CONSIDERATION OF NONSTEADY STATE CRACK GROWTH IN MATERIALS EVALUATION AND DESIGN

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SUMMARY

Fracture mechanics is being used increasingly in the design and reliability assurance of reactor pressure vessels. This technology enables a quantitative assessment of the potential influence of environment enhanced crack growth on vessel integrity. The basis of such an assessment is a one-to-one relationship between the rate of crack growth and K, the applied value of crack-tip stress intensity factor. The purpose of this work is to examine the uniqueness of this relationship and also to elucidate and assess the significance of any deviations from such a relationship.

Data on a variety of low alloy steels, exposed to aqueous environments, are presented which demosntrate that under certain conditions the K versus growth rate relationship appears not to be unique — that is, for a given value of K, several distinctly different rates can occur. Tests conducted under both static and cyclic loading are shown to exhibit this behavior following test start-up, test interruptions, or changes in loading variables such as cyclic frequency. In order to understand this phenomenon, experiments were conducted on a quenched and tempered low alloy steel exposed to distilled water. Using specimens in which K remains constant, as the crack grows under constant load, data have been obtained which demonstrate that this behavior is due, at least in part, to nonsteady state crack growth. Initially rates are significantly less than the steady state rate, and although crack growth eventually accelerates to the steady state rate, significant transient periods occur. A unique, geometry independent relationship only exists between crack growth rates and crack-tip stress intensity factor provided these nonsteady state effects are eliminated.

For a given material, the duration of this transient period appears to be dependent on environment chemistry, thereby suggesting that the phenomenon is controlled by the kinetics of underlying chemical processes which lead to the material's degradation. A kinetic model based on the concept of a hydrogen embrittled volume of material at the crack tip provides a unified understanding of the various transient behavior in the steels considered herein.

The practical significance of this time dependent behavior is that it can cause laboratory data to misrepresent the growth rates which occur under operating conditions in reactor pressure vessels. Recommendations are provided for identifying these nonsteady state effects when acquiring laboratory data. Approaches to dealing with transient crack growth rates in design and reliability assessments are also outlined.

1. Introduction

Much work is currently underway to assess the influence of reactor water environments and applied loading variables on the fatigue crack growth behavior of nuclear pressure vessel and piping materials. Recent papers have summarized this effort [1,2]. Because this information is needed for design and reliability assurance of reactor components, basic fatigue crack growth rate data are being generated within the framework of linear elastic fracture mechanics. The basis of this fracture mechanics approach is a one-to-one relationship between the rate at which cracks grow and the mechanical "driving force" which is characterized in terms of the crack-tip stress intensity factor.

The objective of this paper is to critically examine the uniqueness of this fundamental relationship. In so doing, a variety of crack growth rate phenomena — primarily associated with test start-up, test interruptions and changes in loading variables — which have heretofore been labeled anomalous are reviewed and discussed. An attempt is made to provide a general explanation of these results in terms of underlying kinetic mechanisms. Examples are drawn from both static and cyclic crack growth in low alloy ferritic and martensitic steels exposed to a variety of aqueous environments. Although cyclic loading is of paramount importance to pressure vessel and piping applications, crack growth under static loading is also presented to examine the general nature of these phenomena. The practical significance of these phenomena to materials evaluation and design is also discussed.

2. Crack Growth Under Static Loading

Static-load crack growth rates as of function of applied stress intensity factor, K, for a 4340 steel exposed to room temperature distilled water are shown in Fig. 1 [3]. As is typical for environment induced, static crack growth, these results exhibit two distinctly different regimes — in Stage I the rates are strongly dependent on K, while in Stage II the rates become independent of K.* The K-independent rate in Stage II results from a rate limiting process which has been identified as the slow, second step of the surface reaction of H_2O and clean fracture surfaces [11]. This reaction produces the hydrogen required for subsequent embrittlement.

However, of greater importance for our purposes here is the fact that different Stage I curves were observed upon conducting experiments at different initial stress intensity factors, K_I. As a result, for a given value of applied K, a variety of different growth rates occur. Thus, the practical question arises as to which Stage I curve is appropriate for use in materials evaluation and design? Furthermore, the fact that the da/dt versus K relationship is nonunique would appear to violate a basic tenent of the fracture mechanics approach to environment induced cracking.

In order to shed some light on this apparent dilemma, the authors' have generated some data under constant-K conditions, enabling crack growth rates to be solely examined as a function of time [4]. These results were obtained using a constant applied load and the constant-K specimen illustrated in Fig. 2; the material and environment were the same as those of Ref. [3] and Fig. 1.

As shown in Fig. 2, the growth rates were found to change initially with time over a period of about 20 minutes. During this transient, or nonsteady state period, the crack

*A third regime, Stage III, where rates again become strongly K-dependent as mechanical instability is approached, was not measured in these particular experiments.

growth continued to accelerate until finally a rate was established which was no longer time dependent — that is, a steady state rate was achieved. These steady state rates are in good agreement with the uppermost data in Fig. 1 at K values of 21 MPa$\sqrt{m}$ and 30 MPa$\sqrt{m}$. It follows that the rates in Fig. 1 which are below the solid curve (defined by the uppermost data) are influenced by nonsteady state behavior. Therefore, the nonuniqueness of the Stages I rates in Fig. 1 appears not to be due to the different initially applied stress intensity conditions per se, but rather to the initial time dependency of the growth rates following loading. The agreement between the steady state rates generated from center cracked panel specimens (Fig. 1) and tapered double cantilever beam specimens (Fig. 2) clearly demonstrates that a unique, geometry-independent relationship exists between da/dt and K, provided steady-state conditions prevail.

3. Crack Growth Under Cyclic Loading

Since the aforementioned nonsteady state crack growth rate behavior appears to be inextricably associated with the presence of the aggressive environment, one might expect to observe the same behavior under cyclic as well as static loading. This in fact appears to be the case based on recently observed environment enhanced fatigue crack growth rate data.

Results from Scott on a structural steel exposed to natural seawater at room temperature provide a clear example of this behavior as shown in Fig. 3 [5]. These experiments, which were conducted at a test frequency of 0.1 Hz and a load ratio (R = minimum load/maximum load) of 0.5, result in about a factor of three enhancement in the fatigue crack growth rates relative to rates measured in laboratory air. Moreover, the growth rates show a dependence on the initially applied stress intensity range, ΔK_1, which is analogous to the static-load growth rate behavior of Fig. 1.

Similar behavior has been reported by Bamford, et al. for pressure vessel steels exposed to a pressurized water reactor environment at 560°K [6]. However, in this case the transient growth rates following initial loading were of significantly longer duration. In fact, data from some tests started at high ΔK values never achieved the higher growth rates established during separate tests started at lower ΔK values. Since these tests were conducted at cyclic frequencies on the order of 0.01 Hz, transient periods were on the order of thousands of hours. These results clearly indicate that the magnitude of the transient period is a strong function of the material-environment system.

Transient growth rate behavior is not limited to the period following initial commencement of fatigue loading — transient periods have also been observed following test interruptions and changes in loading variables such as cyclic frequency.

Figure 4 shows the effect of an overnight test stoppage on the crack length versus elapsed cycle curve for a center-cracked-panel specimen of 4340 steel exposed to distilled water at room temperature [7]. A transient growth rate period, introduced by the test interruption at about 3000 cycles, is manifested by a sharp change in slope of the measured curve. The dashed curve illustrates the behavior which would be expected had the interruption not occurred. As indicated in Fig. 4, the slope of the curve eventually returns to the expected steady state growth rate following a transient period of about 3000 cycles. It is relevant to note that this specimen was cleaned and dried immediately following the interruption of cyclic loading, thus the observed transient is not attributable to a temporary blunting of the crack-tip by general corrosion during the test stoppage.

An example of the effect of a test interruption on the da/dN versus ΔK curve is provided by data of Bamford and Ceschini shown in Fig. 5 [8]. This particular fatigue crack gorwth rate test, involving a pressure vessel steel exposed to a pressurized water reactor environment, was interrupted for 10 days during which time the specimen was removed from the environment and thereby allowed to dry. Crack growth rates measured immediately following the test interruption were four times slower than those immediately preceding the interruption. Moreover, subsequent fatigue cycling never achieved the steady-state growth rates established using other uninterrupted specimens. Interestingly, the retarded growth rates measured after the interruption were the same as those obtained by starting a new test at a ΔK value of 33 MPa$\sqrt{m}$. Therefore, the implication is that the transient growth rates associated with different initial test starting conditions, and those associated with test interruptions, are one and the same phenomenon.

Transient growth rates can also be produced by changes in cyclic loading history other than test interruptions. For example, the fatigue crack growth rates in 4340 steel exposed to water vapor which are given in Fig. 6, clearly show a region of transient growth rates following a change in cyclic frequency from ^{10} Hz to 0.1 Hz [9]. The faster, steady state rates corresponding to 0.1 Hz were eventually established after 0.1 cm of crack growth. Transient responses in the opposite direction were also observed after increases in the cyclic frequency. Since growth rates in inert environments are not influenced by changes in cyclic frequency, these results must result from material-environment interactions.

4. Discussion

The aforementioned growth rate phenomena are believed to be related in that all are primarily caused by nonsteady state growth which is controlled by underlying kinetic processes in the material-environment interaction. This concept provides a consistent view of transient growth rates associated with test start-up, test interruptions and changes in cyclic frequency and is supported by the following evidence.

First, nonsteady state growth rates have been measured for environment induced crack growth under static load and shown to be the cause of the dependence of Stage I growth rates on the initially applied stress intensity factor. In addition, when the nonstady state effects are eliminated, a unique geometry-independent relationship exists between da/dt and K.

Secondly, the duration of the transient period is strongly dependent on environment. For example, Fig. 7 shows fatigue crack growth rate data on a pressure vessel steel exposed to a H_2S environment which demonstrates the absence of any measurable transient associated with four separate tests each conducted at different initial ΔK values [10]. This steel is for all practical purposes identical to that of Fig. 5 which, when exposed to a pressurized water environment, exhibits large transient periods, both on initial test start-up and following test interruptions. In general, this difference in transient response for essentially identical material exposed to different environments is understandable if one considers that the detailed kinetic processes which are essential for environment enhanced crack growth can differ greatly for different environments. For example, basic surface chemistry studies have established that the rate limiting step in the reaction of H_2S with steel is about 10^9 times faster than the corresponding step in the reaction of water vapor with steel [11,12]. The relative insensitivity of fatigue crack growth rates in H_2S to cyclic frequency, except at very low pressures, attests to these rapid kinetics. This

behavior is in contrast to the strong frequency and waveform dependency of fatigue crack growth rates when this same steel is exposed to pressurized water [1].

Finally, the fact that transients occur after changes in cyclic frequency — an important variable for crack growth in aggressive environments, but not for growth in inert environments — virtually eliminates an explanation of these phenomena based on purely mechanical events. The long-range nature of the transients also supports this view. The extensive amounts of crack extension under transient conditions preclude arguements based on crack blunting due to general corrosion, or residual stress/crack closure due to inadvertent specimen overloading since both of these effects would diminish after relative small amounts of crack extension — on the order of several crack-tip root radii or plastic zone sizes.

Although the above arguements clearly support the concept that the kinetics of underlying physio-chemical processes control the observed crack growth rate phenomena, the specific mechanism involved is not firmly established. However, some insight is provided by general kinetic considerations. Pao, et al. have proposed a kinetic model based on the establishment of a steady state volume (as opposed to surface) of hydrogen damaged material at the crack tip [9]. The embrittled volume ahead of the crack tip would be larger for the slower cyclic frequencies because of the increased reaction time and thus the amount of hydrogen produced per cycle. Thus, as the frequency is changed the size of the embrittled volume will change with time according to the governing kinetics and a corresponding transient crack growth rate results. Obviously, this model applies only to material-environment systems where the damaging mechanism involves hydrogen embrittlement. However, since hydrogen embrittlement has been identified as the mechanism for crack growth in steels exposed to water and water vapor, this kinetic model appears viable for the material-environment systems considered herein [1-3].

The model also provides a rationale for the transient crack growth rates which follow initial test start-ups, since time would be required for the volume of hydrogen damage material to increase to its steady state size. The transient crack growth rates following test interruptions can also be explained in a similar fashion, provided an alteration of the crack tip hydrogen concentration, and corresponding damaged volume, can occur during the interruption. This alteration could conceivably occur by bulk diffusion of hydrogen from the crack tip while the specimen is unstressed. Subsequently, the steady state, embrittled volume would have to be reestablished when the test is restarted. Alternatively, it is possible that the size of the embrittled volume could be altered without hydrogen diffusion from the crack tip. In liquid environments, for example, it may require some time to reestablish the proper crack-tip chemical/electrochemical conditions so that sufficient hydrogen is available to maintain the embrittled volume at its former steady state size.

One final point on mechanisms is appropriate. The above kinetic model involving hydrogen embrittlement should not be taken to imply that transient crack growth rate phenomena will not occur in material-environment systems which crack due to damaging mechanisms other than those involving hydrogen. In fact, the occurrence of these transient crack growth rates is expected to be a general phenomenon and would be governed by whatever kinetic processes leads to the damaging effects.

5. Practical Significance of Transient Crack Growth Rates

Transient growth rate phenomena are of practical significance to: 1) obtaining representative materials data and 2) formulating realistic design philosophies. With respect

to the former, there is a danger associated with not recognizing the presence of nonsteady state effects and thereby making improper inferences about crack growth rates which are presumed to represent steady-state behavior. For example, this can occur when data are generated under K-increasing conditions with all tests started at the same ΔK value. The sharply accelerating fatigue crack growth caused by initial transient behavior could be misinterpreted as defining the threshold stress intensity condition required for environment enhanced crack growth. The presence of such nonsteady state behavior can be identified by performing K-increasing tests at different starting ΔK levels. These transients can also be more directly identified by conducting constant ΔK tests analogous to those used to obtain the static load data in Fig. 2. The advantage of the constant ΔK test is that it can unequivocally define the steady-state rate at a given ΔK value; the disadvantage is that many more tests are required to define the da/dN-ΔK curve.

Transient crack growth rates are significant in design considerations since most applications involve interruptions to the typical load history due to operation shutdowns — these being equivalent to test interruptions. As illustrated by data in Fig. 5, these shutdowns can have a significant impact on the environment enhanced fatigue crack growth rates. Currently no methodology exists for incorporating these transient effects into design and reliability considerations. One could take the approach that transients should be eliminated from laboratory generated data, and that designs be based on steady state fatigue crack growth rates. This approach would add conservatism to the design — perhaps to an unrealistic extent — since under certain conditions shutdowns could retard the fatigue crack growth rates relative to the steady-state rates. The task of incorporating expected transient growth rate behavior into design and reliability considerations in a quantitative manner appears formidable from two viewpoints: (1) Much information would be needed to determine the shutdown conditions which strongly influence the transients. For example, must the environment be removed, and for how long, to induce a transient? (2) In order to take advantage of the retarded growth rates, detailed information would be required about the anticipated or experienced shutdown history for design and reliability assessments, respectively.

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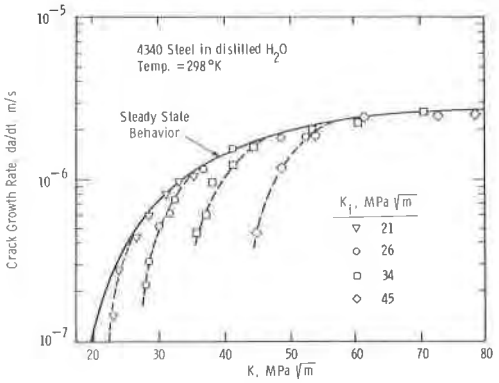

Fig. 1 — Dependence of static-load crack growth kinetics on initially applied stress intensity factor, K_I

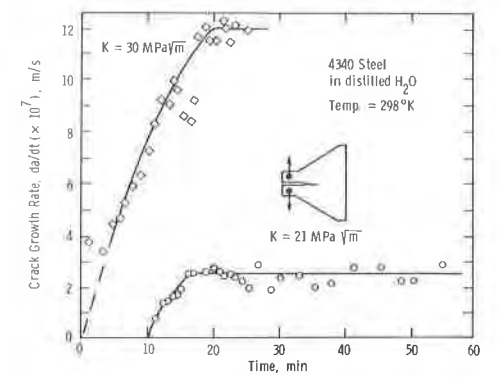

Fig. 2 — Static-load crack growth rates under constant stress intensity factor conditions showing transient and steady-state behavior

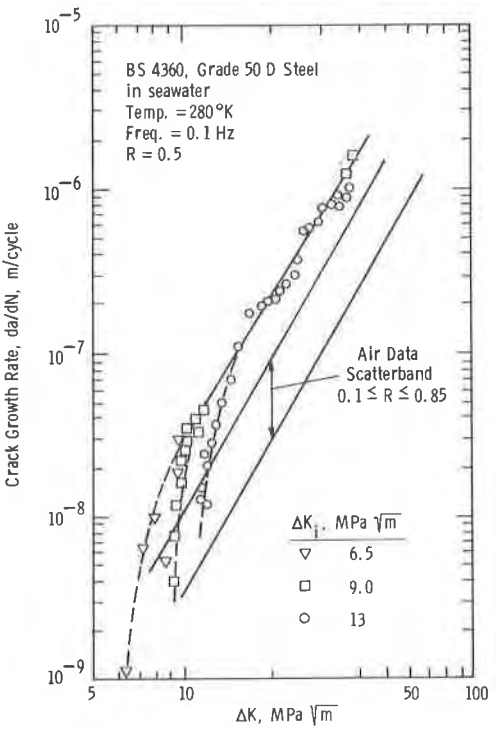

Fig. 3 — Dependence of fatigue crack growth kinetics on initially applied stress intensity factor range, ΔK_I

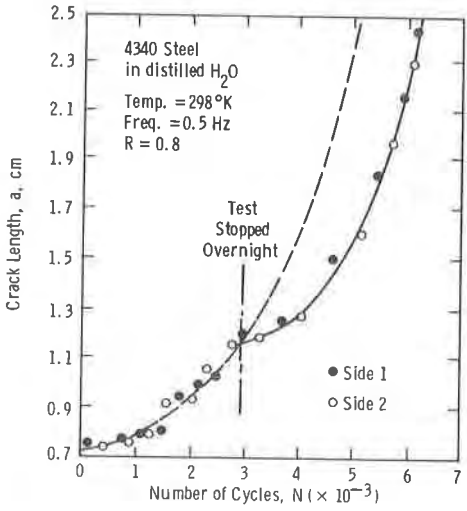

Fig. 4 — Effect of test interruption on the crack length versus elapsed cycles curve for fatigue loading

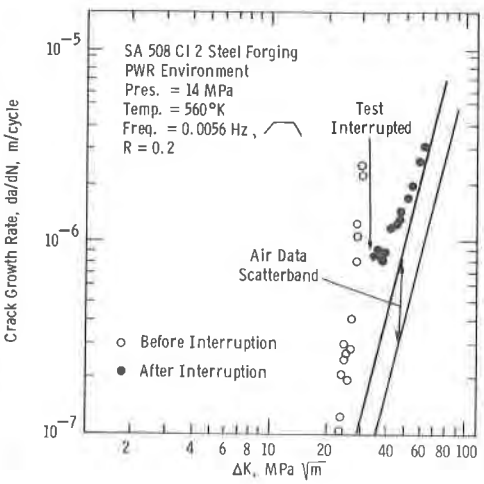

Fig. 5 — Effect of test interruption on fatigue crack growth kinetics

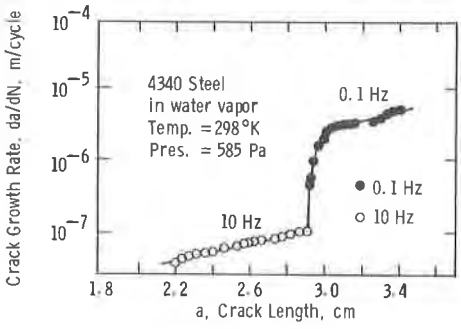

Fig. 6 — Fatigue crack growth rate response resulting from a change in cyclic loading frequency

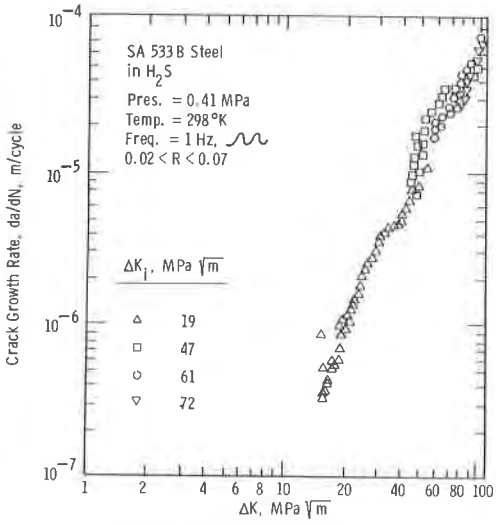

Fig. 7 — Independence of fatigue crack growth kinetics in H_2S on initially applied stress intensity factor range, ΔK_I