



A High Strength, Corrosion-Resistant Alloy Solves Fastener Problems in the Marine Industry

by

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Introduction

Vessels and equipment built for service in seawater and other marine environments must employ fasteners that are resistant to corrosion by the aggressive service conditions to which they are exposed. Contractors and fabricators who build ships for the U.S. Navy must recognize this requirement, as a structure is no stronger or more reliable than its weakest member. Failure of a nut or bolt can have catastrophic results.

Because the fastener is generally much smaller than the components it is used to support, the fasteners generally must be more corrosion resistant to offset any effects of galvanic corrosion. Should the fastener be anodic to the remainder of the structure, the relative size effect could cause severe corrosion and degradation of the fastener in a short period of time. Thus, corrosion-resistant nickel-base fasteners have been extensively used in marine service. For example, MONEL® alloy K-500 (UNS N05500) fasteners are used with alloy steel in a seawater environment. However, the resulting galvanic coupling can induce hydrogen charging and subsequent embrittlement of the fasteners, and failures of the alloy K-500 have occurred. Consequently, more noble high strength bolting materials are needed.

INCONEL® alloy 686 (UNS N06686) is a high performance nickel-base alloy that exhibits high tensile strength and fracture toughness. It offers excellent resistance to corrosion in marine environments, superior even to alloy K-500, which has set the standard for marine performance for many years. In addition, the strength of alloy 686 can be further enhanced by cold work. Thus, bolts with yield strength levels up to 150 ksi (equivalent or superior to alloy K-500) can be produced. An extensive program has been conducted to qualify the alloy 686 fasteners for marine service on naval vessels and equipment.

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INCONEL alloy 686

INCONEL alloy 686 is a nickel base alloy enhanced by its content of chromium, molybdenum, and tungsten. The typical chemical composition of the alloy is reported in Table 1. The content of chromium gives the alloy resistance to oxidizing corrodents while molybdenum and tungsten allow it to resist reducing media and seawater. All these elements have the effect of solid solution strengthening the alloy. Alloy 686 is covered by ASTM, SAE, and AWS specifications and is approved for ASME and VdTÜV construction. It is approved under NACE MR0175 for service in severe sour gas environments.

Table 1 – Chemical Composition (%) of INCONEL alloy 686

Ni	Cr	Mo	W	Fe	C
58	21	16	4	1	0.006

Comparative Corrosion Resistance

By virtue of its high content of alloying elements, alloy 686 offers excellent resistance to corrosion by a variety of aggressive media. To demonstrate its resistance to various marine environments many types of corrosion tests were conducted.

A standard test for comparing the corrosion resistance of alloys is the ASTM G48 method. A temperature to induce pitting and crevice corrosion in acidified ferric chloride is determined. The critical pitting temperature (CPT) is determined by raising the temperature incrementally until the onset of corrosion. Alloys are then ranked by their relative values. The minimum accepted CPT for North Sea offshore applications is 40°C (104°F), while in pulp and paper bleaching environments, this temperature is typically 50°C (122°F). A ranking of alloys is shown in Table 2.

Corrosion Resistance in Seawater

Since most intended applications will expose the fasteners to seawater, alloy 686 was extensively tested in marine media. Figure 1 displays the air and seawater high cycle fatigue curves for cold worked alloy 686 bar in ambient seawater and, for comparison, in air. It is seen that the curves are essentially identical, indicating that the seawater has no effect on the performance of the alloy.

Crevice corrosion data for alloy 686 and similar alloys evaluated in quiescent seawater at 25°C (77°F) for 60 days are shown in Table 3. The alloy 686 plate and alloy 686 weldment samples were resistant to crevice corrosion, as was the alloy C-276 (UNS N10276) plate samples. While alloy 625 (UNS N06625) is widely used in marine construction, the samples corroded in this test demonstrating the superior performance of alloy 686.

Crevice corrosion tests were also performed in flowing seawater. Tube sections with vinyl sleeve crevices were exposed in flowing seawater at 14.4°C (58°F) for 180 days. 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.).

Since the fastener material is often dissimilar to the components being joined (which also may be dissimilar), a galvanic coupling often exists. This can induce galvanic corrosion. To evaluate the galvanic compatibility of alloy 686 with other corrosion resistant alloys, tests were performed in ambient temperature seawater for 180 days. Alloy 686 was determined to be galvanically compatible with alloys 625, 400, and K-500. It is noted that significant size differences can affect this compatibility.

Seawater is used on board vessels for various reasons. The water is chlorinated to avoid fouling. The addition of chlorine to the seawater increases its corrosivity. Crevice corrosion tests of a number of alloys were conducted in chlorinated seawater at 60°C (140°F) for 60 days and 200°C (392°F) for 90 days. Of the alloys tested at 60°C (140°F), only alloy 686 showed no evidence of crevice attack under these conditions. At 200°C (392°F), only alloys 686 and grade 2 titanium were free of attack

Hydrogen Embrittlement

As stated earlier, hydrogen embrittlement has been a problem with marine fasteners, especially when dissimilar material are coupled. Alloy 686 was shown to be resistant to hydrogen embrittlement in the NACE International TM0177 sulfide stress cracking test.

To further quantify the alloy's resistance to hydrogen embrittlement, notched specimens were exposed under stress in seawater for 5,000 hours and charged with hydrogen. The ratio of the strength of such specimens determined under slow strain conditions to that of unexposed specimens is an indication of the alloy's resistance to hydrogen. The ratios of the alloy 686 specimens were 0.96, indicating excellent resistance.

Mechanical Properties

Alloy 686 is a solid solution strengthened, single phase, austenitic alloy. While its strength at room temperature is high, it can be enhanced by cold work (Figure 2). Alloy 686 exhibits an excellent combination of strength, ductility, and toughness when either annealed or cold worked. The tensile properties of the alloy at room temperature are seen in Table 4. The yield strength and impact strength of cold worked alloy 686 bar are reported in Table 5. Alloy 686 bar cold worked to a yield strength of 148.0 ksi (1020 MPa) exhibited 54.1 % tensile elongation and an impact strength of 98 ft-lb (133 N-m) at 32°F (0°C). Materials worked to a yield strength of 114.8 ksi (792 MPa) exhibited 56.8 % tensile elongation and an impact strength of 177 ft-lb (240 N-m).

Fracture toughness was evaluated for alloy 686 plate cold rolled to yield strengths of 108 to 120 ksi (745 to 827 MPa) exhibited excellent fracture toughness values of 319 to 362 ksi(in.^½), 351 to 398 MPa(m^½), at 75°F (24°C) as determined by ASTM Standard Test Method E992, the equivalent energy methodology (K_{EE}).

Fastener Properties

Threaded fastener tensile and 10° wedge tensile values (ASTM F606) were determined for ½ in. x 13 (manufactured from 114.8 ksi yield strength / 144.0 ksi tensile strength stock), 7/16 in. x 14 (manufactured from 148.0 ksi yield strength / 161.7 ksi tensile strength stock), and 5/16 in. x 16 (manufactured from 95.3 ksi yield strength / 130.3 ksi tensile strength stock) hex head bolts made to ANSI B18.2.1 with Class 2A threads formed by chasing. Tensile data for the bolts tested are presented in Tables 6 and 7. As is seen, the properties of the bolts essentially match those of the starting stock.

The untested nut and bolt and a tested bolt are shown in Figure 3. It is seen that the fracture is ductile.

Fastener Specifications

Requirements for INCONEL alloy 686 fasteners are contained in the common specifications including ASTM F467, F467M, F468, and F468M and SAE J2271, J2280, J2295, and J2485. The ASTM fastener grade designations are:

Ni 686 Grade 1	F467BN	85-ksi min. yield strength
Ni 686 Grade 2	F467BN	125-ksi min. yield strength
Ni 686 Grade 3	F467BN	150-ksi min. yield strength

In addition, three strength grades of the alloy will be added to the next edition of MIL-DTL-1222.

Summary

INCONEL alloy 686 has been tested and qualified for manufacture of fasteners for service in aggressive marine environments. By cold working, fasteners with yield strength levels up to 150 ksi can be made. The resulting products exhibit excellent resistance to corrosion by seawater and hydrogen embrittlement. Alloy 686 fasteners are galvanically compatible with the common materials of marine construction. The high strength fasteners exhibit good ductility and fracture toughness. Thus, alloy 686 fasteners are expected to solve many of the problems encountered with existing grades of corrosion-resistant marine fasteners. Several companies have demonstrated their ability to manufacture alloy 686 fasteners and hardware, which means that the products should be readily available.

For more information on INCONEL alloy 686 the readers are invited to visit the Special Metals website, www.specialmetals.com or contact Lewis Shoemaker by telephone at (304) 526-5664 or by e-mail at Lshoemaker@specialmetals.com.

TABLE 2				
CRITICAL CREVICE AND CRITICAL PITTING TEMPERATURES IN AN ACIDIFIED 6% FERRIC CHLORIDE SOLUTION (ASTM G48 C & D)				
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
304SS	<0	<32	15	59

**TABLE 3
CREVICE CORROSION OF WROUGHT AND WELD SAMPLES OF ALLOYS 686, 625
& C-276 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 (SMC)	0/6	0.00 (0.000)
alloy C-276 (non-SMC)	1/2	0.02 (0.001)
Weldments		
alloy 686	0/6	0.00 (0.000)
alloy 625	1 / 2	0.49 (0.019)

**TABLE 4
ROOM TEMPERATURE TENSILE PROPERTIES
OF COLD WORKED ALLOY 686**

Cold Work (%)	Test Location	0.2% Yield Strength (ksi)	Tensile Strength (ksi)	Elongation (%)
0	Typical	52	105	52
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 5
CHARPY-V-NOTCH IMPACT STRENGTH OF
COLD WORKED ALLOY 686 BAR AT 0°F (-18°C)**

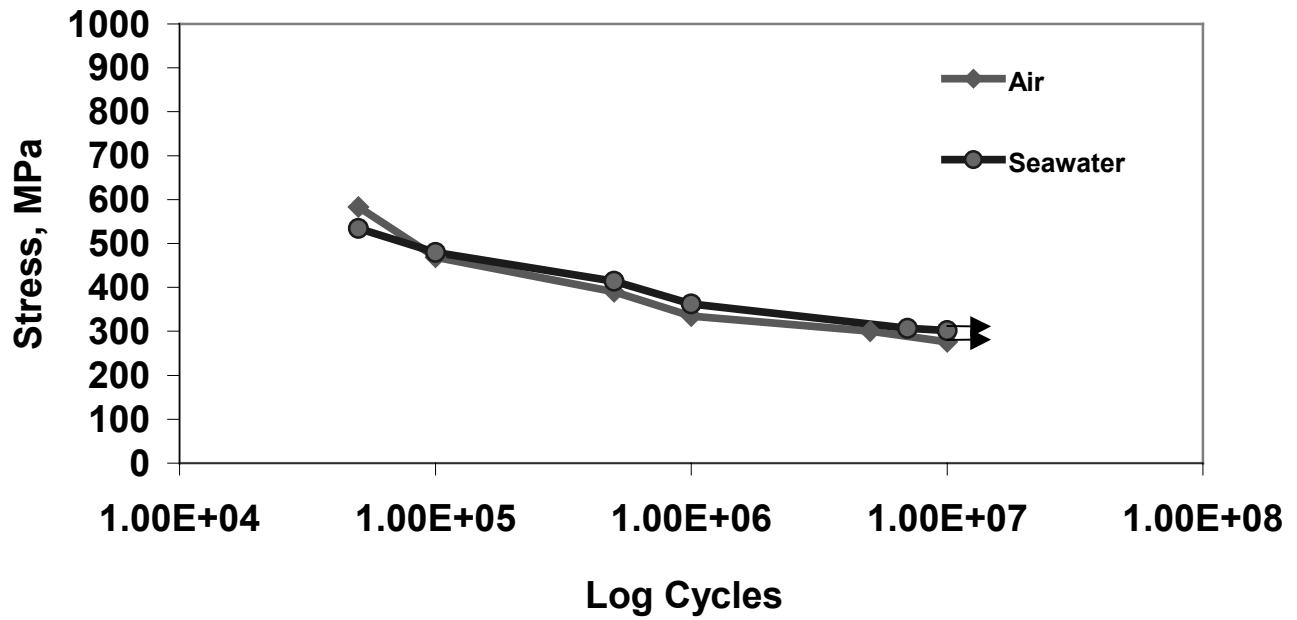
Yield Strength (ksi)	Impact Energy, ft-lb (N-m)	Lateral Expansion in. (mm)
148.0	98 (133)	0.046 (1.17)
114.8	177 (240)	0.068 (1.73)
95.3	178 (241)	0.058 (1.47)

TABLE 6
ROOM TEMPERATURE THREADED FASTENER TENSILE TEST DATA
FOR COLD WORKED ALLOY 686 BOLTS

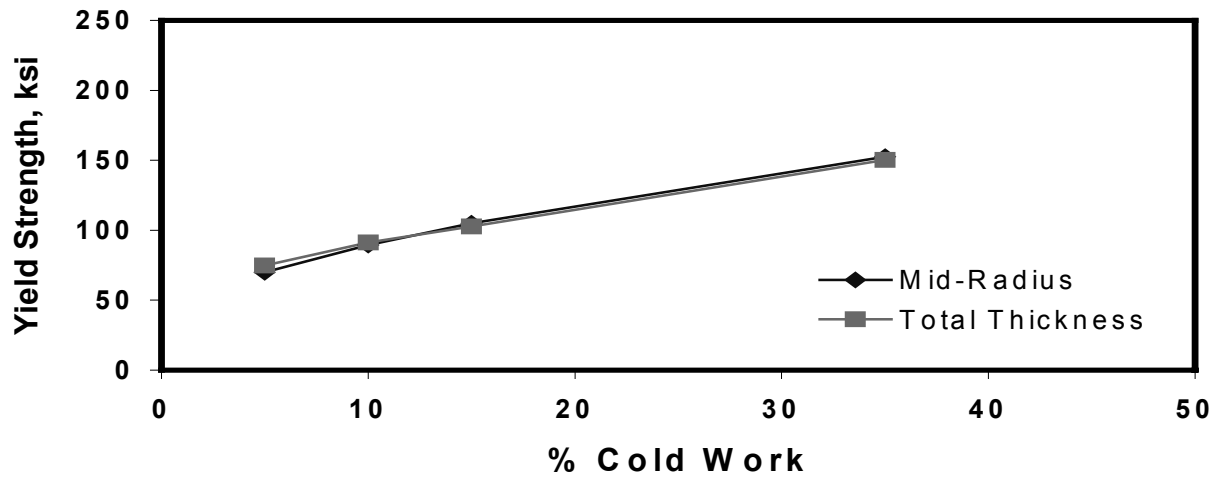
		Ultimate Tensile Load, lb	Ultimate Tensile Strength, ksi (MPa)	0.2% Yield Load, lb	0.2% Yield Strength, ksi (MPa)
1/2 in. x 13 Bolt	Average	19,660	138 (952)	16,741	118 (814)
	Minimum	19,471	137 (945)	16,569	117 (807)
	Maximum	19,749	139 (958)	16,877	119 (821)
7/16 in. x 14 Bolt	Average	16,761	158 (1089)	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)

TABLE 7
ROOM TEMPERATURE 10° 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)



**FIGURE 1 High Cycle Fatigue Data for Alloy 686
0.75 in. (19 mm) Bar Cold Worked to 145 ksi Yield Strength**



**FIGURE 2 Effect of Cold Work on Yield Strength
of Alloy 686 (UNS N06686)**



FIGURE 3 – INCONEL alloy 686 5/16 in. X 16 Bolts and Nut. The fracture surface of the bolt broken during tensile testing exhibits ductile fracture .