FATIGUE CRACK GROWTH THRESHOLDS IN D6AC STEEL

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Abstract

The fatigue crack growth threshold defines the stress intensity level, ΔK, below which a crack will not propagate. Recent research has shown some of the threshold data generated within test standards defined by ISO and ASTM has exposed some limitations in the standards that could affect the data in unforeseen ways. One of these limitations is the development, or lack thereof, of the steady-state condition. Steady-state cracking is defined as a crack that has advanced slowly until the crack-tip plastic zone size and crack-tip sharpness remain constant with further crack extension. The development of the steady-state condition is dictated by the full development of plasticity-, roughness- and environment-induced closure. The authors studied the behaviour of D6AC steel using standard and alternative test methods to determine steady-state conditions near threshold. Preliminary findings indicate that steady-state does not occur for more than 80 hours at a specific near-threshold ΔK, rendering most standard test methods unrepresentative of steady-state.

Introduction

The fatigue crack growth threshold defines the stress intensity level, ΔK, where a crack will arrest or begin to propagate. The threshold is used in the aerospace industry to define a durability lifetime (or safe operating time) for a component, the same way an endurance limit is used in stress-life based design methods. Therefore, accurate threshold data is critical to the safety of durability based designs. The development of fatigue crack growth threshold data is standardized within organizations such as ISO and ASTM. The standards outline experimental procedure, specimen geometry and crack configurations along with tolerances on dimensions and operating parameters. Recent research into the fatigue crack growth threshold has exposed some limitations in the standards that could affect the data in unforeseen ways [1 - 7]. One of these limitations is the development, or lack thereof, of the steady-state condition.

Several researchers have proposed using constant ΔK testing to define steady-state conditions [8, 9]. Constant ΔK testing holds the driving force constant, which in turn develops the steady-state plasticity condition. If the test is conducted long enough, *i.e.* there is significant crack growth, the steady-state roughness condition will develop. If the environment where the test is being conducted is also controlled, then steady-state environmental conditions will develop, and subsequently steady-state cracking will exist [10]. Pippan, *et al.* [11] and James, *et al.* [12] have proposed using compression precracking to generate a sharp crack at a notch that can then be propagated at near-threshold levels. Therefore, compression precracking followed by constant ΔK testing should give an accurate representation of steady-state crack growth behaviour near threshold. The objective of this paper is to use compression precracking followed by constant ΔK testing to determine the steady-state behaviour of D6AC steel near threshold.

Steady-State

The definition of a steady-state crack is given in ASTM E1823 [13] as “a crack that has advanced slowly until the crack-tip plastic zone size and crack-tip sharpness remain constant with further crack extension.” It has been postulated in the literature [14] that there are three distinct mechanisms that affect crack-tip plastic zone size and sharpness: plasticity-, roughness- and environment-induced closure. The full development of each of these closure mechanisms defines steady-state. Plasticity-induced crack closure is described by the development of a uniform plastic zone ahead of the crack tip and a well-defined crack wake [15]. The development of plasticity-induced closure is a function of both crack length and number of cycles, *i.e.* a cyclic phenomenon. Roughness-induced closure is described as the contact of crack wake asperities behind the crack tip [16]. The development of roughness-induced closure is a function of crack length and loading level, *i.e.* a physical phenomenon. Finally, environment-induced crack closure is described as the build-up of debris in the crack wake and blunting of the crack tip from chemical modification of the material due to environment [17 - 19]. The development of environment-induced closure is a function of time, *i.e.* a progressive phenomenon. The authors will look at each of these mechanisms to describe stead-state behaviour near threshold.

Threshold testing

Constant R = 0.1 load reduction tests were performed at room temperature in laboratory air in accordance to ASTM E647 using compact tension specimens, C(T) [20], to define the threshold regime. Two specimen geometries were tested with the following dimensions: specimen width (W) = 51 mm, specimen thickness (B) = 5.1 mm and notch length (a_N) = 10.2 mm, and W = 76 mm, B = 12.7 mm and a_N = 19.1 mm. The tests were performed using computer controlled servo-hydraulic test machines. The test systems were calibrated to meet or exceed the requirements of ASTM E647. The displacement gages, strain gages and signal conditioners were calibrated to assure linearity in the operating regime. All testing was conducted under K-control with all crack length measurements verified using microscopes on travelling stages. The visual measurements were used to correct the compliance-based crack length values prior to data reporting per ASTM E647. The testing complied with ASTM E647 having the following exceptions: the 76 mm wide compact tension specimen notch height exceeded the tolerances set by the fatigue crack growth standard E647 by 7% and the 51 mm wide specimen was precracked at a crack growth rate above the recommended rate for threshold testing. The excessive notch height should not have an effect on the data because the specimens were precracked to a length of a/W = 0.28, *i.e.* any crack growth data reported would be outside the influence of the notch. The high precracking level used on the 51 mm specimen may have induced remote plasticity-induced closure resulting in an elevated threshold [2]. Further testing at lower precracking levels is required to evaluate if plasticity-induced remote closure occurred.

The results of the constant R = 0.1 load reduction tests using 51 and 76 mm wide specimens are shown in Figure 1. The specimen width and identification number are denoted in the figure legend with the identification number in parentheses. A 51 mm wide specimen (9) was precracked at a constant ΔK of 29.1 MPa $m^{1/2}$ (above the ASTM E647 precracking limit for threshold testing) and load was shed at a K gradient of C = –0.08 mm^{-1} and loading frequency of 20 Hz resulting in a threshold of 4.36 MPa $m^{1/2}$. A 76 mm wide specimen (8) was precracked at a constant ΔK of 11.6 MPa $m^{1/2}$ and load was shed at a K gradient of C = –

0.08 mm^{-1} and loading frequency of 40 Hz resulting in a threshold of 6.45 MPa $m^{1/2}$. At this point the test was converted into a load increasing test with an initial ΔK of 6.45 MPa $m^{1/2}$ and a K gradient of C = 0.08 mm^{-1} and loading frequency of 40 Hz until specimen failure. A 76 mm wide specimen (28) was precracked at a constant ΔK of 11.7 MPa $m^{1/2}$ and load was shed at a K gradient of C = –0.08 mm^{-1} and loading frequency of 20 Hz to a ΔK of 7.66 MPa $m^{1/2}$ (not the threshold) where the test was cycled at a constant ΔK of 7.67 MPa $m^{1/2}$. The 51 and 76 mm wide specimen data agree in the Paris regime, but are significantly different near threshold. The difference between the near-threshold data is discussed in the next section.

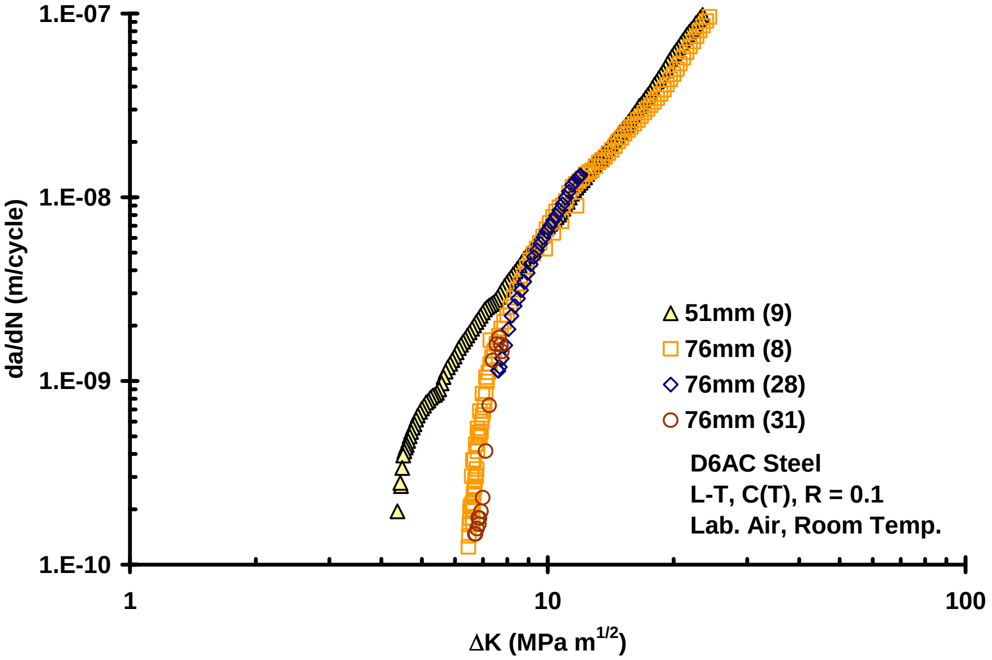

FIGURE 1. Constant R = 0.1 load reduction test data for D6AC steel.

Constant ΔK testing

Constant ΔK testing has traditionally been used to define steady-state conditions because the driving force is held constant, which in turn develops the steady-state plasticity condition [10]. Furthermore, if the there is significant crack growth during a constant ΔK test, the steady-state roughness condition will also develop. Lastly, if the environment where the test is being conducted is also controlled, then steady-state environmental conditions will develop, and subsequently steady-state cracking will exist. Using the threshold data presented in Figure 1 as a reference, constant ΔK testing was initiated at values of 4.39 MPa $m^{1/2}$ and 7.69 MPa $m^{1/2}$, near the threshold values obtained from the 51 mm and 76 mm constant R load reduction tests respectively.

The compression precracking was performed on 76 mm wide specimens with initial maximum and minimum loads of –0.445 N and -26.7 N respectively and a loading frequency of 5 Hz. Precracking was conducted under load control by applying compressive loads at the top and bottom of the specimen via loading blocks fit between the specimen and the clevises. In this arrangement, load is transferred through the top and bottom of the specimen, instead of the pins, to avoid cracking at the pin holes [11]. Then, constant ΔK was applied via pin loading and the specimen was tested using K control per the standards of ASTM E647 as discussed previously.

The first subcomponent of the steady-state condition investigated is plasticity-induced crack closure because it is the simplest of the three closure conditions to identify. Plasticity-induced crack closure is a cyclic phenomenon, and steady-state plasticity develops rapidly at the crack tip during a constant ΔK test, within a million cycles [2]. For this study, it was presumed that plasticity-induced closure had developed a steady-state condition when the slope of the crack growth versus cycles plot became linear over one million cycles. This amount of cycles was chosen because it is significant with respect to the crack growth rate, *i.e.* enough damaging cycles accrue that a steady-state plasticity condition exists along both the crack tip and wake. Specimen (11) was compression precracked then cycled at a constant ΔK of 7.75 MPa m$^{1/2}$ with a loading frequency of 10 Hz. The results of the test are plotted as crack growth versus cycles in Figure 2. Unfortunately, the specimen grew out of crack front straightness (front-back) so the test was stopped. Only the data within the ASTM E647 limit (B/4) for crack front straightness is shown. However, specimen (11) did develop a steady-state plasticity crack growth rate of 3.35E-9 m/cycle within one million cycles.

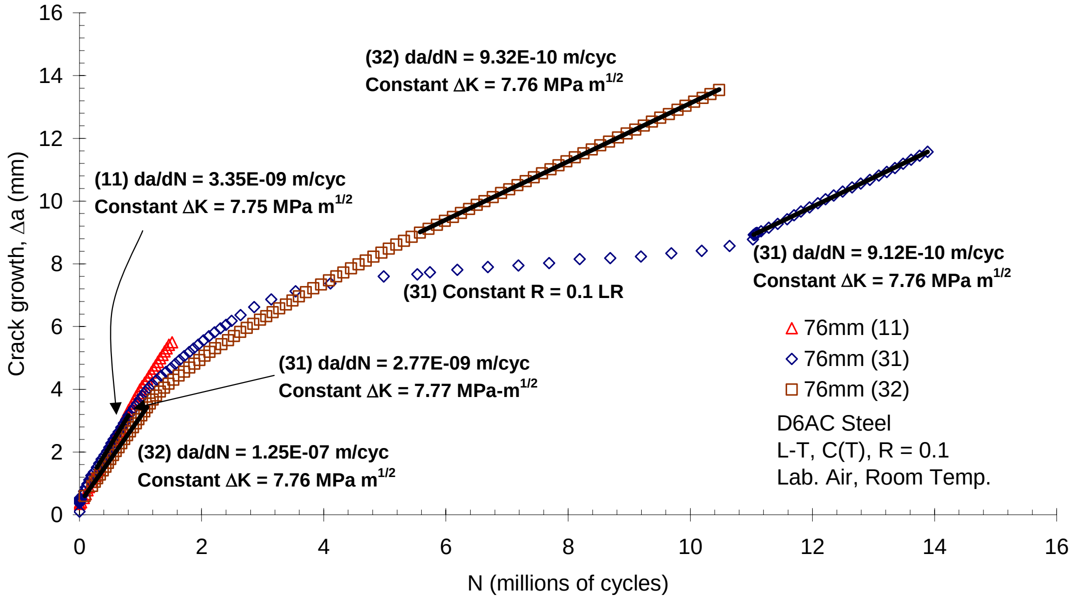

FIGURE 2. Compression precrack, constant ΔK ~ 7.7 MPa m$^{1/2}$ test data for D6AC steel.

Specimen (31) was also compression precracked and cycled at a constant ΔK of 7.77 MPa m$^{1/2}$ with a loading frequency of 20 Hz. Specimen (31) achieved a steady-state plasticity condition growth rate of 2.77E-9 m/cycle within one million cycles. Since this test behaved similar to specimen (11), a load reduction test was performed on the same specimen to determine the threshold. Load was shed at a rate of C = –0.08 mm^{-1} with a loading frequency of 20 Hz resulting in a threshold of 6.68 MPa m$^{1/2}$. This threshold was very similar to the other threshold data obtained for 76 mm wide specimens (see Figure 1). Specimen (31) was then tested at a constant ΔK of 7.76 MPa m$^{1/2}$ to reinforce the previous constant ΔK test data generated on this specimen. The resulting crack growth rate from the second constant ΔK test was 9.12E-10 m/cycle, nearly one-third the growth rate of the previous constant ΔK test on the same specimen.

The difference in crack growth rate from the two constant ΔK tests conducted on specimen (31) was puzzling. Therefore, specimen (32) was compression precracked and cycled at a constant ΔK of 7.76 MPa m$^{1/2}$ with a loading frequency of 20 Hz. The results of this test are presented in Figure 2 as crack growth versus cycles. In this case, the constant ΔK test was conducted for more than 10 million cycles and 13 millimetres of crack growth. An initial steady-state condition developed within the first million cycles producing a crack growth rate of 3.18E-9 m/cycle. Similar to the growth rates obtained from specimens (11) and (31). However, a definite transition in crack growth rate occurred near one and one-half million cycles that did not stabilize for nearly five million cycles. A new steady-state condition developed (defined as a linear slope of the crack growth rate versus cycles plot over one million cycles), resulting in a crack growth rate of 9.32E-10 m/cycle. Similar to the crack growth rate observed during the constant ΔK test from specimen (31) following the load reduction test.

Additionally, there does not appear to be a simple explanation to why different specimen configurations yield different threshold values. To determine if a crack would propagate below the threshold defined using the 76 mm wide specimens, specimen (10), a 76 mm wide specimen, was compression precracked then cycled at a constant ΔK of 4.5 MPa $m^{1/2}$ with a loading frequency of 18 Hz, near the threshold generated using the 51 mm wide specimen. A plot of crack length versus cycles for specimen (10) is shown in Figure 3. The crack growth rate generated during the constant ΔK test stabilized within one million cycles to a crack growth rate of 8.89E-10 m/cycle. A clear transition to a different, slower crack growth rate occurred at approximately five million cycles. The new crack growth rate was 1.61E-10 m/cycle, less than one-quarter the original crack growth rate. This test showed similar trends to the constant ΔK ~ 7.7 MPa $m^{1/2}$ tests, an initial steady-state condition transitioning to a slower steady-state crack growth rate.

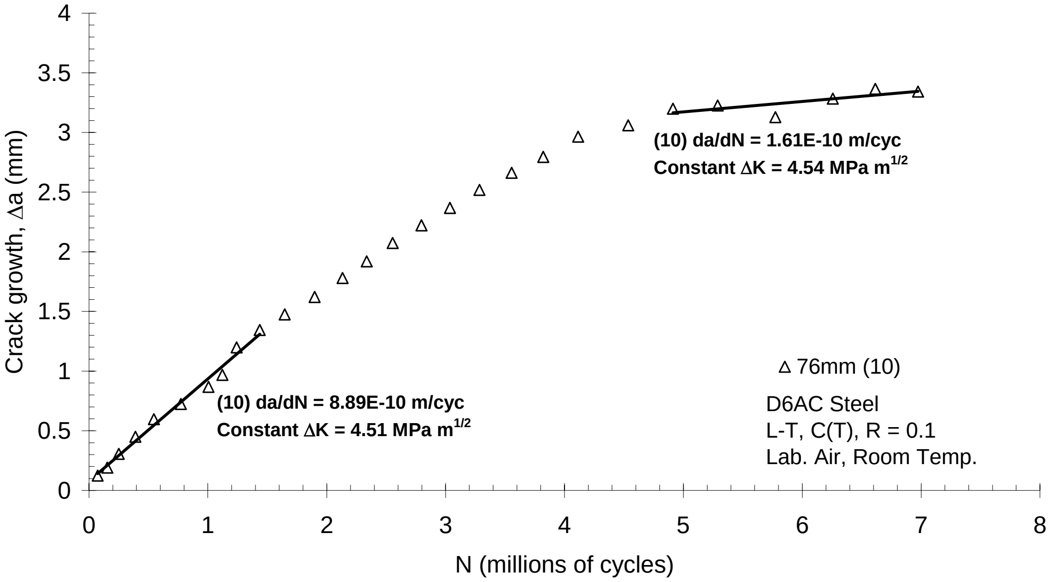

FIGURE 3. Compression precrack, constant ΔK ~ 4.5 MPa $m^{1/2}$ test data for D6AC steel.

To reiterate, plasticity-induced crack closure is a cyclic phenomenon, and steady-state plasticity develops during a constant ΔK test when the slope of the crack growth versus cycles plot becomes linear over one million cycles. Therefore, it could be inferred from the data presented in Figures 2 and 3 that plasticity-induced crack closure has achieved a steady-state condition within the first million cycles of constant ΔK testing. This would support the argument that the constant R load reduction test, when conducted within the guidelines of ASTM E647, is representative of a plasticity-based steady-state since both the 51 mm (9) and 76 mm (8) tests propagated between a rate of approximately 2 and 3E-9 m/cycle when ΔK was approximately 7.7 MPa $m^{1/2}$ (Figure 1). However, this does not explain why the threshold generated using the 76 mm wide specimens is nearly one and one-half times that of the 51 mm specimen. Nor does plasticity-induced crack closure explain why the constant ΔK of 4.5 MPa $m^{1/2}$ test propagated below the 76 mm wide specimen threshold. Finally, plasticity-induced crack closure does not explain the clear transition in crack growth rate observed in the constant ΔK tests.

Discussion

Each of the constant ΔK tests eventually transitioned to a significantly slower fatigue crack growth rate (see Figures 2 and 3). Assuming that steady-state plasticity had developed, this leaves roughness- and environmental-induced crack closure as possible factors contributing to a new stabilized crack growth rate. Roughness-induced closure is a physical phenomenon, typically developing a steady-state condition with increasing crack length [16]. For this study, it was presumed that roughness-induced closure had developed a steady-state condition when the slope of the crack growth versus cycles plot became linear over crack growth of Δa ~ 1 mm. This amount of crack growth is significant with respect to the size of the microstructure of D6AC steel, approximately 2 to 30 μm in diameter, leading to a crack front and wake that will span several grains [21]. The results of the constant ΔK tests presented in Figures 2 and 3 show that the steady-state roughness-induced crack closure condition developed concurrently with the plasticity-induced crack closure steady-state. Without evaluating the specimens under a scanning electron microscope, or equivalent, the actual amount of crack face roughness cannot be determined.

Consequently, environmental-induced closure remains as the primary reason for the retardation of crack growth rate in the constant ΔK tests (Figures 2 and 3). Environmental-induced closure develops over time [10], as the crack tip is blunted and oxide/fretting debris builds on the crack face. For this study, steady-state environment-induced crack closure is defined as a linear relationship between crack growth rate and time. Figure 4 is a log-linear plot of crack growth rate versus time for each of the tests at a ΔK ~ 7.7 MPa $m^{1/2}$. The axis of time is computed from the point at which the test was within 5% of ΔK = 7.7 MPa $m^{1/2}$ (time = 0). For instance, specimen (8) was a constant R load reduction test that passed through a ΔK of 7.7 MPa $m^{1/2}$. The time point of zero for this test would be at approximately 8.1 MPa $m^{1/2}$ (105% of 7.7 MPa $m^{1/2}$). Further, a load increasing test was performed on specimen (8) after threshold was reached. This data would include the time spent below a ΔK of 7.7 MPa $m^{1/2}$. This time is included because it may be important to any time dependent closure mechanisms that are developing in the specimen. Two crack growth rates, plotted as a function of time because the tests were run at different frequencies, are highlighted in Figure 4 with 20% bounds on either side (solid lines and dashed lines). The faster crack growth rate (5.8E-8 m/second) corresponds to the initial crack growth rate obtained from the constant ΔK tests. The second, slower crack growth rate (1.8E-8 m/cycle) corresponds to the final crack growth rate obtained from the constant ΔK tests performed on specimens (28), (31) and (32). All of the constant ΔK crack growth rate data presented in Figure 4 exhibits a definite trend with respect to time.

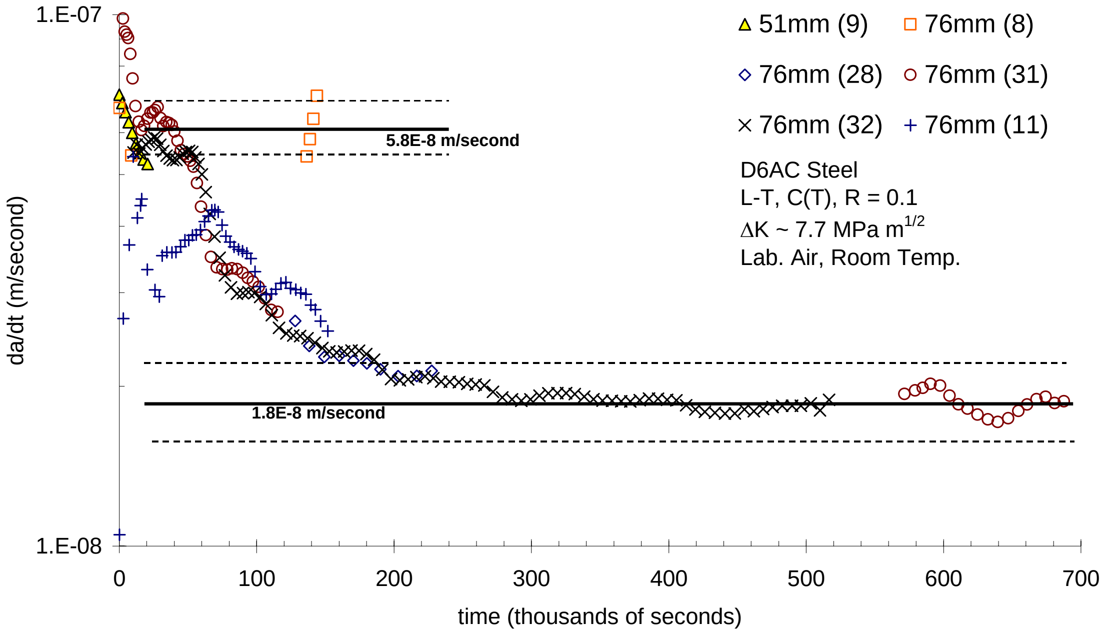

FIGURE 4. Crack growth rate versus time for ΔK ~ 7.7 MPa $m^{1/2}$ in D6AC steel.

The relationship between specimens (8) and (28) is of note. Specimen (8) was a constant R load reduction test, followed by a constant R load increasing test. Whereas, specimen (28) was a constant R load reduction test followed by constant ΔK testing at approximately 7.7 MPa $m^{1/2}$. The constant R load reduction, and increasing, data relates to the initial, higher crack growth rate presented in Figure 4. Implying that steady-state plasticity and roughness have developed as discussed previously. However, the constant ΔK test performed after the constant R load reduction test developed a steady-state environment-induced closure condition. The corresponding crack growth rate is nearly identical to that developed from the constant ΔK test performed on specimen (32). Based on the results presented in Figure 4, it can be inferred that environmental-induced closure takes a significant amount of time (more than 80 hours) to develop a steady-state condition.

Conclusions

Compression precracking, constant ΔK data is presented in this paper to determine the development of steady-state cracking and evaluate the integrity of the standard constant R method. Constant ΔK testing of D6AC steel has shown that fatigue crack growth in this alloy is a function of time. Agreement between constant R and ΔK testing indirectly shows that steady-state plasticity- and roughness-induced crack closure develop rapidly, within one million cycles and approximately 1 mm of crack growth respectively. However, the constant ΔK testing shows that environmental-induced crack closure does not reach steady-state conditions for more than 80 hours. Since the constant R test method does not usually spend this much time at a specific ΔK, it is only representative of plasticity- and roughness-induced crack closure. A true steady-state crack does not develop for more than one million cycles, 1 mm of crack growth and 80 hours at a specific ΔK.

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