Review of Subcritical Crack Growth under Sustained Load

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Crack growth under sustained load in the ambient environment at stress intensities appreciably less than K_{Ic} has been reported in a number of structural alloys. Subcritical crack growth in steels has been attributed to moisture-dependent stress corrosion, internal hydrogen embrittlement, and creep failure processes. In titanium alloys subcritical crack growth has been attributed either to internal hydrogen embrittlement or to creep failure processes while in aluminum alloys it has been attributed to moisture-dependent stress corrosion. Since subcritical crack growth under sustained load can result in failure if sufficient time is available, this phenomenon must be considered when using fracture mechanics in structural design. Additional study to define the conditions controlling subcritical crack growth under sustained load in structural alloys is recommended.

Introduction

LINEAR elastic fracture mechanics has shown that a unique relationship exists between the nominal stress (σ) necessary to cause fracture in a material containing a sharp crack and the crack size (a)

$$\sigma(\pi a)^{1/2} = \text{Const}$$

This constant, which can be determined by relatively simple laboratory tests, is referred to as the critical stress intensity (K_{Ic} of K_c). Modification of the basic relationship is usually necessary to compensate for the effects of specimen shape and plastic flow at the crack tip. However, despite the complexity which the modified relationship may exhibit in some cases, the basic relationship between stress and crack size remains essentially as shown in the preceding.

The use of fracture mechanics in design is based upon an initial assumption of the maximum size crack likely to be present in a structure followed by computation of the maximum allowable stress level from the previously measured critical stress intensity of the material. Implicit in this approach is a second assumption, that the crack size does not increase at stress intensities less than the critical stress intensity. This is known to be incorrect in at least two common cases, under fatigue loading and in the presence of certain corrosive environments. The effects of fatigue loading can be compensated for by knowledge of the rate of crack growth (da/dN) as a function of cyclic stress intensity range while the effects of corrosion can be compensated for by knowledge of the rate of crack growth (da/dt) in the corrosive environment as a function of sustained stress intensity.

It is less well-known, although extensively documented in the literature, that subcritical crack growth occurs in many structural materials under sustained load in the ambient environment at stress intensities appreciably below the critical stress intensity. Such behavior has been attributed by various investigators to moisture-dependent stress corrosion, to internal hydrogen embrittlement, or to creep rupture processes. It is the purpose of this paper to review present knowledge regarding subcritical crack growth under sustained load in the ambient environment, to analyze the significance of this information, and to stimulate additional study of this phenomenon.

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Characteristics of Subcritical Crack Growth

Subcritical crack growth under sustained load in the ambient environment has been observed in a number of important structural alloys. The characteristics of subcritical crack growth in several of these alloys as affected by the primary test variables—stress intensity, environment, and stress mode—are described in the following. Data are presented so as to emphasize differences in crack growth behavior among different alloys. In a later section, an effort is made to show the origin of these differences.

Stress Intensity

A material is considered susceptible to subcritical crack growth if precracked specimens show crack extension under sustained load at stress intensities less than the critical stress intensity under plane strain conditions K_{Ic}. If the specimen design is such that stress intensity increases as the crack grows, the crack will ultimately reach a size such that the critical stress intensity is attained. At this point the specimen will fail.[1] As initial stress intensity decreases, time to failure increases; an inverse relationship between time to failure and stress intensity is commonly observed. Behavior of this type is shown in Fig. 1 for annealed Ti-4Al-3Mo-1V alloy compact tension specimens held under constant load in either vacuum or moist air.[2] Failure occurred in about the same time in tests conducted in vacuum as in moist air.

Data of the type shown in Fig. 1 can be used to define a threshold stress intensity K_{th} below which failure will not occur. Based upon failure within 100 hr under load, a threshold stress intensity of about 33 ksi-in.$^{1/2}$ in the ambient environment would be selected for this alloy. Rising load tests on 0.75-in.-thick compact tension specimens of this alloy provided a K_Q value of 71 ksi-in.$^{1/2}$† Thus the threshold stress intensity for this alloy, based upon a 100-hr test period, was apparently no higher than 0.46 K_{Ic}. Appreciable subcritical crack growth have been reported in steels. Time to failure in a high-strength martensitic steel, AISI 4340, heat treated to a tensity of 30.7 ksi-in.$^{1/2}$ and, if the test period had been longer, failure undoubtedly would have occurred. It is apparent that threshold stress intensity is quite dependent upon the time selected for its measurement.

†Specimen dimensions were inadequate to provide a valid K_{Ic} measurement. Nonvalid K_{Ic} data are designated K_Q in this review. It should be noted that in tests of inadequately dimensioned specimens, the applied stress intensity K_i may be such that $K_{Ic} < K_i < K_Q$. Crack growth occurring under these conditions cannot be considered subcritical crack growth.

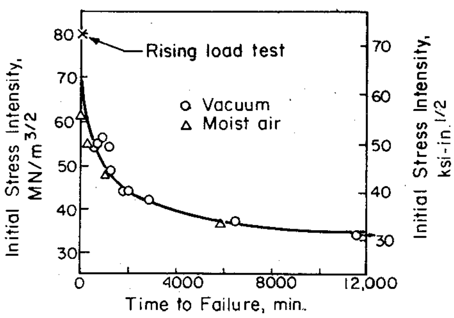

Fig. 1 Variation of time to failure with initial stress intensity.[2] 0.25-in.-thick compact tension specimens of Ti-4Al-3Mo-1V (TL orientation) in two environments.

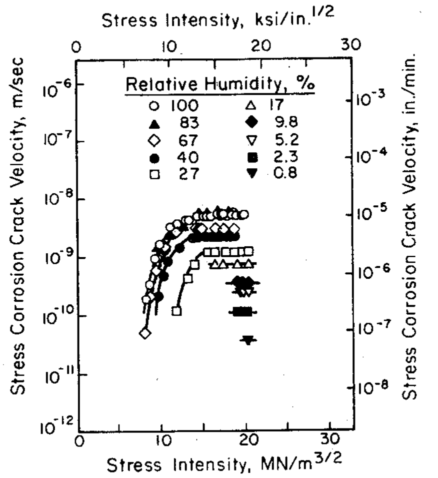

Fig. 2 Variation of crack growth rate with stress intensity.[3] 1-in.-thick double cantilever bend specimens of 7075-T651. (TS orientation) in air of various moisture contents.

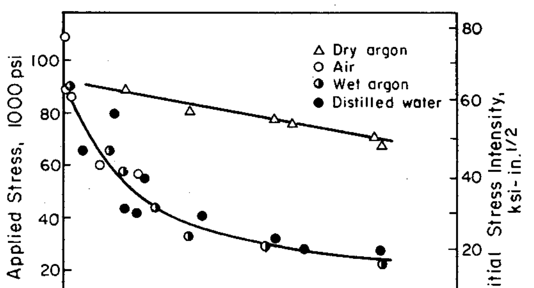

Fig. 3 Variation of time to failure with applied stress in AISI 4340 steel as a fuction of environment.[12] 0.065-in.-thick center notched sheet specimens (LT orientation).

Threshold stress intensity values determined on the basis of time to failure as a function of initial stress intensity will be quite sensitive to specimen design as well as to the maximum test period. The more rapidly stress intensity increases with increased crack length at constant load, the shorter will be the time to failure and the lower the measured threshold stress intensity selected on the basis of a specific failure time.

The effect of specimen design on the increase in stress intensity with crack growth can be eliminated if threshold stress intensity is determined from measurements of crack growth rate as a function of stress intensity as shown by the data in Fig. 2.[3] If threshold stress intensity is defined as that producing a crack growth rate less than 10^{-7} in./min. 7075-T651 aluminum alloy in humid air would be assigned a threshold stress intensity of about 7 ksi-in.$^{1/2}$, a value no higher than 0.35 K_{Ic}. The absence of a true threshold stress intensity is readily apparent in the data in Fig. 2. As was the case in defining threshold stress intensity of Ti-4Al-3Mo-1V in terms of time to failure, the value is dependent upon the crack growth rate selected for its definition. It is noteworthy that measurement of crack growth rates as low as 2.4×10^{-7} in./min. (10^{-10}m/sec) by conventional methods may require a test duration as long as one month.[4]

The measurement of threshold stress intensity is also affected by stress mode, as will be discussed in more detail in a following section. Crack growth rates at a constant stress intensity are markedly retarded by reducing the extent of plane strain loading at the crack front. As a result, measurements of threshold stress intensity, whether defined in terms of time to failure or crack growth rate, will show a significant dependence upon those specimen design factors that affect the stress mode.

Crack growth rate might be expected to increase continuously as stress intensity increased, and such behavior has been reported in studies of annealed Ti-8Al-1Mo-1V alloy,[5] of precipitation-hardened AM 350 austenitic steel,[6] and of air-hardened H-11 die steel.[7] However, although aluminum alloys exhibit increasing crack growth rate with increasing stress intensity at low stress intensities, at intermediate and high stress intensities a constant rate of subcritical crack growth is observed, as is illustrated by the data shown in Fig. 2. Crack growth rate has also been reported to remain constant over a broad range of intermediate stress intensities in heat treated AISI 4340 martensitic steel.[8]

Environment

The behavior of the alpha-beta titanium alloy described in Fig. 1 is typical of that observed in a number of titanium alloys susceptible to subcritical crack growth under sustained load.[5,9,10,11] Crack growth is observed at stress intensities well below K_{Ic} when precracked specimens are exposed in the ambient environment under sustained load. It has also been shown that crack growth occurs in titanium alloys as rapidly in vacuum or dry air as in moist air.[2,5] In contrast to the behavior observed in titanium alloys, subcritical crack growth in aluminum alloys is highly sensitive to the moisture content of the environment. This is indicated by the measurements of crack growth under sustained load for the high-strength heat-treated aluminum alloy 7075-T651 shown in Fig. 2. Although the threshold stress intensity in humid air was as low as 0.35 K_{Ic}, negligible crack growth occurred in dry air at stress intensities only slightly less than K_{Ic}. Although similar behavior was observed in a number of aluminum alloys,[3,4] crack growth was encountered only in alloys known to be sensitive to stress corrosion in an aqueous environment and in specimen orientations allowing crack growth in a plane perpendicular to the short transverse direction.

Both moisture-sensitive and moisture-insensitive subcritical crack growth have been reported in steels. Time to failure in a high-strength martensitic steel, AISI 4340, heat treated to a yield strength of 214 ksi, is shown as a function of applied stress in Fig. 3.[12] These tests were performed using 0.065-in.-thick center cracked sheet specimens of similar dimensions such that the initial stress intensity may be assumed to be proportional to the applied stress ($K_i \sim 0.7\sigma_a$ based upon the reported specimen design). Assuming that the critical stress intensity was equal to the value of K_i leading to failure within a few minutes, 63 ksi-in$^{1/2}$, the threshold stress intensity in dry argon based upon a failure time of 100 hr was about $0.78K_Q$. Similar behavior has been reported in another study of subcritical crack growth in heat-treated AISI 4340 steel.[8] In this study 0.125-in.-thick center cracked sheet specimens of AISI 4340 heat treated to a yield strength of 195 ksi showed subcritical crack growth in a dry argon environment at initial stress intensities as low as $0.7K_Q$. In moisture-containing air, as shown in Fig. 3, the threshold stress intensity of AISI 4340 defined by failure in 100 hr was as low as $0.3K_Q$. Thus, it appears that heat-treated AISI 4340 is susceptible to subcritical crack growth in both dry and moisture-containing air environments, but that the threshold stress intensity is quite sensitive to the presence of moisture.

H-11, an air-hardened martensitic die steel, is reported to show appreciable subcritical crack growth in moist argon at a yield strength of 230 ksi.[7] The K_{th} was reported to vary from 1.0 K_{Ic} in a dry argon environment to as low as 0.45 K_{Ic} in a moisture-saturated argon environment based upon measurements of crack growth rate as a function of stress intensity using 0.080-in.-thick center notched sheet specimens. However, discontinuous or arrested crack growth was observed in some specimens tested in dry argon at stress intensities less than K_{Ic}, suggesting that tests of longer duration or with a greater degree of plane strain loading might have shown subcritical crack growth in a moisture-free environment at stress intensities less than K_{Ic}. The sustained load in these tests was applied in small increments; the load was increased after 5 min if no crack growth was observed within this time period. Based upon the reported ability to detect cracks 0.004 in. or longer (using resistance measurements), crack growth rates less than 8×10^{-4} in./min would not have been detected. This, of course, is a fairly high rate of crack growth, so the ability of the test procedure to detect subcritical crack growth at low stress intensities is limited. Interestingly, addition of a small quantity of oxygen to a moisture-containing argon environment has been reported to stop subcritical crack growth in H-11 almost instantly.[13] This study also employed quite short sustained loading periods in the detection of crack growth.

In contrast to the behavior of AISI 4340 and H-11 steels, the threshold stress intensity of a precipitation-hardened austenitic steel, AM 350, heat treated to a yield strength level of about 165 ksi and exposed in argon environments of varying humidity, was reported to remain about constant at 0.81 K_Q regardless of moisture content.[6] Test were conducted with 0.068-in.-thick center notched sheet specimens, with test procedures similar to those used in the studies of H-11 steel referred to in the preceding. At the higher humidity levels some arrested crack growth was observed at stress intensities as low as $0.64K_Q$. Thus, an effect of moisture on subcritical crack growth might have been detected with more sensitive test procedures.

Subcritical crack growth under sustained load has also been reported in TRIP-type austenitic steels tested in moderately humid air (40% relative humidity).[14] These tests, which were performed using 0.5-in.-thick compact tension specimens, suggested a threshold stress intensity of about 0.5 K_{Ic} based upon failure within 24 hr. Unfortunately, companion tests in a dry environment were not carried out.

Stress Mode

The fraction of the crack front that is stressed under plane strain conditions has a significant effect on subcritical crack growth under sustained load. Early observations of crack growth were made with specimens under plane stress loading, and it was initially though that subcritical crack growth might be dependent upon the presence of a high degree of mixed mode loading.[15] However, studies of the effects of specimen dimensions on crack growth have shown this is to be incorrect. In the case of titanium alloys, for example, plane strain conditions quite markedly increase the sensitivity to cracking under sustained load, the threshold stress intensity being reduced and the crack growth rate being increased as the amount of plane strain loading is increased.[9,16] A similar situation apparently exists in the case of steels as indicated by study of the effect of mixed mode loading on the threshold stress intensity for crack growth in hydrogen-containing AISI 4340 steel.[17]

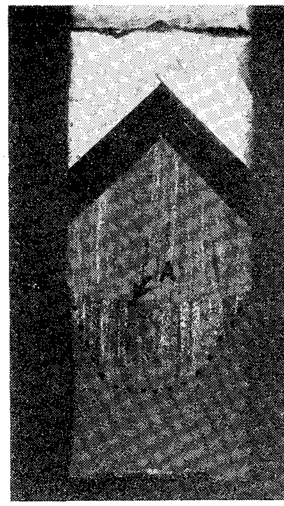

Fig. 4 Crack tunneling in a 0.25-in.-thick compact tension specimen of Ti-4A1-3Mo-1V alloy as observed after failure under sustained load.[16] 8X. Initial fatigue crack position marked *A*. Extent of subcritical crack growth prior to a final unstable fracture shown by dotted line.

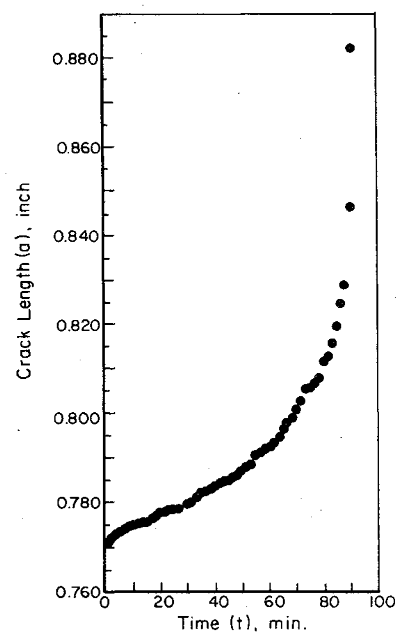

Fig. 5 Three-stage crack growth kinetics in Ti-6A1-4V.[11] 1-in.-thick single edge notched bend specimen, $K_i = 67$ ksi-in ½.

Subcritical crack growth under sustained load proceeds almost exclusively in material under plane strain loading. This leads to extensive crack front bowing or tunneling as illustrated in Fig. 4. As the crack grows in the central region of the crack front, the surface material under plane stress loading deforms in a ductile manner. The deformation behavior of this more ductile surface material is probably responsible for the distinctive three-stage crack growth kinetics often observed in measurements of subcritical crack growth using specimens having a high degree of mixed mode loading. A typical example of three-stage crack growth behavior is shown in Fig. 5. Examination of the effect of stress mode on subcritical crack growth using compact tension specimens of the Ti-4A1-3Mo-1V alloy under constant load has shown that, as the specimen thickness is increased to increase the fraction of the crack under plane strain loading, crack growth kinetics change.[16] Thin specimens, under mixed-mode stress conditions, show distinct three-stage crack growth kinetics of the type illustrated in Fig. 4, but thicker specimens under essentially full plane strain conditions, show a continuously accelerating rate of crack growth.

Mechanism of Subcritical Crack Growth

As the preceding discussion has shown, subcritical crack growth under sustained load exhibits quite different characteristics in aluminum, steel, and titanium alloys. Thus, it is not surprising that, depending upon the material being investigated, different mechanisms have been proposed to explain its occurrence. These include moisture-dependent stress corrosion, hydrogen embrittlement as a result of stress-induced concentration of dissolved hydrogen, and progressive creep rupture of material at the highly stressed crack root. These proposed mechanisms are discussed in the following.

Stress Corrision

When subcritical crack growth in the ambient environment is observed in aluminum alloys, it seems clearly to be the result of stress corrosion processes. A stress corrosion mechanism has been proposed in which water vapor reacts with freshly exposed aluminum metal at the crack root to form aluminum oxide and hydrogen. Hydrogen then diffuses into and embrittles the aluminum alloy.[3] Presumably, plastic flow at the crack root is necessary to expose oxide-free aluminum metal to the environment in order to initiate the reaction.

Susceptibility to subcritical crack growth in aluminum alloys is restricted to a limited number of high-strength alloys tested in such a way that the short transverse direction is placed under a high triaxial tensile stress. The restrictive conditions necessary to cause embrittlement may result from either the relative insensitivity of aluminum alloys to hydrogen embrittlement or the need to develop a very high elastic triaxial stress field if a significant quantity of hydrogen is to be absorbed.

A similar stress corrosion mechanism has been proposed to explain subcritical crack growth in high-strength martensitic steels when stressed in moisture-containing air.[12] As might be anticipated from their much greater susceptibility to hydrogen embrittlement, steels show crack growth under a broader range of test conditions than do aluminum alloys. Several anomalies are apparent in examining the subcritical crack growth behavior of steel, however. As noted earlier, although H-11 steel tested in argon environments of varying moisture content showed a strong correlation between the moisture content of the environment and threshold stress intensity, the addition of small quantities of oxygen to the environment appeared to completely suppress crack growth regardless of the moisture content. It was suggested that this could be attributed to the formation of an iron oxide surface film impervious to hydrogen penetration.[13] If so, it must also be assumed that the oxide formed on this alloy by reaction with water is much less protective than that formed by reaction with oxygen. Unfortunately, as noted earlier, loading periods in these studies were quite short. Longer test periods might show that both variations in the moisture content and the presence of small quantities of oxygen have less effect on subcritical crack growth than these data would suggest, affecting crack growth rate rather than threshold stress intensity. Furthermore, these tests were performed using specimens exposed to mixed-mode stresses, a factor also known to retard hydrogen-induced brittle failure.[17]

Deficiencies in the test procedure may also explain the failure to observe a pronounced effect of variation in moisture content in an argon environment on the threshold stress intensity for subcritical crack growth in AM 350.[6] In addition, the much lesser sensitivity of austenitic steels to hydrogen embrittlement may have contributed to this observed behavior. Despite these factors, the observation of arrested crack growth at relatively low stress intensities in the higher humidity environments suggests that, if test conditions were modified to favor a more sensitive determination of crack growth, a significant effect of moisture on the subcritical crack growth behavior of this material would have been obtained.

Additional evidence supporting the assumption that a hydrogen-related stress corrosion mechanism controls the crack growth behavior of steels in moisture-containing air is the observation of a correlation between the mechanical instability of a series of austenitic TRIP steel and their sensitivity to subcritical crack growth during tests in moist air. Increased mechanical instability of an austenitic TRIP steel would increase the amount of strain-induced martensite formed at the crack front which, in view of the more rapid diffusion rate of hydrogen in martensite as compared to austenite, should increase the susceptibility to moisture-dependent stress corrosion cracking.[14]

Surprisingly, titanium alloys, despite their known sensitivity to hydrogen embrittlement, appear insensitive to the presence of moisture in the environment. No indication that subcritical crack growth is affected by the presence of moisture has been observed in studies of titanium alloys. In fact, some evidence has been obtained suggesting that the presence of moisture may actually retard crack growth slightly.[5] The absence of an effect of moisture on the tendency for subcritical crack growth in titanium alloys may result from the ability of the surface oxide formed during the reaction between titanium and water vapor to prevent absorption of hydrogen. Studies of the reaction between titanium and water vapor have indicated that hydrogen absorption does not accompany reaction at temperature below 1100°F[18]

In summary, stress corrosion processes involving absorption of hydrogen formed at the crack root by reaction of the alloy with moisture in the environment appear to explain subcritical crack growth under sustained load in high-strength steel and aluminum alloys. The necessary conditions for the stress corrosion process seem to be: 1) Exposure of a fresh metal surface at the crack root, presumably by plastic flow. 2) Reaction between the exposed metal and water vapor to form hydrogen and a hydrogen-permeable surface oxide. 3) Absorption of a sufficient quantity of hydrogen to embrittle the alloy material in the immediate vicinity of the crack root. Variations in subcritical crack growth under sustained load in the ambient environment can be attributed to different response by different alloys to one or more of these factors. Similarly, test variables that affect stress intensity or the degree of triaxiality at the crack root can be expected to affect subcritical crack growth occurring by a moisture-dependent stress corrosion process.

Hydrogen Embrittlement

Subcritical crack growth in titanium alloys has been attributed to hydrogen embrittlement resulting from the presence of a small amount of hydrogen in solution.[5,9] Hydrogen in amounts appreciably less than the normally specified maximum (125 or 150 ppm) has a marked effect on subcritical crack growth as shown by data for Ti-6A1-4V alloy in Fig. 6.[5] Both the rate of crack growth and the threshold stress intensity, at least as determined in tests of 20-hr duration or less, appear to be dependent upon hydrogen content. Maximum sensitivity to subcritical crack growth as defined in terms of threshold stress intensity in a 20-hr test period is apparently obtained with as little as 50-ppm hydrogen. Moreover, crack growth is still observed in titanium alloys at the lowest hydrogen contents which it has been possible to attain by vacuum annealing. Since hydrogen contents of less that 50 ppm would be very difficult to achieve in commercial practice, subcritical crack growth under sustained load may be a particularly serious problem in titanium alloys.

High-strength steels are quite sensitive to hydrogen embrittlement and crack growth occurs rapidly at very low stress intensities when hydrogen is present, as is shown by the data in Fig. 7 for three maraging steels and a conventional martensitic steel, all heat treated to high yield strength levels (247-293 ksi).[19] Tests were performed using 0.5-in.-thick cantilever

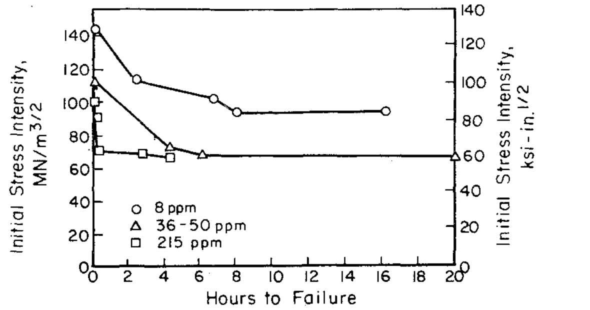

Fig. 6 Effects of hydrogen content of Ti-6Al-4V on subcritical crack growth under sustained load.[5] 1-in.-thick cantilever bend specimens (TL orientation).

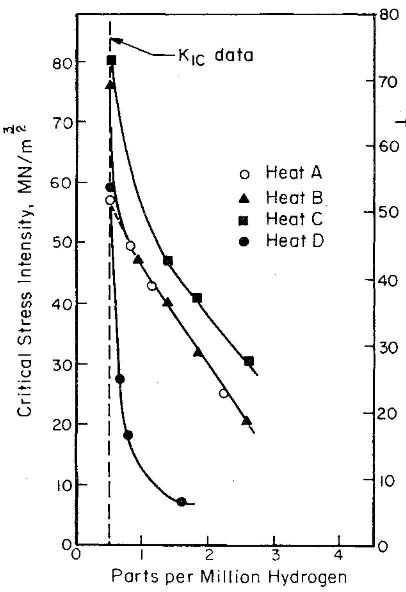

Fig. 7 Effects of hydrogen content on the threshold stress intensity of four high-strength steels.[19] Heats *A*, *B*, and *C* are maraging steels. Heat *D* is a martensite steel, 300 *M*.

bend specimens held under load for a period of 16 hr. The specimens were electroplated with cadmium after cathodic charging to prevent hydrogen loss and then were baked to produce a uniform initial hydrogen distribution. As is shown in Fig. 7, quite small average quantities of hydrogen produced dramatic reductions in the stress intensity required to initiate subcritical crack growth. The martensitic steel, which was most seriously affected by charging with hydrogen, showed subcritical crack growth at stress intensities less than 0.15 K_{Ic} at an average hydrogen content of about 1.6 ppm. These data indicate that subcritical crack growth in high-strength steels is highly sensitive to the initial hydrogen content of the steels. However, in contrast to the behavior of hydrogen in titanium alloys, hydrogen is quite readily removed from martensitic or ferritic steels by thermal treatment at relatively low temperature. Because hydrogen diffuses rapidly in martensitic and ferritic steels even at room temperature, it is difficult to retain a significant quantity of hydrogen in steels of relatively thin section without special precautions to avoid its loss. In addition, the relative ease with which steels absorb hydrogen from a moisture-containing environment under conditions conducive to subcritical crack growth may mask the effects of small differences in the initial hydrogen content on subcritical crack growth in the ambient environment. On the other hand, it is probable that subcritical crack growth in inert environments as observed at stress intensities of 0.7 K_{Ic} or higher in several high-strength steels could be attributed to hydrogen embrittlement from a small amount of hydrogen initially in solution.

Aluminum alloys are not able to retain hydrogen in solution under normal conditions and thus would not be expected to be susceptible to subcritical crack growth as a result of internal hydrogen. This may explain the absence of measureable crack growth in aluminum alloys in inert environment at sustained loads just below K_{Ic}.

A quantitative mechanism has been proposed to explain subcritical crack growth in hydrogen-charged steels that appears equally applicable to hydrogen-containing titanium alloys.[17] It is proposed that crack growth results from the development of a critical concentration of hydrogen in regions of high triaxial stress immediately ahead of the crack due to hydrogen migration in a stress field. This mechanism successfully predicts the variation of threshold stress intensity for subcritical crack growth with type of steel, yield strength, initial hydrogen content, stress intensity, mixed-mode loading, and temperature. Moreover, the mechanism can provide a semiquantitative explanation of the effects of hydrogen absorption from an external source on subcritical crack growth.

An interesting feature of this proposed mechanism is the prediction that even quite small amount of hydrogen in solution may result in subcritical crack growth; K_{th} is proportional to ln $(1/Co)$ where Co is the initial hydrogen content. This is in agreement with both the behavior of titanium alloys, in which crack growth has been observed at extremely low hydrogen contents, and the suggestion that subcritical crack growth observed in high-strength steels in an inert environment may be related to a small residual hydrogen content. Thus, it is concluded that a mechanism of subcritical crack growth under sustained load in the ambient environment which considers the effects of both hydrogen absorbed from the environment and hydrogen initially present in solution in the alloys can satisfactorily explain observed crack growth behavior in steels, titanium alloys, and aluminum alloys.

Creep Rupture

Measurements of the rate of subcritical crack growth often provide curves of the type shown in Fig. 5.[11] Three-stage crack growth rate behavior of this type is reminiscent of primary, secondary, and tertiary creep behavior, and has led to the suggestion that subcritical crack growth is controlled by creep rupture.[8,15,16,10] At even moderate stress intensities, appreciable plastic flow must occur at the crack root in ductile structural alloys, and might result in progressive crack extension as creep rupture occurred in the material immediately in front of the crack. Correlation between stress/time behavior in uniaxial creep and stress intensity/crack growth rate behavior under sustained load have been developed to explain subcritical cracking in titanium and steel.[8,20] As noted earlier, however, it seems probable that three-state crack growth kinetics are a function of mixed mode loading and that, although creep related, they are due to creep deformation of the surface material which is deforming plastically to accommodate crack growth occurring in material under plane strain loading. This latter material is presumably showing progressive cracking due to some other factor. If creep rupture processes are responsible for crack growth under sustained load in the central triaxially stressed crack region, correlation should be sought with time-dependent fracture ductility under plane strain conditions rather than with uniaxial creep behavior.

The conclusion that creep rupture processes are not the cause of subcritical crack growth is strengthened by the absence of measureable crack growth in aluminum alloys tested in an inert environment at stress intensities approaching K_{Ic}. Aluminum alloys should be as susceptible to creep rupture as high-strength martensitic steels or titanium alloys.

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