# ALLOYS FOR MARINE FASTENERS

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## ABSTRACT

Nickel-containing alloys are identified as candidate materials for fasteners used in seawater or sea atmospheres. The alloys are super high-strength Cu-Ni, stainless steel, and nickel-base alloys. The marine corrosion of the alloys is briefly reviewed. Galvanic and crevice corrosion are critical conditions to consider when selecting fastener alloys. Guidelines are presented to assist designers in the selection of the nickel-containing alloys for marine fastener applications.

Keywords: marine, corrosion, fasteners, copper, nickel, stainless steel, aluminum, steel, alloys, galvanic, atmospheric, immersion, crevice corrosion, stress corrosion, hydrogen embrittlement, guidelines

## INTRODUCTION

In a previous paper, the marine corrosion resistance of copper, iron, nickel, aluminum, and titanium-base alloy fasteners were reviewed.' Various forms of corrosion and several failure mechanisms affecting fasteners performance in marine applications were discussed. Galvanic compatibility was identified as the most critical consideration for marine fasteners. The authors offered guidelines to assist designers in the selection of appropriate materials for marine fasteners.

This paper is an update of the previous work. The information on marine corrosion of fastener systems is based upon a literature search and personal experience of the author. Its purpose is to provide useful guidelines on the selection of marine corrosion-resistant fasteners and to introduce nickel-containing alloys which offer improved marine corrosion resistance and higher strength.

Satisfactory service performance of fasteners can be achieved in the marine environment if proper materials are chosen initially. The goal of this paper is to help prevent fastener failures with the application of cost-effective, safe, and reliable materials.

## NICKEL-CONTAINING MARINE FASTENER ALLOYS

Nickel-containing alloys for marine fastener applications are identified in Tables 1-6. Two super high strength precipitation hardening copper-nickel alloys are available.[2] They contain about 18% nickel and 5% manganese and are strengthened by additions of aluminum, chromium, iron, and niobium (Table 1). Both alloys have excellent resistance to seawater similar to 90%Cu-10°/oNi. Table 2 shows two duplex and a 6% molybdenum stainless steel alloys. These alloys offer higher strength, better resistance to chloride stress corrosion cracking, and improved crevice corrosion in seawater compared to type 316 stainless steel.

The nickel-base alloys containing about 9-16% molybdenum are extremely resistant to seawater (Table 3). They can be cold-worked to give good mechanical properties. These alloys are used where corrosion is not acceptable.

The precipitation hardening nickel-base alloys are given in Table 4[3,4,5]. They are strengthened by additions of aluminum, titanium, niobium, and cobalt. High strength is derived through cold work and aging treatments. These alloys are also extremely resistant to seawater because of their high levels of molybdenum and chromium. Alloy 925, however, must be used with cathodic protection because its seawater resistance is not much better than type 316 stainless steel; i.e., both alloys' Mo content is about the same.

An important requirement for fastener materials is strength. The two Cu-Ni alloys shown in Table 5 offer outstanding strength for copper-base alloys. The other nickel-containing alloys listed offer good strength levels. The alloys shown in Table 5 can be strengthened by cold work. This may provide higher strength levels needed for many fastener requirements versus the annealed condition, and designers should be aware of this material property for these alloys.

The precipitation hardening nickel-base alloys are excellent candidate alloys for very high strength fasteners (Table 6). Yield strength of 120-138 Ksi (825-952 MPa) can be obtained with these nickel-base alloys. MP35N is also given. It is not a common alloy, and may be new to many designers who are not aware of its properties. MP35N properties are similar to titanium alloys; i.e., immune to seawater corrosion, provides very high strength, and shows excellent fatigue resistance. Alloy 925 is included because of its high strength; however, its seawater corrosion resistance is not much better than type 316 stainless steel. Alloy 925 should be protected by a cathodic protection system if immersed in seawater. Above water, it should be resistant to corrosion, if the alloy is not continually wetted.

When stainless steel and nickel-base alloy fasteners are submerged (partial or fully) in seawater environments, crevice corrosion resistance is the primary limiting property. Crevice corrosion varies with alloy composition, metallurgical condition, and severity of the crevice. Many of the more highly alloyed stainless steels and nickel-base alloys, particularly those containing higher levels of chromium, molybdenum, and nitrogen, have excellent resistance to crevice corrosion in seawater (Table 7).[6,7]

A common indicator frequently used to rate crevice corrosion resistance of stainless steels in seawater is the pitting resistance equivalent (PRE) number. It is based on the composition of the alloy. The PRE number is a good indication of the relative resistance of Fe-Cr-Ni-Mo and Ni-Cr-Mo alloys to crevice corrosion in marine applications. These alloys should have a PRE number >40 to be considered for seawater applications, although alloys with <40 have worked. Nickel-base alloys with a PRE >60 are considered immune to crevice corrosion in seawater.

## GUIDELINES FOR MARINE FASTENER SELECTION

The marine corrosion resistance of the various metals used in fastener systems is well documented in the literature'. This information and the author's experience is the basis for the marine fastener guidelines presented in Tables 8-11. A brief discussion of the guideline tables will provide information needed to help engineers select the appropriate fastener material for a particular seawater environment, whether the fastener is installed in other metals, wood, plastic, or other non-metallics.

**Below The Waterline**

Tables 8 and 9 offer guidelines for the use of the nickel-containing alloy fasteners below the waterline. Some of the common materials to be fastened or bolted are other metals, such as steel, aluminum, copper, stainless steels, and Ni-Cr-Mo alloys (Table 8); and various non-metallics (Table 9). The three ratings used for the fastened or bolted system are:

(1) G = Generally OK or satisfactory.

(2) **?** = may be satisfactory, more information needed and/or limited information available. Suggest caution.

(3) ∅ = Avoid. The combination of materials should be avoided due to known galvanic problems, crevice corrosion susceptibility, or poor corrosion resistance of the fastener.

Fasteners exposed below the waterline, such as bolts in the keel and bilge areas, are an integral part of the safety considerations of all boats and ships at sea. For steel hulls, all of the fasteners listed in Table 8 are cathodic to steel. Thus, these fastener combinations receive a **G** rating to indicate the system is satisfactory. Generally, the fastener material should always be cathodic to the metals to be attached. This is the reason alloy 925 receives a satisfactory rating because it is not susceptible to crevice corrosion when coupled to large surface areas of steel (cathodic protection from a steel anode).

It is important to remember in this analysis that we are assuming the fastener is the smaller area in relation to the larger anode area which is being fastened. Also, if a metal has paint or other coating applied, the galvanic area relationship may change to an unfavorable ratio and cause corrosion or crevice attack of the fastener.

Very few fasteners can be used successfully with aluminum when immersed in seawater. The reason is that the bolt or fastener hole tends to enlarge from galvanic corrosion. Aluminum and stainless steel alloy fasteners that are noble to the aluminum base plate are preferred, if it is possible to add a sealant (insulates and keeps the bolt hole watertight) between the alloy fasteners and aluminum. However, this countermeasure to prevent fastener hole corrosion of aluminum may be short term, and should not be used for critical applications. Copper-containing fasteners should be avoided when joining aluminum as indicated in Table 8. The use of a sealant is the reason that the stainless steel and nickel alloy fasteners receive a **?** rating. It may or may not work, and success depends upon the application.

Because of potentially poor galvanic relationships, copper-base alloys and stainless steels should be avoided (or carefully evaluated before use) when joining copper, stainless steel, or Ni-Cr-Mo alloys. Pitting or crevice corrosion may be a problem with these fastener joints. The higher alloyed Ni-Cr-Mo alloys can be used in all of the base plates, except as described above with aluminum.

The non-metallic base plate materials present another challenge to the fastener materials. Under the waterline, a fastener used in wood, concrete, plastic, or rubber will not receive any benefit of cathodic protection; i.e., when a fastener is attached to a more anodic metal. The non-metallic material usually produces a severe (tight) crevice condition. Therefore, the fastener's performance depends mostly on the seawater crevice corrosion resistance of the alloy used.

Table 9 presents the guidelines for alloy fastener selection in non-metallic base materials below the waterline. The "avoid" or "caution" ratings for fasteners exposed in graphite warns against the use of any graphite-containing lubricant, packing, or gasket in contact with these materials. Similarly, the use of rubber containing >10% graphite should be avoided or carefully evaluated. The carbon (graphite) galvanic couple with most metals in seawater greatly accelerates corrosion of the less noble metal. This galvanic combination may be harmful to the corrosion-resistant nickel-base alloys, such as alloys 625, 725, C-276, 59, 686, and MP35N. This is the reason the Ni-Cr-Mo alloys were given a precautionary rating. Note that considerable caution is advised when using any fastener alloy in graphite composites due to lack of reported experience with this system.

As expected, all of the highly corrosion-resistant alloys perform well in most of the other non-metallic base materials. Because wood produces tight crevices and can sometimes contain acidic preservative chemicals, alloy 925 fasteners should be avoided. Alloy 925 is also limited in use in plastic and rubber below the waterline due to poor crevice corrosion resistance (3% Mo content is too low).

Some small boat manufacturers have reported good performance for type 316 stainless steel bolting in fiberglass-reinforced plastic (FRP) hulls. The bolts were used below the waterline. They were packed with a water repellant lubricant and recessed in the FRP. The use of graphite-free, water repellant lubricants that fill the bolt hole is also very good practice for less corrosion-resistant stainless steel and nickel-base alloys above the waterline. The lubricants may improve performance below the waterline, but should be used with discretion and not as an alternative to fastener alloys that do not rely on lubricant protection for good performance.

The improved rating for alloy 925 in concrete is based upon the fact that the alkalinity of the concrete has been found to protect type 316 stainless steel partially embedded in concrete for several inches beyond the concrete surface.

All of the high strength alloys may be subject to embrittlement from hydrogen generated by coupling with sacrificial anodes or in structures protected with impressed current. Caution and careful materials evaluation are required before using any of the alloys for fasteners under these conditions.

**Above The Waterline**

Fasteners are generally not subjected to as critical conditions above the waterline with respect to vessel, platform, or structure safety. Consequently, there is much greater use of coated carbon steel fasteners. However, the thin coatings do not provide long term corrosion protection, especially when fasteners are exposed at or near the mean high tide of the seawater. Continual maintenance of the fastener system appears to be more acceptable above the waterline since it is more accessible and may not be as critical service conditions.

Similar to the below waterline guidelines, fasteners can be used successfully in all of the metal base plates, except aluminum (Table 10). There is still concern for galvanic and crevice corrosion of the fastener alloys, but to a lesser degree than full-immersion. This is especially true where care is taken to pack bolt holes with a water repellant, graphite free lubricant, or other sealant. This protection method has been used quite successfully with stainless steel fasteners in aluminum hulls.

Copper-base, stainless steel, and nickel-base alloys are often specified for fasteners above the waterline. Even type 304 stainless steel is used. The free-machining grades, type 303 and the 400 series stainless steels should be avoided since rapid corrosion is possible in marine environments.

Again, caution is advised in the application of metallic fasteners in graphite composites even above the waterline (Table 11). All of the alloy fasteners should perform well in the various non-metallic base materials, but performance is dependant upon how close the system is to the seawater environment and how long the fastener is wetted. For example, type 304 stainless steel (no molybdenum) bolting has survived over 20 years in a wood jetty just above the tidal zone. However, severe crevice corrosion caused failures of the stainless steel bolting in the tidal zone after less than 6 months of exposure. Nickel-base alloy 400 (70%Ni-30%Cu) bolting has provided indefinite (>50 years) service in wooden structures and steel piling in marine splash and spray environments.

## SUMMARY

1. In the marine environment, the corrosion behavior of the fastener system is critical to the long term performance, integrity, and safety of the total system.

2. Galvanic considerations tend to control the corrosion behavior when fasteners are of a different composition than the alloy being fastened.

3. The fastener should be selected so that it will be galvanically protected by the fastened material or base plate. There are two major exceptions to this principal:

   (a) In aluminum structures, enlargement of the fastener hole by galvanic corrosion with stainless steel has led to failures even though the stainless steel fastener used was galvanically protected. (The same problem is expected for nickel-base alloy fasteners.)

(b) Copper alloys will not entirely suppress crevice corrosion of stainless steel and nickel-base alloy fasteners (if the alloy is susceptible to crevice corrosion in seawater) even though these alloys are the more noble material.

4. When the fastener is the same composition as the material being fastened and/or when fastening non-metallic materials, the fastener should be selected from materials that are fully resistant to seawater or sea atmospheric corrosion.

5. Nickel-containing alloys can provide the properties required to give long service life for marine fastener applications.

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## UNS NUMBERING SYSTEM CROSS-REFERENCE

| Alloy | UNS Number |
|---|---|
| 2507 | S32750 |
| 255 | S32550 |
| 6% Mo | S31254, N08026, N08031, N08367, N08926, N08932 |
| 625 | N06625 |
| C-276 | N10276 |
| 59 | N06059 |
| 686 | N06686 |
| 925 | N09925 |
| 725 | N07725 |
| 625+ | N07716 |
| MP35N | R30035 |

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## Table 1
## Precipitation Hardening Copper-base Fastener Alloys Composition, °/a by Wt.

| Alloy | Cu | Ni | Mn | Other |
|---|---|---|---|---|
| Cu-Ni + | Bal | 18 | 5 | Al,Cr,Fe,Nb |
| Cu-Ni 130 | Bal | 14.5 | 0.3 | 3% Al,Fe |

## Table 2
## Stainless Steel Fastener Alloys Composition, % by Wt.

| Alloy | Fe | Cr | Mo | Other |
|---|---|---|---|---|
| 2507 | Bal | 25 | 4 | 7%Ni,N |
| 255 | Bal | 25 | 3.5 | 6%Ni,Cu,N |
| 6%Mo | Bal | 20 | 6 | 25%Ni,Cu,N |

## Table 3
## Nickel-base Fastener Alloys Composition, % by Wt.

| Alloy | Ni | Cr | Mo | Other |
|---|---|---|---|---|
| 625 | Bal | 22 | 9 | Fe,Nb |
| C-276 | Ba l | 16 | 16 | Fe,W |
| 59 | Bal | 23 | 16 | Fe |
| 686 | Bal | 21 | 16 | Fe,W |

## Table 4
## Precipitation Hardening Nickel-base Fastener Alloys Composition, % by Wt.

| Alloy | Ni | Cr | Mo | Other |
|---|---|---|---|---|
| 925 | Bal | 21 | 3 | 32%Fe,Cu,Nb,Ti,Al |
| 725 | Bal | 21 | 8 | 8%Fe,Nb,Ti, Al |
| 625 + | Bal | 21 | 8 | 7%Fe,Nb,Ti, Al |
| MP35N | 35 | 20 | 10 | 35% Co |

## Table 5
## Mechanical Properties Fastener Alloys

| Alloy | TS Ksi | TS MPa | YS Ksi | YS MPa |
|---|---|---|---|---|
| Cu-Ni + | 126 | 870 | 101 | 700 |
| 255 | 125 | 860 | 105 | 725 |
| 6%Mo | 100 | 690 | 48 | 331 |
| 625 | 140 | 965 | 70 | 479 |
| C-276 | 110 | 761 | 52 | 359 |
| 59 | 100 | 690 | 45 | 310 |
| 686 | 117 | 810 | 52 | 359 |

## Table 6
## Mechanical Properties Precipitation Hardening Nickel-base Fastener Alloys

| Alloy | TS Ksi | TS MPa | YS Ksi | YS MPa |
|---|---|---|---|---|
| MP35N | 286 | 1970 | 255 | 1757 |
| 725 | 180 | 1240 | 130 | 896 |
| 625 + | 184 | 1269 | 138 | 952 |
| 925 | 170 | 1172 | 120 | 825 |

## Table 7
## Crevice Corrosion of Fastener Alloys

| Alloy | % Mo | PRE | Days | Max. Attack, Mils (mm) |
|---|---|---|---|---|
| 316 | 2 | 25 | 60 | 85 (2.17) |
| 2507 | 3 | 42 | 60 | 5 (0.13) |
| 255 | 3 | 44 | 90 | 3.5 (0.09) |
| 6% Mo | 6 | 49 | 90 | 0 - 7.5 (0.19) |
| 625 | 9 | 52 | 30 | 0 - 26 (0.66) |
| 725 | 9 | 52 | 30 | 0 |
| C-276 | 16 | 69 | 60 | 0 |
| 59 | 16 | 76 | 60 | 0 |
| 686 | 16 | 76 | 60 | 0 |

## Table 8
## Fastener Selection - Below Water

| | <-Material To Be Fastened-> | | | | |
|---|---|---|---|---|---|
| **Fastener** | **Steel** | **Al** | **Cu** | **SS** | **Ni-Cr-Mo** |
| Cu-Ni + | G | ∅ | ? | ∅ | ∅ |
| 255 | G | ? | ? | G | ? |
| 6%Mo | G | ? | ? | G | ? |
| 925 | G | ? | ∅ | G | ∅ |
| 625,725 | G | ? | G | G | G |
| C-276 | G | ? | G | G | G |
| 59, 686 | G | ? | G | G | G |
| MP35N | G | ? | G | G | G |

**G = Generally OK. ? =May be satisfactory, more information needed and/or limited information available. Suggest caution. ∅ =Avoid.**

## Table 9
## Fastener Selection - Below Water

| | <-Material To Be Fastened-> | | | | |
|---|---|---|---|---|---|
| Fastener | Graphite Composite | Wood | Concrete | FRP | Rubber |
| Cu-Ni + | ∅ | G | G | G | G |
| 255 | ∅ | G | G | G | G |
| 6%Mo | ? | G | G | G | G |
| 925 | ∅ | ∅ | ? | ∅ | ∅ |
| 625,725 | ? | G | G | G | G |
| C-276 | ? | G | G | G | G |
| 59, 686 | ? | G | G | G | G |
| MP35N | ? | G | G | G | G |

G = Generally OK. ? = Maybe satisfactory, more information needed and/or limited information available. Suggest caution. ∅ = Avoid.

## Table 10
## Fastener Selection - Above Water

| | <-Material To Be Fastened-> | | | | |
|---|---|---|---|---|---|
| Fastener | Steel | Al | Cu | SS | Ni-Cr-Mo |
| Cu-Ni + | G | ∅ | G | ? | ? |
| 255 | G | ? | G | G | G |
| 6%Mo | G | ? | G | G | G |
| 925 | G | ? | G | G | G |
| 625,725 | G | ? | G | G | G |
| C-276 | G | ? | G | G | G |
| 59, 686 | G | ? | G | G | G |
| MP35N | G | ? | G | G | G |

G = Generally OK. ? = Maybe satisfactory, more information needed and/or limited information available. Suggest caution. ∅ =Avoid.

# Table 11
# Fastener Selection – Above Water

| | <-Material To Be Fastened-> | | | | |
|---|---|---|---|---|---|
| Fastener | Graphite Composite | Wood | Concrete | FRP | Rubber |
| Cu-Ni + | ? | G | G | G | G |
| 255 | ? | G | G | G | G |
| 6%Mo | ? | G | G | G | G |
| 925 | ? | G | G | G | G |
| 625,725 | ? | G | G | G | G |
| C-276 | G | G | G | G | G |
| 59, 686 | G | G | G | G | G |
| MP35N | G | G | G | G | G |

G = Generally OK. ? =May be satisfactory, more information needed and/or limited information available. Suggest caution.