ASSESSMENT OF RESIDUAL LIFE OF COMPONENTS SUBJECT TO ENVIRONMENTALLY ASSISTED CRACKING

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Environmentally Assisted Cracking (EAC) is one of the aspects to be considered when assessing the behaviour of components working in contact with aggressive environments. Fracture mechanics can be a part of a fracture control plan to prevent or control EAC in service. Depending on the class of material, it may be necessary to put the emphasis on prevention, but the control of crack growth is sometimes possible for thick-walled components and ductile materials. This paper provides a review of the methods for obtaining and using EAC test data for different materials and industrial applications. Both fracture mechanics and non-fracture mechanics tests are considered, but the emphasis is on using fracture mechanics for preventing and, if possible, controlling EAC in service.

INTRODUCTION

There is an increasing demand for longer operating lives of components in engineering structures, for example many industrial plants and the "ageing aircraft" problem. It is therefore becoming more important to assess the behaviour of materials and structures both when they contain -or may contain- defects or cracks (damage-tolerant design approach) and in the presence of aggressive environments.

The interaction between loading and environmental parameters is the cause of damage mechanisms such as corrosion fatigue, stress corrosion, corrosion-erosion, which become important as the life requirements of the components increase. However, owing to the complexity of experimental techniques and to the large number of variables, the level of knowledge of mechanical-environmental effects is still far from sufficient.

One of the main goals of research in Environmentally Assisted Cracking (EAC) is to develop the capability of predicting, for design and for life optimization purposes, the time evolution of a crack present in a component,

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under the combined influence of loading and a particular set of environmental conditions. Fracture mechanics is an important tool for use in such predictive analyses (1), since it permits a quantitative approach to EAC. However, it must be stated immediately that such analyses are relevant only to ductile materials (generally steels) in industrial plants, and not to high strength aerospace alloys, for which EAC cannot be permitted (2). In this paper indications will be given as to how crack growth due to corrosion processes can interact with the mechanical behaviour of ductile materials, particularly during service transients.

ENVIRONMENTALLY ASSISTED CRACKING AND FRACTURE MECHANICS

Stress Corrosion Cracking (SCC) occurs when a susceptible alloy is exposed to an aggressive environment at a stress above a critical value (3). As schematically shown in figure 1a, SCC is controlled by microstructure, environment and stress conditions. Crack propagation occurs when the parameters defining each of these conditions reach critical values, and so if conditions change and one of the parameters becomes non-critical, cracking may cease. With increased knowledge of cracking mechanisms it has become evident that there is a spectrum of operating and material conditions between the modes of failure semantically entitled Stress Corrosion, Hydrogen Induced Cracking and Corrosion Fatigue (Fig. 1b, (4)). The complete range of phenomena indicated in figure 1b are described under the name "Environmentally Assisted Cracking (EAC). Loading frequency and durations of transients or sustained loads are the parameters controlling time-dependent effects.

Turning now to the relevance of fracture mechanics, it must first be noted that there are two basic philosophies of structural design:

- The SAFE-LIFE approach
- The DAMAGE TOLERANCE approach.

The Safe-Life approach means designing for a finite service life during which significant damage (i.e. cracking) will not occur. Also, there is no provision -at least in the design stage- for in-service inspection in order to detect damage.

More recently, in the power generation, petrochemical, and chemical industries, interest has been focussed on extending component life past the original design life (5). If this is to be done it must be shown that damage (cracks) will be detected by routine inspection before the damage reaches a level where the residual strength of the component is reduced below a safe level. The damage tolerance approach has been devised to meet this requirement. This approach:

(1) Accounts for the possibility of cracks or flaws already in a new structure.
(2) Allows structures to be inspectable or non-inspectable in service.

For establishing design and inspection procedures, the knowledge of material properties is essential. One of the most important issues is subcritical crack growth. In the presence of an environment, use of the damage tolerant approach must take into account the effect of corrosion and SCC. Accordingly, since damage tolerance design methods, including leak-before-break, are based on fracture mechanics, this becomes an important tool for crack growth prediction. The knowledge of models and mechanisms of crack propagation is also important.

Figure 2 shows in a general way the engineering aspects of cracks in structures, and the important questions which fracture mechanics attempts to answer, via the characterization of subcritical crack growth, which includes EAC, and of fast fracture due to overload. The answers to questions (1) and (2) in figure 2 are usually obtainable. However, the answers to questions (3) - (5), which concern subcritical crack growth, are more difficult to obtain. This is especially true for EAC. For a successful approach to life prediction for industrial components, it is necessary to follow a fracture control plan which integrates the knowledge of working conditions of the component, materials properties and models and mechanisms for crack propagation. Such an approach is schematically shown in figure 3, where the use of laboratory tests, in-field observations and theoretical studies for cracking mechanisms and models to obtain life prediction is shown.

FRACTURE MECHANICS TESTS IN ENVIRONMENTS

Tests in environments can be made using mechanically-based fracture mechanics test techniques and data reduction methods. Specific SCC tests are also done using precracked specimens, but in this case data reduction only involves Linear Elastic Fracture Mechanics parameters. It is important to study the test techniques keeping in mind the likelihood of time dependent effects and their meaning for life prediction purposes.

The behaviour of ductile materials subject to loading in the presence of aggressive environments has been studied at CISE in cooperation with ENEL, the Italian electric board. In particular, studies have been made of EAC behaviour of low alloy steels for power generation plant in service-simulating environments, using a fracture mechanics test technique (J-R curves) and SCC tests on smooth and precracked specimens. J-R tests in environments have been performed on Compact Tension (CT) specimens following standard procedures.

To account for time dependent processes, the effect of specimen opening rate was investigated.

It is well-known from laboratory tests that strain rate is the key parameter for the analysis of EAC laboratory results, to compare the results obtained with different loading techniques (constant load, fatigue and increasing load), and to predict the presence of SCC (6). Results of J-R tests in environments also show that J_{IC} (and K_{IC}) values depend on the opening rate, as observed for instance for low alloy steel in pure oxygenated water (Fig. 4 (7)). Similar behaviour was observed also for aluminium in synthetic sea water (8). When the loading rate is low enough the measured K_{IC} is equal to K_{ISCC}.

The decrease of J_{IC} when the loading rate decreases means that a crack in an environment requires a lower amount of energy to propagate. This is due to the availability of chemical/electrochemical energy at the crack tip. As the loading rate decreases, longer time is available for chemical processes to act. At high loading rates there is no time available for corrosion processes and mechanical effects are dominant.

The environmental effect becomes evident also from the observation of the load-displacement curve. See for instance in figure 5 two examples obtained at different loading rates on specimens of the same material with the same geometry. This figure shows some important features:

1) The specimen compliance decreases when the loading rate decreases. This is associated with a decrease of the stretch zone width, and shows that the presence of an environment causes a kind of "embrittlement" of the material, similar to the one observed also during environmental fatigue tests (9).
2) The load-displacement curve in an environment is not substantially different from the same curve obtained in air. The observed change of slope is however due not only to plasticity, but to crack growth, as shown schematically in figure 6, where load-displacement curves in air at different starting crack length are compared with a curve in environment, where crack growth is due to corrosion. It is important to be able to discriminate -also on a quantitative basis- between plasticity and crack growth effects.

Fracture mechanics test techniques in environments and data reduction are being studied in the frame of a European Community programme (10). This study is very important, since as shown previously, the materials properties in an environment change and the parameter "time" assumes much importance.

Thus it is possible that different test recommendations need to be formulated. It is for instance predictable that the approach of Linear Elastic Fracture Mechanics in environment is valid for a wider range of specimen dimensions than in air, owing to "brittle" behaviour enhanced by the environmental effect. Moreover, it may also be advisable that the minimum value for crack propagation is smaller than 0.2 mm, since the blunting is reduced. In figure 7 a plot of the crack growth rate (measured using P.D. technique) as a function of J (calculated according to ASTM) for a test in an environment is shown. This curve shows that:

1) J_{IC} calculated according to ASTM corresponds to the region where crack growth rate starts to be of the same order of magnitude as the loading rate.

2) the value of J corresponding to a crack growth rate above the threshold is much closer to J_{ISCC}, also in the cases where corrosion is not dominant.

The considerations here show that it is necessary to further study fracture mechanics tests in environments, to be able to understand the change in the material properties and to account quantitatively for the time-dependent effects.

APPLICATION TO SERVICE COMPONENTS

In service, components may be found cracked during inspections and will usually be replaced. However, this is not always possible, owing to replacements being unavailable or to inaccessibility during service. The possible use of crack growth data for ductile materials in aqueous environments depends on the value of da/dt. For some material-environment combinations subcritical crack growth rates are very high, of the order of 0.1 mm per day, or more. In this case, service lives for components with continuously growing cracks will be too short and a change to another material or heat treatment would be advisable.

In practice, subcritical crack growth rate for a given material-environment couple is often lower, because the crack is growing only when a set of conditions (mechanical, microstructural and environmental -see Fig. 1a-) are fulfilled together with time requirement (strain rate, see Fig. 1b). In such cases there is a possibility of "living with a crack" using a damage tolerant approach, which, while more difficult to realize, permits an extension of the life of the plant and economical benefits over the long term.

Crack increments are likely to occur due to fatigue, or during transients when a slow strain rate is created at the crack tip and service environments are more aggressive. As schematically shown in Fig.1(b), there is a continuum passage between corrosion fatigue and stress corrosion cracking, due to variations in R ratio and frequency, but the cracking mechanisms are substancially the same. The strain rate is the key parameter to evaluate and predict crack growth. There are, however, some difficulties in the application of laboratory test results to components, owing to the difficulty of estimating crack tip strain rate. The use of a simpler parameter, such as loading rate, can be effective (11). Crack tip strain rate is a function of the applied loading rate and of the effective crack growth rate. In the case of fatigue loading, the combination of loading rate and crack growth rate is indicated as the "envelope" displacement shown in Fig.8, while during single transients the "single cycle" displacement is to be considered.

Following the approach outlined in figure 3, the assessment of EAC behaviour of ductile materials can be done by comparing service data and laboratory test results: time-dependent effects are considered via the loading rate. Materials properties change in environments and components can suffer different amounts or types of damage depending not only on transient loading, but also on transient duration. It is important to spend a few words illustrating with an example how time-dependent effects have consequences on crack growth behaviour during transients:

- In figure 9 crack growth rate values for low alloy steel in oxygenated water are plotted versus load line displacement rate. In the absence of corrosion the values lie on a straight line (comparable to a Paris line). As the loading rate decreases (and frequency decreases too, if there is fatigue loading), time dependent effects become increasingly important, until the crack growth rate reaches a plateau value, corresponding to "pure SCC" crack growth rate (the same that can be measured when testing wedge-loaded specimens). If the crack grows, loading rate (or strain rate) is never equal to zero. For each value of loading increment during a transient, a line with the same shape as the one shown in figure 9 can be drawn.
- In figure 10, the same data have been used to predict the crack length increment during a single transient, as a function of transient time. Also in this case, for a quantitative prediction it is necessary to know the loading increment during the examined transient (here there is an indication of the effect of load increase). In this picture, two regions are evident:

1) A plateau region, where crack increment is constant and not depending on transient duration. Here the mechanical effect is dominant and the crack increment depends only on material properties.
2) A region where corrosion processes (time-dependent) are dominant, and the crack increment is larger as the transient time increases.

It is important, moreover, to point out that the position of the "transition point" corresponding to the onset of corrosion processes (transition from the plateau region in Fig. 9) is also a function of transient time and crack opening.

CONCLUSIONS

Environmentally Assisted Cracking has been considered in this paper with particular attention to the role of time-dependent parameters. It has been shown that if chemical conditions are favourable then SCC occurs over a range of displacement rates, and that crack velocity in a transient depends on loading rate and transient duration. Fracture mechanics tests techniques and data reduction methods are useful tools for the understanding of EAC, but there is a need of further study to take into account the time-dependent effects. Displacement rate is one of the key parameters to be used for life assessment in the case of subcritical crack growth. It is simple to calculate, and allows application of the results obtained on laboratory specimens to industrial components.

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REFERENCES

(1) Ewalds, H.L. and Wanhill, R.J.H., "Fracture Mechanics", Edited by Edward Arnold and Delftse Uitgevers Maatschappij, London, UK, and Delft, The Netherlands, 1984.

(2) Wanhill, R.J.H., "Fracture control guidelines for stress corrosion cracking of high strength alloys", ESIS DI-92, 1992.

(3) Parkins, R.N., "An overview - Prevention and control of stress corrosion cracking", Metals Performance, Vol. 24, No. 8, 1985, pp. 9-20.

(4) Ford, F.P., "Mechanisms of Environmental Cracking in Systems Peculiar to the Power Generation Industry" EPRI NP-2589, Project 1332-1, Final Report, September 1982.

(5) "Life prediction", Mat. Sci. and Engng., special issue, Vol. A103, 1988.

(6) Shoji, T., et al., "Mechanistic understanding of environmentally assisted cracking of RPV steels in LWR primary coolants", Proc. of IAEA Specialists Meeting on Subcritical Crack Growth, Sendai, Japan, Edited by W.H. Cullen, USNRC NUREG/CP-0067, April 1986.

(7) Gabetta, G., Rinaldi, C. and Radaelli, M.M., "Stress corrosion tests in water at 288 °C, using the unloading compliance technique" ECF8 Preprints "Fracture Behaviour and Design of Materials and Structures", Edited by D. Firrao, EMAS, U.K., 1990.

(8) Dietzel, W., Schwalbe, K.H. and Wu, D., "Application of fracture mechanics techniques to the environmentally assisted cracking of Aluminium 2024", Fat. Fract. Engng. Mater. Struct., Vol. 12, No. 6, 1985, pp. 495.

(9) Gabetta, G. and Rinaldi, C., "Evidence of embrittlement and its prediction during environmental fatigue of pressure vessel steels" in Predictive Capabilities in Environmentally Assisted Cracking, R. Runga Ed., ASME, PVP Vol. 99, 1985, pp. 107-126.

(10) ESIS P4-92D, "Recommendations for stress corrosion testing using pre-cracked specimens", European Structural Integrity Society, Technical Committee 10.

(11) Gabetta, G., "Loading rate as a parameter for Environmentally Assisted Cracking of steels", British Corrosion Journal, Vol. 28, No. 2, 1993, pp. 107-111.

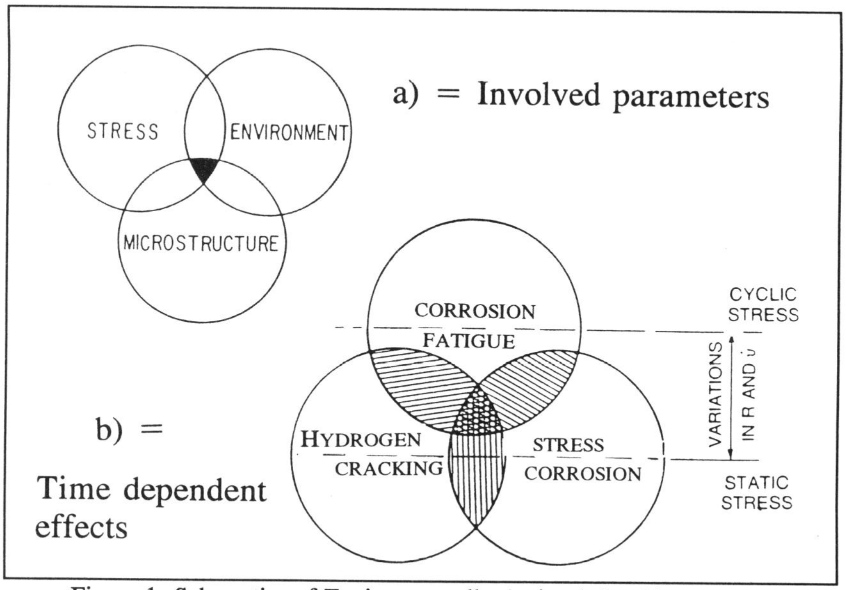
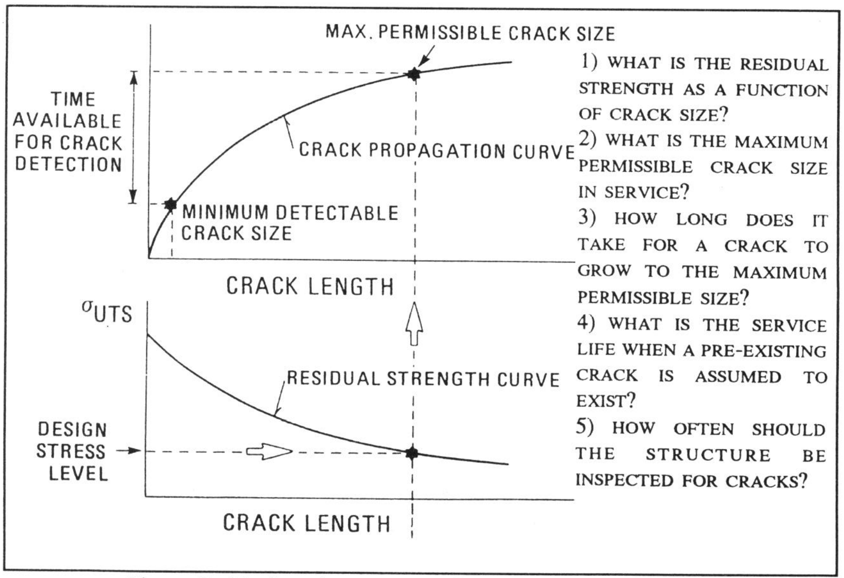


Figure 1 Schematics of Environmentally Assisted Cracking (EAC).



1) WHAT IS THE RESIDUAL STRENGTH AS A FUNCTION OF CRACK SIZE?
2) WHAT IS THE MAXIMUM PERMISSIBLE CRACK SIZE IN SERVICE?
3) HOW LONG DOES IT TAKE FOR A CRACK TO GROW TO THE MAXIMUM PERMISSIBLE SIZE?
4) WHAT IS THE SERVICE LIFE WHEN A PRE-EXISTING CRACK IS ASSUMED TO EXIST?
5) HOW OFTEN SHOULD THE STRUCTURE BE INSPECTED FOR CRACKS?

Figure 2 Engineering aspects of cracks in structures (2).

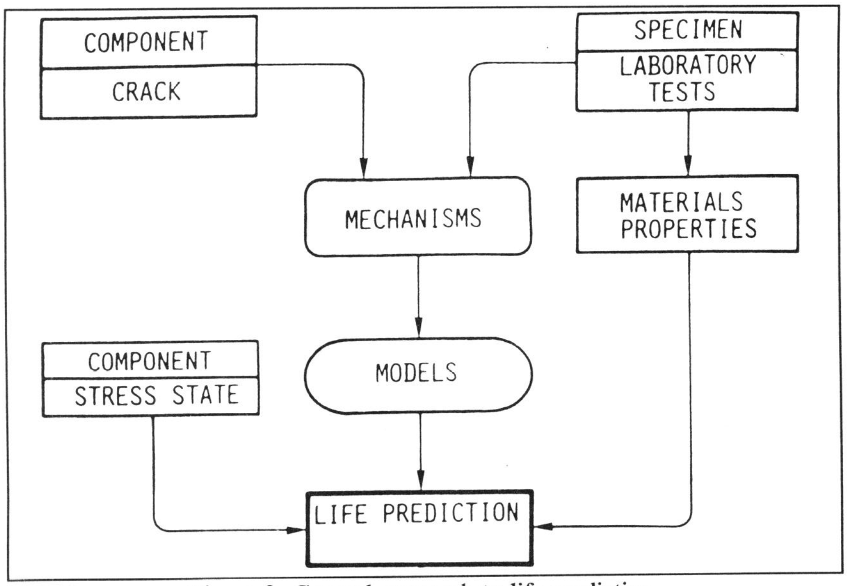


Figure 3 General approach to life prediction.

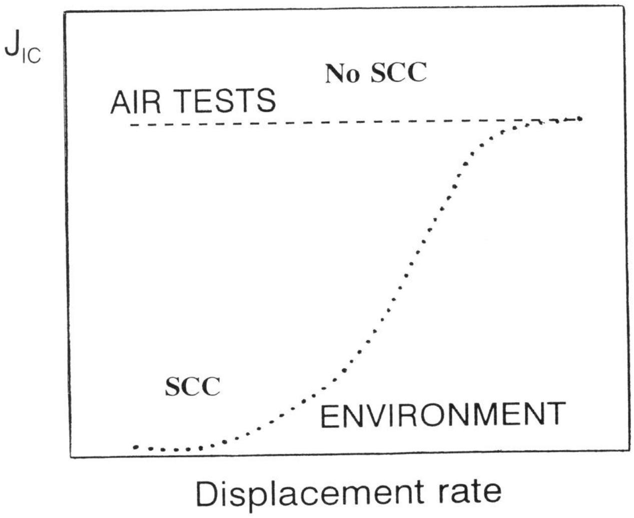


Figure 4 J_{IC} as a function of loading rate, for low alloy steel in water.

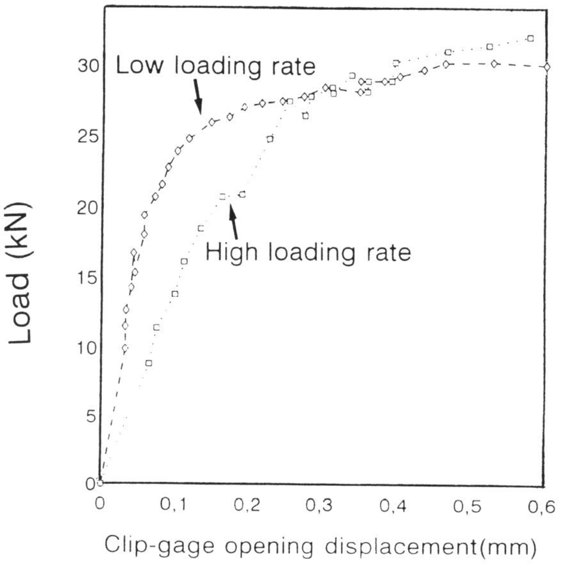


Figure 5 Load-displacement curves at different loading rate in environment.

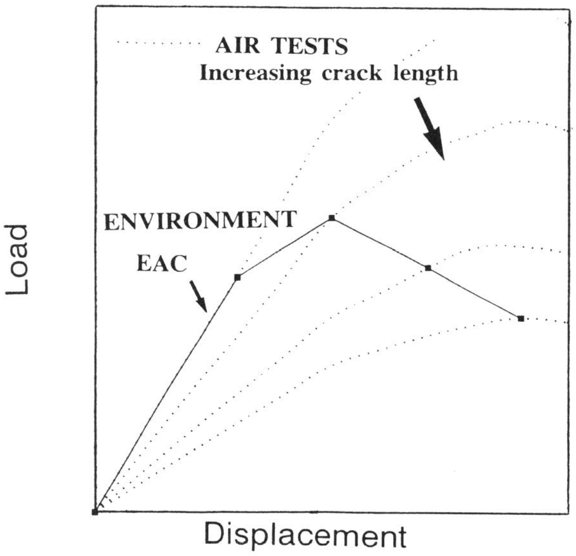


Figure 6 Schematics of load-displacement curves in air and in environment.

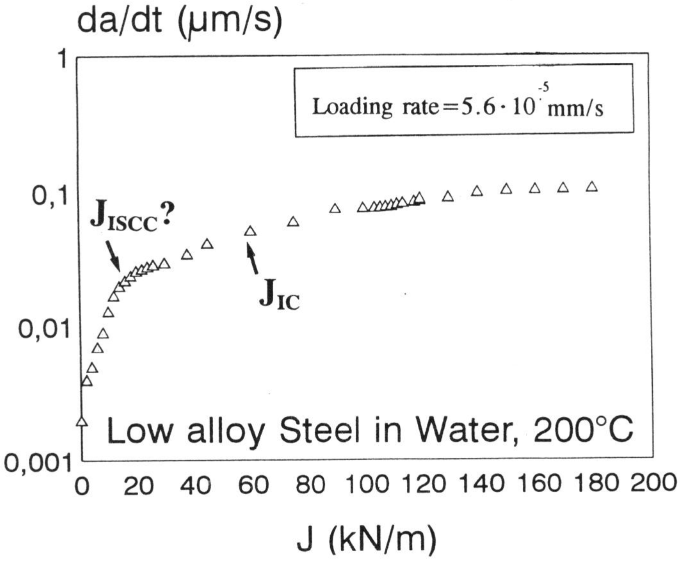


Figure 7 Crack growth rate as a function of J for a test in environment.

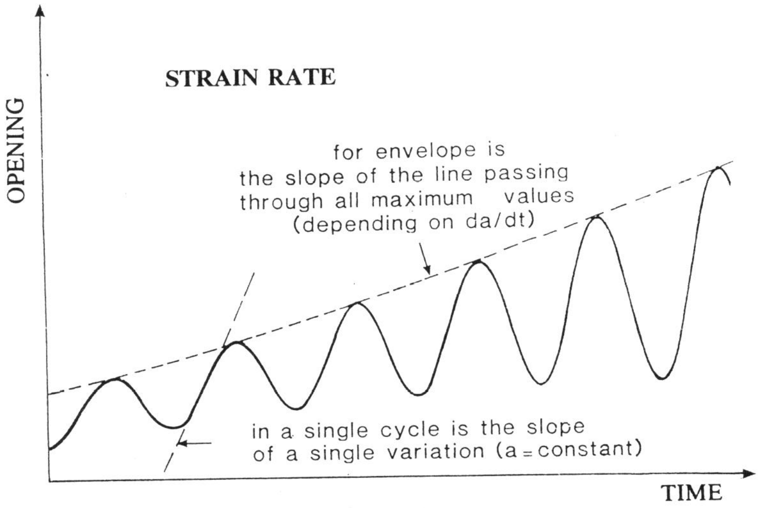


Figure 8 Trend of the strain rate during time variable loading.

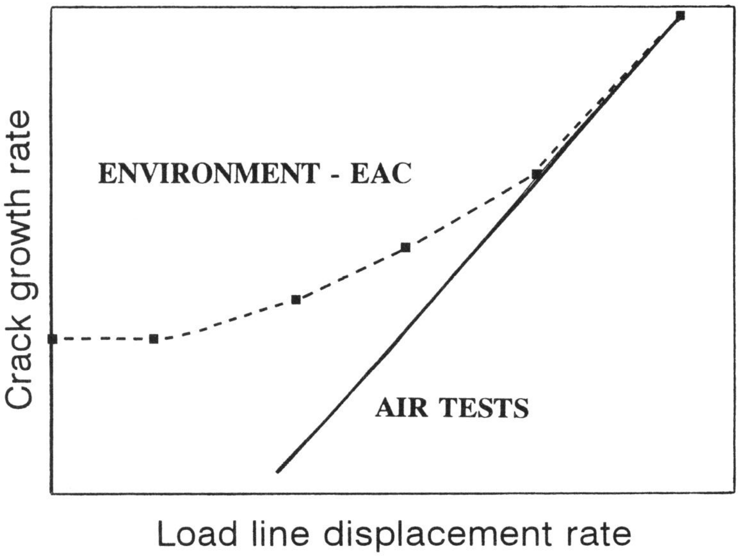


Figure 9 Expected crack growth rate in air and in environment.

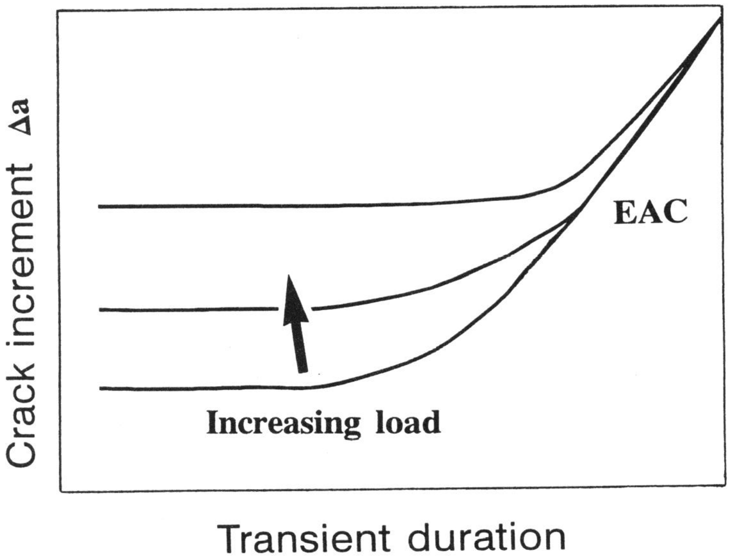


Figure 10 Expected crack increment as a function of transient time.