

The Effect of Alternate Immersion on Stress Corrosion Cracking Behavior of Steel and Nickel Alloys in Natural Seawater

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ABSTRACT

Stress corrosion cracking susceptibility of selected high strength alloys was evaluated during exposure in alternate immersion conditions using bolt loaded compact test geometries with a strain gauge positioned at the back-face to allow a large sample throughput while including sensitive monitoring of crack progression during exposure. This approach combines advantages of a traditional K_{ISCC} exposure testing and laboratory-based instrumentation-intensive test methods. Crack length was continuously monitored by specimen compliance during up to 2 years of alternate immersion exposure in unfiltered natural seawater. These wet and dry cycles alternated 6 times a day, and the wet cycle was approximately 15 minutes long. The back-face strain gauge test method proved reliable for up to 20 months of exposure with a crack growth resolution of approximately 25-50 $\mu\text{m/day}$.

Alternate immersion SCC testing of high strength materials, steels and nickel-based alloys: UNS K91973, ASTM⁽¹⁾ A722, UNS S66286, UNS N05500, UNS N07718 API⁽²⁾ 6A and AMS⁽³⁾ 5664, and UNS R30035 is presented. A key finding was that alternate immersion significantly decreased SCC resistance of some alloys, while other alloys proved to be resistant. Incubation times alternated with periods of fast crack growth were observed in most cases.

Key words: Stress Corrosion Cracking, Alternate Immersion, Natural Seawater, High Strength Alloys

INTRODUCTION

Stress Corrosion Cracking is most commonly evaluated by simulated testing in the laboratory or by direct environmental exposure of precracked and pre-loaded samples (e.g., ASTM E1681¹). Laboratory testing allows the use of crack monitoring techniques such as sample compliance or potential drop to

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measure crack growth rates. The latter method typically requires a dedicated testing machine and data acquisition system for each test, limiting the sample throughput and the ability to characterize large sample sets, e.g., sample to sample and batch to batch variability. Testing of precracked and pre-loaded samples allows for high throughput testing to identify SCC thresholds, but typically without the ability to monitor the progression of the crack at the same fidelity as laboratory testing.

The main focus of this testing program is the SCC behavior of high strength materials, particularly steel and nickel alloys, typically used as fastener materials in marine applications under alternating immersion conditions to evaluate their K_{IEAC} . This paper discusses a new testing methodology that uses bolt loaded compact test geometries with a strain gauge positioned at the back-face to allow a large sample throughput and sensitive monitoring of crack progression suitable for a wide array of environmental exposure conditions, such as atmospheric exposure, simulated sea spray, and alternate or full immersion conditions. The crack length was constantly monitored while the samples were in test and statically loaded by a tightened bolt of the same material to reduce galvanic effects. As the SCC crack progresses, the Stress Intensity Factor (SIF), K , decreases, yielding lower growth rates until a K_{IEAC} condition is achieved. The importance of direct exposure with continuous monitoring also lies in the improved understanding of SCC behavior, with information on thresholds, incubation periods and growth rates.

Materials

The list of materials tested in this study is shown in Table 1. The list encompasses a set of materials typically used in marine applications: Ni-based alloys UNS N05500 (Monel K-500*) and UNS N07718, both 718 API 6A and 718 AMS 5664 specifications, Ni-Co alloy UNS R30035 (MP-35N*), Fe-Ni-Cr alloy UNS S66286 (A286*), a high-strength and high-toughness low alloy steel UNS K91973 (Ferrium M54*), and a high-strength low alloy steel A722, for pre-stressed concrete applications. The yield strengths range between 90 and 250 ksi (621 and 1724 MPa).

Table 1
List of materials tested

Material	Specification	Yield Strength, 0.2%
UNS K91973	NA: Equivalent to AMS 6516 alloys	250 ksi (1724 MPa)
UNS R30035	AMS 5844	170 ksi (1172 MPa)
A722	ASTM A722	120 ksi (827 MPa)
UNS N05500	QQ-N-286	90 ksi (621 MPa)
UNS N07718 – 5664	Navy Drawing 7329673, AMS 5664	150 ksi (1034 MPa)
UNS N07718 – API6A	API 6A	140 ksi (965 MPa)
UNS S66286	AMS 5737	95 ksi (655 MPa)

Geometry

The sample geometry is based on a typical fracture mechanics specimen, with a straight crack front progressing along the mid-plane of the sample: the geometry is similar to a compact tension C(T) specimen, with longer width and different H/W ratio. ² This geometry is referred in some literature as a wedge opening load (WOL) specimen, as earlier work used wedges between the crack faces to apply a desired crack opening displacement (COD). ³ The geometry is named bolt-loaded CT specimen per ASTM E1681. The sample geometry is shown in Figure 1. Considering the differences in strengths, three different values of width, W , and thickness, B , are used, depending on the material, to comply with ASTM standard and ensure proper constraints at the crack tip for all levels of K tested. ¹

All samples are extracted from bar stock form, as it is more representative of the typical form used for fasteners. All bolts and pins are made of the same material and with their longitudinal axis oriented

* Trade Name

along the longitudinal bar direction. The samples are oriented in the L-R direction. Because of its very high strength, the dimensions of the sample for UNS K91973 are a width of 1.255 inches (31.9 mm) and a thickness of 0.5 inches (12.7 mm); the sample is extracted from a 2.40 inches (61 mm) diameter bar. A 1/4-20 bolt is used with this geometry. A 3.5 inches (89 mm) diameter bar of UNS R30035 material is used to excise samples 2.51 inches (63.8 mm) wide and 1 inch (25.4 mm) thick; a bar stock of 3.0 inches (76.2 mm) in diameter is used for A722 steel for the same final geometry. A 1/2-20 bolt is used for this geometry. Bar stock of 3.75 inches (95.2 mm), 4.25 inches (108 mm), and 4.00 inches (101.6 mm) in diameter are respectively used for, UNS N05500, UNS N07718 API6A, UNS N07718 AMS 5664, and UNS S66286; the samples are 3.1375 inches (79.7 mm) wide and 1.25 inches (31.8 mm) thick. A 5/8-18 bolt is used for this geometry.

All specimens were fatigue precracked according to ASTM E647 guidelines and using the load shedding method.⁴ The fatigue precrack length was approximately 0.5 W for all samples. A final $K_{\max}$ lower than any of the applied K at the beginning of the test was reached during precracking per ASTM standard guidelines. All materials were tested in replicates of 3 samples at the same level of K. Some materials that showed cracking were tested at different K conditions to augment the da/dt vs K data collected. The final precracking levels and the initially applied K levels are shown in Table 2.

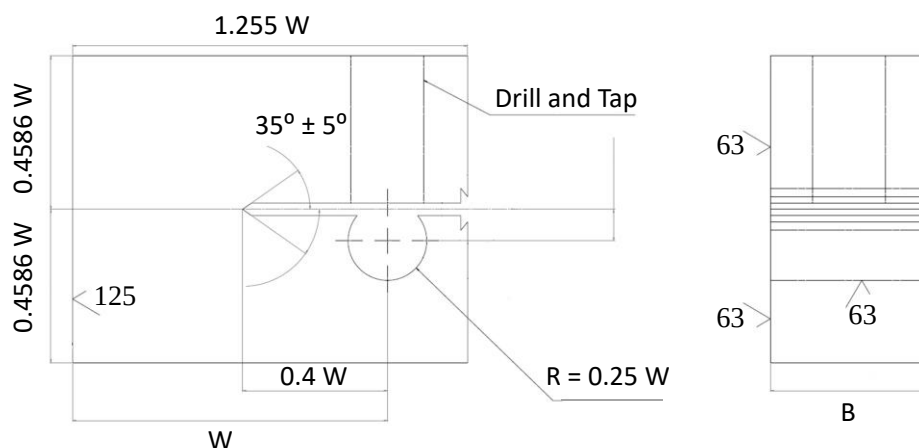


Figure 1: Bolt-loaded SCC sample geometry.

Initial K Condition

The expected K for a crack in a fastener in service is estimated by using the SIF solution for a fastener with major diameter between 0.5 inches and 2.25 inches (12.7 and 57.1 mm). We assume that a thumbnail crack forms at the thread root of the fastener and that 2/3 of the yield strength is the applied preload. The crack depth is conservatively assumed to be 1/16 inches (1.6 mm). Mettu et al. published a general SIF solution for cracks in threaded fasteners with specific SIF solutions for standard aerospace bolt sizes.⁵ The equations also allow for sizes that are applicable to other industrial applications and for the sizes in this work. Based on this SIF solution, an initial assessment of SIF conditions reveals a range of K between 35 and 74 ksi $\sqrt{\text{in}}$ (38.5-81.3 MPa $\sqrt{\text{m}}$) depending on material and strength of the fastener. For all materials in this investigation, no data are available to verify whether SCC is expected within this range of K. Specifically, no K_{ISCC} data exist for alternate immersion in natural seawater. Based on these calculations and the yield strengths of the materials tested in this effort, the initial conditions for testing are shown in Table 2. The data are obtained directly from the initial measurements of K, as will be described in the following sections.

Table 2
List of starting stress intensity factors for all samples tested in phase 1 and 2

Material	Sample Name	Final K _{max} Fatigue Precracking	Initial K	Final K _{max} Fatigue Precracking	Initial K
		(ksi $\sqrt{\text{in}}$)	(ksi $\sqrt{\text{in}}$)	(MPa $\sqrt{\text{m}}$)	(MPa $\sqrt{\text{m}}$)
UNS K91973	S4	36.0	60.9	39.6	66.9
	S5	36.0	60.4	39.6	66.4
	S6	36.0	64.2	39.6	70.5
	S7	39.0	80.1	42.9	88.0
	S8	39.0	80.2	42.9	88.1
	S9	39.0	80.4	42.9	88.3
UNS R30035	S1	25.0	123.5	27.5	135.7
	S2	25.0	123.5	27.5	135.7
	S3	25.0	123.9	27.5	136.1
A722	S6	33.0	57.1	36.3	62.7
	S7	39.0	66.1	42.9	72.6
	S8	39.0	65.2	42.9	71.6
	S9	39.0	65.4	42.9	71.9
UNS N05500	S1	17.0	68.1	18.7	74.8
	S2	17.0	68.0	18.7	74.7
	S3	17.0	67.5	18.7	74.2
UNS N07718 718 – API6A	S1	23.0	92.9	25.3	102.1
	S2	23.0	91.4	25.3	100.4
	S3	23.0	92.1	25.3	101.2
UNS N07718 718 – 5664	S1	27.0	106.0	29.7	116.5
	S2	27.0	104.9	29.7	115.3
	S3	27.0	106.1	29.7	116.6
UNS S66286	S3	21.0	84.2	23.1	92.5
	S5	21.0	85.3	23.1	93.7
	S6	21.0	84.9	23.1	93.3
	S7	21.0	85.5	23.1	94.0

EXPERIMENTAL PROCEDURE

The initial load is applied by tightening of the bolt. The more the bolt is tightened the more the crack mouth is opened, increasing the SIF applied to the fatigue crack. A clip gauge is used to monitor the applied bolt pre-load allowing a real-time calculation of applied K, as shown in Figure 2. A sample of UNS R30035 material assembled with its machined bolt and flattened pin is also shown prior to being instrumented with the back-face strain gauge.

The correlation between measured CMOD and back-face strain is calculated at the beginning of the test by a developed code that records both the clip gauge and the back-face strain signals. Once the target K is reached the clip-gauge is removed and the sample is deployed in the desired environment. The strain is continuously monitored throughout the test by a quarter bridge configuration and a National Instrument (NI) acquisition board and chassis. Data is collected periodically every 10 minutes and at the beginning and end of each immersion cycle. The change in back-face strain as a function of crack length is obtained using numerical analysis (as shown later). During exposure, if a change in crack length occurs, the applied load decreases as a function of crack length. By knowing the initial conditions of the sample, namely the initial crack mouth opening displacement (CMOD), initial K, and crack length, an updated measure of crack length can be obtained from the value of back-face strain.

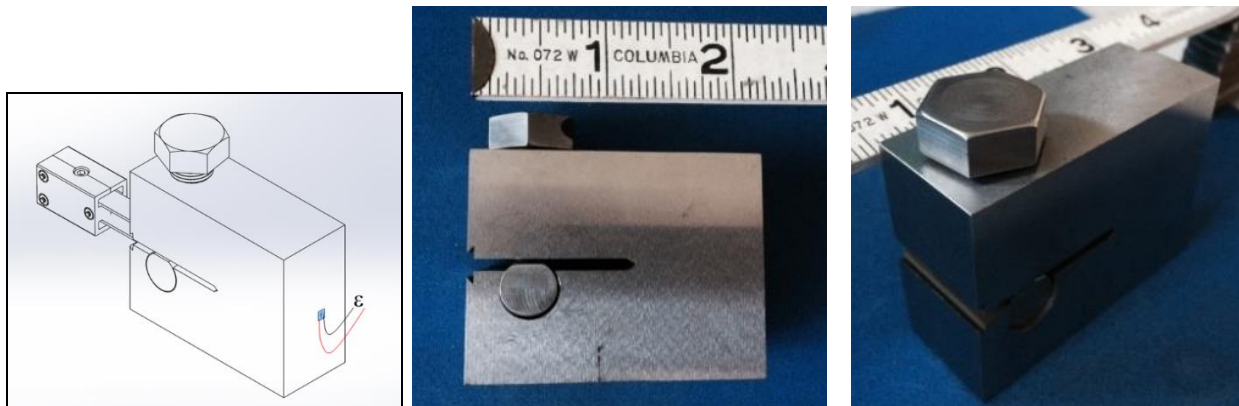


Figure 2: Schematic of geometry and loading methods with monitoring of back-face strain and SCC sample assembled with bolt and flattened pin before being instrumented with back-face strain gauge.

The loading curve is recorded using a custom-developed program that serves as monitor during loading to achieve the desired K level. The CMOD information is collected and regressed in real time to allow the operator, tightening the bolt with a torque wrench, to see the progress in loading the sample and stop at the desired maximum K. The recorded CMOD vs time data for a UNS K91973 sample tested at an initial K of 80 ksi $\sqrt{\text{in}}$ (87.9 MPa $\sqrt{\text{m}}$) is shown in Figure 3. The final value of CMOD is used for all further calculations of crack length and estimated applied load, as it is kept constant by the tightened bolt.

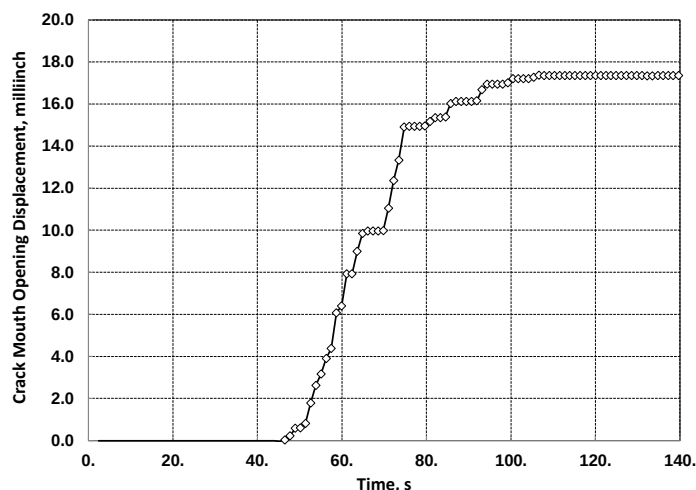


Figure 3: Recorded data with clip gauge applied at the mouth of the crack from loading of the sample before exposure to alternate immersion.

Strain Gauge Application

The instrumented samples are prepared according to a validated procedure for exposure protection of strain gauges to extreme environments: the back face of the samples is sanded with 320 grit silicon-carbide paper in horizontal, vertical and 45 degree directions, the surface is then wetted with a phosphoric-acid compound that acts as a mild etchant and accelerates the cleaning process, followed by neutralization step that is used to stop any chemical reaction introduced by the conditioner and to produce an optimum surface for the strain gage adhesives. The surface is then prepared with tape to allow only a small area, just larger than the size of the strain gauge to bond gauge and metal. A two-part epoxy bonding agent was used to bond the strain gauge to the back-face of the sample. After curing, the tape is removed and a layer of nitrile-rubber coating is applied to both the gauge and