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Remaining Life Calculations and Crack Growth Rate for Various Forms of Stress Corrosion Cracking as a Function of Temperature

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ABSTRACT

In this work, we demonstrate a methodology to perform Fitness-for-Service assessments (FFS) for various forms of stress corrosion cracking (SCC) as a function of temperature. Data were gathered from the literature to summarize crack growth rates in the different combinations of material and environment. Case study remaining life calculations were performed to provide a reference to quickly determine if a Level 3 FFS assessment would be a viable option given the damage mechanism, temperature, and time until repair could be made. Conservative crack growth rates for chloride SCC of stainless steel, caustic SCC of stainless steel, and caustic SCC of carbon steel were gathered for specific environments. At 160°F (71.1°C) and up to 33 ksi-in^{1/2} (36.3 MPa-m^{1/2}), the crack growth rates are 0.033 inches/month (3.21 x 10⁻⁷ mm/sec), 0.240 inches/month (2.35 x 10⁻⁶ mm/sec), and 0.214 inches/month (2.10 x 10⁻⁶ mm/sec), respectively. These crack growth rates correspond to conservative remaining lives of 18 months, 2.5 months, and 2.1 months, respectively, for the pressure vessel geometry and initial flaw sizes that were evaluated. The analysis provides a methodology that can be extended to other materials and service conditions for which the necessary data are available.

Key words: stress corrosion cracking, fitness for service assessment, chloride stress corrosion cracking, caustic stress corrosion cracking, remaining life, fracture, standardization

INTRODUCTION

Throughout the mid-20th century, alloys resistant to stress corrosion cracking (SCC) were developed, particularly nickel-based alloys¹. However, billions of dollars of existing equipment used in pressurized environments remain susceptible to SCC. Practically, due to the cost of replacement, it will be decades

before this equipment can be upgraded to more failure resistant materials. For this reason, the industry focus has been on inspecting the existing equipment to find cracks and repair or replace damaged equipment before it leaks.

To prioritize which equipment was to be inspected, it was necessary to obtain a better understanding of the key factors that influence SCC crack growth rate; including pH, concentration of the corrosive component, and temperature. Throughout the 1980's, Speidel², Kane, and others conducted significant laboratory testing, determining some crack growth rates for various forms of SCC³⁻⁸. However, most of these works focused on only one form of SCC at one set of operating conditions (one combination of pH, concentration, and temperature).

The American Petroleum Institute (API)⁽¹⁾ created the API RP 579 Fitness-for-Service (FFS) document in 2000⁹, which standardized the approach for assessing whether or not a crack-like flaw in a structure is acceptable for continued operation. However, that document and subsequent editions^{10,11} do not give specific values that should be used for SCC crack growth rates in a FFS analysis. Instead, API RP 579 refers the user to several of the previously mentioned papers from the literature published in the 1980's and 1990's. It is the user's responsibility to locate these papers and determine which, if any, contain a crack growth rate that can be applied to their industrial application. Many sites do not have access to these papers and most API 579 users are not experts in SCC, so locating and deciphering these papers would take weeks to be able to use the information in a practical analysis. Thus, the existing analysis procedure is inefficient, leading to delays when deciding whether equipment should be shut down and flaws repaired or if it can continue operating until it can be replaced with new equipment.

To reduce delays during FFS assessments, it would be useful for industry to have one central work that summarizes crack growth rates for all forms of SCC for which adequate data are available, and at several operating conditions for each type of SCC. Cayard and Kane's 1996 study¹² did include a comparison of crack growth rates for several forms of SCC. However, that paper provided crack growth rate ranges of 2-3 orders of magnitude for each type of SCC. One reason these ranges are large is that they include the effect of a changing applied stress intensity factor. There is an opportunity to provide more precise crack growth rates based on a narrower range of applied stress intensity to those doing FFS assessments. The crack growth rates in the 1996 paper also lack the detail needed to quickly apply specific crack growth rates to industry situations to predict remaining life of in-service equipment.

The goal of the present work is to provide an initial process for standardizing SCC crack growth rates for three damage mechanisms, while future work could continue the standardization for additional damage mechanisms. This work goes one step further than most previous research, in that these crack growth rates are applied to two different configurations of equipment in a FFS analysis to determine the remaining lives of various forms of SCC for various temperatures. This process starts to build a practical approach to determining which crack growth rate variables have the most significant effect on remaining life.

This information will be useful for most API 579 users by decreasing the time required to perform FFS analyses and will enable more efficient engineering decisions based on science. The case study remaining life calculations provide the user with a reference to quickly determine whether a FFS assessment would be a viable option given the damage mechanism, temperature, and time until repair could be made. This approach could improve the reliability and life prediction of equipment containing SCC flaws, as well as improve the efficiency with which these assessments are performed and decisions in industry made.

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ANALYSIS METHODOLOGY

Background

The correlations of crack growth rates in the present study are based on the stress intensity factor from linear elastic fracture mechanics (LEFM), K .

K is used to determine the state of stress near the tip of a crack caused by a remote load. The most generic form of the equation is shown in Equation 1, where σ is the applied stress, and a is the crack length.

$$K \propto \sigma (\pi a)^{1/2} \quad (1)$$

Therefore, stress intensity near the tip of a crack increases as applied stress and crack length increase. Stress corrosion crack growth rate is a function of K , as described in Figure 1 taken from API 579⁹.

As shown in Figure 1, there is a minimum or threshold stress intensity, K_{ISCC} , for SCC to occur for a given material and the given environment. Above this threshold stress intensity is Stage 1 SCC, where the crack growth rate significantly increases with small increases in stress intensity, until the crack growth rate begins to level off. The solid line in Figure 1 illustrates that for Hydrogen-Assisted Cracking (HAC) environments, the crack growth rate continues to increase in Stage 2 as stress intensity increases. However, the damage mechanisms studied in this work follow the dotted line in Figure 1 which illustrates that there is a plateau region during Stage 2 SCC where the crack growth rate remains constant and does not increase with increases in stress intensity. Finally, in Stage 3 SCC, there is an exponential increase in crack growth rate with increasing stress intensity, until failure at the critical stress intensity, K_{IC} .

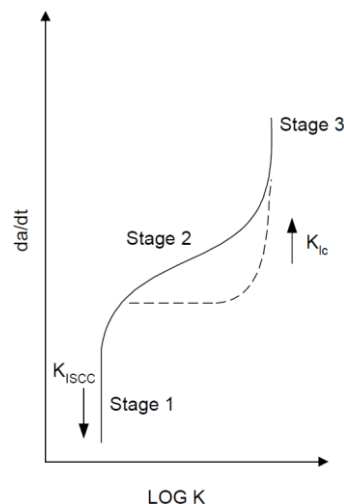


Figure 1: Schematic of Crack Growth Rate as a Function of Stress Intensity Factor During SCC⁹

Unfortunately, there is an inconsistent approach in the literature regarding how stress corrosion crack growth rates are reported. A variety of test methods have been used, and most papers do not report the stress intensity factor used during measurement of the SCC growth rate. It is difficult to gain meaningful information from such results and even more difficult to reliably use them in a FFS assessment, since stress intensity has such a dramatic effect on SCC growth rate. In this study, the literature was reviewed, and only SCC crack growth rates with an associated stress intensity factor were used so that the data could be more accurately compared. Table 1 below shows the ranges of stress intensity factors that are associated with the crack growth rates for each type of SCC. This attempt to keep the variable of stress intensity essentially fixed enables effective analysis of the effect of temperature on the SCC crack growth rates described in the Results and Discussion section.

Table 1: Ranges of Stress Intensity Associated with Crack Growth Rates

Type of SCC	Range of Stress Intensity Factors
Chloride SCC of Stainless Steel ²	36.4 – 45.5 ksi-in ^{1/2} (40 – 50 MPa-m ^{1/2})
Caustic SCC of Carbon Steel ¹³	28.2 – 39.1 ksi-in ^{1/2} (31 – 43 MPa-m ^{1/2})
Caustic SCC of Stainless Steel ¹⁴	39.3 – 50.2 ksi-in ^{1/2} (43.2 – 55.2 MPa-m ^{1/2})

Section 9: Crack-like Flaws of API 579⁹ outlines 3 levels of assessments that can be used to determine whether a structure containing a flaw is acceptable for continued operation. A Level 3 FFS analysis is the most detailed level of assessment and is required if a stress corrosion crack continues to operate in a SCC environment. Level 3 FFS assessments were conducted in this work, including the required application of SCC crack growth rates. A Failure Assessment Diagram (FAD) is used to determine whether a structure containing a flaw is acceptable for continued operation. Figure 2 shows a schematic of a typical FAD. The toughness ratio, K_r , (y axis) is equal to the applied stress intensity factor divided by the material's fracture toughness. A low toughness ratio corresponds to an applied stress intensity that is much less than the fracture toughness, while a toughness ratio of 1 at the top left side of the FAD is reached when the applied stress intensity factor is equal to the fracture toughness.

The load ratio, L_r , (x axis) is equal to the stress from primary loads divided by the yield strength. A low load ratio corresponds to an applied stress that is much less than the yield strength, while a load ratio of 1 or more at the far-right side of the FAD is when the stress is equal or greater than the yield strength.

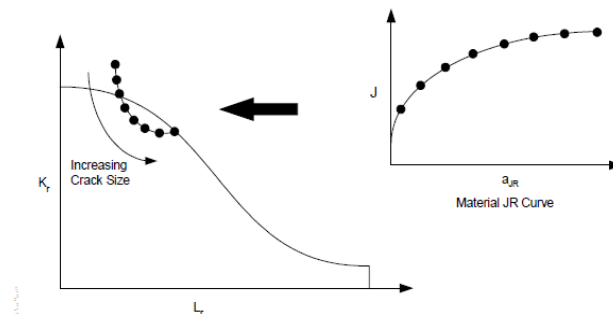


Figure 2: Failure Assessment Diagram and Material JR Curve⁹

By design, most materials used for pressure-containing equipment are high toughness and ductile, allowing a significant amount of plasticity before complete failure. For most materials and structures covered by API 579⁹, it is possible to measure fracture toughness in terms of the critical value of the J integral (J_{crit}), but not in terms of the critical stress intensity factor, K_{IC} , which can only be accurately measured for brittle materials or thick sections. J is equal to the rate of change of energy as the crack grows (per fracture surface area) for an elastic-plastic material. Critical values of the J integral (J_{crit}) correspond to critical crack extension and these values are summarized in Table F.5 of API 579⁹ for several materials.

Equivalent values of K_{IC} , expressed as K_{JC} , are derived from the critical J values following Section F.4.2.1 of API 579⁹ procedure and Equation 2. These values of K_{JC} are used to determine each y-coordinate toughness ratio of the assessment points on the FAD. In Equation 2, E represents Young's modulus and ν represents Poisson's ratio of the material.

$$K_{JC} = [(J_{crit} E) / (1 - \nu^2)]^{1/2} \quad (2)$$

Figure 2 shows the typical shape of a material JR Curve. In this curve, the y axis represents J_{crit} and the x axis represents the change in crack depth. As the JR curve shows, there is an increase in the material's resistance to tearing as the crack grows. One reason for this is due to a larger plastic zone, and larger amount of plasticity, at the crack tip as the crack grows. J-R tearing resistance curve data

from Table F.5⁹ were used in the FFS assessments for Generic SS/SAW and Generic CS-1 materials. These materials had the lowest J_{crit} values for stainless steel and carbon steel, respectively, and correlate to conservatively low K_{JC} material fracture toughness values to use in the assessment. These K_{JC} values are conservative, but still much higher than LEFM fracture toughness values for brittle materials which do not account for macroscopic plasticity.

The Level 3 procedure involves assessing the growing crack several times throughout its proposed remaining life, then comparing those assessments to the FAD. Each point on the FAD represents one of these assessments, and as the crack length increases, the assessment points typically form a “fish-hook” shape. Figure 3 below describes what is considered acceptable and not acceptable for continued operation of equipment containing a crack-like flaw.

If all assessment points are below and to the left of the FAD curve (as the open circles in Figure 3), then no mechanical crack growth will occur, and the crack-like flaw is acceptable for continued operation. The crack still grows due to stress corrosion cracking, but there is enough remaining fracture toughness to resist rapid ductile tearing mechanical crack growth. If some of the assessment points are above the FAD curve (as the filled circles are in Figure 3), and then the assessment points cross and remain below the curve (open circles), then the crack-like flaw is also acceptable for continued operation. In this case, the crack will mechanically grow in a stable manner, until the stress intensity factor falls below the remaining fracture toughness to resist mechanical crack growth. If all assessment points are above and to the right of the FAD curve (as the filled circles are in Figure 3), then the crack-like flaw is not acceptable for continued operation, since this would result in ductile instability (applied stress is sufficient to cause rapid ductile tearing failure).

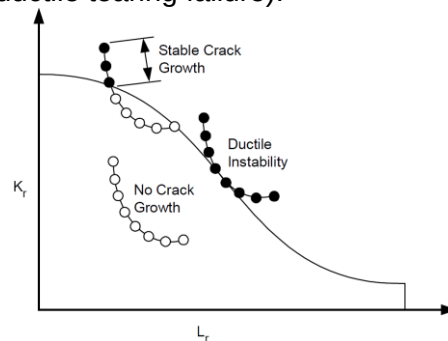


Figure 3: Failure Assessment Diagram and Possible Outcomes⁹

Case Study Design

The main goal of this work was to provide remaining life assessments for several types of SCC at several temperatures each. A secondary goal was to identify case studies that relate to a wide variety of pressurized equipment. Figure 4 shows the cross section of a pressurized component containing a semi-elliptical internal surface crack configuration used in this work, with ‘a’ being the radial crack length from the inner diameter surface (or crack depth), and ‘2c’ being the circumferential crack length.

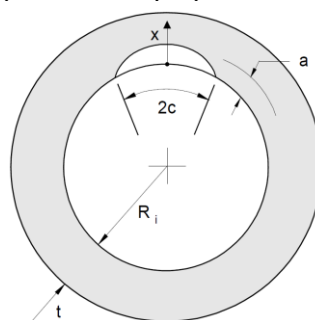


Figure 4: Cylinder Containing a Semi-elliptical Circumferential Surface Crack