High Strength, Corrosion-Resistant Superalloy Fasteners, Springs, and Hardware for Marine Service

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ABSTRACT

Corrosion-resistant, nickel-base alloys have long been used for marine engineering due to their corrosion-resistance, strength, and ease of fabrication. The evolution of high-performance marine vessels requires increased levels of strength corrosion resistance over that of the alloys commonly used in the past. New high performance nickel-base alloys exhibit excellent resistance to seawater corrosion and hydrogen embrittlement. The strength of solid solution materials such as INCONEL alloy 686 (UNS N06686) is enhanced by cold work. Other highly resistant alloys such as alloy INCONEL alloy 725 (UNS N07725) are precipitation hardened by heat treatment. Both the cold worked and the precipitation hardened alloys exhibit exceptional strength, ductility and toughness.

Keywords: age-hardenable, solid solution, nickel-base alloys, seawater, pitting, crevice corrosion, fatigue resistance, bolting, springs

INTRODUCTION

Construction of U.S. Navy and other marine vessels and equipment require the use of corrosion-resistant fasteners for joining corrosion-sensitive materials such as alloy steel requiring cathodic protection. For example, MONEL alloy K-500 (UNS N05500) fasteners are used with high strength alloy steel in seawater service. The steel receives cathodic protection from sacrificial anodes. The protection is extended to the alloy K-500 fasteners. Failures of the alloy K-500 components have occurred due to hydrogen embrittlement and corrosion resulting from galvanic interaction with more noble materials. Thus, there is a need for improved materials for such applications. INCONEL alloy 686 (UNS N06686) and INCONEL alloy 725 (UNSN07725) are highly corrosion-resistant, nickel-base alloys, which exhibit high strength and toughness along with ease of forming and fabricability. Welding products of these compositions (INCO-WELD 686CPT and 725NDUR) are also useful for weld overlay of steel components for marine service.

INCONEL alloy 686 is a solid solution nickel-base alloy capable of being cold worked to high yield strengths, such as 90 to 150 ksi (620 to 1035 MPa). Alloy 686 was originally developed for flue gas desulfurization (FGD) and chemical process applications. INCONEL alloy 725 is an precipitation-hardenable nickel-base alloy capable of being aged to the minimum yield strength of 120 ksi (7830 MPa). Alloy 725 is strengthened by precipitation of gamma double-prime [Ni_3 (Nb, Ti, Al)]. Alloy 725 was developed for oilfield applications.

INCONEL alloys 686 and 725 are resistant to hydrogen embrittlement in the NACE International TM0177[1] sulfide stress cracking test and are listed in the NACE MR0175[2] document "Standard Material Requirements – Sulfide Stress Cracking Resistant Metallic Materials for Oilfield Equipment" and to chloride stress corrosion cracking in severe sour brine environments. Sulfide stress cracking is considered in the oilfield to be the most severe for hydrogen embrittlement. Depending on the alloy, applications include use in chemical and food processing, marine and offshore platform equipment, oilfield wellhead and subsurface equipment and tubular goods for severe sour service, salt plant evaporators, air pollution control systems, condenser tubing, service water piping and feedwater heaters in the power industry.

DISCUSSION

Testing

Unless otherwise specified, duplicate corrosion specimens were tested and INCONEL alloy 725 test specimens were solution annealed and age-hardened. The alloys are generally compared with materials that are commonly used as marine fasteners.

Composition and Mechanical Properties

The limiting chemical compositions of the alloys are listed in Table 1.

Table 2 exhibits the room temperature tensile (RTT) properties for cold worked INCONEL alloy 686. The material displays excellent strength, ductility and toughness in the cold worked condition.

Table 3 displays the average room temperature tensile and Charpy-V-Notch (CVN) impact properties for alloy 725, 0.625 to 8.0 in. (16 to 203 mm) diameter hot finished, solution annealed plus age-hardened bar. Excellent strength, ductility and toughness are observed. These are average properties and do not represent specification minimums, which are a function of hot finish technique and bar diameter. Longitudinal and transverse orientations exhibit similar properties[3].

The 0°F (-18°C) fracture toughness data for alloy 725 bar is >300 ksi(in.^{½}), >330 MPa(m^{½}), as determined by ASTM Standard Test Method E992[4], the equivalent energy methodology (K_{EE}).

Table 4 displays the room temperature tensile and Charpy-V-Notch impact test data for alloy 725 0.686 to 1.250 inch (17 to 32 mm) round bar in solution annealed, cold worked and age-hardened condition. Round bar of less than 210 ksi (1448 MPa) yield strength was cold worked approximately 23%. Likewise, bar of greater than 210 ksi (1448 MPa) yield strength was cold worked over 23%. The data in Table 4 shows that solution annealed, cold worked and age-hardened alloy 725 has the strength, toughness and ductility necessary for military spring applications.

Figures 1 and 2 show the effect of cold work on the room temperature yield strength and impact strength, respectively, for alloy 686. As seen in Figure 1 for material cold worked from 5 to 15%, similar properties are observed for mid-radius and total thickness. This indicates consistent properties throughout the cross-section.

Tables 5 and 6 display RTT and 0°F (-18°C) Charpy-V-Notch impact test data for cold worked alloy 686 0.75 in. and 1.50 in. (19 mm and 38 mm) diameter round bar and 0.562 in. (14.3 mm). Cold worked alloy 686 exhibited excellent strength, ductility and toughness. For example, the 0.75 in. (19 mm) diameter bar exhibited a room temperature yield strength of 148.0 ksi (1020 MPa) with 54.1 % elongation and an impact strength of 98 ft-lb (133 N-m) at 32°F (0°C). The 1.5-in. (38 mm) diameter bar exhibited a room temperature yield strength of 114.8 ksi (792 MPa) with 56.8 % elongation and an impact strength of 177 ft-lb (240 N-m) at 32°F (0°C). Note that Table 5 also displays RTT data for 0.875-in. (22.5 mm) thick cold worked alloy 686 plate.

Table 7 shows room temperature fracture toughness data for alloy 686 plate, cold rolled to yield strengths of 108 to 120 ksi (745 to 827 MPa). The cold worked alloy 686 exhibited excellent fracture toughness, that is 319 to 362 ksi(in.^{½}), 351 to 398 MPa(m^{½}), at 75ºF (24ºC) as determined by ASTM Standard Test Method E992, the equivalent energy methodology (K_{EE}).

Both solid solution and age-hardenable nickel-based alloys typically exhibit fracture toughness values of ≥ 300 ksi-in^{½} at 0ºF (-18ºC) as determined by ASTM Standard Test Method E992, the equivalent energy methodology (K_{EE}).

Tables 8 and 9 display room temperature threaded fastener tensile data and 10º wedge tensile data, respectively, for ½ in. x 13 and $^{7}/_{16}$ in. x 14 cold worked alloy 686 hex head bolts made to ANSI B18.2.1 with Class 2A threads formed by chasing. Five specimens of each bolt size were tested, per ASTM Standard Test Method F606. Tables 8 and 9 also contain similar data from $^{5}/_{16}$ in. x 16 hex head bolts. Duplicate specimens were tested. Figure 3 displays an untested nut and bolt, and a tested bolt produced from $^{5}/_{16}$ in. hex bar. Note the classic ductile fracture behavior

The ½ in. x 13 bolts were manufactured from 1.5 in. (38 mm) diameter cold worked alloy 686 round bar with a standard RTT ultimate tensile strength of 144.0 ksi (993 MPa). These threaded bolts exhibited excellent properties in the Threaded Fastener and Wedge Tensile tests. That is, the ultimate tensile strength of the ½ in. x 13 bolts was close to that exhibited by the bar from which they were produced, 134 to 140 ksi (923 to 965 MPa) for the bolts and 144.0 ksi (993 MPa) for the 1.5 in. (38 mm) diameter starting bar.

The $^{7}/_{16}$ in. x 14 bolts were manufactured from 0.75 in. (19 mm) diameter cold worked alloy 686 round bar with a standard RTT ultimate tensile strength of 161.7 ksi (1115 MPa). The ultimate tensile strength of the $^{7}/_{16}$ in. x 14 bolts was also close to that exhibited by the bar from which they were produced, 156 to 159 ksi (1076 to 1096 MPa) for the bolts and 161.7 ksi (1115 MPa) for the 0.75 in. (19 mm) diameter starting bar.

The $^{5}/_{16}$ in. x 16 bolts were manufactured from 0.562 in. (14 mm) cold worked alloy 686 hex bar with a standard RTT ultimate tensile strength of 130.0 ksi (896 MPa). The ultimate tensile strength of the $^{5}/_{16}$ in. x 16 bolts was also close to that exhibited by the bar from which they were produced, 127 to 128 ksi (876 to 882 MPa) for the bolts and 130.0 ksi (896 MPa) for the 0.562 in. (14 mm) starting hex bar.

Tables 10 displays room temperature threaded fastener tensile data for ½ in. x 13 and 7/16 in. x 14 cold worked alloy 686 hex head nuts made to ANSI B18.2.2 with Class 2B threads and for the 5/16 in. x 16 hex nuts. Multiple specimens were tested per each nut size, per ASTM Standard Test Method F606[5] Proof Load Test. The Proof Load was the lowest recorded tensile load for each matching bolt size. All specimens passed the Proof Load Test.

General Pitting and Crevice Corrosion

The critical pitting temperature (CPT) test involves exposing samples to 6% ferric chloride solutions, ASTM Standard Test Method G48[6], and raising the temperature by incremental amounts until the onset of pitting. New unexposed test specimens and fresh ferric chloride solution are used at each test temperature. The minimum accepted CPT for North Sea offshore applications is 40°C (104°F), while in the pulp and paper bleaching environments, this temperature would typically be 50°C (122°F)[7]. A ranking of alloys can be achieved as shown in Table 11.

The critical crevice temperature (CCT) test[8] involves exposing samples to the same aggressive ASTM test solution, as above, with a multiple crevice device (TFE-fluorocarbon washer) attached to the surface of the specimen. The results are also shown in Table 11 where the temperatures recorded show the onset of crevice corrosion.

INCONEL alloy 686 – a Solid-Solution, Corrosion-Resistant, Nickel-Base Alloy

Corrosion Resistance to Seawater. Figure 4 displays the air and seawater fatigue curves for mill annealed alloy 686 in ambient seawater. The alloy exhibited excellent seawater fatigue resistance in the tension-tension test conducted at LaQue Center for Corrosion Technology, sine wave 10 Hz, temperature 20ºC, load ratio (R) = 0.1.

Figures 5 and 6 display the air and seawater high cycle fatigue curves for cold worked 0.75 in. and 1.50 in. (19 mm and 38 mm) diameter alloy 686 bar, respectively, in ambient ASTM Substitute Ocean Water (ASTM D1141, synthetic seawater). The high cycle fatigue curves were determined on notched specimens at R of 0.1 with a stress concentration factor of 3.0. Notched specimens of cold worked alloy 686 bar exhibited excellent seawater fatigue resistance when tested per the ASTM Standard Practice for Conducting Controlled Constant Amplitude Axial Fatigue Tests of Metallic Materials, E466[9].

Figure 7 shows fatigue crack growth rate (da/dN) data for 0.875 in. (22.2 mm) thick cold rolled plate with the RTT properties listed in Table 3. In comparing triplicate specimens tested in air and in ASTM Substitute Ocean Water, no effect of the synthetic seawater on crack growth rate is observed for the cold worked alloy 686 when tested per ASTM Standard Test Method for Crack Growth Rates, E647[10]. The material again exhibited excellent cracking resistance.

Table 12 displays crevice corrosion data for both wrought plate and all-weld-metal (weldment) samples of INCONEL alloys 686, 625 and/or C-276, evaluated in quiescent seawater at 25ºC (77ºF) for 60 days[11]. The INCONEL alloy 686 plate and INCO-WELD 686CPT weld samples were resistant to crevice corrosion, as was the alloy C-276 (UNS N10276) plate samples. The alloy 625 (UNS N06625) plate and weldment samples crevice corroded in this test.

Crevice corrosion test results for machined tube sections with vinyl sleeve crevices on the O.D., evaluated with flowing seawater on the I.D. at 14.4ºC (58ºF) for 180 days, are shown in Table 13. Alloys 686 and C-276 did not crevice corrode, while alloy 625 specimens crevice corroded to a maximum depth of 0.11 mm (0.0043 in.).

A comparative study of crevice corrosion resistance was conducted by the Naval Research Laboratory to evaluate the flouroelastomeric gasket peculiarities influence on seawater crevice corrosion susceptibility of Ni-Cr-Mo alloys[12]. In comparison to other Ni-Cr-Mo alloys utilized in this study, alloy 686 demonstrated superior crevice corrosion resistance in elevated temperature seawater.

In galvanic compatibility tests performed in ambient temperature seawater for 180 days at LaQue Center for Corrosion Technology, Inc., in Wrightsville Beach, NC, alloys 686 and 625 were determined to be galvanically compatible. As expected, coupling a large surface area of alloy 686 to less resistant alloy 400 promoted corrosion of the alloy 400. Similar results were observed earlier when a large surface area of alloy 686 was coupled to alloy K-500.

Corrosion Resistance to Chlorinated Seawater. Crevice corrosion tests of a number of alloys were conducted in high temperature seawater at 60°C (140°F) for 60 days and 200°C (392°F) for 90 days. The seawater was chlorinated with 1 to 2 ppm free chlorine to simulate service conditions employed in offshore oil and gas industry seawater service and shipboard piping. The results from these tests are shown in Tables 14 and 15, respectively. Of the alloys tested at 60°C (140°F), only alloy 686 showed no evidence of crevice attack under these conditions. When INCONEL alloy 686 and grade 2 Titanium were tested at 200°C (392°F), there was also no evidence of crevice attack. However, grade 2 Titanium exhibits very low fracture toughness, about 14 ksi(in.^{½}) [15 MPa(m^{½})] compared to alloy 686, 319 to 362 ksi(in.^{½}) [351 to 398 MPa(m^{½})] at 75ºF (24ºC).

Hydrogen Embrittlement in NACE TM0177. INCONEL alloy 686, is resistant to hydrogen embrittlement (HE) in the NACE International TM0177[1] sulfide stress cracking test and is listed in the NACE MR0175[2] document "Standard Material Requirements – Sulfide Stress Cracking Resistant Metallic Materials for Oilfield Equipment". It is also resistant to chloride stress corrosion cracking in severe sour brine environments. Sulfide stress cracking is considered in the Oilfield to be the most severe for hydrogen embrittlement.

Long Term Exposure Notched Tensile Tests. For both the 114.8 ksi (792 MPa) and the 148.0 ksi (1,020 MPa) yield strength cold worked alloy 686 bar, notched tensile specimens were stressed in proving rings and subjected to slowly refreshed natural seawater (sw) for 5000 hours. All specimens were loaded to 90% of the 0.2% offset yield strength. Duplicate specimens of each strength level were polarized to -1.0 V (Ag/AgCl/sw) and duplicate specimens were also exposed without polarization for the 5000-hour test period. After 5000 hours of exposure, all the specimens were tested at a slow strain rate of $1x10^{-6}$ in/in/sec. Specimens of each strength level in the as-produced condition (no seawater exposure) were also tested at $1x\ 10^{-6}$ in/in/sec, as a base line for comparison. Maximum stress ratios were calculated as follows:

$$\text{Ratio} = \frac{\text{Max. stress for exposed specimens}}{\text{Max. stress for unexposed specimens}} \qquad \text{(Equation 1)}$$

The material exhibited excellent HE resistance. For both strength levels of the cold worked alloy 686 bar, the maximum stress ratio for all the specimens subjected to -1.0 V (Ag/AgCl) for 5000 hours was 0.96. Scanning Electron Microscope (SEM) examination of the fracture surfaces of the notched tensile specimens showed classic ductile behavior. The TTF (time to failure) ratio for all the specimens exposed without polarization for 5000 hours was 0.99 to 1.00, excellent TTF ratios. See Table 16.

Slow Strain Rate Tests. For the 114.8 ksi (792 MPa) yield strength cold worked alloy 686 bar, duplicate notched tensile specimens were slow strain rate tested at a displacement rate of 9 x10^{-7} in/sec in air and in ambient ASTM Substitute Ocean Water (ASTM D1141, synthetic seawater), freely corroding and polarized to –0.850 V and -1.000 V (Ag/AgCl). The air to environment ratios for specimens tested freely corroding and polarized to –0.850 V and -1.000 V were 0.98 to 1.03, which were judged to be excellent values. See Table 17.

INCONEL alloy 725 – an Age-Hardenable, Corrosion-Resistant, Nickel-Base Alloy

Table 17 shows crevice corrosion data for INCONEL alloys 725 and 625, evaluated in quiescent seawater at 30ºC (86ºF) for 30 days using acrylic plastic crevice devices torqued to 25 in-lb. Alloy 725 exhibited excellent crevice corrosion resistance, no attack. Alloy 625 samples crevice corroded during the test to a maximum depth of 0.66 mm (0.026 in.).

Crevice corrosion test results for INCONEL alloys 725 and 625 machined tube sections with vinyl sleeve crevices on the O.D., evaluated with flowing seawater on the I.D. at 14.4ºC (76ºF) for 180 days, are shown in Table 18. Duplicate specimens of alloy 725 in the solution annealed condition did not crevice corrode. Two of three specimens of alloy 725 in the solution annealed and age-hardened condition suffered slight crevice corrosion attack to a maximum depth of only 0.04 mm (0.0015 in.), and the third specimen was not attacked. Duplicate specimens of alloy 625 crevice corroded to a maximum depth of 0.78 mm (0.031 in.).

Table 19 displays corrosion fatigue strength for commercially significant alloys determined by the tension-tension test in seawater at 10^7 cycles. Alloy 725 exhibit excellent fatigue strength relative to its tensile strength.

In galvanic compatibility tests performed in ambient temperature seawater for 92 days at the LaQue Center for Corrosion Technology, Inc., alloys 725 and 625 were determined to be galvanically compatible. As expected, coupling a large surface area of alloy 725 to alloy K-500 promoted corrosion of the less resistant alloy K-500.

C-ring stress corrosion cracking (SCC) tests of alloy 725 bar products were conducted for six months in NACE Materials Requirement MR0175 Level VI and VII sour brine Oil Patch environments relative to severe Mobile Bay applications where elemental sulfur is not present. The NACE Level VI and VII sour brine environments containing (a) deaerated 20% NaCl + 508 psi (34.5 bar) H_2S + 508 psi (34.5 bar) CO_2 at 347 ±9°F (175 ±5°C) and (b) deaerated 25% NaCl + 508 psi (34.5 bar) H_2S + 508 psi (34.5 bar) CO_2 at 401 ±9°F (205 ±5°C), respectively.

The C-rings were deflected to obtain a stress of 100% of the yield strength per NACE Test Method TM0177 Method C. Triplicate specimens of each alloy were tested for six months at SourTest Laboratory in the NACE Materials Requirement MR0175 Level VI and VII sour brine environments. No SCC was observed for C-rings of alloy N07725 evaluated during the six-month exposure to the NACE Materials Requirement MR0175 Level VI and VII severe sour brine environments. There was no discernable pitting of the C-rings. The present maximum allowable hardness limit in NACE Material Requirement MR0175 for alloy N07725 is 43 HRC. Three of the heats evaluated in this study exhibited a hardness of 43 HRC, the remaining heats exhibited hardnesses of 44, 45 and 47 HRC. The results of this study clearly show that alloy N07725 is acceptable to NACE Level VII environment at a maximum hardness of 44 HRC. In sulfide stress cracking (SSC) tests conducted on duplicate specimens in accordance with NACE Test Method TM0177 Method A galvanically couple to steel for 720 hours, this material easily passed.

Specifications – INCONEL alloy 686

INCONEL alloy 686 product forms are contained in the following specifications:

Rod, Bar, Wire and Forging Stock - ASTM B 462, B 564 and B 574, ASME SB-462, SB-564 and SB-574

Plate, Sheet and Strip - ASTM B 575 and B 906, ASME SB-575 and SB-906

Pipe and Tube - ASTM B 163, B 619, B619, B 571, B 775 and B 829, ASME SB-163, SB-619, SB-619, SB-571, SB-775 and SB-829

Welding Products - INCO-WELD Filler Metal 686CPT - AWS A5.15 / ERNiCrMo-14 and INCO-WELD Welding Electrode 686CPT - A5.11 EniCrMo-14

Fasteners - ASTM F 467, F 467M, F 468, F 468M, SAE/AMS J2295, J2271, J2280, J2484, and J2485, MIL-DTL-1222K.

Allowable Design Stresses - ASME Section VIII, Division 1 incorporated in sections II and IX of the Boilercode (formerly found in ASME Code Case 2198).

Corrosion Resistance – NACE International oil patch MR0175/ ISO 15156, sulfuric acid RP0391 and RP0592, flue gas desulfurization RP0292.

Specifications – INCONEL alloy 725

INCONEL alloy 725 product forms are contained in the following specifications:

Rod, Bar, Wire and Forging Stock - ASTM B 443, B 444, B 446, B 564 and B 805, ASME SB-443, SB-444, SB-446, SB-564 and SB-805, SMC HA-91.

Allowable Design Stresses - ASME Section VIII, Division 1 and 2, reference ASME Code Case 2217.

Corrosion Resistance – NACE International oil patch MR0175/ ISO 15156.

Welding Products - INCO-WELD Filler Metal 725NDUR AWS A5.15 / RENiCrMo-15

SUMMARY

High strength nickel-alloys such as INCONEL alloys 686 (UNS N06686) and 725 (UNS N07725) and INCO-WELD 686CPT weldments and overlays exhibit excellent resistance to hydrogen embrittlement and seawater corrosion resistance and, therefore, are excellent candidate for fastener materials and other marine applications.

Solution annealed, cold worked and age-hardened INCONEL alloy 725 has the strength, toughness and ductility necessary for military fastener and spring applications in marine environments.

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TABLE 1 LIMITING CHEMICAL COMPOSITION (WT.%)									
	Ni	Cr	Mo	Fe	Cu	Al	Ti	Nb	W
Alloy 686 (UNS N06686)	Balance	19.0 – 23.0	15 - 17	1 max.	-	-	0.02 – 0.25	-	3.0 – 4.4
Alloys 725 (UNS N07725)	55 - 59	19 – 22.5	7 – 9.5	7 - 11	-	0.35 max.	1.0 – 1.7	2.75 – 4.0	-

TABLE 2 ROOM TEMPERATURE TENSILE PROPERTIES FOR COLD WORKED ALLOY 686				
% Cold Work	Test Location	0.2% Yield Strength (ksi)	Tensile Strength, ksi	% Elongation
5	Mid- Radius	67.8	117.3	56
	Total Thickness	72.8	116.0	56.5
10	Mid- Radius	99.5	131.7	41.5
	Total Thickness	90.6	123.7	48.8
15	Mid- Radius	103.8	134.3	38.5
	Total Thickness	98.5	126.0	44.3

TABLE 3 AVERAGE ROOM TEMPERATURE TENSILE AND CHARPY V-NOTCH IMPACT PROPERTIES FOR ALLOY 725, 0.625 TO 1.25 IN. (16 TO 203 MM) DIAMETER HOT FINISHED, SOLUTION ANNEALED PLUS AGE-HARDENED BAR									
Alloy	Room Temperature Tensile						-75ºF (-59ºC) Charpy V-Impact			
	0.2% Yield Strength		Tensile Strength				Energy		Lateral Expansion	
	Ksi	MPa	ksi	MPa	%El	%RA	ft-lb	J	in.	mm
725 (UNS N07725)	130	896	180	1241	30	44	95	129	0.047	1.19

TABLE 4 AVERAGE ROOM TEMPERATURE TENSILE AND CHARPY V-NOTCH IMPACT PROPERTIES FOR DALLOY 725, 0.686 TO 1.25 IN. (17 TO 32 MM) DIAMETER SOLUTION ANNEALED, COLD WORKED PLUS AGE-HARDENED BAR

Bar Diameter, in.*	Heat	Condition **	Room Temperature Tensile							-75ºF (-59ºC) Charpy V-Impact			
			0.2% Yield Strength		Tensile Strength		%RA	%El	HRC	Energy		Lateral Expansion	
			ksi	MPa	ksi	MPa				ft-lb	J	in.	mm
0.686	1	A	196.8	1357	214.7	1480	31.8	17.0	43	21	28	0.010	0.25
	2	A	198.7	1370	223.6	1542	25.6	19.9	46	…	…	…	…
	3	A	218.3	1505	231.0	1593	37.1	14.4	47	…	…	…	…
	1	B	173.8	1198	200.2	1380	34.6	20.6	41	24	33	0.011	0.28
0.875	1	A	195.0	1345	215.6	1487	31.4	16.5	34	21	28	0.010	0.25
	2	A	192.6	1328	214.5	1479	31.9	16.2	46	…	…	…	…
	3	A	217.3	1498	230.7	1591	28.8	11.2	49	12	16	0.011	0.28
	1	B	174.3	1202	201.6	1390	42.4	18.6	42	24	33	0.013	0.33
1.00	3	A	214.1	1476	225.1	1552	32.2	11.7	47	15	20	0.007	0.18
1.187	1	A	193.2	1332	213.7	1473	34.2	17.1	39	27	37	0.013	0.33
	2	A	189.8	1309	212.1	1462	34.1	18.2	44	…	…	…	…
	1	B	168.8	1164	199.5	1376	38.1	21.8	41	32	43	0.019	0.48
1.250	3	A	225.1	1552	238.4	1644	32.2	11.7	47	15	20	0.007	0.18

* 1 inch = 25.4 cm
** A = Aged at 1350ºF (732ºC) / 8h, FC to 1150ºF (621ºC) / 8h/ AC
B = Aged at 1400ºF (760ºC) / 6h / AC

TABLE 5
ROOM TEMPERATURE TENSILE PROPERTIES FOR COLD WORKED ALLOY 686

Size, Mill Form/ % Cold Work	Room Temperature Tensile Properties				Hardness, HRC
	0.2% Yield Strength, ksi (MPa)	Tensile Strength, ksi (MPa)	% Reduction of Area	% Elongation	
0.875 in. Plate/ 10%	110.7 (763)	136.5 (941)	65.4	36.1	29
0.75 in. Bar*/ 32%	148.0 (1020)	161.7 (1115)	54.1	23.1	36
1.5 in. Bar*/ 17%	114.8 (792)	144.0 (993)	56.8	34.6	27
0.562 in. Hex Bar/ 8%	95.3 (657)	130.3 (896)	64.5	47.6	26

Note: in. x 25.4 = mm * Round bar.

TABLE 6 CHARPY-V-NOTCH DATA AT 0°F (-18°C) FOR COLD WORKED ALLOY 686 BAR		
Bar Diameter	**Energy, ft-lb (N-m)**	**Lateral Expansion, in. (mm)**
0.75 in.*	98 (133)	0.046 (1.17)
1.50 in.**	177 (240)	0.068 (1.73)
0.562 in. hex	178 (241)	0.058 (1.47)
* Material yield strength = 148.0 ksi (1020 MPa), round bar. ** Material yield strength = 114.8 ksi (792 MPa), round bar.		

TABLE 7 FRACTURE TOUGHNESS DATA FOR COLD WORKED ALLOY 686, TESTED AT 75°F (24°C) PER ASTM STANDARD TEST METHOD E992			
Heat Number	**Test Orientation**	**Fracture Toughness**	
		ksi(in)½	**MPa(m)½**
1*	longitudinal	319; 332	351; 365
2**	longitudinal	356; 356	391; 391
	transverse	362; 362	398; 398
* Material yield strength = 120 ksi (827 MPa) ** Material yield strength = 108 ksi (745 MPa)			

TABLE 8 ROOM TEMPERATURE THREADED FASTENER TENSILE TEST DATA FOR COLD WORKED ALLOY 686 BOLTS					
		Ultimate Tensile Load, lb	**Ultimate Tensile Strength, ksi (MPa)**	**0.2% Yield Load, lb**	**0.2% Yield Strength, ksi (MPa)**
1/2 in. x 13 Bolt*	**Average*******	19,660	138 (952)	16,741	118 (814)
	Minimum	19,471	137 (945)	16,569	117 (807)
	Maximum	19,749	139 (958)	16,877	119 (821)
7/16 in. x 14 Bolt**	**Average*******	16,761	158 (1089)	15,776	148 (1020)
	Minimum	16,669	157 (1083)	15,683	148 (1020)
	Maximum	16,871	159 (1096)	15,890	149 (1027)
5/16 in. x 16 Bolt***	**Average*******	9,895	128 (883)	-	98 (676)
	Minimum	9,870	127 (876)	-	97 (669)
	Maximum	9,920	128 (883)	-	98 (676)
* Bolt produced from 1.5 in. (38mm) bar with standard RTT properties listed in Table 4. ** Bolt produced from 0.75 in. (19mm) bar with standard RTT properties listed in Table 4. *** Bolt produced from 0.562 in. (14mm) hex bar with standard RTT properties listed in Table 4. **** Multiple specimens were tested per each bolt size, per ASTM Standard Test Method F606. Note: lb x 0.4536 = kg					

TABLE 9 ROOM TEMPERATURE 10º WEDGE TENSILE TEST DATA FOR THREADED BOLTS OF COLD WORKED ALLOY 686 BAR			
		Ultimate Tensile Load, lb	**Ultimate Tensile Strength, ksi (MPa)**
1/2 in. x 13 Bolt*	**Average*******	19,568	138 (952)
	Minimum	19,030	134(924)
	Maximum	19,820	140 (965)
7/16 in. x 14 Bolt**	**Average*******	16,814	158 (1098)
	Minimum	16,560	156 (1076)
	Maximum	16,910	159 (1096)
5/16 in. x 16 Bolt***	**Average*******	9,840	127 (876)
	Minimum	9,840	127 (876)
	Maximum	9,840	127 (876)

* Bolt produced from 1.5 in. (38mm) bar with standard RTT properties listed in Table 4.
** Bolt produced from 0.75 in. (19mm) bar with standard RTT properties listed in Table 4.
*** Bolt produced from 0.562 in. (14mm) hex bar with standard RTT properties listed in Table 4.
**** Multiple specimens were tested per each bolt size, per ASTM Standard Test Method F606.
Note: lb x 0.4536 = kg

TABLE 10 ROOM TEMPERATURE THREADED FASTENER TENSILE TEST DATA FOR COLD WORKED ALLOY 686 NUTS		
	Proof Load, lb*****	**Pass/Fail**
1/2 in. x 13 Nut*	19,471	Pass, all test specimens
7/16 in. x 14 Nut**	16,669	Pass, all test specimens
5/16 in. x 16 Bolt***	10,090	Pass, all test specimens

* Bolt produced from 1.5 in. (38mm) bar with standard RTT properties listed in Table 4.
**Bolt produced from 0.75 in. (19mm) bar with standard RTT properties listed in Table 4.
*** Bolt produced from 0.562 in. (14mm) hex bar with standard RTT properties listed in Table 4.
**** The Proof Load was the lowest recorded tensile load for the bolts.
***** Multiple specimens tested per each nut size, per ASTM Standard Test Method F606 Proof Load Test.
Note: lb x 0.4536 = kg, in. x 25.4 = mm

TABLE 11

CRITICAL CREVICE AND CRITICAL PITTING TEMPERATURES IN AN ACIDIFIED 6% FERRIC CHLORIDE SOLUTION*

Alloy	Critical Crevice Temperature		Critical Pitting Temperature	
	ºC	ºF	ºC	ºF
686	**>85**	**>185**	**>85**	**>185**
C-276	45	113	>85	>185
725	**35**	**95**	**>85**	**>185**
625	30 – 35	86 – 95	>85	>185
925	**5**	**41**	**30**	**86**
825	5	41	30	86
304	<0	<32	15	59

* Per ASTM Standard Test Method G48 – Practices C and D

TABLE 12

CREVICE CORROSION DATA FOR BOTH WROUGHT AND WELDMENT SAMPLES OF ALLOYS 686, 625 AND C-276 EVALUATED IN QUIESCENT SEAWATER AT 25ºC (77ºF) FOR 60 DAYS

Wrought Materials	**Number of Sites Attacked/ Number of Sites Available**	**Maximum Depth of Attack, mm (in.)**
alloy 686	**0/6**	**0.00 (0.000)**
alloy 625	2/6	0.11 (0.004)
alloy C-276	0/6	0.00 (0.000)
C-276 (UNSN10276)**	½	0.02 (0.001)
Weldments		
Alloy 686	**0/6**	**0.00 (0.000)**
Alloy 625	1 /2	0.49 (0.019)

* Acrylic plastic crevice washer torqued to 75 in-lbs (8.47 N-m).
** Different manufacturer

TABLE 13

CREVICE CORROSION RESULTS FOR ALLOYS 686 AND C-276 AND ALLOY 625 MACHINED TUBES WITH VINYL SLEEVE CREVICES ON THE O.D., EVALUATED WITH FLOWING SEAWATER ON THE I.D. AT 14.4ºC (58ºF) FOR 180 DAYS

Alloy	**Mass Loss (g)**	**Crevice Corrosion**	**Max. Depth of Attack (mm)***
625	0.0023	Yes	0.01
	0.0045	Yes	0.02
	0.1652	Yes	0.12
C-276	Nil	No	0
	Nil	No	0
686	**Nil**	**No**	**0**
	Nil	**No**	**0**

* mm x 0.3937 = in.

TABLE 14 CREVICE CORROSION DATA, 75 in-lbs TORQUE USING ACRYLIC PLASTIC WASHERS, ON DUPLICATE 2-in. X 2-in. (50 mm x 50 mm) SAMPLES, ENVIRONMENT: NATURAL SEAWATER WITH 1 TO 2 ppm FREE CHLORINE AT 60°C FOR 60 DAYS.		
Alloy	**Corrosion Rate, mpy**	**Crevice Attack Depth, Mils (mm)**
316 (S31600)	0	2 (0.051)
	0	1 (0.025)
686 (N06686)	**0**	**No**
	0	**No**
25-6MO (N08926)	0	3 (0.076)
	0	3 (0.076)
625 (N06625)	0	0.5 (0.013)
	0	2 (0.051)
Acrylic crevice washers torqued to 75 ft-lbs (102 N·m)		

Table 15 CREVICE CORROSION DATA, 40 in-oz TORQUE USING CERAMIC CREVICE WASHERS, ON DUPLICATE 1 INCH X 2 INCH SAMPLES, ENIRONMENT: ASTM D1141 SUBSITIUTE OCEAN WATER WITH 1 to 2 ppm FREE CHLORINE AT 200°C IN AN AUTOCLAVE FOR 90 DAYS.		
Alloy	**Corrosion Rate, mpy**	**Crevice Attack, mils Depth**
686/UNS N06686	**0**	**No**
	0	**No**
Grade 2 Ti	**0**	**No**
	0	**No**
Ceramic crevice washers torqued to 75 in-lbs (8.5 N·m)		

TABLE 16 SLOW STRAIN RATE TEST DATA FOR DUPLICATE NOTCHED TENSILE SAMPLES* EXPOSED TO NATURAL SEAWATER FOR 5000 HOURS, THEN PULLED AT A STRAIN RATE = $1x10^{-6}$ in/in/sec				
SSRT Environment	**Maximum Stress (psi)**		**Average Air to Environment Ratio**	
	114.8 ksi bar	**148.0 ksi bar**	**114.8 ksi bar**	**148.0 ksi bar**
Air	249,144	265,811	----	----
Freely Corroding	247,344	265,744	0.99	1.00
-1000 mV	239,168	253,913	0.96	0.96
*Duplicate specimens exhibited equivalent behavior.				

TABLE 17 SLOW STRAIN RATE TEST DATA FOR DUPLICATE NOTCHED TENSILE SAMPLES, ENIRONMENT: AMBIENT ASTM D1141 SUBSTITUTE OCEAN WATER, DISPLACEMENT RATE = $9x10^{-7}$ in/sec					
SSRT Environment	**Time to Failure (hrs)**	**Maximum Load (lbs)**	**Notch Dia. (in)**	**Maximum Stress (psi)**	**Average Air to Environment Ratio**
Air	11.2	3139	0.1249	256199	----
Air	13.2	3237	0.1246	265471	----
Freely Corroding	14.9	3151	0.1249	257178	0.99
Freely Corroding	12.1	3268	0.1256	263763	1.03
-850 mV	14.1	3106	0.1248	253912	0.97
-850 mV	13.9	3207	0.1247	262589	1.01
-1000 mV	15.2	3118	0.1249	254485	0.98
-1000 mV	11.2	3150	0.1257	253834	0.99

TABLE 18 CREVICE CORROSION DATA* FOR ALLOY 725 AND ALLOY 625, EVALUATED IN QUIESCENT SEAWATER AT 30ºC (86ºF) FOR 30 DAYS USING ACRYLIC PLASTIC CREVICE DEVICES			
Alloy	**Observed Initiation (days)**	**Percent of Sites Attacked**	**Maximum Depth of Attack (mm)****
625	2 to 5	25 to 75	0.02 to 0.66
725	**None at 30 days**	**0**	**0.00**
* Acrylic plastic crevice torqued to 25 in-lbs, ** 25.4 mm/ 1 in.			

TABLE 19 CREVICE CORROSION RESULTS FOR ALLOY 725 AND ALLOY 625 MACHINED TUBES WITH VINYL SLEEVE CREVICES ON THE O.D., EVALUATED WITH FLOWING SEAWATER ON THE I.D. AT 24.5ºC (76ºF) FOR 148.5 DAYS		
Alloy	**Observed Initiation (days)**	**Max. Depth of Attack (mm)[c]**
625	26 to 40 (no attack of one specimen)	<0.01 to 0.78
725[a]	**0**	**0**
725[b]	**42 to 80 (no attack of one specimen)**	**<0.01 to 0.04**
(a) Solution annealed at 1900ºF (1038ºC)/ 1h/ water quenched (b) Solution annealed at 1900ºF (1038ºC)/ 1h/ water quenched and age-hardened at 1350ºF/ 8h, (732ºC) furnace cool to 1150ºF (620ºC)/8h/air cool (c) 25.4 mm/ 1 in.		

TABLE 20 CORROSION FATIGUE STRENGTH* IN SEAWATER AT 10^7 CYCLES				
Alloy	**Tensile Strength**		**Fatigue Strength**	
	Ksi	**MPa**	**ksi**	**MPa**
MP35N	303	2089	124.1	856
718	238	1641	130.0	896
AISI 4140	236	1624	42.5	293
PH 13-8Mo	219	1510	67.5	465
925	170	1172	72.5	500
725	180	1241	105.8	730
* Tension-Tension Test				

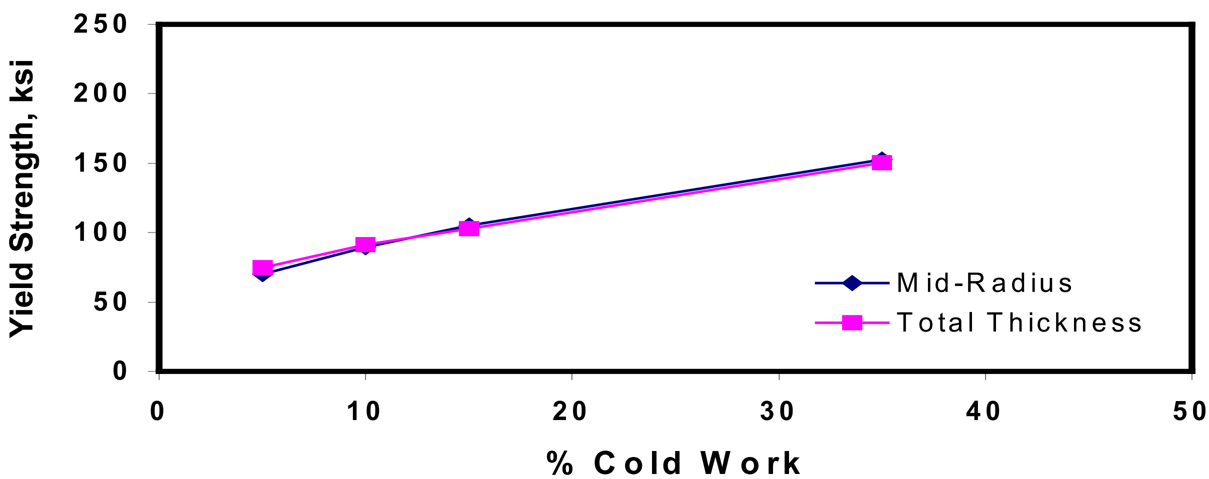

FIGURE 1 Effect of Cold Work on Yield Strength of Alloy 686 (UNS N08868)

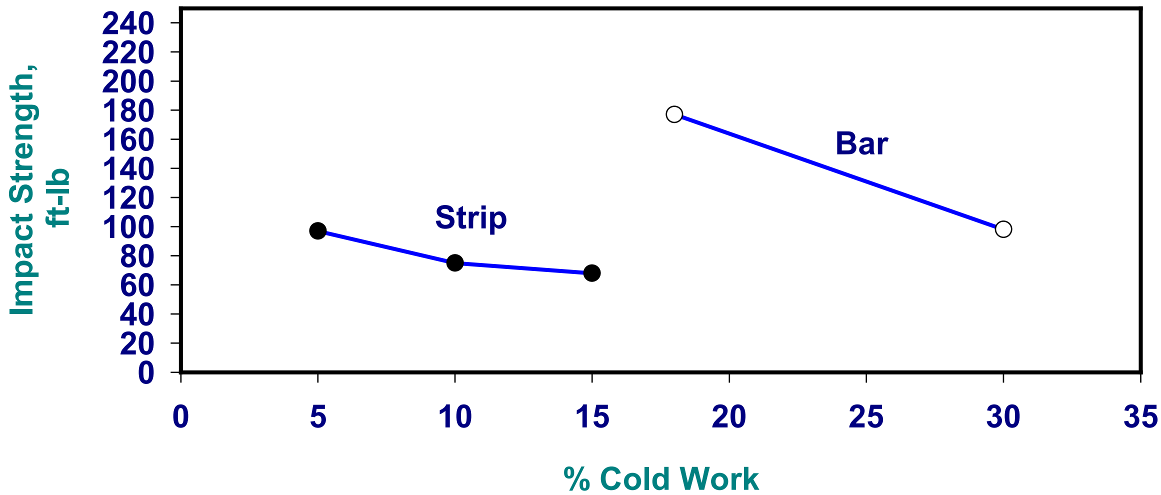

FIGURE 2 Effect of Cold Work on CVN Impact Strength of Alloy 686 (UNS N06686)

FIGURE 3 5/16 in. (14 mm) x 16 Nuts and Bolts, Before and After Testing per ASTM Standard Practice F606.

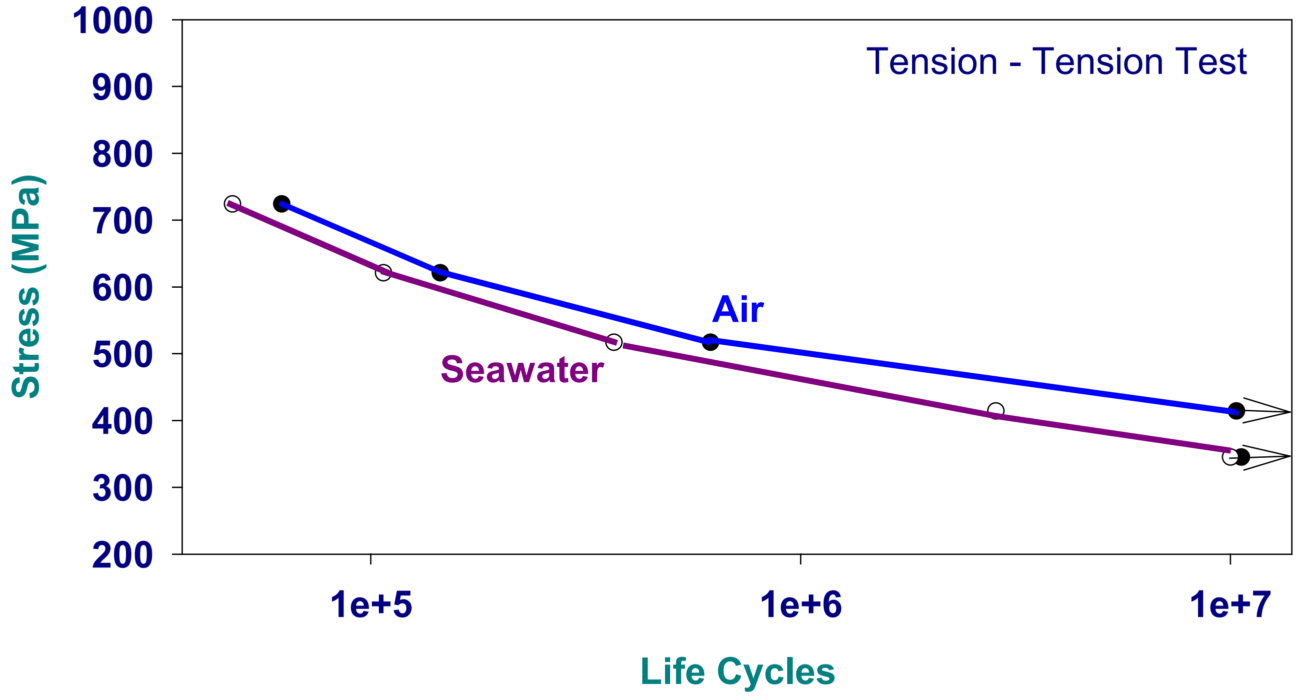

FIGURE 4 Fatigue Curves for Annealed Alloy 686

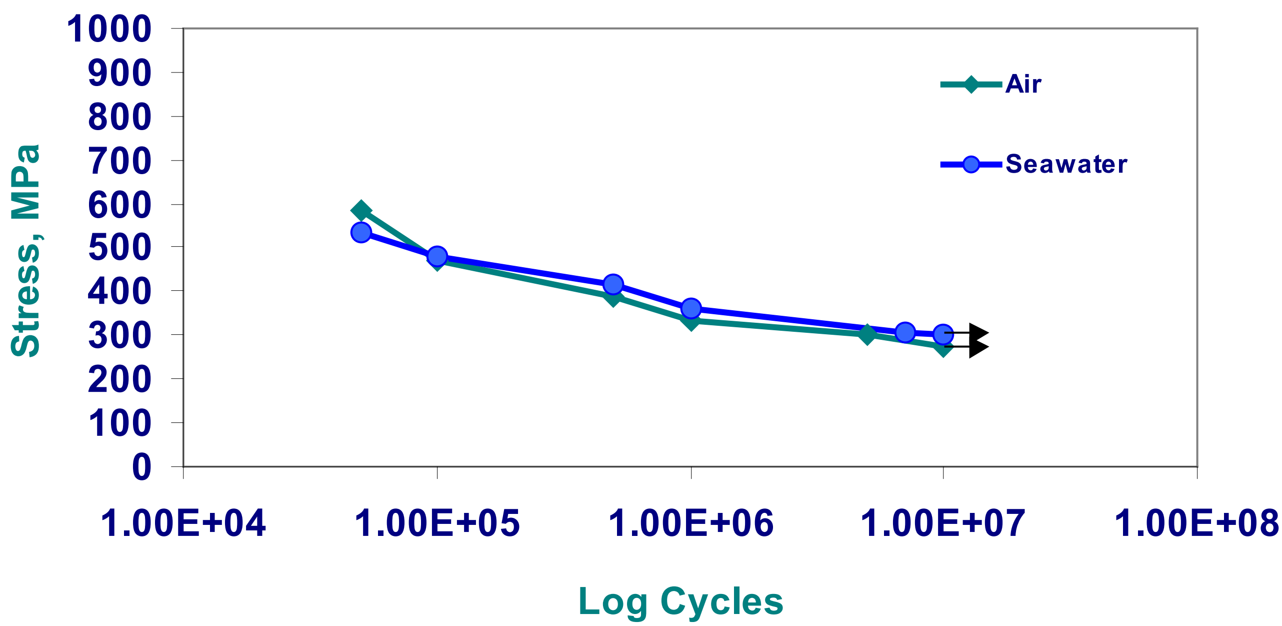

FIGURE 5 High Cycle Fatigue Data for Alloy 686
0.75 in. (19 mm) Bar with a 145 ksi Yield Strength

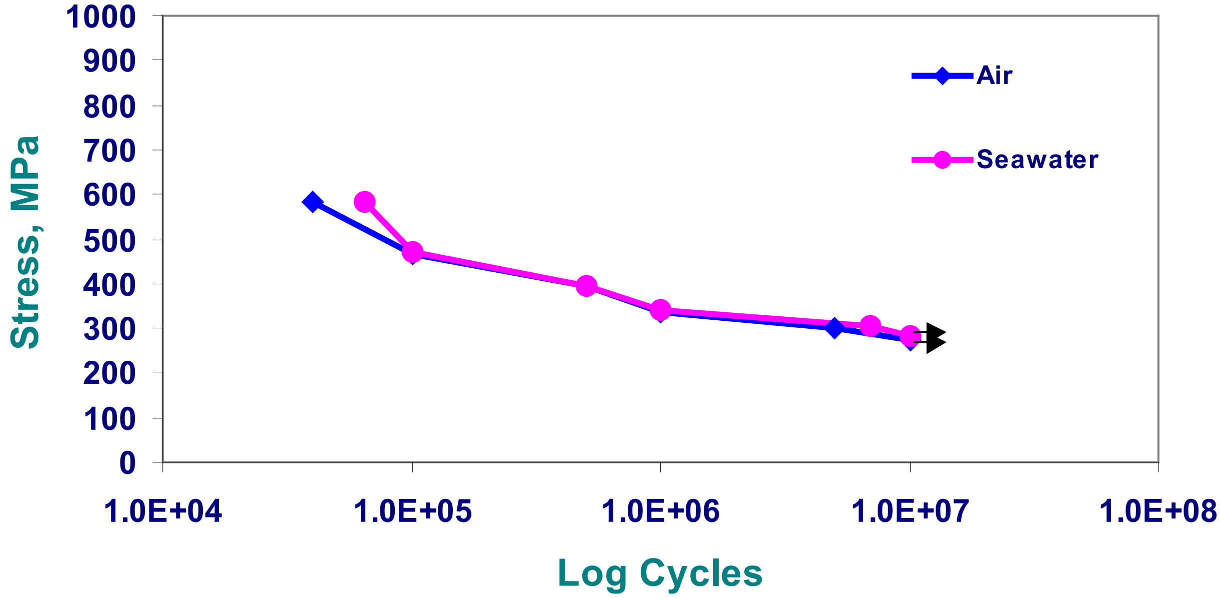

FIGURE 6 High Cycle Fatigue Data for Alloy 686 1.50 in. (38.1 mm) Bar with a 115 ksi Yield Strength

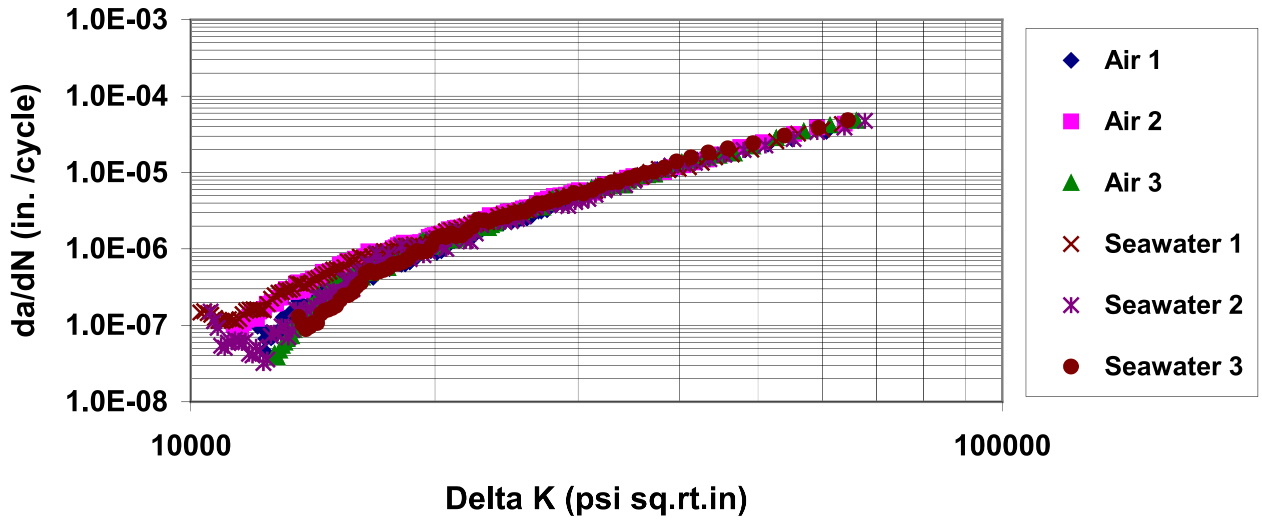

FIGURE 7 Fatigue Crack Growth Rate (da/dN) Data for Alloy 686