THE IMPLICATIONS OF RECENT DEVELOPMENTS IN ELASTIC PLASTIC FRACTURE MECHANICS ON THE GROWTH OF STRESS CORROSION CRACKS

E. Smith

Joint Manchester University/U.M.I.S.T. Metallurgy Department
Grosvenor Street, Manchester M1 7HS, United Kingdom.

ABSTRACT

The paper demonstrates that laboratory stress corrosion crack growth data, i.e. K versus dc/dt plots, can be used to predict the growth of cracks observed in service, provided the applied stress levels are low. When these are high, however, current state-of-the-art fracture mechanics procedures cannot be employed. In such circumstances the author suggests that maximum use should be made of sustained load crack growth data. The paper also provides a starting point for a quantitative consideration of the effect of metallurgical variables on stress corrosion crack growth.

KEYWORDS

Stress corrosion; crack growth; fracture mechanics; life-time predictions; metallurgical variables.

INTRODUCTION

When a crack is observed during in-service inspection of an engineering component, it is obviously important to have some idea of the time required for the crack to grow slowly, by stress corrosion or fatigue, under the operative stress condition, until it reaches the critical length for catastrophic propagation. The subsequent in-service inspection schedule can then be planned in a rational manner. As regards slow crack growth by stress corrosion, the currently accepted procedure for making a life-time prediction is to use laboratory experimental data that relates the crack tip stress intensification K with the crack growth rate dc/dt in an environment that simulates, as close as possible, the actual in-service environment.

This paper highlights the main features of a recent theoretical investigation which focusses on this problem. The general conclusion is that the above procedure is adequate when the operative stress levels are low relative to the material's yield stress. However, if they are high, the procedure is inadequate and an alternative approach must be employed. In such circumstances, the author suggests that sustained load (high stress) crack growth data should be used.

STRESS-CORROSION CRACK GROWTH AT LOW STRESS LEVELS

Laboratory stress corrosion crack growth data is usually obtained in the form of plots of crack tip stress intensification K versus crack growth rate dc/dt. The basic principles behind these plots are that a crack grows under LEFM conditions, i.e. the plastic zone associated with the propagating crack is small compared with the crack size, and that the relation between K and dc/dt is unique for a specific material, environment and test temperature. In applying this data to the behaviour of a crack observed in a service component, it is again assumed that the applied stress level is such that LEFM conditions are operative, and that the K versus dc/dt relation is unique.

There is little or no experimental data available to confirm the uniqueness, or otherwise, of the K versus dc/dt behaviour, and it is against this background that the author has examined the problem. At first sight, it is surprising that the relation should be unique, since stress corrosion crack growth must to some extent be history dependent, in that the deformation associated with a given crack extension increment is influenced by the preceding crack extension. The crucial question, therefore, is whether or not this history dependence is important; this section explores this particular point.

The simplest way of quantifying stress corrosion crack growth is to use Wnuk's modification (Wnuk, 1973) of the DBCS model (Dugdale, 1960; Bilby, Cottrell and Swinden, 1963) in which yield is confined to an infinitesimally thin strip coplanar with the crack. Wnuk's crack growth criterion is that the crack moves forward a distance Δ if the displacement accumulated while a material point is within a distance Δ from the tip, attains a critical value δ. δ and Δ are both envisioned as being characteristic of the material under consideration, with Δ being the fracture process zone size, and represents the spacing between the inhomogeneities that are responsible for the material losing its cohesion. Wnuk's so called "final stretch" crack growth criterion is incremental in character, and is equivalent to a crack tip opening angle (CTOA) criterion in other models (Rice and Sorensen, 1978) with the CTOA $\theta \equiv \delta/\Delta$.

If the fracture process zone size Δ is small compared with the size w of the plastic zone at the crack tip, which in turn is small compared with the crack size c, i.e. $\Delta << w << c$, whereby LEFM condition are operative, application of Wnuk's criterion to the DBCS model gives the crack growth criterion as (Wnuk, 1979; Smith, 1980)

$$\frac{dw}{dc} = \frac{1}{2} \ln \left[\frac{\Delta}{4ew} \exp \left\{ \frac{\pi E \theta}{4(1-v^2)Y} \right\} \right] \qquad (1)$$

where E is Young's modulus, v is Poisson's ratio and Y is the yield stress of the material. Furthermore, in this small scale yielding (LEFM) situation, w is related to the J integral and the crack tip stress intensification K by the relations

$$\frac{\pi K^2}{8wY^2} = \frac{\pi EJ}{8(1-v^2)wY^2} = 1 \qquad (2)$$

whereupon (1) can be expressed in the equivalent form

$$K^2 = \frac{2Y^2\Delta}{\pi e} \exp \left\{ \frac{\pi E \theta}{4(1-v^2)Y} \right\} \exp \left\{ -\frac{\pi}{2Y^2} K \frac{dk}{dc} \right\} \qquad (3)$$

Relation (3) describes the incremental growth of a crack by a stress corrosion mechanism. The crack tip opening angle θ, which is governed by the detailed mechanisms operating within the fracture process zone, depends on the crack growth rate $v \equiv dc/dt$. Thus relation (3) shows that K varies with crack speed, but the relation is only unique provided that the expression within the second exponential bracket is small. In general, this will be the case. To illustrate this point, consider a sustained load test where a constant stress σ is applied to a solid containing an edge crack of depth c. K $\sigma\sqrt{\pi c}$ and the term within the second exponential bracket is equal to $-\pi^2\sigma^2/4Y^2$, which is small if $\sigma << Y$ when LEFM conditions are operative. In situations like this the relation (3) between the crack tip stress intensification K and the crack growth rate v = dc/dt, reduces to

$$K^2 = \frac{2Y^2\Delta}{\pi e} \exp \left\{ \frac{\pi E}{4(1-v^2)Y} \theta(v) \right\} \qquad (4)$$

The relation between K and dc/dt is then unique in the sense that it is independent of the applied loadings or the crack size. This result, for LEFM conditions, underscores the importance and usefulness of laboratory data relating K to dc/dt, and vindicates the application of such data to the growth of cracks found in service. It is interesting to observe that the problem of creep crack growth is completely different (Pilkington and Smith, 1980). In this case, the term in the second exponential bracket in relation (3) need not be small, since the effective value of Y is reduced because of creep. The relation between K and dc/dt is then not unique, a prediction which accords with the variability observed experimentally (Pilkington, 1979).

STRESS CORROSION CRACK GROWTH AT HIGH STRESS LEVELS

Against the background of the preceding section's comments, it is only natural to explore whether or not there exists a unique relation between the J integral and crack growth rate when small scale yielding conditions are inoperative, i.e. at high stress levels. First of all, it is easy to show that there is no unique relation even towards the upper end of the LEFM range. Thus with $\sigma/Y \sim 0.5$ for the sustained load situation described in the preceding section, relation (3) contains the applied stress σ as well as K (J) and θ (dc/dt); consequently the K (J) versus dc/dt relation is not unique. One therefore anticipates that the relation between the J integral and dc/dt is not unique at higher stress levels, where small scale yielding conditions are inoperative.

To confirm this view, again consider the sustained load situation where a constant stress σ is applied to a solid containing an edge crack of depth c. If no restriction is placed on the extent of plastic yielding, the incremental crack growth criterion obtained by applying Wnuk's condition to the DBCS model is (Wnuk, 1979; Smith, 1980).

$$\frac{dJ}{dc} = Y\theta + \frac{4Y^2(1-v^2)}{\pi E} \ln \left\{ \frac{a^2\Delta}{2e(a^2-c^2)c} \right\} \qquad (5)$$

where a is the distance to which the plastic zone spreads, as measured from the solid surface, i.e. the plastic zone size is (a-c). J and a are related by the expression

$$J = \frac{8(1-\nu^2)Y^2c}{\pi E} \ln\left(\frac{a}{c}\right) = \frac{8(1-\nu^2)Y^2c}{\pi E} \ln \sec\left(\frac{\pi\sigma}{2Y}\right) \quad (6)$$

whereupon relation (5) can be re-written in the form

$$\exp\left\{-\frac{\pi EJ}{4(1-\nu^2)Y^2c}\right\} = 1 - \frac{\Delta}{2ec} \exp\left\{\frac{Y\theta - \frac{dJ}{dc}}{\frac{4(1-\nu^2)Y^2}{\pi E}}\right\} \quad (7)$$

This example immediately shows that the crack growth rate, which controls the crack tip opening angle θ, is not uniquely related to the J integral, since relation (7) does not simplify, at high stress levels, to a relation involving only J and θ.

DISCUSSION

The preceding section has shown that there is a unique relation between crack tip stress intensification K and stress corrosion crack growth rate dc/dt, when the applied stress levels are low and LEFM conditions are operative. Under such conditions, laboratory stress corrosion crack growth data in the form of K versus dc/dt plots, can be used to predict the growth of a crack observed during in-service inspection of an engineering component. On the other hand, there is not a corresponding unique relation between the J integral and crack growth rate at high stress levels. This means that K versus dc/dt data, translated via the standard relation $J = (1-\nu^2)K^2/E$, cannot be used to predict the growth of cracks observed in service, if the operative stress levels are high.

Against this background, and particularly since some service failures have occurred at high stress levels, for example due to stress corrosion cracks forming at key-ways in turbine discs (Hodge and Mogford, 1979), it is clear that an alternative lifetime prediction procedure must be employed. In the author's opinion, the only viable approach is to base a lifetime prediction, in such situations, on laboratory data obtained by monitoring crack growth under sustained (high) stress conditions. This procedure ought to be reasonably satisfactory provided the in-service stress gradient is not too severe, and even then an approximate averaging procedure could be used. It may well transpire, of course, that in some practical situations, the crack growth rate may be so rapid that when a crack attains a size at which it can be detected by present day inspection procedures, a repair will have to be effected. This being the case, the problems raised in this paper will not be relevant, although the stress corrosion cracking problem then, of course, becomes very serious.

Finally, it is worth mentioning that this paper's approach provides a starting point for a quantitative consideration of the effect of metallurgical variables on stress corrosion crack growth. Thus, for example, relation (4) gives the crack tip stress intensification in terms of the parameter θ, the crack tip opening angle. The magnitude of this parameter is controlled by the fracture micro-mechanisms within the fracture process zone in the immediate vicinity of a crack tip. Metallurgical variables, such as temper-embrittling elements, which affect these micro-mechanisms should therefore have an influence on the macroscopic stress corrosion cracking behaviour.

CONCLUSIONS

- The relationship between crack tip stress intensification factor K and stress corrosion crack growth rate dc/dt is unique when crack propagation proceeds at low stress levels (LEFM conditions). In such circumstances, laboratory stress corrosion crack growth data in the form of K versus dc/dt plots can be used to predict the growth of a crack found during in-service inspection of an engineering component.

- There is no corresponding unique relation between the J integral and crack growth rate when a crack grows at high stress levels. K versus dc/dt data, converted to give J versus dc/dt data, cannot then be used to predict the growth of a crack observed in-service at a high stress level. In such circumstances, maximum use should be made of sustained load crack growth data. In other words stress corrosion crack growth should be described in terms of a stress versus growth rate relation, rather than a stress intensification versus growth rate relation.

- This paper's approach provides a starting point for a quantitative consideration of the effect of metallurgical variables on stress corrosion crack growth.

REFERENCES

Bilby, B.A., A.H. Cottrell, and K.H. Swinden (1963). Proc. Roy. Soc., A272, 304-314.

Dugdale, D.S. (1960). J. Mechs. and Phys. of Solids, 8, 100-104.

Hodge, J.M., and I.L. Mogford (1979). Proc. Inst. Mech. Engrs., 193, 93-107.

Pilkington, R. (1979). Metal Science, 13, 555-571.

Pilkington, R., and E. Smith (1980). Unpublished work.

Rice, J.R., and E.P. Sorensen (1978). J. Mechs. and Phys. of Solids, 26, 163-186.

Smith, E. (1980). Paper accepted for publication in Jnl. of Materials Science and Engineering.

Wnuk, M.P. (1973). Proceedings of Conference on Dynamic Crack Propagation, Lehigh University, Pa. U.S.A., Ed. G.C. Sih, Noordhoff, 273-280.

Wnuk, M.P. (1979). Proceedings of ICM3 Conference, Cambridge, England, 3, 549-561.