INCONEL alloy 686

The Alloy Solution to Fastener Problems in the Marine Industry

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 fasteners are generally much smaller than the components they attach or support, they should be more corrosion resistant to offset any effects of galvanic corrosion. If the fastener is anodic to the remainder of the structure, the relative size effect can cause severe corrosion and its rapid degradation. For this reason, highly resistant nickel-base fasteners are extensively used in marine service. MONEL® alloy K-500 (UNS N05500) fasteners are used with alloy steel in a seawater service. The alloy steel structures often require cathodic protection. The alloy to steel galvanic coupling and the effects of the cathodic protection can induce hydrogen charging and subsequent embrittlement of the fasteners. Indeed, hydrogen-induced failures of alloy K-500 components have occurred. Consequently, more resistant, 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. While alloy 686 is strong in the annealed condition, its strength can be further enhanced by cold work. Thus, bolts with yield strength levels up to 150 ksi (strength equivalent or superior to alloy K-500) can be produced. An extensive program has been conducted to qualify alloy 686 fasteners for marine service on naval vessels and equipment.

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INCONEL alloy 686

INCONEL alloy 686 (UNS N06686 / Werkstoff Nr.2.4606) is a single phase, austenitic nickel-chromium-molybdenum-tungsten alloy with very limited levels of iron and carbon. It offers outstanding corrosion-resistance in a wide range of severe environments. Its high contents of nickel, molybdenum, and tungsten provide resistance to reducing conditions while its content of chromium imparts resistance to oxidizing media. The alloy's high content of nickel and limited content of iron result in excellent resistance to stress corrosion cracking. Molybdenum and tungsten help the alloy resist localized attack modes such as pitting and crevice corrosion. All these elements have the effect of solid solution strengthening the alloy. Iron is closely controlled to maintain properties. A very low carbon content helps minimize grain boundary precipitation and, thus, maintain corrosion resistance of welded components.

The typical chemical composition of the alloy is reported in Table 1.

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

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

Resistance of an alloy to general, pitting, and crevice corrosion is normally a function of the alloying content of a nickel alloy. The relative corrosion resistance of alloys can be estimated by sum of the alloying elements). It is seen in table 2 that the alloy content of alloy 686 is the highest of the corrosion-resistant alloys. The relative corrosion resistance of alloys can also be estimated by comparing their Pitting Resistance Equivalency Numbers (PREN). Again in Table 2 it is seen that alloy 686 exhibits the highest PREN values of the corrosion-resistant alloys.

Table 2 – Alloy Content and PREN Values of Corrosion-Resistant Alloys

Alloy	**Ni**	**Cr**	**Mo**	**W**	**Nb**	**Alloy Content ***	**PREN ****
N06625	62	22	9	-	4	35	57.7
N10276	58	16	16	3	-	35	73.3
N06022	58	22	14	3	-	39	72.7
N06059	60	23	16	-	-	39	75.8
N06200	58	23	16	-	-	39	75.8
N06686	58	21	16	4	-	41	79.8

* Alloy Content = %Cr + %Mo + %W + %Nb

** PREN = % Cr + 3.3 (%Mo) + 1.5 (%W + %Nb)

INCONEL 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.

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 have been performed.

A standard test for comparing the corrosion resistance of alloys is ASTM G48, Methods C & D. A temperature to induce pitting and crevice corrosion in acidified ferric chloride is determined. Samples for determine the critical pitting temperature (CPT) do not utilize a crevice device while those for determining critical crevice temperature use a PTFE crevice device. Th critical temperatures to induce corrosion are determined by raising the test temperature incrementally until the onset of corrosion is observed. 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 3.

TABLE 3

CRITICAL CREVICE AND CRITICAL PITTING TEMPERATURES IN AN ACIDIFIED 6% FERRIC CHLORIDE SOLUTION (ASTM G48, METHODS C & D)

	Critical Crevice Temperature		Critical Pitting Temperature	
Alloy	°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

Corrosion Resistance in Seawater

Since most marine applications of interest will expose the fasteners to seawater, INCONEL alloy 686 was extensively tested in marine media.

Crevice corrosion data for alloy 686 and similar alloys evaluated in quiescent seawater at 25ºC (77ºF) 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 14.4ºC (58ºF) 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.). Results are reported in Table 4.

TABLE 4
CREVICE CORROSION RESULTS FOR ALLOYS 686 AND C-276 AND ALLOY 625 MACHINED TUBES WITH VINYL SLEEVE CREVICES ON THE SURFACE EVALUATED WITH FLOWING SEAWATER INSIDE 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.

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

Galvanic Corrosion

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.

Hydrogen Embrittlement

As stated earlier, hydrogen embrittlement has been a problem with marine fasteners, especially when dissimilar materials 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.

Effects of Fatigue on Marine Corrosion Resistance

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.

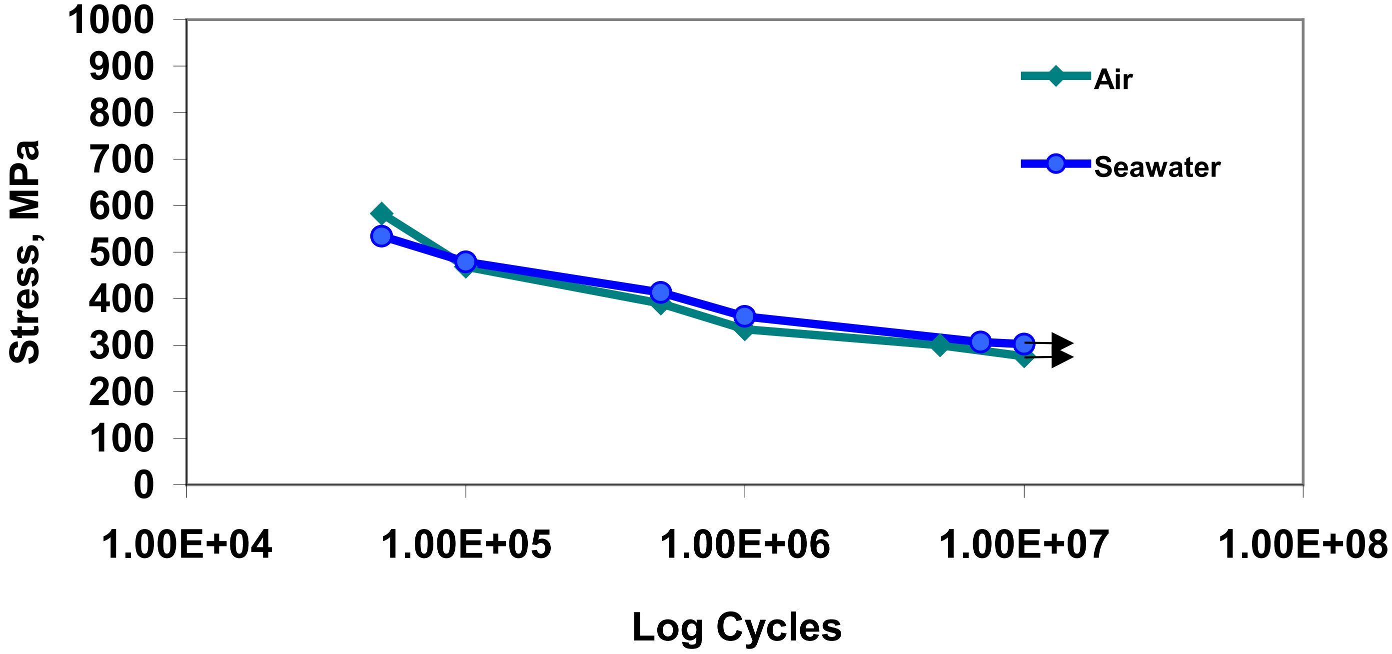

FIGURE 1   High Cycle Fatigue Strength of 145 ksi Yield Strength Bar

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).

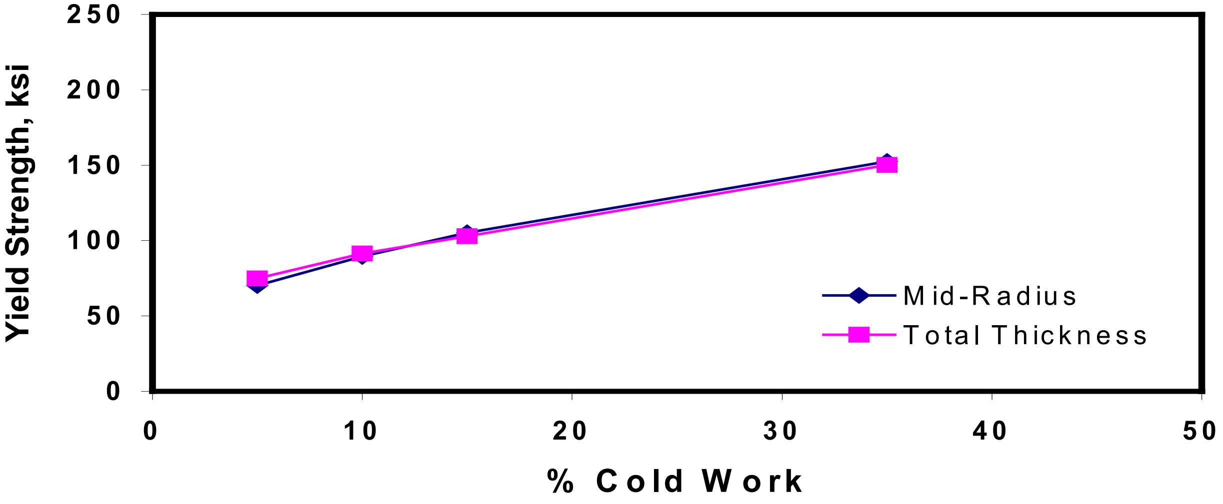

FIGURE 2   Effect of Cold Work on Yield Strength

INCONEL 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.

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.

INCONEL alloy 686 cold worked bar exhibits excellent ductility and impact strength (Table 6). 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).

TABLE 6
CHARPY V-NOTCH IMPACT STRENGTH AT 0°F (-18°C)
COLD WORKED INCONEL 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.

INCONEL alloy 686 plate cold rolled to yield strength levels of 108 to 120 ksi (745 to 827 MPa) exhibited excellent fracture toughness values (Table 7) of 319 to 362 ksi-in.$^{1/2}$ (351 to 398 Mpa-m$^{1/2}$).

TABLE 7
FRACTURE TOUGHNESS (K_{EE}) 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)$^{1/2}$	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)

Fastener Properties

Threaded fastener tensile and 10º 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 8 and 9. As is seen, the properties of the bolts essentially match those of the starting stock.

TABLE 8
ROOM TEMPERATURE 10º WEDGE TENSILE PROPERTIES
COLD WORKED INCONEL ALLOY 686 THREADED BOLTS

		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 9
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)

Protoypical cold worked INCONEL alloy 686 bolts and nuts are shown in Figure 3. The fracture surface of the tested bolt indicates a ductile mode of fracture.

FIGURE 3 5/16 in. (14 mm) x 16 Nut and Bolts
Tested per ASTM Standard Practice F606.

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, J2484 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, the same three strength grades of alloy 686 fasteners are in MIL-DTL-1222, Rev. K, the current government military fastener procurement specification.

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.

INCONEL alloy 686 Availability

INCONEL alloy 686 products are stocked and distributed exclusively in North America by Corrosion Materials, Inc. from operations in Baker, LA and Houston, TX. Products and services from Corrosion Materials are available on the website, www.corrosionmaterials.com. Or, inquirers may contact Ruben Muro at (800) 455-2276 or by e-mail at Rmuro@corrosionmaterials.com.

Need More Information ???

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

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, 2002.

3. E. L. Hibner and R. H. Moeller, "Corrosion-Resistant Alloys UNS N09925 and UNS N07725 for Oilfield Applications," 25th Annual Offshore Technology Conference, 3-6 May 1993, Houston, TX, paper no. 7206.

4. ASTM Standard Test Method E992, Annual Book of ASTM Standards, vol. 06.01 (West Conshohocken, PA: ASTM, 1997).

5. ASTM Standard Test Method F606, Annual Book of ASTM Standards, vol. 01.08 (West Conshohocken, PA: ASTM, 1998).

6. ASTM Standard Test Method G48, Annual Book of ASTM Standards, vol. 03.02 (West Conshohocken, PA: ASTM, 2000).

7. S. A. McCoy and E. L. Hibner, “Developments in High Strength- Age Hardened Corrosion Resistant Nickel Alloys for Sour Service Conditions” EUROCORR 2001, (Riva del Garda, Italy, 2001).

8. E. L. Hibner, Materials Performance, vol. 26, no. 3, p. 37, March 1987.

9. ASTM Standard Test Method E992, Annual Book of ASTM Standards, vol. 06.01 (West Conshohocken, PA: ASTM, 1997).

10. ASTM Standard Test Method E647, Annual Book of ASTM Standards, vol. 03.01 (West Conshohocken, PA: ASTM, 2000).

11. R. M. Kain, Project 111B48 Laboratory Reports of April24, 1995 1n3 April 4, 1996, LaQue Center for Corrosion Technology, Inc., Wrightsville Beach, NC.

12. F. J. Martin, et.al., "Flouroelastomeric Gasket Peculiarities Influence the Seawater Crevice Corrosion Susceptibility of Ni-Cr-Mo Alloys," CORROSION/2004, paper no. 04309, (Houston, TX: NACE, 2004).