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High Strength Corrosion Resistant INCONEL Alloy 686 for Seawater Fastener Service

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ABSTRACT

The excellent corrosion resistance of nickel-alloys has been put to good use in marine engineering for many years. Some applications, such as fasteners, require high levels of strength as well as corrosion resistance. New high strength nickel-alloys and their weldments exhibit excellent resistance to hydrogen embrittlement and seawater corrosion. Solid solution nickel-based alloys such as INCONEL® alloy 686 (UNS N06686) obtain their strength through cold work. Cold worked alloy 686 exhibits excellent resistance to hydrogen embrittlement and corrosion, and exceptional strength, ductility and toughness.

INTRODUCTION

The U.S. Navy often uses corrosion resistant fasteners with corrosion sensitive materials such as steel, which requires cathodic protection. For example, MONEL® alloy K-500 (UNS N05500) fasteners are used with alloy steel in a seawater environment. The steel receives cathodic protection from sacrificial anodes. The protection is extended to the alloy K-500 fasteners. Failures of the alloy K-500 has occurred due to hydrogen embrittlement and galvanic corrosion problems and also due to corrosion resulting from galvanic interaction with more noble materials. The U.S. Navy currently has a need to replace alloy K-500 fasteners, which can suffer hydrogen embrittlement, with a high strength corrosion resistant alloy. INCONEL alloy 686 is a solid-solution nickel-based alloys, which exhibits high strength, toughness and superior corrosion resistance and, therefore, is an excellent candidate material to replace alloy K-500 as a fastener material in various marine applications.

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INCONEL alloy 686 is capable of being cold worked to high yield strengths, such as 100 to 150 ksi (700 - 1035 MPa). This paper presents recently developed seawater corrosion data, and physical and mechanical properties for cold worked alloy 686.

INCONEL alloy 686 was originally developed for Flue Gas Desulfurization (FGD) and chemical process applications. Applications have included use in chemical and food processing, salt plant evaporators, air pollution control systems, condenser tubing, and service water piping in the power industry.

DISCUSSION

Composition and Mechanical Properties

The limiting chemical composition for INCONEL alloy 686 is given 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.

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 3 and 4 display RTT and 0°F (-18°C) Charpy-V-Notch (CVN) Impact Test data for cold INCONEL alloy 686 0.75 in. and 1.50 in. (19 mm and 38 mm) diameter bar. The cold worked INCONEL 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 3 also displays RTT data for 0.875-in. (22.5 mm) thick cold worked alloy 686 plate.

Table 5 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}).

Tables 6 and 7 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.

The ½ in. x 13 bolts were manufactured from 1.5 in. (38 mm) diameter cold worked alloy 686 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 INCONEL alloy 686 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.

Tables 8 displays Room Temperature Threaded Fastener Tensile Data for ½ in. x 13 and $^{7}/16$ in. x 14 cold worked INCONEL alloy 686 hex head nuts made to ANSI B18.2.2 with Class 2B threads. Five specimens were tested per each nut size, per ASTM Standard Test Method F606 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 is performed by exposing samples to 6% ferric chloride solutions, ASTM Standard Test Method G48(3), 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). A ranking of alloys can be achieved as shown in Table 9.

The critical crevice temperature (CCT) test(4) is performed by exposing samples to the same aggressive ASTM test solution as above, but with a multiple crevice device (TFE-fluorocarbon washer) attached to the surface of the specimen. Test results are also shown in Table 9 where the temperatures recorded show the onset of crevice corrosion.

Corrosion Resistance to Seawater

Figure 3 displays the air and seawater fatigue curves for mill annealed INCONEL alloy 686 in ambient seawater. The alloy exhibited excellent seawater fatigue resistance in the tension-tension test.

Figures 4 and 5 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 INCONEL 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 a load ratio (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.

Figure 6 shows fatigue crack growth rate (da/dN) data for 0.875 in. (22.2 mm) thick cold rolled plated, which has 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 INCONEL alloy 686 when tested per ASTM Standard Test Method for Crack Growth Rates, E647. That is, the material again exhibited excellent cracking resistance.

Table 10 displays crevice corrosion data for both wrought plate and all-weld-metal (weldment) samples of alloys 686, 625 and/or C-276, evaluated in quiescent seawater at 25ºC (77ºF) for 60 days. The INCONEL alloy 686 plate and INCONEL alloy 686CPT weldment 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 11. 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.).

In galvanic compatibility tests performed in ambient temperature seawater for 180 days at LaQue Corrosion Services in Wrightsville Beach, NC, alloys 686 and 625 were determined to be galvanically compatible. As expected, coupling a large surface area of INCONEL alloy 686 to alloy 400 (UNS N04400) promoted corrosion of the alloy 400. Similar results were observed earlier when a large surface area of INCONEL 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. The results from these tests are shown in Tables 12 and 13, respectively. Of the alloys tested at 60°C (140°F), only INCONEL alloy 686 showed no evidence of crevice attack under these conditions. For alloys 686 and Ti grade 2 tested at 200°C (392°F), there was also no evidence of crevice attack under these conditions. As is well known, Ti grade 2 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

<u>NACE TM0177</u>. INCONEL alloy 686, is 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.

<u>Long Term Exposure Notched Tensile Tests</u>. For both the 114.8 ksi (792 MPa) and the 148.0 ksi (1,020 MPa) yield strength cold worked INCONEL 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 pull at a slow strain rate of $1\text{x}10^{-6}$ in/in/sec. Specimens of each strength level in the as-produced condition (no seawater exposure) were also pulled at $1\text{x } 10^{-6}$ in/in/sec, as a base line for comparison. Maximum stress ratios were calculated as follows:

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

The material exhibited excellent HE resistance. For both strength levels of the cold worked alloy 686 bar, the maximum stress ratios 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 ratios for all the specimens exposed without polarization for 5000 hours was 0.99 to 1.00, excellent TTF ratios. See Table 14.

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 9×10^{-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, excellent ratios. See Table 15.

Acknowledgement

The authors would like to acknowledge the significant contribution of William A. Edmonds, President of B&G Manufacturing in preparing the cold worked alloy 686 fasteners for testing and evaluation.

SUMMARY

High strength nickel-alloys such as INCONEL alloy 686 (UNS N06686) and alloy 686 weldments exhibit excellent resistance to hydrogen embrittlement and seawater corrosion. INCONEL alloy 686 is, therefore, an excellent candidate materials to replace MONEL alloy K-500 (UNS N05500) as a fastener material for various marine applications.

REFERENCES

1. Standard Test Method TM0177, "Laboratory Testing of Metals for Resistance to Sulfide Stress Cracking in H_2S Environments," NACE International, Houston, TX, USA, 1990.
2. Standard Materials Requirement MR0175, "Sulfide Stress Cracking Resistant Metallic Materials for Oilfield Equipment," NACE International, Houston, TX, USA, 1998.
3. ASTM Standard Test Method G48, Annual Book of ASTM Standards, vol. 03.02 (West Conshohocken, PA: ASTM, 1995).
4. E. L. Hibner, Materials Performance, vol. 26, no. 3, p. 37, March 1987.

TABLE 1

LIMITING CHEMICAL COMPOSITION (WT.%)

	Ni	Cr	Mo	Fe	Ti	W
Alloy 686 (UNS N06686)	Balance	19.0 – 23.0	15 - 17	1 max.	0.02 – 0.25	3.0 – 4.4

TABLE 2
ROOM TEMPERATURE TENSILE PROPERTIES
FOR COLD WORKED INCONEL ALLOY 686 (UNS N06686)

% Cold Work	Test Location	0.2% Yield Strength, ksi (MPa)*	Tensile Strength, ksi (MPa)*	% Elongation
5	Mid- Radius	67.8 (467)	117.3 (809)	56
	Total Thickness	72.8 (502)	116.0 (800)	56.5
10	Mid- Radius	99.5 (686)	131.7 (908)	41.5
	Total Thickness	90.6 (625)	123.7 (853)	48.8
15	Mid- Radius	103.8 (716)	134.3 (926)	38.5
	Total Thickness	98.5 (679)	126.0 (869)	44.3

TABLE 3
ROOM TEMPERATURE TENSILE PROPERTIES FOR COLD WORKED INCONEL ALLOY 686

Mill Form, Size	Room Temperature Tensile Properties				Hardness, HRC
	0.2% Yield Strength, ksi (MPa)	Tensile Strength, ksi (MPa)	% Reduction of Area	% Elongation	
0.875 in. * Plate	110.7 (763)	136.5 (941)	65.4	36.1	29
0.75 in. Bar	148.0 (1020)	161.7 (1115)	54.1	23.1	36
1.5 in. Bar	114.8 (792)	144.0 (993)	56.8	34.6	27

* in. x 25.4 = mm

TABLE 4
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)

* Material yield strength = 148.0 ksi (1020 MPa)
** Material yield strength = 114.8 ksi (792 MPa)

TABLE 5
FRACTURE TOUGHNESS DATA FOR COLD WORKED INCONEL ALLOY 686, TESTED AT 75°F (24°C) PER ASTM STANDARD TEST METHOD E992

Heat Number	Test Orientation	Fracture Toughness	
		ksi(in)$^{1/2}$	MPa(m)$^{1/2}$
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 6
ROOM TEMPERATURE THREADED FASTENER TENSILE TEST DATA FOR COLD WORKED INCONEL 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)

* Bolt produced from 1.5 in. (38mm) bar with standard RTT properties listed in Table 3.
**Bolt produced from 0.75 in. (19mm) bar with standard RTT properties listed in Table 3.
*** 5 specimens were tested per each bolt size, per ASTM Standard Test Method F606.
Note: lb x 0.4536 = kg

TABLE 7
ROOM TEMPERATURE 10º WEDGE TENSILE TEST DATA FOR THREADED BOLTS OF COLD WORKED INCONEL 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)

* Bolt produced from 1.5 in. (38mm) bar with standard RTT properties listed in Table 3.
**Bolt produced from 0.75 in. (19mm) bar with standard RTT properties listed in Table 3.
*** 5 specimens were tested of each bolt size, per ASTM Standard Test Method F606.
Note: lb x 0.4536 = kg

TABLE 8

ROOM TEMPERATURE THREADED FASTENER TENSILE TEST DATA FOR COLD WORKED INCONEL ALLOY 686 NUTS

	Proof Load, lb****	**Pass/Fail**
1/2 in. x 13 Nut*	19,471	Pass, all 5 test specimens
7/16 in. x 14 Nut**	16,669	Pass, all 5 test specimens

* Bolt produced from 1.5 in. (38mm) bar with standard RTT properties listed in Table 3.
**Bolt produced from 0.75 in. (19mm) bar with standard RTT properties listed in Table 3.
*** 5 specimens tested per each nut size, per ASTM Standard Test Method F606 Proof Load Test.
**** The Proof Load was the lowest recorded tensile load for the bolts.
Note: lb x 0.4536 = kg, in. x 25.4 = mm

TABLE 9

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

Alloy	**Critical Crevice Temperature**		**Critical Pitting Temperature**	
	°C	**°F**	**°C**	**°F**
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 10

CREVICE CORROSION DATA FOR BOTH WROUGHT AND WELDMENT SAMPLES OF ALLOYS 686, 625 AND C-276 EVALUATED IN QUIESCENT SEAWATER AT 25°C (77°F) 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)**	1/4	0.02 (0.001)
Weldments		
alloy 686CPT	**0/6**	**0.00 (0.000)**
alloy 625	1 /2	0.49 (0.019)

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

TABLE 11
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 12
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 13
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 14
SLOW STRAIN RATE TEST DATA FOR DUPLICATE NOTCHED TENSILE SAMPLES* EXPOSED TO NATURAL SEAWATER FOR 5000 HOURS, THE PULLED AT A STRAIN RATE = $1\text{x}10^{-6}$ 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 15
SLOW STRAIN RATE TEST DATA FOR DUPLICATE NOTCHED TENSILE SAMPLES, ENIRONMENT: AMBIENT ASTM D1141 SUBSTITUTE OCEAN WATER, DISPLACEMENT RATE = $9\text{x}10^{-7}$ 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

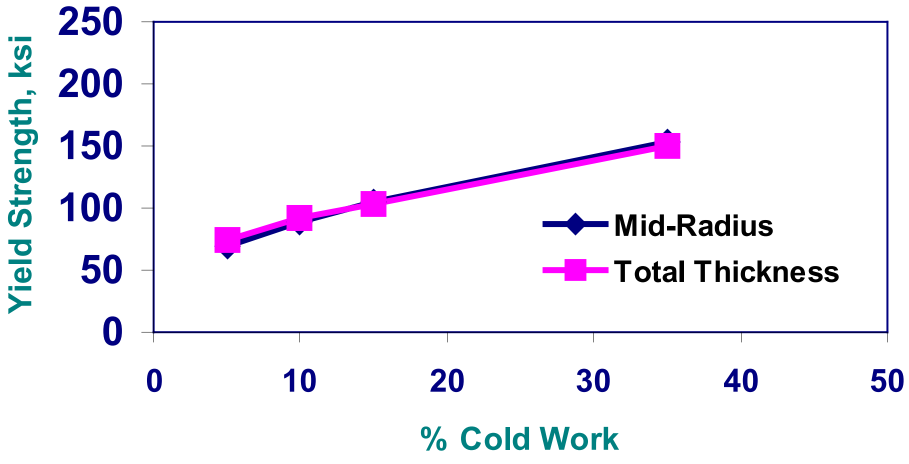

Figure 1 Effect of Cold Work on Yield Strength of Alloy 686 (UNS N06686)

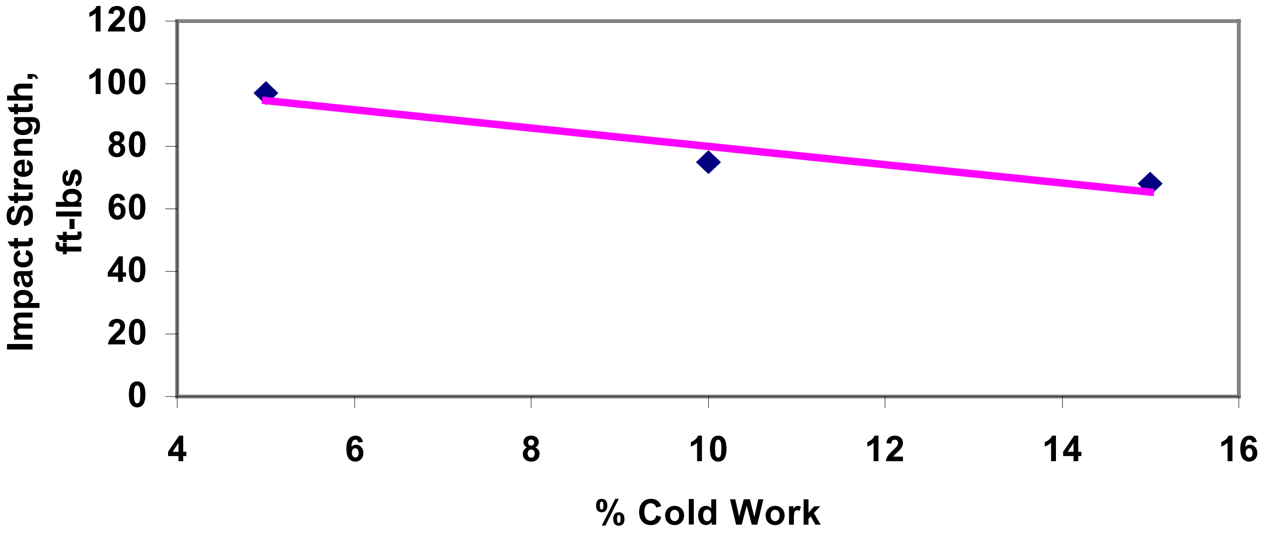

FIGURE 2 Effect of Cold Work on CVN Impact Strength of Alloy 686 (UNS N06686)

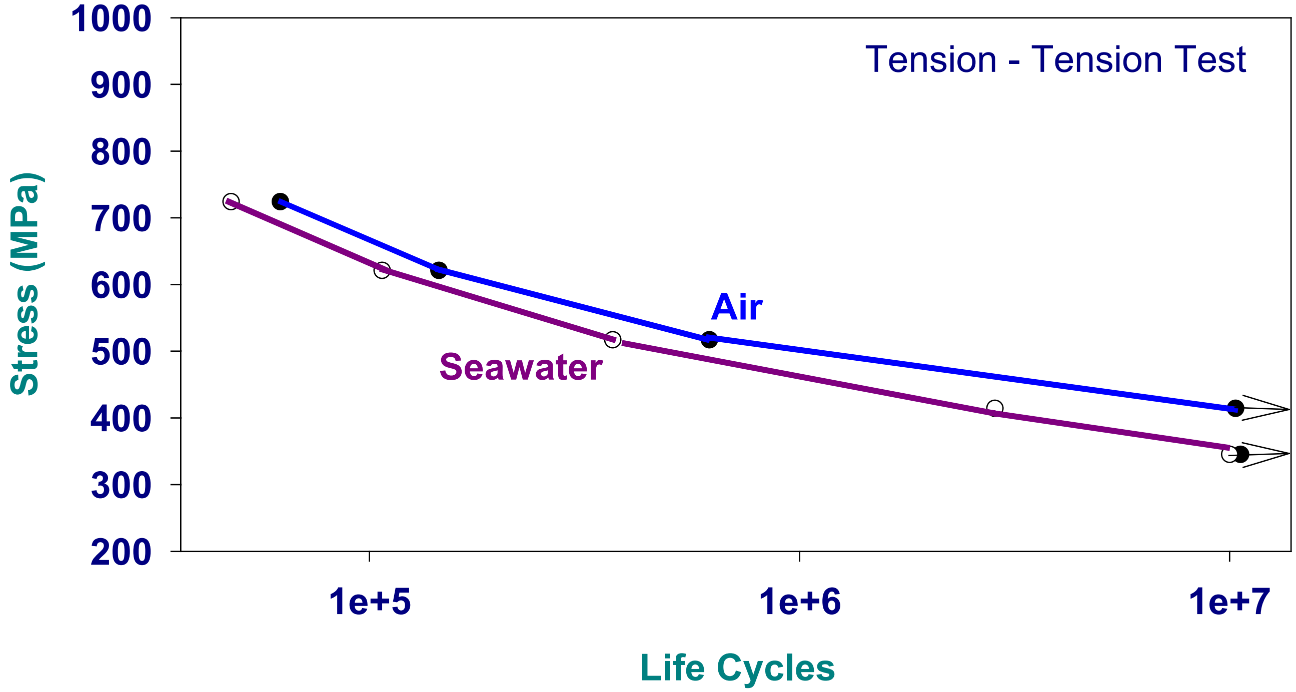

FIGURE 3 Fatigue Curves for Annealed Alloy 686

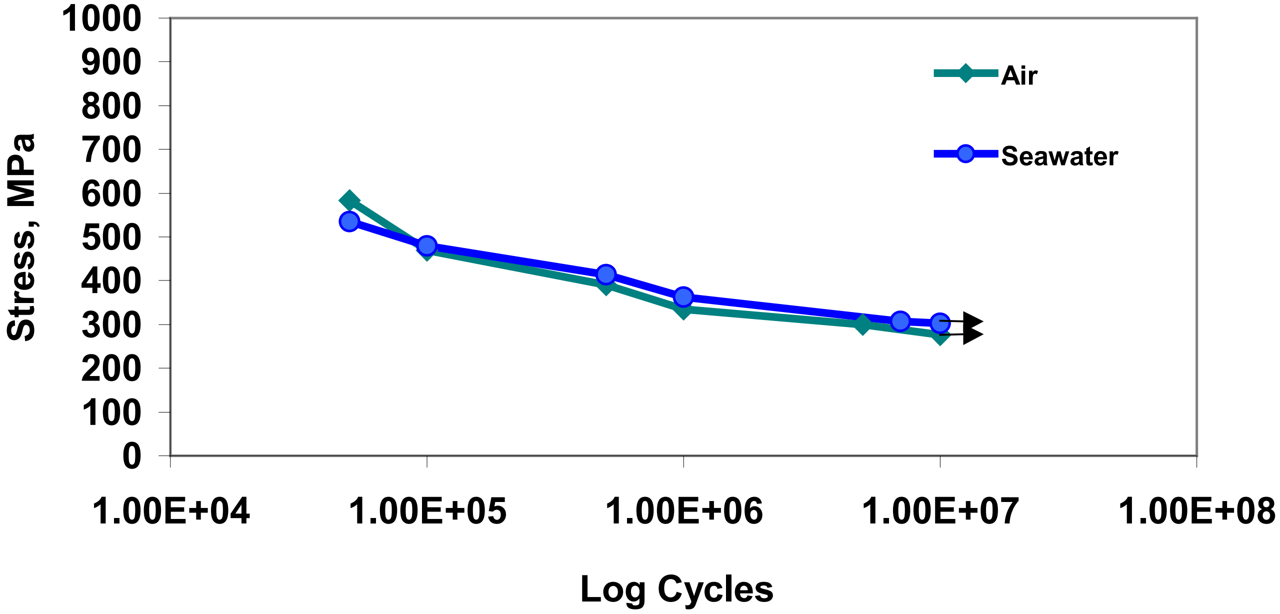

FIGURE 4 High Cycle Fatigue Data for Alloy 686
0.75 in. (19 mm) Bar with a 145 ksi Yield Strength

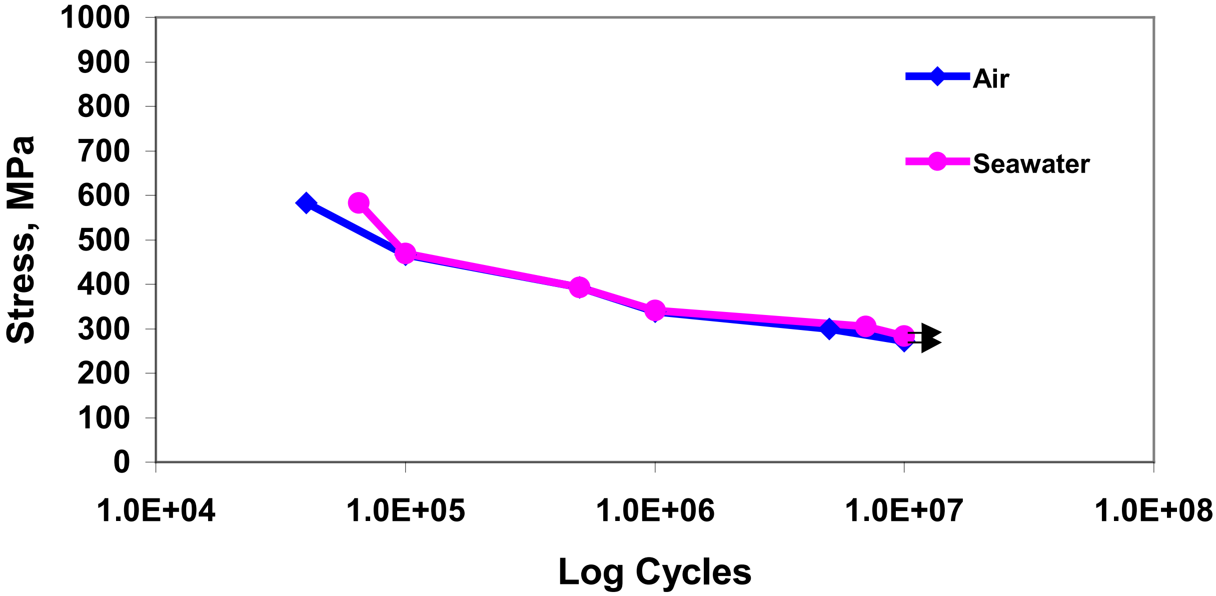

**FIGURE 5 High Cycle Fatigue Data for Alloy 686
1.50 in. (38.1 mm) Bar with a 115 ksi Yield Strength**

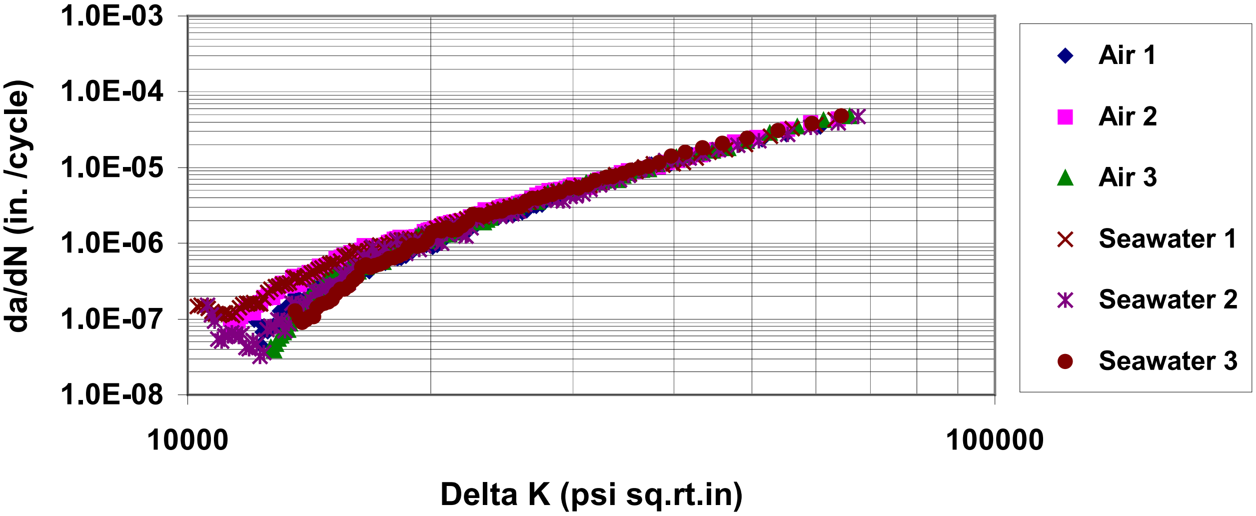

**FIGURE 6 Fatigue Crack Growth Rate
(da/dN) Data for Alloy 686**