Corrosion Resistance of Bolt Coatings

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Hot-Dip Galvanizing

Batch hot-dip galvanizing has been the most commonly used method of protecting steel products from corrosion. The reasons are simple – hot-dip galvanizing (HDG) process has been around for over 200 years, it is well known and understood, it can be well controlled, and it is relatively cheap. What is most important for many industries, however, is excellent corrosion protection that HDG coating provides for steel structures exposed to harsh environments. Bridge, highway, electrical utility, industrial and marine construction projects have all realized the benefits of hot-dip galvanizing. This type of coating is relatively maintenance-free and can commonly prevent corrosion of steel structures for 25 to 75 years in most atmospheric environments (industrial, urban, marine, and rural) with millions of successful projects as a proof of this claim.

Batch hot-dip galvanizing process consists of a number of steps that involve cleaning of the steel parts that produces chemically clean metallic surface and removes surface oxides and then immersing them into a molten zinc bath. During this stage of the process, zinc metallurgically bonds to the steel, creating a series of highly abrasion-resistant zinc-iron intermetallic layers, commonly topped by a layer of impact-resistant pure zinc. After the parts are withdrawn from the galvanizing bath, excess zinc is removed by draining, vibrating or – for small items – centrifuging. The galvanized items are then air-cooled or quenched in liquid.

Hot-dip galvanized coatings are known to provide two types of corrosion protection for steel: barrier and galvanic (cathodic). First, almost like paint, protects steel by means of a semi-impermeable barrier to environment elements that cause corrosion. In addition, presence of zinc in HDG coatings activates cathodic shielding mechanism. Zinc is more electro-negative (i.e. more reactive) than steel, thus when the two are in contact in presence of electrolyte (moisture), it stops normal corrosion of steel by donating its electrons to prevent steel from losing its electrons. In other words, zinc “sacrifices” itself in order to protect steel from corroding. However, because the rate of corrosion of zinc is at least 10 times slower than that of steel, a thin coating of zinc can protect steel for a long time.

Figure 1. Service-life chart for hot-dip galvanized coatings.¹
Although, as mentioned above, hot-dipped galvanized coating provides excellent corrosion protection to steel structures, it becomes less impressive when used on fasteners. The main drawback is the thickness of the HDG coating. Typical coating thickness on bolts can range from 45 to 90 μm (1.8 to 3.5 mils), which can make standard bolt and nut tolerances difficult to maintain for correct assembly. If bolts are galvanized, then the nuts should be oversized to accommodate the 90 to 180 μm (3.6 to 7.0 mils) increase in bolt diameter after galvanizing. If this is not done, then assembly of the fastener system will either become impossible or will result in zinc coating being scraped off the thread surface. Either scenario is unacceptable. In addition, depending on thread pitch of a fastener, HDG process can often result in non-uniform coating thickness on the threads with thicker coat in the “valleys” and thinner coat in the “peaks” of the thread. This can also result in the coating being removed during fastener assembly.

To minimize this drawback hot-dip galvanized nuts are re-tapped or rethreaded to remove the zinc coating and provide clearance for the coated bolt. When such fastener system is assembled, the coating from the bolt is expected to provide galvanic (cathodical) protection for the uncoated nut thread as discussed above. The re-tapping is done on the nut side, as shown in Figure 2, so that no uncoated threads on the bolts are exposed to environment without galvanized protection. A standard practice in fastener industry is to galvanize nut blanks and then to tap the threads after galvanizing. This approach, however, opens up a possibility for development of corrosion cells on nut threads if the proper clearance between nuts and bolts is not maintained well or if HDG coating thickness on bolt threads is not consistent.

In addition, when it comes to hot-dip galvanizing fasteners, there are a few more drawbacks:

- High variability in the relationship between torque and induced tension. Because of this, torque cannot be used as a reliable method for gauging the required minimum bolt tension. High friction of galvanized surfaces and inconsistent torque-tension relationship result in high rate of bolt failures in torsion.

- Second drawback concerns high-strength bolts. Since the 1970s, ASTM A490 standard prohibited the application of metallic coatings on high-strength structural bolts. At the heart of the prohibition was the attempt to eliminate the risk of hydrogen embrittlement. This phenomenon may occur when atomic hydrogen is absorbed by high-strength steel during the acid cleaning process that takes place prior to galvanizing. This leads to significant decrease in ductility of the bolts and permit brittle cracks to grow at fairly low stress levels.

- There is an environmental concern related to hot-dip galvanized products. Hexavalent chromium Cr\(^{6+}\) is found in the acid used in hot-dip galvanizing quench baths and in a solution that is used to prevent wet storage stains on HDG parts. Cr\(^{6+}\) is the most toxic
form of chromium, and its aggressive oxidizing behavior makes exposure to Cr$_{6}^{+}$ a dangerous health risk. A person can be exposed to chromium by eating or drinking contaminated products or breathing contaminated air, by skin contact, etc. Large amounts of chromium can cause serious health problems. In 2006 the RoHS Directive went into effect in the European Union. This document restricts the use of six hazardous materials in the manufacture of various types of electronic and electrical equipment. Hexavalent chromium is among restricted materials. In 2007 European automakers banned using Cr$_{6}^{+}$-coated fasteners in the cars made in Europe, and North American manufacturers are adopting these standards.

**Mechanical Galvanizing**

In an attempt to address aforementioned concerns a process of mechanical galvanizing had been developed. Mechanical galvanizing (MG) is similar to hot-dip galvanizing in that it also applies a coating of zinc on top of bare steel. During MG process fasteners are placed in a large rotary barrel along with zinc powder, special promoters, and glass impact beads. The mechanical energy generated from the barrel’s rotation is transmitted to the glass beads that bombard fastener surface with zinc particles. This causes zinc powder to be mechanically welded to the surface of the fasteners. With a proper glass bead size mix all exposed surfaces can be coated uniformly, and the buoyancy of the glass beads cushions the fasteners in the rotating barrel to minimize thread nicking.

In contrast to HDG fasteners, mechanically galvanized nuts are tapped oversized prior to coating which results in their threads to be coated during the MG process. However, MG plating consists of round particles of zinc loosely bonded together which is believed to be orders of magnitude weaker than the metallurgical bond found in hot-dip galvanized coating. This, in turn, raises concerns about adhesion strength of MG coating. Also, depending on fastener thread pitch and size of glass beads used in MG process, the resulting coating thickness in the thread area can be non-uniform, with “peaks” and “valleys” having thinner than expected coating. These factors might affect long-term corrosion resistance of fasteners.

**GEOMET®**

GEOMET® is a next-generation non-electrolytically applied chromium-free coating developed by Metal Coatings International. It was developed with fastener industry in mind, to address abovementioned drawbacks of hot-dip galvanized and mechanically galvanized structural components. GEOMET® is a proprietary water-based coating dispersion containing metal oxides, metallic zinc and aluminum flakes. The zinc and aluminum platelets align in multiple layers forming a metallic silver-gray coating. Applied as a liquid, the coating becomes totally inorganic after curing at 575-600° F (300-315°C). Below are some features of GEOMET® coating:

- **Excellent Corrosion Protection** – combination of aluminum and zinc provides bimetallic corrosion protection, superior to that of HDG and MG coatings. In addition to barrier and galvanic (cathodic) corrosion protection of galvanized coatings,
GEOMET® coating contain metal oxides which slow down the corrosion reaction of zinc and steel. This results in 3-times greater corrosion protection than pure zinc.

- **Thin Film** - GEOMET® coating is about 10 times thinner than hot-dip galvanized coating. Nut oversizing might not be required.
- **Environmentally Safe** – does not contain any chromium in the solution during coating process or on finished parts. Does not contain any toxic metals, water based.
- **Hydrogen Embrittlement Free Process** – in contrast to hot-dip galvanizing process, GEOMET® coating application process does not require steps that lead to hydrogen embrittlement
- **Solvent Resistant** - inorganic nature of GEOMET® coating causes it to be resistant to organic solvent
- **Heat Resistant** - maintains corrosion resistance even following a heat shock of 3 hours at 550° F (288° C)
- **Conductive** - concentration of metallic flake allows an electrical current to be passed to the substrate

In addition to plain GEOMET® coating, several PLUS® sealers can be applied to the GEOMET®-coated product. These sealers add lubricity to the coating, provide consistent torque/tension values, increase mar resistance and barrier protection, and provide additional barrier corrosion protection to the base metal.

**Corrosion Resistance Testing**

To compare corrosion resistance of fastener coatings discussed in this paper, ASTM B117 salt spray test was used. Currently, this test is the *de facto* industry standard for accelerated corrosion testing of different metallic coatings. The samples are inserted into the temperature-controlled chamber and the 5% salt (sodium chloride – NaCl) salt solution is sprayed as a very fine fog mist over the samples at a constant temperature. Since the spray
is continuous, the samples are constantly wet and, therefore, are constantly subjected to corrosion.

The following coatings were tested:
- Hot-dip galvanized
- Mechanically galvanized + 1 mil thick ZinKlad® – MG coating with a top coat
- Mechanically galvanized + 2 mil thick Polytetrafluoroethylene (PTFE)– MG coating with another top coat
- GEOMET® PLUS® L - GEOMET® coating with a PLUS® sealant
- GEOMET® PLUS® XL - GEOMET® coating with another PLUS® sealant

After 1000 hours of salt spray test:
Application Example

Bolts with corrosion-protective coating are used in multiple products developed at Tyco Electronics. We investigated the use of bolts with coatings discussed in this paper for a Transverse Wedge Connector. This product is used in Power Utility Industry to connect power line wires and for this type of connector corrosion resistance is very important. Again, ASTM B117 salt spray test was used to compare the bolt resistance to corrosion. Images below summarize test results after 1000 hours in a salt-spray chamber. Both hot-dip galvanized and mechanically galvanized bolts were removed from the test after 750 hours because of excessive corrosion.
Conclusion

Several bolt coatings were investigated and compared in their corrosion resistance properties. “Industry standard” hot-dip galvanized coating and mechanically galvanized coating were compared to relatively new chromium-free coatings of GEOMET® family. It was found that bolts coated with GEOMET® finish by far outperformed galvanized bolts in salt spray test. GEOMET® coated bolts did not exhibit any corrosion after 1000 hours in a salt spray chamber neither by themselves or in an assembled Transverse Wedge Connector system. Galvanized bolts, on the other hand, severely corroded even after 750 hours in the salt spray chamber.

References