rate due an infinitesimal change in crack length at a given displacement rate.

EXPERIMENTAL PROCEDURE

Material and Test Apparatus

The material used in this study was a hot-rolled 15 mm thick sheet of a steel having a composition of 0.22% C, 0.70% Mn, 0.05% Si, 0.02% P, 0.03% S and 0.20% Cu. The mechanical properties of this steel are given as follows:

0.2% Yield Strength, MPa	295
Ultimate Tensile Strength, MPa	450
Fracture Strength, MPa	390
Elongation, %	29
Reduction in Area, %	60
Young's Modulus, MPa	1.76×10^5

The test specimens were half inch thick compact tension type with side grooves along the specimen middle plane. A clip-on-gage was attached to two edges to measure the load-line displacement. The crack growth direction was parallel to the rolling direction. The specimens except the grooves were chromium plated to concentrate the effect of the aggressive environment at the crack tip by avoiding general corrosion.

The test temperature was controlled by means of a thermostat to an accuracy of ± 1°C. The crack growth was monitored with an optical microscope to an accuracy of 0.01 mm.

Test Procedure

Stress corrosion crack growth tests were conducted under constant load-line displacement rates using a closed-loop hydraulically activated servo-controlled testing machine, the load frame being in the horizontal position. After precracking by cyclic loads at room temperature, the specimen was placed in the corrosion cell. The test solution was 2N $(NH_4)_2CO_3$ at 75°C, which was reported as the cause of failure of storage vessels containing anhydrous ammonia in the presence of air of normal carbon dioxide content [6].

The displacement rates ranged from 7×10^{-6} mm/sec to 8×10^{-5} mm/sec. The load, load-line displacement, and crack lengths were recorded during the tests. After testing, the specimen was removed from the corrosion cell and broken apart by cyclic loads at room temperature. The fractured surfaces were examined by Scanning Electron Microscope.

DATA REDUCTION

The crack length versus time data were fitted to a second order polynomial from which the crack growth rates were determined. The corresponding C^* values were calculated by the multiple specimen graphical technique developed by Landes and Begley. The steps involved are described fully in Ref. 2. This data reduction procedure requires several specimens to be tested at different displacement rates but yields only few data points. Therefore alternative methods for quantitative determination of C^* have been proposed.

J-integral equations have been modified to estimate C^*-integral analytically by assuming that the uncracked ligament of the specimen creeps at a steady state.

The equations proposed for C^* estimation for the compact tension geometry in plane strain condition that are considered in this paper are as follows:

The C^* expression given by Harper and Ellison [3]:

$$C^* = - \frac{n}{n+1} \frac{P\dot{v}}{BW} \left(\frac{1}{m} \frac{dm}{d(a/W)} \right) \qquad (3)$$

where n is the strain rate hardening exponent of the material, $\dot{v}$ is the dioplacement rate, P is the load, B is the specimen thickness, W is the specimen width and m is the yield load ratio defined as the ratio of the tensile limit load of a cracked specimen to the limit load of an uncracked specimen and it is the function of nondimensional crack length (a/W). The variation of m, dm/d(a/W), and (1/m) $\left(\frac{dm}{d(a/W)}\right)$ with (a/W) is shown graphically in Ref. 3.

For n >5 C^* formula reduces to:

$$C^* = - \frac{P\dot{v}}{BW} \left(\frac{1}{m} \frac{dm}{d(a/W)} \right) \qquad (4)$$

Koterazawa and Mori [4] have given a rather simple expression for C^* for the compact tension specimen when n>>1.

$$C^* = \frac{2P\dot{v}}{Bb} \qquad (5)$$

RESULTS AND DISCUSSION

The crack growth rate, da/dt versus experimentally determined C^* parameter is plotted in Fig.2. Different symbols have been used to represent data from the graphical technique and that obtained from Eqs. 4 and 5.

The discrepancy in estimating C^* from the two analytical solutions is about 14 percent for all displacement rates. However the difference between the C^* values obtained from the graphical technique and the analytical solutions is between 28 to 98 percent, the differences get larger as the displacement rates get slower. This observation can be explained by the effect of corrosion on the crack growth, which is more significant at slower displacement rates. Experimentally determined C^* values include the chemical energy effect due to corrosion whereas the analytical solutions considered in this study are derived by equating the total energy dissipation rate to the power input , i.e., the product of load and displacement rate. The results indicate that in the analytical solutions the contribution from the chemical energy should be considered for the stress corrosion case.

SYMBOLS

a- Crack length (mm)
b- Remaining ligament length of specimen (mm)
B- Thickness of specimen (mm)
C^*- Energy rate line integral (MJ/m^2-hr)
m- Ratio of tensile limit load of a cracked specimen to that of uncracked one (dimensionless)
n- Strain rate hardening exponent given in the equation $\dot{\varepsilon} = A\sigma^n$
P- Load (N)
U^*- Strain energy rate (N.m/hr)
$\dot{v}$- Load-line displacement rate (mm/sec)
W- Width of specimen (mm)

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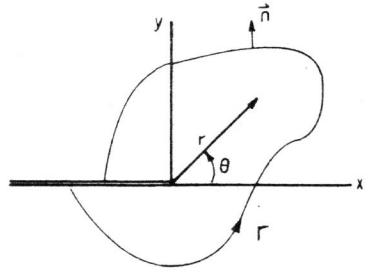

Fig. 1- Crack tip coordinate System and arbitrary line integral contour.

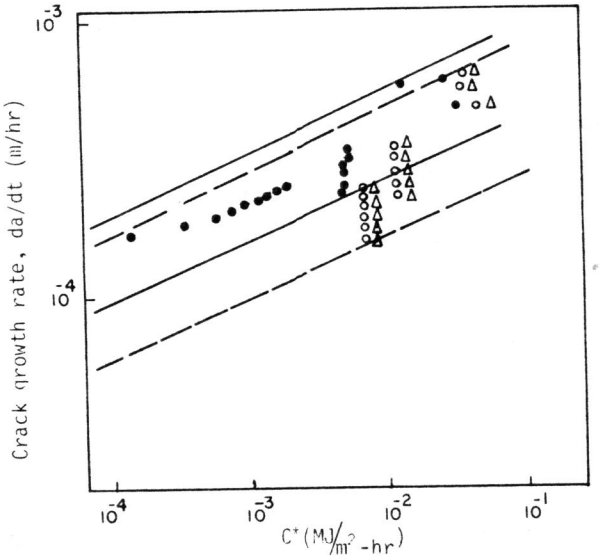

Fig. 2- Stress corrosion crack growth rate of a low strength steel in 2N $(NH_4)_2CO_3$ as a function of C^*-integral.