Materials Selection for Bolting

API TECHNICAL REPORT 21TR1
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Introduction

Fasteners are manufactured to a variety of standards covering dimensions, tolerances, materials, mechanical properties, testing procedures, coating, and other manufacturing processes. This document is intended to provide guidance for the proper selection of materials and manufacturing processes for the oil and gas industry where materials selection and key manufacturing processes are critical barriers to the failure of fasteners. Understanding the failure modes and their associated barriers is critical to the proper selection of fasteners for the specific environmental conditions where they will be installed.

Bolting and bolts are terms used in this document to collectively describe fasteners, including screws, nuts, bolts, washers, and studs. The use of the terms bolt or bolting includes all of the fasteners listed above, unless otherwise specifically noted herein.
1 Scope

This document provides guidance for the selection of materials and manufacturing processes for low alloy steel bolting manufactured in accordance with API Spec 20E and nickel-based and stainless alloys manufactured in accordance with API Spec 20F. Table 2 and Table 3 are provided as guidance for material selection of fasteners.

2 Normative References

The are no referenced documents that are indispensable for the application of this document.

3 Terms, Definitions, Acronyms, Abbreviations and Symbols

3.1 Terms and Definitions

3.1.1 ageing
A thermal cycle which usually follows solution annealing in precipitation hardening materials.

NOTE Aging can be performed at different temperatures and times to strengthen precipitation hardening materials such as some stainless steel grades and nickel based alloys.

3.1.2 annealing
A thermal cycle involving heating to, and holding at a suitable temperature, and then cooling at a suitable rate, for such purposes as reducing hardness, improving machinability, facilitating cold working, producing a desired microstructure, or obtaining desired mechanical or other properties.

3.1.3 banding
The microstructural manifestation of segregated alloy elements.

3.1.4 bolt
A type of fastener with a head on one end of a shank or body and a thread on the other end designed for insertion through holes in assembly parts; it is mated with a tapped nut (see figure 1).

NOTE Tension is normally induced in the bolt to compress the assembly by rotating the nut. This may also be done by rotation of the bolt head.

3.1.5 case hardening
One or more processes of hardening steel in which the outer portion, or case, is made substantially harder than the inner portion, or core. Most of the processes involve either enriching the surface layer with carbon, nitrogen or boron, usually followed by quenching and tempering, or the selective hardening of the surface layer by means of flame or induction hardening.

3.1.6 cold working
When material is shaped or worked below its recrystallization temperature.
3.1.7 cooling rates
The time it takes the steel to solidify from the molten state to solid state.

3.1.8 corrosion
(rust)
Temperature plus the presence of water on the steel surfaces (aqueous phase) and oxygen to drive the reaction producing iron oxide (Fe₂O₃ or Fe₃O₄).

3.1.9 creep
The continued extension of a material subjected to a constant stress and temperatures above 500°F (260°C) for extended periods of time.

3.1.10 dies
Tool used in manufacturing to shape by cutting or pressing the raw material.

3.1.11 fatigue
Progressive cracking or crack growth that occurs at some existing defect in the metal, at a point of high stress such as a notch, and grows in length over time with subsequent loading and unloading.

3.1.12 galling
Severe form of adhesion wear that results in the transfer of metal from one part to the mating part.

3.1.13 hardness
The resistance of a material to plastic deformation.

3.1.14 hot working
When material is shaped or worked after the material has been heated up past its recrystallization temperature.

3.1.15 hydrogen embrittlement
HE
A permanent loss of ductility in a metal caused by hydrogen with or without stress.

3.1.16 immersion zone
The area continuously in contact with seawater.

3.1.17 marine atmosphere
Located above the water level and above tidal and wave action.

3.1.18 marine fouling
Accumulation of micro and macro organisms on immersed surfaces, which can lead to economic, environmental or safety related effects.¹

¹ Journal of Ocean Technology vol 9 #4-2014
3.1.19
mud zone
The area in contact with the bottom sediments in the ocean.

3.1.20
normalizing
A thermal cycle involving heating to and holding at a solutionizing temperature; and then cooling in air to produce material with improved machinability, strength, and toughness.

NOTE This process is often used in combination with quench and temper.

3.1.21
proof load
The point to which a material may be loaded without evidence of permanent deformation.

3.1.22
quench and temper
A process commonly associated with steels which strengthens by martensitic transformation.

NOTE The process consists of heating the material to its solutionizing temperature and holding, followed by rapid cooling (commonly in water, polymer, or oil media). When martensitic structure is obtained, the material is very strong, but extremely brittle. The tempering process reduces stresses and changes the microstructure to tempered Martensite, which gives a very desirable combination of high strength and toughness.

3.1.23
reduction ratio
The change in cross section of material from its initial size to its rolled size.

3.1.24
screw
A headed and threaded bolt used without a nut inserted into an internally tapped hole and tension is induced by rotation of the screw head (see figure 1).

3.1.25
shear
The transverse rupture caused by a pushing or pulling force 90 degrees from the axis of the bolt.

3.1.26
solution annealing
A process of heating the metal to a temperature which allows for alloying elements to be in solution (solutionizing temperature).

NOTE This process is generally followed by controlled cooling; for alloys, which have tendency to form intermetallic phases, it is common to quench after solution annealing to prevent or minimize their formation.

3.1.27
splash zone
The area above seawater level wetted by waves.

3.1.28
stress concentration
Local irregularity of the surface characterized as a notch.

3.1.29
stress relaxation
The decrease of stress with time in a material that has been strained to a constant amount.
3.1.30  
**stress relieving**  
A thermal cycle involving heating to a suitable temperature, usually below the tempering temperature,  
holding long enough to reduce residual stresses from either cold deformation or thermal treatment,  
and then cooling slowly enough to minimize the development of new residual stresses.

3.1.31  
**stud**  
A fastener with no head and is threaded at both ends with an unthreaded shank in between (double-end  
or tap-end), or is threaded from end to end (continuous or full-thread), and is secured into a tapped hole  
and the other end is used with a nut to create tension (see figure 1).

3.1.32  
**stud bolt**  
A fastener with both ends secured with a nut (double-end and continuous studs) (see figure 1).

3.1.33  
**tensile strength**  
The maximum tensile stress in pounds per square inch (psi) which a material is capable of sustaining.

3.1.34  
**torque**  
The twisting load applied to the bolt.

3.1.35  
**yield strength**  
The stress at which a material exhibits a specified deviation from the proportionality of stress to strain.

NOTE The deviation is expressed in terms of strain, and in the offset method, usually a strain of 0.2 percent is  
specified.

![Figure 1 – Types of Fasteners (Brahimi, 2018)](image)
3.2 Acronyms, Abbreviations and Symbols

Cermet Ceramic-metal  
CP  Cathodic Protection  
CRA  Corrosion-resistant Alloy  
CSCC  Chloride Stress Corrosion Cracking  
EAC  Environmentally Assisted Cracking  
EMS  Electromagnetic Stirring  
HIC  Hydrogen Induced Cracking  
HPHT  High Pressure, High Temperature  
HRC  Rockwell C Hardness  
HSC  Hydrogen Stress Cracking  
PH  Precipitation Hardening  
PREN  Pitting-Resistance Equivalent Number  
SCC  Stress Corrosion Cracking  
SSC  Sulfide Stress Cracking  
w t  weight

4 General Design Information

4.1 General  
During the bolting selection process one should consider: 
 a) applicable design codes;  
b) design load case;  
c) environment; and  
d) material selection.

4.2 Applicability  
This document may be useful for material selection in applications such as the ones described in the documents listed in Table 1.

<table>
<thead>
<tr>
<th>Standard</th>
<th>Title</th>
</tr>
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<tbody>
<tr>
<td>API 6A</td>
<td>Specification for Wellhead and Christmas Tree Equipment</td>
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<tr>
<td>API 6D</td>
<td>Specification for Pipeline and Piping Valves</td>
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<td>API 16A</td>
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<td>Specification for Control Systems for Drilling Well Control Equipment and Control Systems for Diverter Equipment</td>
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<td>Recommended Practice for Design, Selection, Operation and Maintenance of Marine Drilling Riser Systems</td>
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<td>API 17D</td>
<td>Design and Operation of Subsea Production Systems-Subsea Wellhead and Tree Equipment</td>
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<tr>
<td>API 17TR8</td>
<td>High-pressure High-temperature Design Guidelines</td>
</tr>
<tr>
<td>API 6DSS</td>
<td>Specification for Subsea Pipeline Valves</td>
</tr>
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Table 1 – Applicable API Standards
4.3 Risk Assessment

4.3.1 General
The risk associated with the use of bolting in the oil and gas industry depends largely on the functional categories and environments in which the bolting is intended to be utilized.

4.3.2 Functional Categories

Some examples of functional categories are:

- Pressure-containing - Part exposed to wellbore fluids whose failure to function as intended would result in a release of wellbore fluid to the environment.
- Pressure-retaining - Part not exposed to wellbore fluids whose failure to function as intended will result in a release of wellbore fluid to the environment.
- Pressure-controlling - Parts intended to control or regulate the movement of wellbore fluids.
- Fatigue sensitive - Susceptible to fatigue loads.
- Structural – primary and non-primary load path.

Bolting generally fall into the pressure-retaining category; however, they also may be classified as fatigue sensitive, primary load path, closure bolting and external loading from environment (vortex induced vibration).

Specifications may have different functional categories. These functional categories should be considered in assessing criticality of components. Based on this assessment, fasteners can be assigned Bolting Specification Levels in accordance with API 20E or API 20F specifications.

In addition to the functional categories, service environments can compound the criticality of fastener components. The two primary service environments in the oil and gas industry are surface and subsea.

Subsea environments can be categorized further into more specific environments which encompass different hazards and risks.

4.3.3 Environmental Considerations

4.3.3.1 General
The environment in which the bolting operates can have a profound effect on the performance of the selected bolting.

4.3.3.2 Offshore environments
The following are examples of offshore environments:

a) Marine Atmosphere
Corrosion is a function of the amount of salt or seawater mist that collects on the metal’s surface in a marine atmosphere. Corrosion may be particularly severe in crevices or low spots where mist or run-off can collect. The concentration of salts in these areas may be much higher than in seawater due to evaporation. Oxygen is readily available to accelerate corrosion. Rainfall may increase or reduce the rate of corrosion depending on circumstances. Heavy rainfall may reduce corrosive attack by rinsing off salt residues on metal surfaces. Rainfall may also accelerate corrosion by providing the moisture necessary for salts on the metal’s surface to stay in an aqueous solution.
b) Splash Zone
For low alloy steels, the splash zone is the most corrosive. The seawater is well oxygenated. The impingement of the waves may mechanically remove corrosion products from the steel's surface thereby exposing fresh metal to further attack and erosion. Metals such as stainless steels and nickel-based alloys that rely on a thin chromium oxide surface layer for their corrosion resistance fare much better in the splash zone than low alloy steels because the well aerated seawater immediately supplies oxygen to repair any damage done to the oxide film. There is little or no marine fouling in the splash zone.

c) Tidal Zone
Steel corrosion is often relatively low in the tidal zone because of the formation of oxygen concentration cells. Metal surfaces in the tidal zone are exposed to well-aerated seawater while adjacent metal surfaces that are submerged are exposed to less oxygen (especially if covered with marine growth). This establishes an oxygen concentration cell with the submerged metal being anodic to the metal in the tidal zone. The submerged metal just below the tidal zone will corrode, but in doing so suppresses corrosion of the metal in the tidal zone (the cathode of the cell). Small, isolated panels of steel in the tidal zone are rapidly attacked by the highly oxygenated seawater. Marine fouling may be present in the tidal zone.

d) Immersion Zone
The rate of corrosion in the immersion zone is primarily dependent on the rate at which oxygen can diffuse through rust, other surface deposits, marine growth, etc., to reach and react with the metal's surface. Water near the surface of the ocean is usually saturated with oxygen. The oxygen content at other depths varies by region. In the Pacific Ocean, the oxygen content at great depths is much lower than at the surface, while in the Atlantic Ocean there is little difference between the two. Marine fouling may be heavy in shallow depths. Marine fouling can produce varied corrosion effects. It may form an effective barrier to the environment under some circumstances or cause accelerated corrosion through oxygen concentration cells in others. At depths below 300 feet where sunlight does not penetrate, there is no plant fouling and greatly reduced animal fouling.

e) Mud Zone
There are several competing processes that make the rate of corrosion in the mud zone difficult to predict. Oxygen concentration cells may establish themselves at the mud-line water interface. Anaerobic bacteria in or on the mud may cause corrosion. The reduction in the corrosion rate of steel well below the mud line is attributable to the lower oxygen content and to the fact that any protective films that form on the steel's surface are protected in turn by the surrounding mud.

f) High Pressure, High Temperature
With the continued exploration of high pressure, high temperature (HPHT) environments, there are additional standards, specifications, and technical recommendations that need to be considered to ensure proper design and qualification of fasteners, such as API 17TR8 and API PER15K.

4.3.3.3 Land environments

The following are examples of land environments:

a) Desert or Arid
Desert environment is the most benign to bolting as humidity is low. The common threats in an arid environment are extreme temperatures and thermal gradients, potentially abrasive action from dust storms, and powdery deposits.

b) Tropical and Subtropical
The effects of a tropical or subtropical environments are like those caused by marine atmosphere except for the presence of corrosive salts. In this environment bolting buried under ground may experience accelerated corrosion from salts and minerals attacking the metal surface in combination with water and humidity.
4.4 Bolting Threats and Barriers

4.4.1 General

The threats to bolting integrity that can lead to bolting failure should be understood. The application of appropriate barriers to mitigate those threats are an important part of the design considerations, materials selection, manufacturing processes, and installation of bolts to ensure satisfactory service life in critical bolting installations. In corrosive environments, involving sour service, or which are outside of typical operating pressures and temperatures additional design considerations may be required. The following section discusses some of the most common threats to bolt integrity and the barriers employed to prevent in-service bolting failures.

4.4.2 Over-torqueing and Under-torqueing

Torque occurs upon installation or in service due to an externally applied load. Over-torqueing and under-torqueing can be prevented by having proper torqueing procedures. Sequence for torqueing bolts should always be taken into consideration. Some coatings can have an effect on the desired torque values, so they should be taken into consideration when writing torqueing procedures. Torqueing is not a direct measure of the load, it is a measure of the frictional resistance. There are a number of influences on torque that make it an unreliable indicator of tension, including thread class, thread fit, thread finish, lubrication, coating, cleanliness, contaminants, mechanical upsets, tears, nicks, dings, etc. Calibration of torqueing equipment should be an integral part of proper torqueing procedures. An alternative method of measuring load may be necessary. In the field this is most easily accomplished through the measurement of the bolt in a relaxed, unloaded state, then again after tightening. As the tightening process stretches the bolt, measuring this stretch directly correlates how much load is introduced.

Over-torqueing can lead to tensile over load and under-torqueing can contribute to fatigue related failures. There are codes and industry standards which deal with torque values and torqueing sequences. For example, ASME-PCC-1 describes the installation procedure for bolting; additionally, API 6A has an informative annex with recommended flange bolt torque.

4.4.3 Shearing (Over-load or ductile failure)

Fasteners for the applications addressed here are not generally designed to be loaded in shear; special consideration should be taken during design to ensure the fastener is not loaded in shear. Shear loads may not come from operational loads, but could be a result of handling, transportation or during installation. If shear cannot be avoided, the fastener should be made from a material with a composition and processing capable of achieving the minimum strength requirements throughout the full cross-section.

4.4.4 Tensile Overload

Tensile overload can be avoided by proper use of safety factors during design, as well as by ensuring material processing results are consistently meeting or exceeding the minimum tensile properties required by the design through testing frequency and appropriate supply chain management.
4.4.5 Stress Concentration

Notches may cause intensification or concentration in the stress field. When shaping the head of a bolt either by forming or machining in the manufacturing process, local notches can be introduced. Common measures such as larger radii or proper tooling can assist in the reduction of stress concentration.

4.4.6 Fatigue

Loading and unloading cycles cause cracks to grow to a critical length and results in complete failure of the bolt. There are many known variables which can cause fatigue failures in fasteners. The most common barriers against fatigue are:

a) Conservative design and allowable stress loads (% of minimum yield or % of minimum tensile strength) should be one of the primary ways to mitigate fatigue.

b) Special consideration given to reduce the effects of loads from vibration. Some equipment may be affected by vortex induced vibrations which should be considered during design.

c) Metal processing practices can greatly improve or degrade fatigue resistance of materials.
   1) Modern melting practices can increase fatigue life through improved material cleanliness.
   2) Heat treatment should also be considered as it can affect fatigue life.
   3) Forming (rolling) threads rather than cutting threads can induce compressive surface stresses which can result in better fatigue resistance of the fastener. Same can be said for other types of surface treatments provided they result in the same type of compressive stresses.

d) Surrounding environments should be considered as some materials can suffer a significant loss in fatigue life (or fatigue resistance) depending on the environment they are operating in. (ex. subsea, land equipment, sour service, etc). This is called corrosion fatigue.

4.4.7 Hydrogen Embrittlement

Externally applied or internal residual stress may expedite the embrittlement process. Depending on different mechanisms for hydrogen intake and load case; hydrogen embrittlement can be referred to as Hydrogen Stress Cracking (HSC), Hydrogen Induced Cracking (HIC), among many other nomenclatures. To address the problem of hydrogen embrittlement, emphasis is placed on controlling the amount of residual hydrogen in steel, controlling the amount of hydrogen pickup in processing, developing alloys with improved resistance to hydrogen embrittlement, developing low or no embrittlement plating or coating processes, and restricting the amount of in-situ hydrogen introduced during the service life.

There is a relationship between the strength and hardness of metals and their resistance to hydrogen embrittlement. For low alloy steels and some martensitic stainless steels, laboratory testing and field experience indicates the threshold between a low alloy steel that is susceptible to hydrogen embrittlement in seawater with cathodic charging and one that is not is approximately 34 HRC. This threshold is approximate however, as the quality of microstructure of the low alloy steel can influence the susceptibility to hydrogen embrittlement. Good metal processing practices which minimize banding and non-metallic inclusions is essential to make these materials less susceptible to hydrogen embrittlement.

Some coating applications produce hydrogen around the material as the coating is being deposited (such as in electro or electroless plating). Other applications which require phosphating prior to coating to create an anchor pattern can also generate hydrogen in the base metal which may be detrimental to the base metal for steel with specified minimum tensile strengths of 125Ksi or higher. The effects of process-induced hydrogen can be mitigated by proper heat treatment immediately following pickling, plating and/or phosphating processes. API 20E or ASTM B850 are sources which provide bake-out procedures and times. Dehydrogenization/hydrogen bake-out should be carried out immediately after plating and/or phosphating processes to prevent hydrogen embrittlement on high strength low alloy steels and martensitic stainless steels.
Cathodic protection in seawater can generate hydrogen around the base metal being protected, which could be detrimental. Typically, hydrogen will combine at the surface of the metal and will depart the system as hydrogen gas. If the CP is improperly applied, the hydrogen ions may persist at the steel surface and can be absorbed into the base metal, causing hydrogen embrittlement. The level of cathodic charging can affect the severity of the environment. Additionally, hydrogen charging can occur in steel from cathodic protection by coatings made of metals such as zinc, aluminum or zinc-nickel which when coupled to steel generates hydrogen. More noble metals are sometimes considered such as nickel, nickel-cadmium, or nickel-cobalt because they do not charge hydrogen into the steel bolting materials or, from a practical standpoint, corrode. When dealing with coatings more noble than the base metal of the bolting, it is important to consider corrosion by pitting of the base material which may occur in areas where discontinuities in the coating are found. The severity of pitting corrosion may vary proportionally to surface area of steel around the discontinuity, and whether the system surrounding the bolting is cathodically protected. Proper assessment of the intended system should be performed before selecting a coating of this type.

In HPHT designs, which need increased capacity over existing stainless steel (Austenitic) or duplex stainless steel bolts, higher strength corrosion-resistant alloy (CRA) materials such as precipitation hardening (PH) nickel-based alloys may be used. The oil and gas industry has also suffered from HSC or HE of bolts manufactured from PH nickel-based alloys in subsea applications due to CP exposure or galvanic coupling.

4.4.8 Liquid Metal Embrittlement

Liquid metal embrittlement occurs when liquid metals cause the ductile metals to lose tensile ductility or causes a brittle fracture. Liquid metals cause decohesion along grain boundaries with the assistance of external tensile stress or internal stress, i.e. residual stresses as consequence from manufacturing. This is commonly associated with improper hot dip galvanizing technique. This can be mitigated by proper process control, such as temperature of the bath and part.

4.4.9 Embrittlement from intermetallic phases (Sigma-phase, Delta-Phase, Sensitizing)

Embrittlement from intermetallic phases often occurs during heat treatment; however, post-processing of base metal can also generate enough heat to cause a phase transformation of materials which can lead to detrimental non-metallic phases. The manufacturer should address proper heating and cooling rates to avoid formation of deleterious non-metallic phases along the grain boundaries. Post processing which can result in detrimental non-metallic phases should be avoided.

4.4.10 Galling

This failure mechanism is often seen in stainless steels, particularly in austenitic stainless steels; however, other fasteners such as aluminum, titanium, low alloy steel, or nickel-based alloy may also be susceptible. Galling can be prevented by the appropriate selection of coatings and materials such as: pairing dissimilar alloys, dissimilar crystal structure, with special consideration not to create large galvanic potential between the two as that could also lead to galling. The use of coatings on fasteners is often the solution to keep galling from occurring. A hardness differential between mating components can also improve resistance to galling. A related failure mechanism is fretting where severe adhesion wear occurs without the transfer of materials between the fastener parts.

4.4.11 Thread Seizing (General Corrosion)

Thread seizing often occurs due to general corrosion while the threads are engaged under high load. Although this does not often result in breaking of a connection, it can be considered a common failure because fasteners are likely to be destroyed or rendered no longer fit for service should they ever come off. Coatings are a good solution to this problem. Durability of the coating should be suitable for the intended service and expected life of the fastener being used.
4.4.12 Stress Relaxation

Increases in temperature above 500°F (260°C) provide enough thermal activity in the material at the atomic level to allow the material to elongate to accommodate the strain, this results in the stress decreasing. Stress relaxation is used to remove residual stresses and reduce the risk of environmental cracking such as stress corrosion cracking or hydrogen embrittlement. Controlling the grain size and an awareness of environmental considerations are mitigation techniques that can reduce this effect.

4.4.13 Creep

When bolt material starts to creep, the bolt extension increases without any increase in the bolt load. This reduces the bolt stress and hence the load retained in the bolt. Because creep is defined as continued extension under constant stress, the effect seen in a bolt is not consistent with the definition of creep. Other terms such as high temperature stress relaxation or creep relaxation are used – but the cause is the same.

4.4.14 Corrosion

4.4.14.1 General

The discussion of corrosion in this section will be limited to some of the most common types of corrosion in the oil and gas industry and its effects on low alloy steel, stainless steel and CRA bolting. This discussion will have a higher focus on external environment than internal environments due to the complexity of environments which can be found in drilling and production environments.

a) Low Alloy Steel Considerations

Steel is considered low alloy if Ni + Cr + Mo + Cu < 5 wt %. For low alloy steel, bolting corrosion occurs predominantly as general corrosion (See Figure 2). For the most part, general corrosion, sometimes called as weight loss corrosion, occurs in moist locations such as offshore topsides or in coastal areas with marine environments. Also, subsea environments lead to general corrosion if the bolting is not protected by the cathodic protection system or by use of barrier coatings.

Figure 2 – Example of Offshore Bolting Corrosion
b) CRA & Stainless Considerations

More aggressive corrosion environments may require corrosion resistant alloys such as stainless, duplex/super duplex, copper alloys, nickel-chrome-molybdenum alloys, cobalt, or super alloys with mostly nickel making up the composition. Crevice corrosion and pitting is more prevalent in CRA materials. Making the right choice of CRA or stainless material will help mitigate the problem of these types of corrosion.

4.4.14.2 Sulfide Stress Cracking (SSC)

Sulfide Stress Cracking (SSC) can occur when low alloy steel bolts are in the presence of a sour service environment under tensile load, tensile components or even in the presence of internal stresses (without exterior load). For low alloy steel bolts that are not directly exposed to production nor process fluids, a sour environment can be produced due to production fluids leakage to areas under insulation. Selecting material in compliance with the requirements of NACE MR0175/ISO 15156 can eliminate the risk of SSC. Bolting material manufactured from CRAs when used for external applications can also be exposed to sour environment when production fluid leaks to areas under insulation. As a result, bolting material when used in aforementioned situation shall comply with requirements of NACE MR0175/ISO 15156-3 to prevent SSC.

4.4.14.3 Environmentally Assisted Cracking (EAC)

Environmentally assisted cracking is a general group of cracking threats that occurs in bolts made from CRA under the conditions of stress, an environment, and a material that is susceptible to cracking due to its properties such as microstructure, hardness, composition, and processing history. EAC in low alloy steel bolting is not considered in this document since low alloy steels do not normally exhibit this mode of failure in low pH environments.

4.4.14.4 Stress Corrosion Cracking (SCC)

Stress corrosion cracking (SCC) may occur in bolts made from CRA’s under stress and exposed to a corrosive environment at elevated temperatures. The stress can be internal (such as residual stress), or external. Failure of an otherwise ductile part occurs at a stress much lower than its yield strength, originating at surface imperfections (typically pits or cracks) created by the corrosive environment. The three factors needed for SCC to occur are a susceptible microstructure, a corrosive environment, and tensile stress. To prevent SCC, one of the three contributing factors needs to be eliminated.

4.4.14.5 Chloride Stress Corrosion Cracking (CSCC)

Bolts made from stainless steels are mostly susceptible to this type of cracking mechanism. This occurs when the stainless steel bolting under stress is exposed to a chloride containing environment such as seawater at elevated temperatures. The concentration of chloride and temperature to promote CSCC depends on the grade of stainless steel. A more obvious means of prevention is selection of other CRA bolting materials other than stainless steels that are fit for purpose. This includes bolts manufactured from nickel based alloys.

4.4.14.6 Localized Corrosion

Bolts manufactured from stainless steels or even higher grade CRA material can be susceptible to localized corrosion (pitting or crevice) if they are not protected by CP. This degradation mechanism can become more prominent in environments with high oxygen and halide anion concentration (such as chloride, Cl) at elevated temperatures. Corrosion pits are very localized and difficult to protect as it can form a pinhole where coating was not properly applied, or has broken down over the service life. Crevice corrosion is equally difficult to protect as it occurs in small crevices between the bolting/flange and bolting/nut areas. Pitting and crevice corrosion can eventually lead to SCC or CSCC of the bolting due to the imposed stresses.
In order to prevent pitting/crevice corrosion bolt material selection for the intended service is extremely important. For seawater applications, industry standards recommend CRA bolting material with high Pitting-Resistance Equivalent Number (PREN). The PREN is based upon the proportions of the elements such as Chromium (Cr), Molybdenum (Mo), Tungsten (W) and Nitrogen (N) in the chemical composition of the alloy. The higher the PREN number the higher the resistance of the CRA material to pitting and localized corrosion. Alloys with PREN greater than 40 have demonstrated adequate resistance to localized corrosion.

Pitting corrosion is a form of localized corrosion which requires only one metal in the presence of an electrolyte to set up an attack system. This type of corrosion begins with the creation of a differential in concentration of oxygen at the metal surface which produces an extremely localized battery effect. Pitting corrosion is more difficult to predict or protect as it can form in very small pinholes where coating was not properly applied, or has broken down over the service life.

Bolting can potentially fail when severe pitting occurs. In order to prevent pitting, proper material selection for the intended service is paramount; in seawater applications, austenitic stainless steels and stainless with a PREN greater than 40 have demonstrated to have good pitting resistance (amongst other materials). Additionally, coatings may be used as a barrier to enhance the pitting resistance of materials otherwise known to be susceptible to pitting in a given environment. It is important to note some coatings may not produce a perfect barrier or may not be durable, may fall off or degrade, and in some cases these conditions can result in more localized and more severe pitting.

4.4.14.7 Corrosion Barriers for Steels
General corrosion is a uniform loss of mass in the metal when it reacts with the surrounding environment. With regards to this document, general corrosion is mostly associated with low alloy steel bolting when exposed to environment without protective barriers.

Corrosion barriers to corrosion threats are surface barriers that limit or stop the bolting steel surface from being wetted by water or exposed to oxygen. Barriers take the form of:

- painting or coating
- plating
- inhibitors/oils

Another approach or mitigation barrier for bolting submerged in water or seawater is cathodic protection which again acts on the steel surface to shift the surface environment to a condition which prevents corrosion.

Painting or coating reduces or mitigates the exposure of bolting to oxygen or water. However, application discontinuities or degradation of the paints or coating over time allows the ingress of oxygen or water to the steel substrate. This happens through coating holidays or voids through mis-application, cracks in the coatings, degradation of the coating by ultraviolent exposure (sunshine), aging resulting in flaking off or cracking of the coating, and finally mechanical damage in-service such as make-up or break-out of bolting and handling.

Plating is a popular approach to mitigating general or crevice corrosion also. Plating applications used in the industry can be chrome, zinc, aluminum, cadmium, nickel-zinc, nickel-cobalt and others. Cadmium is no longer used due to the biohazard nature in the plating process and exposure to the environment. Chrome plating is used in limited applications due to a reputation of cracking and flaking.

Zinc, aluminum and nickel-zinc provide a barrier as a secondary mitigation. The primary barrier is one of cathodic protection which shut down the surface corrosion reaction by shifting the potential (voltage) to a more negative value. This shifting of potential is caused by a galvanic couple between the steel and zinc, aluminum or nickel-zinc. These coatings work fairly well, however the plating is consumed with time requiring more plating to be sacrificed to last years versus months in water (seawater). This fact of more plating being required for sacrificial plating leads to thickness of 2 to 3 mils.
The consequence of requiring more plating may lead to thickness build up and adhesion issues and/or thread interference. To solve this issue of interference, manufacturers have oversized the nuts for bolting which would lead to lower bolting strength and load carry ability. Over-sizing of nuts is not allowed in API 20E, 2nd edition.

Alternate performance plating corrosion barriers which mitigate corrosion include: high phosphorous electroless nickel plating, nickel-cobalt plating, and other non-sacrificial barriers. These plating processes are characterized as barriers that may not require over-sizing of the nut to allow make-up. Some of these plated coatings, such as nickel-cobalt, resist deformation and mechanical damage. Finally, the corrosion resistance of non-sacrificial plating allows easy break out and mitigates seizing after extended service of the bolting.

Inhibitors/oils have shown fair protection of protecting bolting by acting as a barrier to water on the steel surface for short term storage prior to use. However, they work best in mild service condition such as low humidity conditions non-submersed conditions on land. Most successful applications are expected in inside areas protected from the elements on land with low humidity.

### 4.5 Manufacturing Processes

#### 4.5.1 General

This section details some common manufacturing processes that may affect the performance properties of bolting. The quality of the steel and how the bolts are manufactured contributes to different properties within the bolts.

Figure 3 provides an overview of the primary production processes discussed in this document.

![Figure 3 - Overview of Production Processes](image)

#### 4.5.2 Steelmaking

**4.5.2.1 General**

The following steelmaking processes/properties have contributing affects to the performance of bolting. It is up to the discretion of the bolt manufacturer to determine the appropriate thresholds/limits of each of these factors depending on their application.
4.5.2.2 Reduction Ratio
An increase in reduction ratio aids in the homogenization of the microstructure as well as closes any porosity that may present itself during solidification.

Typically based on the starting size of the steelmaking process, ingot cast material tends to have a higher reduction ratio than continuous cast material. The more reduction there is in steel, the smaller the banding wavelength will be.

The reduction ratio in round bar is typically calculated by dividing the starting cross sectional area by the finishing cross sectional area.

Large bars are typically press forged for center soundness. Minimum 4:1 reduction ratio is commonly specified as it produces a fully wrought structure when proper tooling, forging sequence, and forging temperatures are employed.

4.5.2.3 Chemistry Variation
Depending on the steelmaking process, the chemistry may vary throughout the product. Whether it is continuous cast and certain alloying elements coagulate at the end of the pour or if it is ingot cast and there is a difference between the top of the ingots and the bottom of the ingots, there are manufacturing processes such as stirring to ensure the chemistry variation is limited throughout.

To measure chemistry variation, chemical analysis can be performed at different parts of the heat (ingot top and bottom, beginning of heat, end of heat, etc.). Various specifications address this issue, including a magnetic step-down test; for example, SAE AMS 2300.

4.5.2.4 Cooling rates
In terms of banding, if there is no time for carbon diffusion, a martensitic microstructure will result and there will be minimal microstructural banding. Slow cooling allows carbon diffusion during transformation (transegregation) producing microstructural bands non-martensite.

4.5.2.5 Microstructure/macrostructure, grain size
A targeted microstructure of materials can greatly improve the properties of the end product. This can be achieved by establishing controls in melting, hot working, and heat treatment process.

4.5.2.6 Banding
All steel contains some degree of microsegregation (i.e., banding) and will manifest in the microstructure (see figure 4).

During hot rolling, the as-cast dendritic structure is broken down and elongated parallel to the rolling direction. This forms the basis for the visible aligned banding morphology. During cooling after rolling (or heat treatment) alloy interactions modify the local transformation temperature in the microsegregation bands. These affinity differences will determine the final transformation product formed in each microsegregated band.

The initial solidification dendrite structure is driven by the cooling rate and is a function of continuous casting/ingot process (superheating, section size, speed, stirring, specific equipment unit).
Hot rolling breaks up the initial dendritic structure and aligns segregated regions into pancake/needle like regions parallel to the bar.

Besides the microstructural bands observed as a result of the solidification dendrite structure, there also exists a banding phenomenon known as 'white banding'. These white bands are formed during the continuous casting process by the electromagnetic stirring (EMS) operation. EMS stirring aids in the proper distribution of alloying elements within a continuous casting process, but they also form the white bands that consist of a zone of negative segregation where there is solid-liquid interface during stirring and a zone of positive segregation as a result of the cessation of stirring. The positive segregation section of the white bands tends to be solute rich at the end of the stirring operation. The most deleterious feature of the white bands is their cosmetic appearance, but the change from negative to positive segregation (with a transition region in between) does exist\(^2\). It is recommended to optimize the EMS stirring process to minimize the amount of white banding while also ensuring that alloying elements are distributed homogeneously through the material.

While the microstructural manifestation of banding can be masked by heat treatment, banding cannot be eliminated or even significantly reduced by thermal treatment. A homogenous microstructure will lead towards more consistent properties, so a minimized banded structure with as little variation in hardness between bands is desirable. In low alloy steel, common substitutional alloy elements (Cr, Mn, Ni, Mo, Si, Cu) diffuse slowly, so in order to achieve a homogenized microstructure, high temperatures and long durations, followed by grain refinement heat treat cycles is required. For example, if there is no time for C to diffuse, the microstructure will consist fully of martensite with minimal microstructural banding appearance. Slow cooling allows for C diffusion during transformation (transsegregation) producing non-martensite microstructural bands. However, the cooling rates required to reduce/eliminate banding are too great to be commercially viable.

Not all banding is considered deleterious. In fact, for some studies performed, microstructural banding was determined to not be a contributing factor in HIC. The anisotropy index has no relevance to HIC and instead, HIC is most frequently caused by non-metallic inclusions\(^3\).

Tests for banding include those detailed in ASTM A534 and ASTM E1268.

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\(^2\) Bridge & Rogers, September 1984
\(^3\) Kulesza, Fletcher, Shick, & McDowell, March 2016
4.5.2.7 Inclusions

Inclusions are nonmetallic compounds that are usually formed during deoxidation, refining, teeming and/or solidifying processes in steelmaking. Inclusions are categorized as either indigenous or exogenous. Indigenous oxide inclusions originate in the molten steel resulting from deoxidation or reoxidation reactions. This usually involves reactions between dissolved oxygen and deoxidizing elements such as aluminum and silicon.

Other types of indigenous inclusions include sulfides and nitride and carbonitride precipitates. These types of inclusions form by solidification driven segregation. When the solubility product of an inclusion compound is exceeded the compound will form as an inclusion. Common examples of these types of inclusions are manganese sulfides (MnS) and titanium carbonitrides (TiCN). Additions of rare earth elements such as calcium are made during refining and used to modify sulfide shape.

Inclusions are most detrimental in the transverse direction.

Exogenous inclusions form from the entrainment of nonmetallic materials that are in contact with the liquid steel. Exogenous inclusion sources can include slags and refractory material. These types of inclusions are usually trapped by turbulent conditions at the interface during refining and/or casting. Exogenous inclusions are typically large, irregularly shaped, and infrequently spaced in steel. While the size of exogenous inclusions can be particularly detrimental to steel component performance, the probability of these inclusions causing component failure is low due to their low frequency of occurrence as a result of controlled manufacturing processes.

Qualification: The cleanliness of steel may be rated on both macroscopic and microscopic levels. Macro-cleanness may be determined by macroscopic rating methods such as high resolution ultrasonic inspection, macroetch, magnetic particle to qualify a heat to either SAE AMS 2301 or SAE AMS 2304.

Many different microscopic rating methods exist for characterizing and measuring micro-cleanness. One of the most common methods is ASTM E 45-05 Method A (Worst Field Analysis). In this method, inclusions are categorized into the following groups: Type A-sulfides, Type B-alumina, Type C-silicates, and Type D-globular oxides. Brief descriptions of each type are:

Type A - Elongated inclusions, usually sulfides, with aspect ratios 2:1. Typically blue/gray in appearance with rounded ends.

Type B - Aligned cluster (at least 3 individuals) inclusions of angular low aspect ratio (<2:1). The clusters are aligned in the rolling direction. Typically dark/black aluminum oxide particles but may also be sulfides, etc.

Type C - Elongated and continuous inclusions typically with high aspect ratios (2:1), and sharp ends. Often dark/black silicates.

Type D - Isolated (not part of a stringer) low aspect ratio (<2:1) sulfide and oxide inclusions. Rated as number per field.

Once the inclusions are classified by type, they are then classified by their thickness as either Thin or Heavy. Inclusions whose width is less than 2um (0.00008") are not rated. A severity rating is determined for inclusion types A, B, and C by adding together the total inclusion length per field. D type inclusions are counted instead of measured. The length measurements or counts and the severity level table in the ASTM standard are used to generate the severity number for each inclusion type.

Include explanation on Inconel (grain size growth)
4.5.3 Casting

4.5.3.1 General
Subsequent to the steelmaking process, manufacturing operations will also affect the performance of bolting as well as dictate what type of bolting is being produced.

The casting process can be performed either through ingots or a continuous process. The bottom pour ingot making process involves filling an ingot mold with molten steel from the bottom up. Continuous casting is when cast steel is drawn through the bottom of a mold as it solidifies.

4.5.3.2 Ingot versus Continuous Cast
The wire, rod and bar used for bolting or stud manufacture are usually made from raw materials produced either by continuous casting or ingot casting. For continuous casting, the reduction ratio could be very small due to the starting cast size and the final product size. As a result, cast microstructure, porosity, banding, and/or other discontinuities may exist which degrade the bolting mechanical properties and increase susceptibility to HSC.

By contrast, higher reduction ratio is often obtained in bolting manufactured from ingot casting materials, mainly due to the larger starting cast and the subsequent drawing (hot working) process. The resulting materials therefore have desirable wrought microstructure and significantly reduced detrimental features, such as porosity, segregation and banded structure.

The bar stocks (usually large dimensions) for bolting manufacturing can also be made by forging. In this process, a hot ingot is progressively pressed and shaped in a rotating manner until the desirable dimension is reached. Although materials produced by forging exhibit wrought microstructure, the grain flow may not be uniformly linear. Therefore, bolting manufactured by such process may or may not have superior properties than the drawn ingot casting material.

As a result, it was recommended in API 20E, 2nd edition and API 20F, 1st edition that the preferred material processing for bolt manufacturing for fatigue sensitive subsea applications should be either from ingot casting or forging.

Bolts manufactured by continuous casting have been used and still continue to be used. For fatigue sensitive applications, the following conditions should be considered:

- Chemistry of the cast bloom or billet should have the total weight percentage of tramp/residual elements below 0.5% and calcium should be 0.005% max. Boron should not be added intentionally and the max Boron should not exceed 0.0005%.
- Steel microcleanliness should be performed as required by API 20E for BSL3.
- For continuous casting, the starting cast size should be large enough such that the final product size has experienced adequate drawing or hot working which has resulted in a desirable wrought microstructure. The work ratio should be 12:1 minimum
- The wrought microstructure should contain no detrimental features such as porosity, segregation, and an excessively banded structure. This should be validated during first article qualification. Extent of banding should be evaluated per API 20E. One major difference in banded microstructures made from continuous cast steel vs. ingot cast is there is more frequent occurrence of white banding; which is a result from stirring processes common to continuous cast.
- Micro hardness should be performed in the dark and light areas of the microstructure (if apparent) and the hardness should not vary by more than 5 points (whether bands are apparent or not).

Bolts manufactured by forging should have a wrought microstructure free from non-linear grain flow which can result in inferior mechanical properties and HSC resistance. This should be validated during first article qualification.
4.5.4 Heat Treating

Heat treatment covers various techniques that may be used to develop certain end-product characteristics. Common procedures for fasteners include annealing, normalizing, quench and temper, solution annealing, and ageing. Other types of heat treatment may be case hardening, boronizing, and carbon restoration.

Bolting made from high strength 718 nickel based alloys has been known to fail in service due in part to microstructural features which occur when heat treating to achieve high strength. It is recommended when using 718 bolting to select material within the strength limits (as well as all other aspects) of API 6ACRA; unless the application is such that deleterious phases such as delta phase will be of no consequence such as in high temperature applications.

4.5.5 Production of Bolts

4.5.5.1 Starting Stock - Hot and Cold Working

The choice of hot or cold working is dependent on the application, size of the bolting and mechanical requirements. Hot working serves best where higher reductions are required. Cold working serves best when higher strength is required.

4.5.5.2 Cut Versus Rolled Threads

Threads of a mechanical fastener (regardless of whether it is a headed bolt, rod, or bent bolt) can be produced by either cutting or rolling. The differences, advantages, and disadvantages of each method are described in this section.

Cut threading is a process by which steel is cut away, or physically removed, from a round bar to form the threads. The size of the round bar must be equal to or greater than the finished size. Roll threading is a process by which steel is extruded to form the threaded portion of a fastener instead of being removed as in cut threading. In this process a bolt is manufactured from a reduced diameter round bar. Rolled threads require dies to produce threading. Multiple dies would be required to produce different thread patterns. Multiple thread patterns can be achieved by the same machine when cut threading.

![Thread types](image)

Hardness and the susceptibility to fatigue and EAC growth are subjects that require balance in the design, material selection and manufacturing processes specified to minimize the potential of failure for bolts that are susceptible to these failure mechanisms. It has long been a practice to use rolled threads for fatigue resistance. However, it can be counterproductive to resistance to hydrogen cracking in some service environments, particularly in seawater with CP applied.
The severe cold work in the threads imparted by the rolling of the threads produces a high trapping density for hydrogen. The residual internal hydrogen poses a threat to cracking at the location of the highest stress and hardness, increasing the potential for hydrogen cracking in rolled threads. Written procedures and adherence to the post-plating bake out requirements, along with maximum hardness levels, are necessary for minimizing the likelihood of HIC failures in bolts.

Because of the recognized benefit of rolled threads on fatigue resistance of bolts, many industry standards either explicitly or implicitly encourage the application of rolled threads. Many existing standards only require hardness measurements in the bolt core. The required hardness measurement in the bolt core is sufficient to define the mechanical properties of bolting, but does not consider the existence of increased hardness of the rolled threaded area and magnified risk of HE during subsea service and CP. However, stress relieving after a thread rolling operation reduces susceptibility to hydrogen embrittlement. Post rolled thread heat treatment procedures should be qualified by bolting manufacturers to reduce the average near surface thread area hardness to 336 HV10 (34 HRC) for low alloy steels.

For low alloy steel bolting that may be exposed to sour environment due to joint leakage beneath thermal insulation refer to requirements of NACE MR0175/ISO 15156-2. Threads produced using a machine-cut process are acceptable. Threads produced by roll threading are acceptable in low alloy steel bolting that otherwise conform with heat treatment, composition, and hardness requirements of NACE MR0175/ISO 15156-2.

4.5.6 Chemical Composition and Hardenability of Low Alloy Steel Bolting
For low alloy steel bolting it is important to note the mechanical properties may vary through the thickness of the material. Lack of hardenability sometimes causes this variation. This can be due to lean chemical composition or slow quench rate. B7 and L7 are Chromium-Molybdenum low alloy steels used for bolting. Use of these bolting grades should be limited to 2.5 inches in diameter, as the leanest forms of their composition may result in lower mechanical properties through the thickness.

For low alloy steel bolting with a diameter greater than 2.5 inches, it is recommended to use a different composition such as L43 which is based on AISI 4300 series Chromium-Nickel-Molybdenum alloys. If the desire is to maintain the use of B7 or L7 composition, then it is important to modify the chemical composition to produce an Ideal Diameter (Di) or a Critical Diameter (Dc) capable of achieving the desired properties throughout the thickness. The modification of chemical composition can be achieved through the use of multiplying factors for alloying elements and by taking the grain size and severity of quench into account.

See ASTM A255 for guidance on how to calculate Di and Dc.

4.5.7 Mechanical Properties and Testing

4.5.7.1 General
This section describes the different mechanical properties that may be applied to bolting manufacture. Final mechanical property requirements are determined by the user and confirmed by destructive testing.

4.5.7.2 Tensile Test
Tensile properties should be selected such that bolting can take the intended loads of the design. Design codes will often set safety factors on bolting which must be taken into consideration when selecting minimum yield strength and tensile strength. Percent elongation and percent reduction of area should vary from one grade to another based on composition and strength. It is recommended to follow recognized industry standards to set minimum requirements. The testing is generally conducted in accordance with ASTM A370 or ASTM E8.
When strength requirements are moderate, low alloy steel can be tempered to ranges such as those specified in ASTM A193, B7M or ASTM A320, L7M. Other low strength applications may be satisfied by the use of austenitic stainless steel bolting as per ASTM A193.

High-strength fasteners can be made from low alloy steels with medium or high carbon content, or by using precipitation hardening materials. Suitable heat treatment processes may be used to achieve desired properties. The use of high strength bolting in the oil and gas industry is generally limited by effects of environment. Strength limitations on low alloy steel, stainless and nickel based bolting are given in API 20E and API 20F among other codes.

4.5.7.3 Impact Testing
As a minimum, impact testing should be carried out on closure bolting and bolting used in the main load path on primary load carrying members. The testing is generally conducted in accordance with ASTM A370 or ASTM E23. The test temperature should reflect service temperature or lower.

Impact testing has proven to be a good measure of the quality and toughness performance of low alloy steels and can be used as a quality assurance tool to ensure material can be used in low temperature applications. Many codes have acceptance criteria for absorbed impact energy when testing bolting. ASTM A320, L7 and L43, require impact testing and have a good track record of performance in low temperatures in oil and gas applications. ASTM A193 does not require impact testing unless specified as supplemental requirements.

4.5.7.4 Hardness Testing
Hardness is usually measured by the Brinell, Rockwell, or Vickers indentation-hardness test methods. The testing is generally conducted in accordance with ASTM E10, ASTM E18, or ASTM E384 (respectively).

Establishing hardness limits can help mitigate failure in different environments. For fasteners in direct contact with sour service environments, NACE MR0175 has limited the use of low alloy steel bolting to B7M, L7M, and ASTM A194 2HM which are limited in ASTM to 22 HRC maximum. Other standards such as API 20E have limited the hardness of low alloy steel fasteners to 34 HRC to mitigate the effects of hydrogen embrittlement. Hardness is often used as a quality control check to make sure the material is in the required tensile range.

Microhardness is used to evaluate microstructural properties that macrohardness is too large to accurately measure. For example, the hardness variation from banding.

4.6 Protective Coatings

4.6.1 General
Coatings are applied to bolting to protect from corrosive environments or to achieve/enhance desired properties, such as lubricity for consistent torqueing. There are different types of coatings that are used depending on the type of protection and duration of protection required.

4.6.2 Types of Protection
The following are types of protective coatings:

- Sacrificial coating: The electrodeposited coatings are anodic in nature and therefore corrode preferentially to the base metal.
- Barrier coating: Provides protection by isolating the base metal from the environment.
4.6.3 Duration of Protection

The following are types of protection durations:

- Short Term Protection: Typically, thin electrodeposited coatings provide enhanced shelf life, cosmetics, and limited corrosion protection. Phosphating, polytetrafluoroethylene (PTFE) based coatings are examples of short term protective coatings.

- Long Term Protection: Protection generated by sacrificial, barrier or coating systems intended to last for an extended period (typically greater than 4 months). Ceramic-metal (Cermet) coatings, and zinc plating are considered long term protection for shelf life. Nickel-cobalt, cadmium and zinc-nickel plating are longer lasting than the previously mentioned coatings. In aggressive environments, such as seawater, zinc-nickel and cadmium plating may require a barrier coating. Nickel-cobalt will show behavior closer to stainless steels and CRA.

4.6.4 Types of Coating and Plating

Metallic coatings are applied to fasteners for corrosion resistance, decorative purposes, and extended shelf-life. Metallic coatings are primarily sacrificial in nature. The most common electrodeposited metallic coatings for use on fasteners are zinc, cadmium, and zinc-nickel. Corrosion resistance is limited due to the minimal coating thickness (typically .2 - .3 mils, although thicker deposits can be achieved). Hot dipped galvanizing is also a fastener coating but is used less because of interference issues that arise due to inconsistent coating thickness and tight tolerances.

Cermet coatings, typically aluminum filled, are used extensively as base coats, but require top coats (typically fluoropolymer) for lubricity required for uniform torque.

The electroplating process varies on types and desired results. Most plating processes generate hydrogen. Post-baking after plating is used to diffuse internal hydrogen. If the post-bake temperature is not high enough, the hydrogen does not diffuse. If the post-bake temperature is too high, the plating can be compromised. If plating temperature exceeds the optimized operating limits of the bath or if improper temperature control during post-bake occurs, it can lead to premature bolt failures due to hydrogen embrittlement and loss of corrosion protection.

The following precautions should be noted:

- a) The plating material is usually the controlling factor for maximum service temperature.
- b) Hydrogen embrittlement is possible with most common methods of plating, unless special manufacturing procedures are used.
- c) The use of dissimilar materials can create galvanic corrosion issues.
- d) Improper installation may contribute to stress relaxation and fatigue issues.

Non-metallic coatings for fasteners typically are fluoropolymers offering a combination of corrosion resistance, wear resistance and lubricity. They can be applied over phosphate etched substrate where lubricity only is required, or as a topcoat to zinc plate or cermet base coats for more corrosion resistant coating systems. Some examples are:

- Corrosion Protection: Fluoropolymer coatings offer corrosion resistance where the film is not damaged or breached. However, they can be subject to extensive damage during the installation (Mechanical or UV exposure), thus exposing the substrate to corrosion.
- Lubricity: Fluoropolymer fastener coatings are used primarily as a dry film lubricant, offering consistent torque values. Typically, no additional lubricants, greases, or otherwise, are required with fluoropolymer coatings due to the PTFE content.

Marine epoxy topcoats can be applied to fasteners after assembly, for additional protection (specifically for offshore environments) but are not considered fastener class coatings due to thicknesses which may impair fit and function.
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<table>
<thead>
<tr>
<th></th>
<th>B7</th>
<th>L7</th>
<th>B7M/L7M</th>
<th>L43</th>
</tr>
</thead>
<tbody>
<tr>
<td>105 Minimum Yield, 35 HRC Max, not impact tested</td>
<td>105 Minimum Yield, 35 HRC Max, impact tested</td>
<td>Minimum Yield strength is 80,000 psi but requirement varies with diameter</td>
<td>105 Minimum Yield, 35 HRC Max, not impact tested</td>
<td></td>
</tr>
<tr>
<td>Generally suitable for land and subsea with CP applications where low temperature is not anticipated on the design.</td>
<td>Generally suitable for land and subsea with CP applications.</td>
<td>Generally suitable for land and subsea with CP applications.</td>
<td>Generally suitable for land and subsea with CP applications.</td>
<td></td>
</tr>
<tr>
<td>Can be used as closure bolting including in sour service applications where bolting is not directly exposed to the environment and hydrogen has means of escaping to the environment (See NACE MR0175). Since impact testing is not required, L7 is generally a better option for this application.</td>
<td>Can be used as closure bolting including in sour service applications where bolting is not directly exposed to the environment and hydrogen has means of escaping to the environment (See NACE MR0175).</td>
<td>Bolting to this grades is suitable for sour service environments</td>
<td>Can be used as closure bolting excluding sour service applications.</td>
<td></td>
</tr>
<tr>
<td>Can be used in primary load path components for designs where low temperature is not an issue, but it is considered better suited for structural bolting not in the primary load path due to lack of impact test requirements.</td>
<td>Can be used in primary load path components.</td>
<td>L7M and B7M may both be used in primary load path; however, L7M is impact tested for low temperature service.</td>
<td>Can be used in primary load path components.</td>
<td></td>
</tr>
<tr>
<td>For most applications B7 will require a barrier coating against environment both for shelf life and service environments.</td>
<td>For most applications L7 will require a barrier coating against environment both for shelf life and service environments.</td>
<td>For most applications, these grades will require a barrier coating against environment both for shelf life and service environments.</td>
<td>For most applications L43 will require a barrier coating against environment both for shelf life and service environments.</td>
<td></td>
</tr>
<tr>
<td>B7 Bolting is not recommended when the design requires the fasteners to exceed 2.5 inches in diameter. It is generally recommended to use L43, or to specify a B7 composition with a minimum ideal diameter for the size of the fastener.</td>
<td>L7 Bolting is not recommended when the design requires the fasteners to exceed 2.5 inches in diameter. It is generally recommended to use L43, or to specify an L7 composition with a minimum ideal diameter for the size of the fastener.</td>
<td>The properties of these grades may degrade in larger diameter due to alloy content. For larger diameter bolting, adjusting the ideal diameter (by composition) may be necessary.</td>
<td>Due to its alloy composition, L43 is very well suited for low temperature applications and for bolting in which diameter exceeds 2.5 inches.</td>
<td></td>
</tr>
<tr>
<td>Special measures are required to minimize risk of hydrogen embrittlement when exposed to environments which produce hydrogen ions, such as plating, phosphating or some chemical cleaning operations; these can be</td>
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<td></td>
<td>Special measures are required to minimize risk of hydrogen embrittlement when exposed to environments which produce hydrogen ions, such as plating, phosphating or some chemical cleaning operations; these can be alleviated by Hydrogen bake out.</td>
<td></td>
</tr>
</tbody>
</table>
Table 2 – Carbon and Low Alloy Steel Bolting Selection Guide and Limitations

<table>
<thead>
<tr>
<th>ASTM A453 Gr 660D</th>
<th>Alloy 718</th>
</tr>
</thead>
<tbody>
<tr>
<td>105Ksi Minimum Yield, 24 – 35 HRC Hardness range</td>
<td>120Ksi Minimum Yield, 40 HRC Max,</td>
</tr>
<tr>
<td>Generally suitable for land and subsea with CP applications.</td>
<td>Generally suitable for land and subsea with CP applications, but mostly used in aggressive environments where high strength and resistance to general corrosion is required.</td>
</tr>
<tr>
<td>Can be used in primary load path components.</td>
<td>Suitable for sour service applications provided it is in compliance with NACE MR0175</td>
</tr>
<tr>
<td>Gr 660 bolting should be made from material made in accordance with API Standard 6ACRA.</td>
<td>Alloy 718 bolting should be made from material made in accordance with API Standard 6ACRA.</td>
</tr>
</tbody>
</table>

Table 3 – CRA Bolt Selection Guide and Limitations

NOTE The Bolting Selection Guide tables are not inclusive of all available bolting, and are only to be used as guidelines. These tables are not intended to supersede requirements from applicable specifications and or construction codes.
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[16] ASTM E45-05, Standard Test Methods for Determining the Inclusion Content of Steel
[18] ASTM E1268, Standard Practice for Assessing the Degree of Banding or Orientation of Microstructures
[21] SAE AMS2300, Steel Cleanliness, Premium Aircraft-Quality Magnetic Particle Inspection Procedure
[22] SAE AMS2301, Steel Cleanliness, Aircraft Quality Magnetic particle Inspection Procedure
[23] SAE AMS2304, Special Aircraft-Quality Steel Cleanliness Magnetic Particle Inspection Procedure

4 American Society of Mechanical Engineers, Two Park Avenue, New York, NY 10016-5990.
5 ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA, 19428-2959.
6 NACE International, 15805 Park Ten Place, Houston, TX, 77084.
7 SAE International, 400 Commonwealth Drive, Warrendale, PA, 15096.