All fastened joints are, to some extent, subjected to corrosion of some form during normal service life. Design of a joint to prevent premature failure due to corrosion must include considerations of the environment, conditions of loading, and the various methods of protecting the fastener and joint from corrosion.

Three ways to protect against corrosion are:

1. Select corrosion-resistant material for the fastener.
2. Specify protective coatings for fastener, joint interfaces, or both.
3. Design the joint to minimize corrosion.

The solution to a specific corrosion problem may require using one or all of these methods. Economics often necessitate a compromise solution.

**Fastener Material**

The use of a suitably corrosion-resistant material is often the first line of defense against corrosion. In fastener design, however, material choice may be only one of several important considerations. For example, the most corrosion-resistant material for a particular environment may just not make a suitable fastener.

Basic factors affecting the choice of corrosion-resistant threaded fasteners are:

- Tensile and fatigue strength.
- Position on the galvanic series scale of the fastener and materials to be joined.
- Special design considerations: Need for minimum weight or the tendency for some materials to gall.
- Susceptibility of the fastener material to other types of less obvious corrosion. For example, a selected material may minimize direct attack of a corrosive environment only to be vulnerable to fretting or stress corrosion.

Some of the more widely used corrosion-resistant materials, along with approximate fastener tensile strength ratings at room temperature and other pertinent properties, are listed in Table 1. Sometimes the nature of corrosion properties provided by these fastener materials is subject to change with application and other conditions. For example, stainless steel and aluminum resist corrosion only so long as their protective oxide film remains unbroken. Alloy steel is almost never used, even under mildly corrosive conditions, without some sort of protective coating. Of course, the presence of a specific corrosive medium requires a specific corrosion-resistant fastener material, provided that design factors such as tensile and fatigue strength can be satisfied.

**Protective Coating**

A number of factors influence the choice of a corrosion-resistant coating for a threaded fastener. Frequently, the corrosion resistance of the coating is not a principal consideration. At times it is a case of economics. Often, less-costly fastener material will perform satisfactorily in a corrosive environment if given the proper protective coating.

Factors which affect coating choice are:

- Corrosion resistance
- Temperature limitations
- Embrittlement of base metal
- Effect on fatigue life
- Effect on locking torque
- Compatibility with adjacent material
- Dimensional changes
- Thickness and distribution
- Adhesion characteristics

**Conversion Coatings:** Where cost is a factor and corrosion is not severe, certain conversion-type coatings are effective. These include a black-oxide finish for alloy-steel screws and various phosphate base coatings for carbon and alloy-steel fasteners. Frequently, a rust-preventing oil is applied over a conversion coating.

**Paint:** Because of its thickness, paint is normally not considered for protective coatings for mating threaded fasteners. However, it is sometimes applied as a supplemental treatment at installation. In special cases, a fastener may be painted and installed wet, or the entire joint may be sealed with a coat of paint after installation.

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**TABLE 1 – TYPICAL PROPERTIES OF CORROSION RESISTANT FASTENER MATERIALS**

<table>
<thead>
<tr>
<th>Materials Stainless Steels</th>
<th>Tensile Strength (1000 psi)</th>
<th>Yield Strength at 0.2% offset (1000 psi)</th>
<th>Maximum Service Temp (F)</th>
<th>Mean Coefficient of Thermal Expansion (in./in./deg F)</th>
<th>Density (lbs/cu in.)</th>
<th>Base Cost Index</th>
<th>Position on Galvanic Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>303, passive</td>
<td>80</td>
<td>40</td>
<td>800</td>
<td>10.2</td>
<td>0.286</td>
<td>Medium</td>
<td>8</td>
</tr>
<tr>
<td>303, passive, cold worked</td>
<td>125</td>
<td>80</td>
<td>800</td>
<td>10.3</td>
<td>0.286</td>
<td>Medium</td>
<td>9</td>
</tr>
<tr>
<td>410, passive</td>
<td>170</td>
<td>110</td>
<td>400</td>
<td>5.6</td>
<td>0.276</td>
<td>Low</td>
<td>15</td>
</tr>
<tr>
<td>431, passive</td>
<td>180</td>
<td>140</td>
<td>400</td>
<td>6.7</td>
<td>0.280</td>
<td>Medium</td>
<td>16</td>
</tr>
<tr>
<td>17-4 PH</td>
<td>200</td>
<td>180</td>
<td>600</td>
<td>6.3</td>
<td>0.282</td>
<td>Medium</td>
<td>11</td>
</tr>
<tr>
<td>17-7 PH</td>
<td>200</td>
<td>185</td>
<td>600</td>
<td>6.7</td>
<td>0.276</td>
<td>Medium</td>
<td>14</td>
</tr>
<tr>
<td>AM 350</td>
<td>200</td>
<td>162</td>
<td>800</td>
<td>7.2</td>
<td>0.282</td>
<td>Medium</td>
<td>13</td>
</tr>
<tr>
<td>15-7 Mo</td>
<td>200</td>
<td>155</td>
<td>600</td>
<td>–</td>
<td>0.277</td>
<td>Medium</td>
<td>12</td>
</tr>
<tr>
<td>A-286</td>
<td>150</td>
<td>85</td>
<td>1200</td>
<td>9.72</td>
<td>0.286</td>
<td>Medium</td>
<td>6</td>
</tr>
<tr>
<td>A-286, cold worked</td>
<td>220</td>
<td>170</td>
<td>1200</td>
<td>–</td>
<td>0.286</td>
<td>High</td>
<td>7</td>
</tr>
</tbody>
</table>
**Electroplating:** Two broad classes of protective electroplating are: 1. The barrier type—such as chrome plating—which sets up an impervious layer or film that is more noble and therefore more corrosion resistant than the base metal. 2. The sacrificial type, zinc for example, where the metal of the coating is less noble than the base metal of the fastener. This kind of plating corrodes sacrificially and protects the fastener.

Noble-metal coatings are generally not suitable for threaded fasteners especially where a close-tolerance fit is involved. To be effective, a noble-metal coating must be at least 0.001 in. thick. Because of screw-thread geometry, however, such plating thickness will usually exceed the tolerance allowances on many classes of fit for screws.

Because of dimensional necessity, threaded fastener coatings, since they operate on a different principle, are effective in layers as thin as 0.0001 to 0.0002 in.

The most widely used sacrificial platings for threaded fasteners are cadmium, zinc, and tin. Frequently, the cadmium and zinc are rendered even more corrosion resistant by a post-dipping-chrome-type conversion treatment. Cadmium plating can be used at temperatures to 450°F. Above this limit, a nickel cadmium or nickel-zinc alloy plating is recommended. This consists of alternate deposits of the two metals which are heat-diffused into a uniform alloy coating that can be used for applications to 900°F. The alloy may also be deposited directly from the plating bath.

Fastener materials for use in the 900 to 1200°F range (stainless steel, A-286), and in the 1200°F to 1800°F range (high-nickel-base super alloys) are highly corrosion resistant and normally do not require protective coatings, except under special environment conditions.

Silver plating is frequently used in the higher temperature ranges for lubrication to prevent galling and seizing, particularly on stainless steel. This plating can cause a galvanic corrosion problem, however, because of the high nobility of the silver.

**Hydrogen Embrittlement:** A serious problem, known as hydrogen embrittlement, can develop in plated alloy steel fasteners. Hydrogen generated during plating can diffuse into the steel and embrittle the bolt. The result is often a delayed and total mechanical failure, at tensile stress levels far below the theoretical strength, high-hardness structural parts are particularly susceptible to this condition. The problem can be controlled by careful selection of plating formulation, proper plating procedure, and sufficient baking to drive off any residual hydrogen.

Another form of hydrogen embrittlement, which is more difficult to control, may occur after installation. Since electrolytic cell action liberates hydrogen at the cathode, it is possible for either galvanic or concentration-cell corrosion to lead to embrittlement of the bolt material.

**Joint Design**

Certain precautions and design procedures can be followed to prevent, or at least minimize, each of the various types of corrosion likely to attack a threaded joint. The most important of these are:

- **For Direct Attack:** Choose the right corrosion-resistant material. Usually a material can be found that will provide the needed corrosion resistance without sacrifice of other important design requirements. Be sure that the fastener material is compatible with the materials being joined.

  Corrosion resistance can be increased by using a conversion coating such as black oxide or a phosphate-base treatment. Alternatively, a sacrificial coating such as zinc plating is effective.

  For an inexpensive protective coating, lacquer or paint can be used where conditions permit.

- **For Galvanic Corrosion:** If the condition is severe, electrically insulate the bolt and joint from each other.

  The fastener may be painted with zinc chromate primer prior to installation, or the entire joint can be coated with lacquer or paint.

  Another protective measure is to use a bolt that is cathodic to the joint material and close to it in the galvanic series. When the joint material is anodic, corrosion will spread over the greater area of the fastened materials. Conversely, if the bolt is anodic, galvanic action is most severe.

**For Concentration-Cell Corrosion:** Keep surfaces smooth and minimize or eliminate lap joints, crevices, and seams. Surfaces should be clean and free of organic material and dirt. Air trapped under a speck of dirt on the surface of the metal may form an oxygen concentration cell and start pitting.

For maximum protection, bolts and nuts should have smooth surfaces, especially in the seating areas. Flush-head bolts should be used where possible. Further, joints can be sealed with paint or other sealant material.

**For Fretting Corrosion:** Apply a lubricant (usually oil) to mating surfaces. Where fretting corrosion is likely to occur: 1. Specify materials of maximum practicable hardness. 2. Use fasteners that have residual compressive stresses on the surfaces that may be under attack. 3. Specify maximum preload in the joint. A higher clamping force results in a more rigid joint with less relative movement possible between mating services.

![FIG. 1.1 – A method of electrically insulating a bolted joint to prevent galvanic corrosion.](image)
For Stress Corrosion: Choose a fastener material that resists stress corrosion in the service environment. Reduce fastener hardness (if reduced strength can be tolerated), since this seems to be a factor in stress corrosion.

Minimize crevices and stress risers in the bolted joint and compensate for thermal stresses. Residual stresses resulting from sudden changes in temperature accelerate stress corrosion.

If possible, induce residual compressive stresses into the surface of the fastener by shot-peening or pressure rolling.

For Corrosion Fatigue: In general, design the joint for high fatigue life, since the principal effect of this form of corrosion is reduced fatigue performance. Factors extending fatigue performance are: 1. Application and maintenance of a high preload. 2. Proper alignment to avoid bending stresses.

If the environment is severe, periodic inspection is recommended so that partial failures may be detected before the structure is endangered.

As with stress and fretting corrosion, compressive stresses induced on the fastener surfaces by thread rolling, fillet rolling, or shot peening will reduce corrosion fatigue. Further protection is provided by surface coating.

TYPES OF CORROSION

Direct Attack...most common form of corrosion affecting all metals and structural forms. It is a direct and general chemical reaction of the metal with a corrosive medium-liquid, gas, or even a solid.

Galvanic Corrosion...occurs with dissimilar metals contact. Presence of an electrolyte, which may be nothing more than an individual atmosphere, causes corrosive action in the galvanic couple. The anodic, or less noble material, is the sacrificial element. Hence, in a joint of stainless steel and titanium, the stainless steel corrodes. One of the worst galvanic joints would consist of magnesium and titanium in contact.

Concentration Cell Corrosion...takes place with metals in close proximity and, unlike galvanic corrosion, does not require dissimilar metals. When two or more areas on the surface of a metal are exposed to different concentrations of the same solution, a difference in electrical potential results, and corrosion takes place.

If the solution consists of salts of the metal itself, a metal-ion cell is formed, and corrosion takes place on the surfaces in close contact. The corrosive solution between the two surfaces is relatively more stagnant (and thus has a higher concentration of metal ions in solution) than the corrosive solution immediately outside the crevice.

A variation of the concentration cell is the oxygen cell in which a corrosive medium, such as moist air, contains different amounts of dissolved oxygen at different points. Accelerated corrosion takes place between hidden surfaces (either under the bolt head or nut, or between bolted materials) and is likely to advance without detection.

Fretting...corrosive attack or deterioration occurring between containing, highly-loaded metal surfaces subjected to very slight (vibratory) motion. Although the mechanism is not completely understood, it is probably a highly accelerated form of oxidation under heat and stress. In threaded joints, fretting can occur between mating threads, at the bearing surfaces under the head of the screw, or under the nut. It is most likely to occur in high tensile, high-frequency, dynamic-load applications. There need be no special environment to induce this form of corrosion...merely the presence of air plus vibratory rubbing. It can even occur when only one of the materials in contact is metal.

Stress Corrosion Cracking...occurs over a period of time in high-stressed, high-strength joints. Although not fully understood, stress corrosion cracking is believed to be caused by the combined and mutually accelerating effects of static tensile stress and corrosive environment. Initial pitting somehow takes place which, in turn, further increases stress build-up. The effect is cumulative and, in a highly stressed joint, can result in sudden failure.

Corrosion Fatigue...accelerated fatigue failure occurring in the presence of a corrosive medium. It differs from stress corrosion cracking in that dynamic alternating stress, rather than static tensile stress, is the contributing agent.

Corrosion fatigue affects the normal endurance limit of the bolt. The conventional fatigue curve of a normal bolt joint levels off at its endurance limit, or maximum dynamic load that can be sustained indefinitely without fatigue failure. Under conditions of corrosion fatigue, however, the curve does not level off but continues downward to a point of failure at a finite number of stress cycles.
GALVANIC CORROSION

FIG. 19 – Metals compatibility chart