APPLICABILITY OF ENERGY RATE LINE INTEGRAL TO CREEP CRACK GROWTH

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ABSTRACT

Energy rate line integral C^* has been widely tried in recent times to describe crack growth in creep. However, published data on different materials clearly indicate a systematic scatter and load dependence of the relation. The derivation of the parameter from the first principle and the systematic scatter in da/dt vs C^* relation are discussed and an alternative approach to creep crack growth is indicated in the paper.

KEYWORDS

Creep crack growth; energy rate line integral; energy approach; R-parameter.

INTRODUCTION

Crack growth in creep has interested many researchers, as several in-service failures in power generating plants have been found to be mainly due to growth of creep cracks. To assess the reliability of structures operating in creep range, it is important to consider creep crack propagation. Different parameters like stress intensity factor, net section stress, COD and reference stress, have been tried to correlate the creep crack growth and a brief discussion of these methods has been given by Fu (1980).

ENERGY RATE LINE INTEGRAL C^*

The path independent line integral J has been extended to creep crack growth by Landes and Begley (1976) and for a given displacement rate $\dot{\Delta}$ it is given as

$$C^* = \frac{-\,d\dot{U}}{B\,da}\bigg|\,\dot{\Delta}_1 \qquad (1)$$

where $\dot{U}$ is the energy associated with P-$\dot{\Delta}$ relation upto $\dot{\Delta}_1$ and B the thickness of the specimen. Attempts have been made to evaluate C^* which is given by Koterazawa and Mori (1977) for CC and CT type of specimens as

$$C^* = \frac{n-1}{n+1}\,\sigma_{net}\,\dot{\Delta} \propto \frac{P\,\dot{\Delta}}{B\,(W-a)} \qquad (2)$$

and Nikbin, Webster and Turner (1977) for TDCB specimen as

$$C^* = \frac{\eta}{B\,(n+1)}\;\frac{P\,\dot{\Delta}}{a} \qquad (3)$$

where η, n and B are constants. W is the width of the specimen and $\underline{a}$ the crack length. Analysis by Hutchinson, Needleman and Shih (1978) leads to an expression for CC specimen in the form

$$C^* = A\,\frac{P^{n+1}a}{(W-a)^n}\;g(\tfrac{a}{W}) \propto P\,\dot{\Delta}\;a \qquad (4)$$

where A is a constant and g is a function of (a/W). Creep crack growth rate da/dt has been correlated with C^* and published data under load controlled condition from different sources are reproduced in Figs.1 to 6 for 304 type stainless steel (Koterazawa and Mori, 1977; Taira, Ohtani and Kitamura, 1979), Udimet (Sadananda and Shahinian, 1978), Cr-Mo-V steel (Harper and Ellison, 1977; Pilkington, Miller and Worswick, 1980) and type 316 stainless steel (Sadananda and Shahinian, 1981). The full lines in the figures are due to the present author. It can be observed that <u>in all the cases</u> there is systematic scatter and the relation da/dt vs C^* is load dependent. For a given load the relation is non-linear on the log-log plot. The scatter in data, typically in 316 type stainless steel is by a factor of 50.

PARAMETER DERIVATION

Fig.7 shows the data reduction procedure from the first principle. While coming to step II, there are three possibilities for the relation $\dot{U}$ vs $\underline{a}$, i.e., (A) a convex curve, (B) a straight line or (C) a concave curve for a given $\dot{\Delta}$. In (A) at higher loads J^* will be smaller and in (C) at higher loads J^* will be larger. This implies that under condition (A), the change in energy for a small change in crack length at higher P will be smaller and vice versa in condition (C). The corresponding relation between $\dot{\Delta}$ and $\dot{a}$ is also shown at the bottom. In condition (A) $\dot{a}$ will be smaller (as is J^*) at higher loads and opposite is the case in condition (C). The relation between $\dot{a}$ and $\dot{\Delta}$ can be given by

$$\dot{a} \propto \dot{\Delta}\,/\,[P] \quad \text{for condition (A)} \qquad (5a)$$

$$\propto [\,\dot{\Delta}\,] \quad \text{for condition (B)} \qquad (5b)$$

$$\propto \dot{\Delta}\,[P] \quad \text{for condition (C)} \qquad (5c)$$

Square brackets indicate functions. The possibility (B) has been observed for creep brittle materials (Haigh, 1975; Radhakrishnan and McEvily, 1981a) where there is very little plastic deformation in the crack front region and the crack growth rate is a function of the COD rate or load point deflection rate only. The $\dot{\Delta}$ - $\dot{a}$ relation is a validity test to know which possibility - (A), (B) or (C)- is applicable for a given material. However, no published data of the relation $\dot{\Delta}$ - $\dot{a}$, excepting for 6061 Al alloy (Radhakrishnan and McEvily, 1981b) and 316 type stainless steel (Sadananda and Shahinian, 1983), are available for creep ductile materials. The relation between $\dot{U}$ and crack length for 316 type stainless steel is shown in Fig.8 (the raw data are from Sadananda and Shahinian (1983) and the full line is due to the present author) which confirms very well the description under possibility (A). The relations between $\dot{\Delta}$ and $\dot{a}$ for 316 type stainless steel (Sadananda and Shahinian, 1983) and 6061 Al alloy (Radhakrishnan and McEvily, 1981b) for CC specimen are shown in Figs.9 & 10, which show the load dependence as indicated in possibility (A). The corresponding crack growth relation for the applied bending type of load is shown in Fig.11, according to the relation (5a).

$$\dot{a} \propto \dot{\Delta}\,/\,(M/M_0)^{\alpha} \qquad (6)$$

for two types of specimen geometries - deep notched CT specimen and large centre cracked specimen. The description appears to be very good and creep ductile materials appear to follow the possibility (A) indicated in Fig.7.

DISCUSSION

Possibility (A) appears to be more probable because with increasing crack length the compliance, C will increase and in creep condition the change in compliance, dC with change in crack length, da at larger values of $\underline{a}$ will be more than at smaller values of $\underline{a}$, as indicated in Fig.7. So if the compliance is taken as

$$C = \left(\frac{\Delta_0}{P_0}\right)\left(\frac{a}{a_0}\right)^{\gamma} \qquad (7)$$

where Δ_0, P_0, a_0 and γ are constants, we get the rate of compliance change as

$$\frac{dC}{dt} = \frac{dC}{da}\,\frac{da}{dt} = \left(\frac{\Delta_0}{P_0}\right)\frac{\gamma}{a_0}\left(\frac{a}{a_0}\right)^{\gamma-1}\dot{a} \qquad (8)$$

The deflection and load are related in a cracked elastic material as $\Delta = CP$ and the deflection rate in a visco-elastic material under constant load can be given as

$$\frac{d\Delta}{dt} = \frac{d\Delta}{dC}\,\frac{dC}{dt} = P_0\,\dot{C}\,(P/P_0)^{\alpha} \qquad (9)$$

Combining (8) and (9) and rearranging we get

$$\dot{a} = \frac{\dot{\Delta}\,a_0}{\gamma\Delta_0}\left(\frac{a_0}{a}\right)^{\gamma-1}\left(\frac{P_0}{P}\right)^{\alpha} = R \qquad (10)$$

Taking $C^* \propto \dot{\Delta}P\,/\,(W-a)$ we get from eqn (10)

$$\dot{a} \propto C^*\,\frac{(W-a)}{P^{\alpha+1}\,a^{\gamma-1}} = C^*\beta \qquad (11)$$

It can be seen that the factor β will decrease as $\underline{a}$ increases for a given P. So if β is not considered; then $\dot{a}$ vs C^* relation will have a larger value on the C^*-axis for a given $\dot{a}$ and this will result in a drooping or flattening curve, as seen in Figs. 1 to 6. β is also load dependent; it decreases with increasing load. It can be seen in Figs.1 to 6 that curves for higher loads get shifted to the right. If β is also included as indicated in eqn (11), then the decreasing effect of β with increasing load will compensate for the shift observed in the $\dot{a}$ - C^* relation and a single master curve can be obtained for all load conditions.

In some materials the exponent (γ-1) in eqn (10) may be small. Also if the total variation in crack length is limited, then the contribution of $(a)^{\gamma-1}$ to the deflection rate may be negligible and so the creep crack growth rate can be given by

$$\dot{a} \quad \propto \quad \dot{\Delta} / (P)^{\alpha} \qquad (12)$$

Such a type of behaviour has been observed in 6061 Al alloy as shown in Fig.9.

Tests have also been carried out under deformation controlled condition (Landes and Begley, 1976; Saxena, 1980) in which the load P and the deformation rate are controlled in contrast to only one controlled variable, namely, load in creep tests where the deformation rate is allowed to attain its own natural level. The load and the crack length both increase till P reaches P_{max} : then P starts decreasing as $\underline{a}$ increases bringing in instability condition. In a typical case (Saxena, 1980) the increase in P upto P_{max} is nearly for 3/4th of the total test period for 304 type stainless steel at 595°C. These deformation controlled experiments are similar to normal tensile testing with a very slow strain rate. The first step in the data reduction procedure (Fig.7) will not be applicable till P reaches P_{max}. After P_{max} the remaining portion indicates only unstable crack growth. Results of deformation controlled tests can represent that of load controlled ones only when the deformation rate is dependent purely on the current values of crack growth rate and load and should be independent of the load history. In creep brittle materials the deformation rate will be dependent only on $\dot{a}$ and not on load (possibility (B)). In such a case the deformation controlled test can be similar to the load controlled tests in which $\dot{\Delta} \propto [\dot{a}]$. A typical example is the Discaloy tested by Landes and Begley (1976). In creep ductile materials deformation controlled tests cannot represent load controlled tests and so no attempt has been made here to analyse the data obtained under deformation controlled conditions.

CONCLUSIONS

A critical assessment of the experimental data on a - C^* relation reveals systematic scatter and load dependence. Parameter analysis from first principle indicates three possibilities for the energy variation with crack growth. The most probable among these for ductile materials leads to the parameter R which is able to describe the creep crack growth rate in a ductile material. The reasons for the systematic scatter and load dependence of the relation $\dot{a}$ - C^* are explained through the factor β which relates C^* and R.

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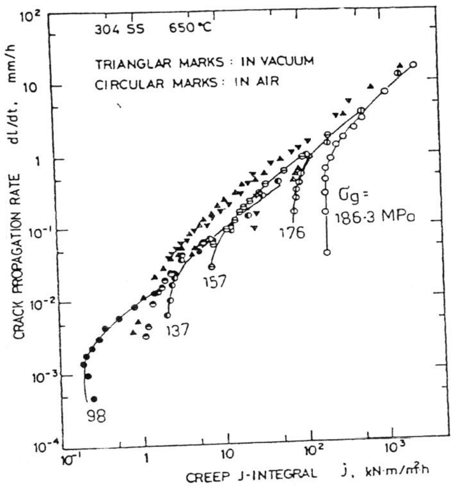

Fig. 1. Relation between $\dot{a}$ and J^* (raw data from Taira, Ohtani and Kitamura, 1979).

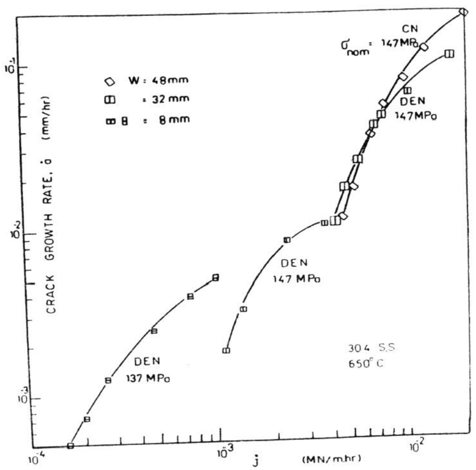

Fig. 2. Relation between $\bar{a}$ and J^* (raw data from Koterazawa and Mori, 1977).

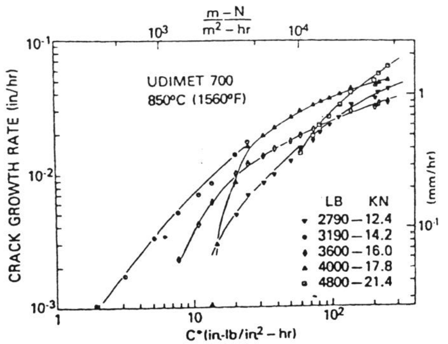

Fig. 3. Variation of crack growth rate with C^* (raw data from Sadananda and Shahinian,1978)

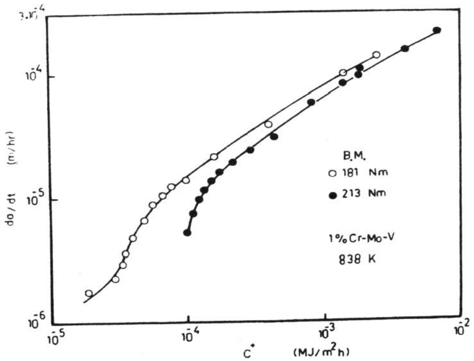

Fig. 4. Dependence of da/dt on C^* (raw data from Harper and Ellison, 1977)

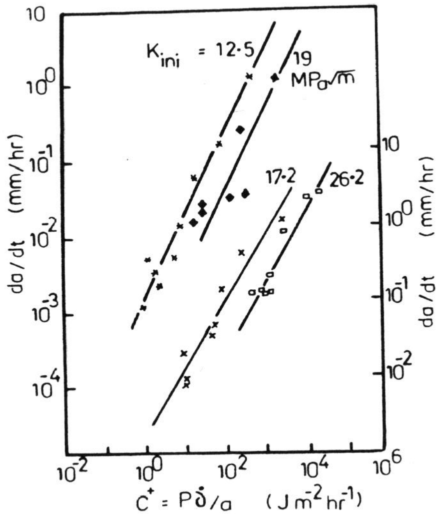

Fig. 5. Dependence of da/dt on C^* for 1/2 Cr-Mo-V steel (raw data from Pilkington, Miller and Worswick, 1980)

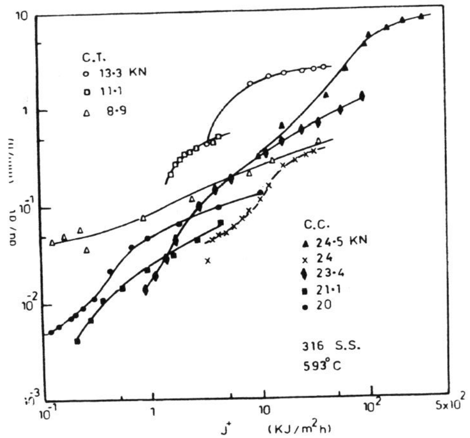

Fig. 6. Relation between da/dt and J^* (raw data from Sadananda and Shahinian, 1981)

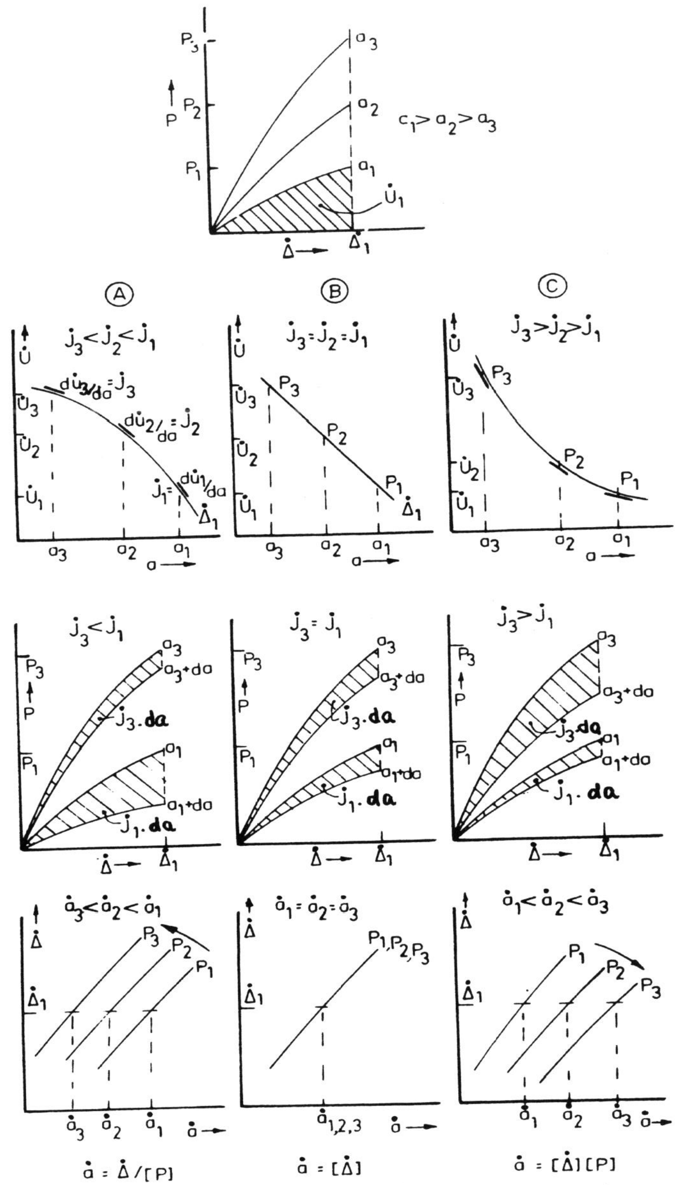

Fig. 7. Data reduction procedure

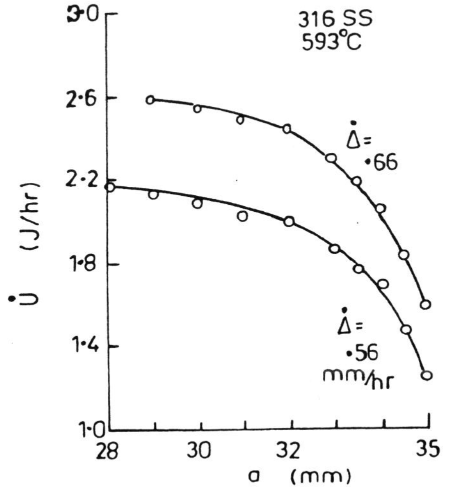

Fig. 8. Relation between $\dot{U}$ and crack length (raw data from Sadananda and Shahinian, 1983)

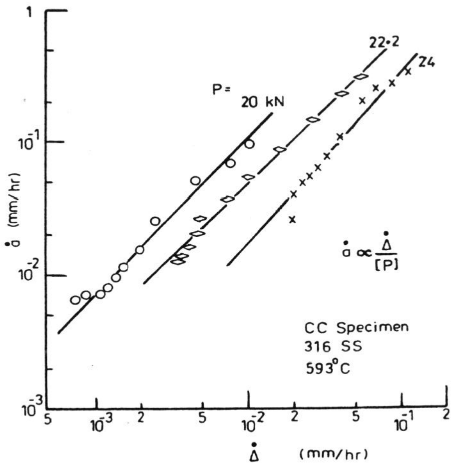

Fig. 9. Dependence of $\dot{a}$ vs $\dot{\Delta}$ on load (raw data from Sadananda and Shahinian, 1983)

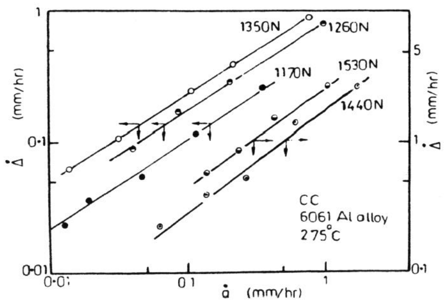

Fig. 10. Dependence of $\dot{\Delta}$ vs a on load (raw data from Radhakrishnan and McEvily, 1981b)

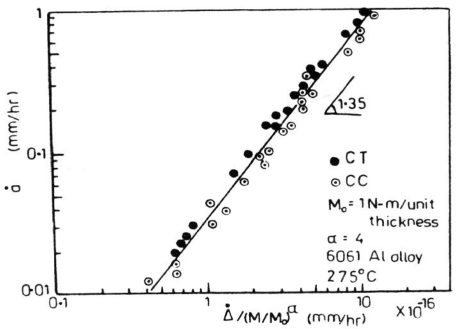

Fig. 11. $\dot{a}$ vs the parameter R