

Corrosion Resistant Coating Systems: UV Cured "Liquid Powders"

By

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ABSTRACT

This paper presents a unique new corrosion resistant coating system that combines mechanical and chemical properties to achieve superior anti-corrosive and chemical resistant performance. Unlike conventional primer and topcoat systems, this two-coat system incorporates the use of an engineered tiecoat and topcoat. The semi-soft tiecoat combines chemical protection with enhanced adhesion and flexibility resulting in a stable surface to which the engineered topcoat is applied and bonded. The topcoat is engineered for additional chemical resistance, mechanical properties and aesthetic requirements.

Corrosion resistance test data and field data will be presented along with an examination of secondary and tertiary advantages realized in the implementation and use of this coating system.

INTRODUCTION

UV curable coatings are polymeric coatings that are:

- A. Applied as a liquid at room temperature;
- B. Solidified nearly instantaneously upon exposure to UV light into a protective coating, and;
- C. Capable of “lock-and-key” engineering of their physical properties.

Previously UV coating systems were not known for their anti-corrosive properties. However, recent investigations into multiple coat ‘lock-and-key’ coating systems have resulted in significant advances in the development of anti-corrosive UV curable coatings.

A full understanding of the root causes of corrosion is necessary prior to examining and understanding the anti-corrosive lock-and-key mechanism of the tiecoat/topcoat UV coating system.

Universally, the first step in corrective action is to identify the cause of the problem. As such, we must first ask the question: “what is corrosion?” This simple question will yield many answers depending on who you ask. Some forms of corrosion have and will effect everyone who uses manufactured metal products. Corrosion on this planet is so universal that it is simply viewed as a constant to be dealt with by using effective preventative measures.

Metal corrosion poses an interesting paradox. The business of corrosion control is large, however, not as large as the business of replacing corroded metal goods. The world economy simply could not survive without the effects of corrosion. How long would automotive companies fare if automobiles stopped rusting? How long would companies stay in business if manufactured metal goods no longer had to be replaced due to corrosion? Fortunately, corrosion can be controlled, but it can not be eliminated.

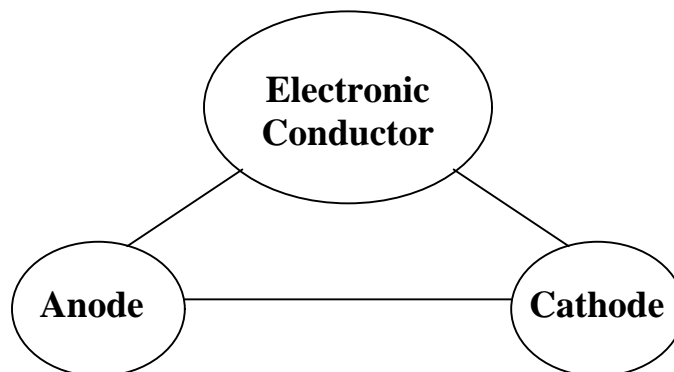
This paper will concern itself with common, ambient terrestrial forms of metallic corrosion and will not contemplate such unusual corrosive systems such as High Vacuum or Ultra High Vacuum electrochemistry, high energy oxygen (a space craft consideration) or other non-metallic ‘corrosion’ systems.

METALLIC CORROSION

Oxygen, the life giving element which allows us to live comprises 21% of the atmosphere which we breathe. Eliminate this highly corrosive element from the atmosphere and you effectively solve all corrosion problems – and complaints. As this is not a viable solution, we must face the fact that except for gold, platinum and palladium, all metals spontaneously corrode in this planet’s atmosphere.

Corrosion is essentially an electrochemical phenomenon. Hence, corrosion is effectively an inefficient battery. This allows us to examine corrosion in terms of ‘half-cell’ reactions. One half-cell focuses on the anode and the other half-cell on the cathode. Together the two half cells describe the total corrosive (electrochemical/battery) system.

At times this model of examining corrosion may not be obvious because such electrochemical cells may be microscopic (see pitting corrosion) in manifestation and occur anywhere the three requisite factors for corrosion exist:



A ‘corrosion cell’ is created where all three factors of corrosion are present. Once a corrosion cell is created, an electric current will flow and metal will be consumed (corroded) at the anode. The rate of corrosion is directly proportional to the rate of current flow. Remove any one of the above three factors and corrosion is effectively stopped. Reduce the activity of anyone of the three corrosive factors and corrosion is correspondingly reduced.

The most commonly encountered corrosion system on this planet is that of Iron. Buried iron pipes rust with time, however the rate of corrosion is not necessarily constant along the length of a pipeline. The iron pipe itself acts as anode and cathode while moisture in the soil acts as the ionic conductor (usually as an aqueous film containing ions on the pipe’s surface).

As the iron pipe corrodes, the iron is converted to an oxide which is dissolved into the surrounding ground. In this system there are three possible cathodic reductions: water, oxygen and the hydrogen ion.

The following example illustrates how Electrochemical half cell reaction equations may be used to determine the parameters for corrosion associated with buried iron pipes.

If a sample of the soil in which the pipe is buried has a pH of 6, then the corrosion reaction is:



By using physical constants tables to look-up the electrical potential for iron under these conditions, the equilibrium constant favors the reaction direction as the following calculations show:

$$E(\text{Fe}) = -0.44 - 0.03 \log ([\text{Fe}]/[\text{Fe}_2^+]) = -0.44 + 0.03 \log [\text{Fe}_2^+]$$

Where:

[Fe] = The concentration of iron ground state atoms, and;

[Fe₂⁺] = The concentration of iron ions

$$E(\text{H}_2) = 0 - 0.03 \log ([\text{H}_2]/[\text{H}^+]^2)$$

Where:

[H₂] = Concentration of hydrogen gas, and;

[H⁺] = Concentration of hydrogen ions

Since the potential of the iron couple, E(Fe), at equilibrium must be equal to the potential of the hydrogen ion/hydrogen couple E(H₂),

$$-0.44 = -0.03 \log ([\text{H}_2][\text{Fe}_2^+] / [\text{H}^+]^2)$$

$$14.7 = \log ([\text{H}_2][\text{Fe}_2^+]) - \log (1 \times 10^{-12}); 2.7 = \log (p(\text{H}_2)[\text{Fe}_2^+])$$

This can only be true if both p(H₂) and [Fe₂⁺] are high, since their product is about 500. In any acidic soil, then, the spontaneous process is the corrosion of metallic iron which produces gaseous hydrogen and water soluble Fe₂⁺ ions. The hydrogen gas is lost to the atmosphere while the Fe₂⁺(aq) dissolves away into the surrounding soil.¹

It is not necessary to have two dissimilar metals to create a cathode and anode. Even though there is a single metallic body, different areas of the metal surface will effectively act as cathode and anode by virtue of differences in localized ion concentrations in the water film on the metal surface (See: Concentration Cell Corrosion). The electrical potential between such areas, which are anodic and cathodic in nature, results in a migration of electrons from the anode to the cathode along the conductive path. In this case the aqueous film on the iron surface.

The loss of electrons at the anode causes positively charged iron atoms to remain which combine with negatively charged (OH⁻) ions in the environment to form ferrous hydroxide, which in turn usually reacts further to form ferric hydroxide (rust). The (OH⁻) comes from the water (H₂O) which was consumed to produce hydrogen gas.

Thus, corrosion of buried pipe will vary directly with variation of the soil pH in which the pipe is buried. Similar model calculations can be done for corrosion of other metals.

The cathode, having a surplus of electrons from the anode causes gaseous hydrogen (H₂) gas to form from the positively charged hydrogen ions near the cathode (See Hydrogen Embrittlement). The following points should be remembered in terms of conventional current flow:

- A. In the electrolyte (aqueous film), electrical current flows from the anode to the cathode;
- B. In the metal, electrical current flows from the cathode to the anode;
- C. Metal corrodes where electrical current leaves the metal (anode) and enters the electrolyte;
- D. Metal receiving electrical current (cathode) from the electrolyte does not corrode.

COMMON TYPES OF CORROSION CELLS²

CONCENTRATION CELL CORROSION

Concentration cell corrosion occurs when two or more areas of a metal surface are in contact with different concentrations of the same aqueous solution. There are three general types of concentration cell corrosion:

- A. Metal Ion Concentration Cells;
- B. Oxygen Concentration Cells, and;
- C. Active-Passive Cells.

METAL ION CONCENTRATION CELLS

In the presence of water, a high concentration of metal ions will exist under layered metallic surfaces and a low concentration of metal ions will exist adjacent to the crevice created by the layered surfaces. The ionic gradient creates an electrical potential between the two points. The cathode (area of the metal in contact with the low concentration of metal ions) will be protected, and the anode (area of metal in contact with the high metal ion concentration) will be corroded. (See Pitting Corrosion)

OXYGEN CONCENTRATION CELLS

Water normally contains dissolved oxygen. An oxygen cell can develop at any point where ambient oxygen is prevented from diffusing uniformly into the aqueous solution, thereby creating an oxygen concentration gradient between two points. Oxygen concentration cells are typically found under either metallic or nonmetallic deposits (dirt) on metal surfaces and under layered surfaces such as riveted lap joints. Oxygen cells can also develop under gaskets, wood, rubber, plastic tape, and other materials in contact with the metal surface. Corrosion will occur at the area of low-oxygen concentration (anode).

ACTIVE-PASSIVE CELLS

Active-passive cells can corrode metals that depend on a tightly adhering passivating film (usually an oxide) for corrosion protection. The corrosive action usually starts as an oxygen concentration cell. Salt deposits on the metal surface in the presence of water containing oxygen can create the oxygen cell. If the passive film is flawed during application creating holidays or breached during use beneath the salt deposit, the active metal beneath the film will be exposed to corrosive attack. An electrical potential will develop between the large area of the cathode (passive film) and the small area of the anode (active metal). In the case of passivating oxide films, rapid pitting of the active metal will result, or if the protective film is flexible, blistering of the protective film will result.

COMMON MANIFESTATIONS OF CORROSION³

CORROSION FATIGUE

(A.K.A. STRESS CORROSION CRACKING)

Corrosion fatigue, or Stress Corrosion Cracking (SCC) is a special case of stress corrosion caused by the simultaneous effects of tensile stress (i.e. applied loads, residual manufacturing stresses, or combination of both) and corrosive environment. No metal is immune from some loss of its resistance to cyclic stressing if the metal is in a corrosive environment. Damage from corrosion fatigue is greater than the sum of damage caused from cyclic stresses and corrosive environment independently.

CREVICE CORROSION

(A.K.A. CONTACT CORROSION)

Crevice corrosion is produced at the contact point of metals with metals or metals with nonmetals. It may occur at washers, under barnacles, at sand grains, under applied protective films, and at pockets formed by threaded joints. Whether or not stainless steels are free of pit nuclei, they are always susceptible to this kind of corrosion because a nucleus is not necessary. See Common types of Corrosion Cells for specific types of crevice corrosion.

DE-ALLOYING

De-Alloying is a rare form of corrosion found in alloys such as copper alloys, gray cast iron, and other alloys. De-Alloying occurs when the alloy loses the active component of the metal and retains the more corrosion resistant component in a porous "sponge" on the metal surface. It can also occur by re-deposition of the noble component of the alloy on the metal surface. Also see Galvanic Corrosion.

EXFOLIATION CORROSION

Exfoliation, a form of intergranular corrosion, manifests from the forced displacement of surface metal grains by expanding corrosion products occurring at the grain boundaries just below the surface. It is visible evidence of intergranular corrosion and is most often seen on extruded sections where grain thickness is less than in rolled forms. This form of corrosion is common on aluminum, and it may occur on carbon steel.

Concrete is a widely used structural material that is frequently reinforced with carbon steel reinforcing rods (rebar), post-tensioning cable or pre-stressing wires. The steel is necessary to maintain the strength of the cementaceous structure.

Modern concrete formulations contain a large amount of fly ash and hence allow water and salt (chloride ion) permeation of the cementaceous structure. The chloride corrodes the imbedded reinforcing metal and as the metal corrodes, the exfoliant corrosion expands and builds pressure that eventually will burst the cementaceous matrix.

FILIFORM CORROSION

This type of corrosion occurs under painted or plated surfaces when moisture permeates through coating holidays, imperfections or breaches. Such breaches often occur from airborne dirt trapped into protective coatings. Such contaminants channel water through the protective coating film. Lacquers and "quick-dry" paints are most susceptible to the problem due to their propensity to form thin films. Their use should be avoided unless absence of an adverse effect has been proven by field experience.

FRETTING CORROSION

Rapid corrosion that occurs at the juncture between highly loaded metal surfaces when subjected to slight vibratory motions is known as fretting corrosion. This type of corrosion is most common in bearing surfaces in machinery, such as connecting rods, splined shafts, and bearing supports, and often causes a fatigue failure. It can occur in structural members such as trusses where highly loaded bolts are used and some relative motion occurs between the bolted members.

GALVANIC CORROSION

Galvanic corrosion is an electrochemical reaction between two dissimilar metals in the presence of an electrolyte and an electron conductive path. This form of corrosion is characterized by aggravated corrosion at the joint between the dissimilar metals. For example, when aluminum alloys or magnesium alloys are bolted with steel (carbon steel or stainless steel), galvanic corrosion can occur at the juncture.

Inherent differences in metal potentials produce galvanic corrosion. If electrical contact is made between any two of these materials in the presence of an electrolyte, a galvanic cell (battery) is formed and current will flow between them. The farther apart the metals are in the galvanic series, the greater the galvanic corrosion effect or rate. The more active metal is the anode, which will corrode, while the cathode will not.

Cathodic protection can also be used to control galvanic corrosion effects. This incorporates a sacrificial cathode, which intentionally corrodes to protect the anode (Galvanization). See preventative measures, Cathodic Protection.

THE ELECTRONEGATIVE (GALVANIC) SERIES³

+

Magnesium
Magnesium Alloys
Zinc
Beryllium
Aluminum 1100, 3003, 3004, 5052, 6053
Cadmium
Aluminum 2017, 2024, 2117
Steel 1018, 1038, or Wrought Iron
HSLA Steel, Cast Iron
Chrome Iron (active)
430 Stainless (active)
302, 303, 321, 347, 410, 416 Stainless Steel (active)
Ni-Resist Cast Iron
316, 317 Stainless (active)
Carpenter 20Cb-3 Stainless (active)
Aluminum Bronze (CA 687)
Hastelloy C, Inconel 625, Titanium (active)
Lead
Tin
Inconel 600 (active)
Nickel (active)
Inconel Nickel-Chromium Alloy (active)
Hastelloy B (active)
Naval Brass (CA 464), Yellow Brass (CA 268)
Red Brass (CA 230), Admiralty Brass (CA 443)
Copper (CA 102)
Manganese Bronze (CA 675), Tin Bronze (CA 903 & CA 905)
410, 416 Stainless (passive) Phosphor Bronze (CA 521 & CA 524)
Silicon Bronze (CA 651 & CA 655)
Nickel Silver (CA 732, 735, 745, 752, 754, 757, 765, 770, 794)
Copper Nickel 90-10
Copper Nickel 80-20
430 Stainless (passive)
Copper Nickel 70-30
Nickel Aluminum Bronze (CA 630 & CA 632)
Monel 400, K500
Nickel (passive)
60% Ni 15% Cr (passive)
Inconel 600 (passive)
80% Ni 20% Cr (passive)
Chrome Iron (passive)
302, 303, 304, 321, 347 Stainless (passive)
316, 317 Stainless (passive)
Carpenter 20Cb-3 Stainless, Incoloy 825 (passive)
Silver
Titanium, Hastelloy C & C276, Inconel 625 (passive)
Graphite
Zirconium
Gold
Platinum

Electric current flows from plus to minus

Direction of attack

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HYDROGEN EMBRITTLEMENT

(A.K.A. HYDROGEN DAMAGE)

Hydrogen embrittlement is an engineering consideration with high-strength steels, titanium, and other high-strength specialty metals.

Hydrogen blistering can occur when hydrogen enters metal as a result of the reduction reaction on a metal cathode (See Metallic Corrosion example). Single-atom nascent hydrogen atoms diffuse through the metal until they meet and bond with another nascent hydrogen, usually at inclusions or defects in the metal. The resultant stable diatomic hydrogen molecules are then too large to permeate the metallic grain structure to out-gas and become trapped. Eventually a gas blister builds up and may split the metal as shown in the photo below.

INTERGRANULAR CORROSION

Intergranular corrosion occurs at or adjacent to the grain boundaries of an alloy. A highly magnified cross section of commercial alloys will show a granular structure. Individual grain has a clearly defined boundary that chemically differs from the metal within the grain center. Heat treatment of stainless steels and aluminum alloys accentuates this problem.

PITTING CORROSION

Passive metals, such as stainless steel, resist corrosive media and can perform well over long periods of time. However, if corrosion does occur, it forms randomly in the form of pits. Pitting is most likely to occur in the presence of chloride ions, combined with such depolarizing agents as oxygen or oxidizing salts.

UNIFORM CORROSION

(A.K.A. GENERAL CORROSION, UNIFORM ETCH CORROSION)

Uniform corrosion is a surface effect, resulting from a uniform chemical etching of the metal surface. Etching may be caused by any chemical agent which is capable of attacking the metal surface. This type of corrosion on polished surfaces first manifests as a dulling of the surface followed by roughening or a 'frosted' appearance of the once polished metal surface. Discoloration or dulling as a result from exposure to elevated temperatures should not be confused with uniform corrosion.

PREVENTATIVE METHODS

Now that the mechanisms of corrosion and the factors contributing to corrosion are understood, a meaningful examination of conventional preventative measures may be undertaken. Given the fact that a single metallic body may itself act as both anode and cathode, there are effectively two basic methods of protecting metals from corrosion.

A. PROTECTIVE COATINGS

Slowing down the corrosion process is done with protective coatings. These help to keep out oxygen, water, and electrolytic salts. Protective coatings are effective in preventing corrosion as long as they adhere firmly to the surface of the metal to be protected and are free of holidays or other breaches.

B. ELECTRONIC PROTECTION

Transfers the electrons by electronic conduction to a location where the corrosion can occur without harm. Another method is the use of imposed electric potentials from external power supplies. However this method is less common due to economic factors.

CHROMATE CONVERSION COATINGS

(A.K.A. IRIDITE, ALODINE, AND CHROMATE ALSO SEE ANODIC PROTECTION OF METALS)

Applicable Specifications: Military specification is MIL-C-5541C

Description: Chromate conversion coatings are produced on various aluminum alloys by chemical treatment with mixtures of hexavalent chromium and certain other chemicals in water solution. This treatment converts the aluminum surface to a thin layer containing a complex mixture of chromium compounds. The coatings are usually applied by immersion, although spraying, brushing, or swabbing methods may be used. Physical variations in the surface finish, such as those produced by polishing, machining or etching can effect the final color of the chromate film. The color of the coating produced on aluminum is specified by the customer and can vary from clear to an iridescent gold.

Function & Physical Finish: The purpose of chromate conversion coating is to improve the corrosion resistance of the aluminum surface and can be used to increase the adhesion of conventional paints and coatings on aluminum parts.

The chromate film is soft and gelatinous when first formed. It slowly age-hardens and therefore should not be handled for 25 hours after treatment. Exposure of the chromate film to temperatures in excess of 150 degrees F may

damage the film. Variegated colors are normal and are the result of physical variations in the metal surface or non-homogeneous alloys.

Where corrosion resistance is required, coating should be thick and colors correspondingly dark. Where conventional paint adhesion is required, the coating thickness should be relatively thin with a gold appearance. Chromate conversion coatings are not recommended for purposes of adhesion promotion for UV curable coatings.

Examples of Use: Automotive components, electrical equipment, aircraft components, and aluminum parts which require enhanced corrosion resistance.

PHOSPHATE COATINGS

A.K.A. PARKOLUBERIZE, BONDERITE, PHOSPHATIZING

Applicable Specifications: The military specifications for phosphate coatings is DOD-P-16232.

Description: Phosphate conversion coatings provide a clean surface and an improved base for other materials (i.e., paint, rubber, etc.). Phosphate crystals add corrosion protection when saturated with oils containing corrosion inhibitors and provide an excellent surface mechanism for holding drawing compound, lubricants or coatings.

Function & Physical Finish: Phosphate coatings are usually specified as a coating weight per area instead of thickness. A typical coating for heavy zinc phosphate is 11-grams/sq. meter. A typical coating for manganese phosphate is 16-grams/sq. meter. Both offer excellent surfaces for oil absorption. Where untreated surfaces of steel are corrosion prone, phosphate conversion coatings provide a more stable and corrosion resistant surface. The non-metallic crystal structure is absorbent and acts as reservoir for rust-preventative compounds. Phosphate coatings stabilize the metal surface and provide a permeable substrate, which promotes adhesion and service life of coatings.

Examples of Use: Corrosion protection on steel parts used in machine assemblies with low corrosion concerns; primer preparation on steel components to be painted; and lubricating protection on steel parts coming in contact with other steel components such as gears. Manganese phosphate is often used to aid in the break-in of closely mated parts.⁴

ELECTROCOAT (E-COAT)

Applicable Specifications: The military specifications for phosphate coatings is DOD-P-16232.

Description: Electrocoating is an *organic finishing method*, which uses electrical current to deposit a protective, corrosion resistant coating to a metallic substrate. The process works on the principal of "Opposites Attract". The primary difference between electroplating and electrocoating (also known as e-coating) is that electroplating applies an inorganic (metal) deposit whereas e-coating deposits an organic coating. Both use the fundamental physical principle of applying materials with opposite electrical charges which attract each other. An electrocoat system applies a DC charge to a metal part immersed in a bath of oppositely charged paint particles. The paint particles are drawn to the metal part and paint is deposited on the part, forming an even, continuous film over the entire surface; until the coating reaches the desired thickness. At that thickness, the film insulates the part, so attraction stops and electrocoating is complete. Depending on the polarity of the charge, electrocoating is classified as either anodic or cathodic.

Function & Physical Finish: There are numerous formulations available with various performance characteristics designed to meet a wide variety of applications.

Anodic Epoxy Electrocoat. The cure attributes of anodic epoxies offer the advantages of low-temperature cure (180°F), good weatherability, high gloss, and the ability to coat recessed areas.

Anodic Acrylic Electrocoat. Anodic acrylics offer economical, one coat, interior finishes. These products have an ultra smooth appearance with excellent color, gloss control, film hardness, chemical resistance, and corrosion protection.

Cathodic Epoxy Electrocoat. Cathodic epoxies define the global e-coat benchmark for corrosion resistance, throw power, and operational reliability. They also give the user the optimum selection of film builds with throw power that keeps film thickness uniform over every area of a part.

Cathodic Acrylic Electrocoat. These types of coatings combine strong corrosion and chemical resistance with the aesthetics and color control necessary in decorative applications. Cathodic acrylic coatings serve as primers for other topcoat finishes, i.e., liquid and powder.

Cathodic Acrylated Alkyd Electrocoat. This technology can be modified to cure at temperatures as low as 160° F. It has oxidative cure characteristics that allow it to complete the curing process after the part has exited the oven. Can be applied at a film thickness as high as 2 mils.

Examples of Use: Electrocoat is found in a variety of industrial market segments. Each of these markets has specific performance requirements.^{5,6,7}

SYSTEM	PROPERTIES	END USERS
Anodic Epoxy	Low Temp Cure	Agricultural Implements Automotive Parts Structural Steel
Anodic Acrylic	Color Control Gloss Control Interior Use Economical	Metal Office Furniture Air Diffusers Shelving Wire Screen & Hangers
Cathodic Epoxy	Corrosion Resistance Chemical Resistance	Automobiles & Parts Transformers Appliances
Cathodic Acrylic	UV Durability Corrosion Resistance Color Control	Lawn & Garden Agricultural Implements Trim Appliances
Cathodic Alkyd	Low Temp Cure High Gloss Weatherability High Film Build	Agricultural Equipment Engines

ELECTRONIC PROTECTION OF METALS

CATHODIC PROTECTION

Cathodic corrosion protection occurs when a metal to be protected is forced to be the cathode of the corrosion cell by coupling it to a metal more easily oxidized than itself. Galvanizing them can protect steel goods, which consists of coating them with zinc metal. The galvanized metal will not corrode until after the zinc coating does, since zinc corrodes more readily than iron. Protection of an oil pipeline with a magnesium sacrificial anode also works this way. The anode will corrode but the pipeline will not. Additionally, an inert or iron anode can replace the magnesium anode if a continuous external power source is used to hold the iron anode at magnesium potential. Metal potentials are commonly available in engineering reference books.

ANODIC PROTECTION OF METALS

(A.K.A. ANODIZATION)

Applicable Specifications^{8,9}:

MIL-A-8625: Anodic Coatings for Aluminum and Aluminum Alloys

Type I - Conventional chromic acid anodize

Type II - Conventional sulfuric acid anodize

Class 1 - Non-dyed coatings

Class 2 - Dyed Coatings

Type III - Hard Coatings

Class 1 - Non-dyed coatings

MIL-A-63576: Aluminum Oxide Coatings, Lubricative, for Aluminum and Aluminum Alloys

Type I - Anodic coating with the unsealed surface impregnated with PTFE

Type II - Anodic coating where the unsealed surface is coated with a PTFE thermoplastic resin

Type III - Anodic coating where the unsealed surface is coated with a PTFE thermosetting resin

AMS-2469: Process and performance requirements for hard coating treatment of aluminum alloys

AMS-2468: Hard coating treatment of aluminum alloys

AMS-2470: Anodic treatment of aluminum alloys, chromic acid process

AMS-2471: Anodic treatment of aluminum alloys, sulfuric acid process, un-dyed coating

AMS-2472: Anodic treatment of aluminum alloys, sulfuric acid process, dyed coatings

Description: Anodization is a process in which aluminum is made the anode of an electrolysis cell using an aqueous acidic electrolyte for a few minutes at relatively low current densities. The resultant oxide film makes the aluminum more resistant to corrosion. The film can also be dyed as it is more porous and absorbent than the original metallic aluminum. Anodization is also performed with magnesium, zinc, and titanium.

Function & Physical Finish: Anodic protection of metal is accomplished by briefly causing the metal to take a positive charge in order to form a stable oxide film on its surface. The stable oxide film then protects the underlying metal from corrosion. This is effective for some steel alloys. Other metals such as aluminum form a protective adherent oxide film by themselves. Due to their high nickel/chromium content stainless steels form a protective film of nickel/chromium. Aluminum metal is highly reactive to oxygen, but in the presence of air it spontaneously and rapidly forms a tough resistant film of aluminum oxide which protects the bulk of the metal from corrosion. The oxide film can be enhanced, and its properties changed, by anodization.

Examples of use: There are now four types of anodizing referred to as chromic acid anodizing, sulfuric acid anodizing, hard coat or hard anodizing, and PTFE (Teflon) anodizing. Each coating differs in their basic properties as well as their end uses.

UV CURABLE POLYMERIC COATINGS: “LIQUID POWDER”

Having the benefits of both liquid and powder coating systems, UV curable coatings also have the ability to be engineered for ‘lock-and-key’ applications. One such application is corrosion control on metal. As examined above, anti-corrosive coating systems must provide not only physical protection but must also possess chemical properties to retard the corrosive attack on metal. It must be stressed that the corrosive process can only be delayed, not eliminated.

Multi functional systems such as oil laden phosphate coatings and e-coat systems have an advantage over single coat, single function protective films. The advantage is their ability to effectively protect the metal surface by acting as a barrier to oxygen and water. In the case of phosphate coatings, deposited phosphate crystals act as a reservoir of oil borne corrosion inhibitors which displace water and passivate metal with the inhibitors. E-coat forms an effective barrier by being deposited into a near perfect barrier film.

The ability to engineer coatings with specific physical properties coupled with multiple coats creates a formidable weapon for corrosion control. This allows two or more coating layers to contribute complimentary anti-corrosive properties into a single effective anti-corrosion tool. Such lock-and-key engineering of supplemental and complimentary anti-corrosive properties make UV curable coatings an effective tool against corrosion.

FUNCTIONAL ROLES OF THE TIECOAT AND TOPCOAT

THE TIE COAT

The tie coat’s function is two fold:

1. To provide near structural adhesive properties to the metal substrate, and;
2. Act as a mechanical ‘buffer’ between substrate and top coat.

In and of itself the tie coat provides good corrosion resistance, however the primary purpose of the tie coat is to provide a highly adhesive, conforming coating which adheres to the metal and eliminates water permeation to form an electrolytic solution at the metal surface. Thereby, the tie coat impedes the electrolytic conductive requirement of corrosion cells.

Additionally, the tie coat is ‘soft’ relative to the topcoat. The almost ‘gummy’ physical property of the tie coat provides the coating system greater latitude against physical impact which may breach the topcoat. Yet the relative hardness between the tie coat and the topcoat is not so great as to raise shear separation concerns within the tiecoat itself. Thus the topcoat will not delaminate from the metal by splitting the tiecoat layer as a result of shear forces within the tie coat itself.

THE TOP COAT

Independently, the topcoat is an effective anti corrosive coating. However, it is engineered to provide physical protection to the relatively soft tie coat immediately below the topcoat. On it’s own the topcoat does not protect from impact forces but does provide protection against abrasive wear. The following table illustrates the relative wear resistance between a typical UV anti-corrosive topcoat and two generic e-coat systems.

Relative Abrasion Resistance on Cold Rolled Steel (CRS)¹⁰	
COATING SYSTEM	MILLIGRAMS LOST PER 1000 REVOLUTIONS
Z-VOC Anti-Corrosion Topcoat on CRS	3
Zinc E-Coated CRS	2108
Zinc-Cobalt E-Coated CRS	337
Procedure and Parameters: ASTM D 4060; Wheel: CS-10; Weight: 1,000 grams	

TIE COAT/TOPCOAT SYSTEM

Together, the tie coat and topcoat system is an effective tool against the most common failure of anti-corrosion coatings: filiform corrosion. Filiform corrosion occurs on the metal surfaces under coated or plated areas where water permeates or breaches the protective coating. Such breaches are caused by:

- A. A protective coating not having effective water barrier properties i.e. porous film, machined contours (look for patterned blistering which follows machining);
- B. Coating holidays i.e. bubbles in the coating from application or permeation of pigments;
- C. Piercing of the coating from handling or service environment;
- D. Airborne contaminants imbedded during the coating process, which may channel water through the film.

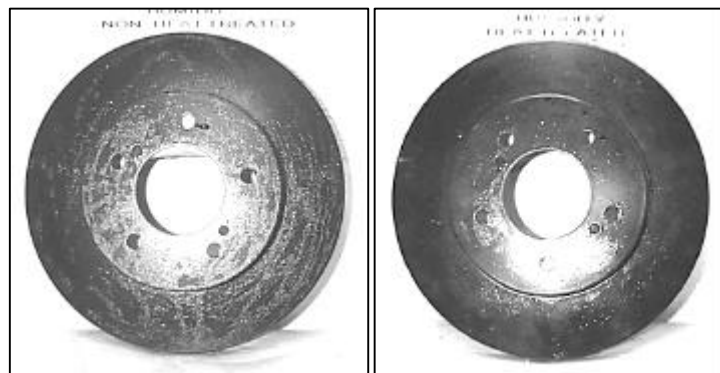
Typically filiform corrosion begins as a pinpoint blister. Initially, water permeation establishes an *Oxygen Concentration Cell*, which is the undetected initiating corrosion cell of a blister. This corrosion cell then progresses to become an *active-passive cell* and finally a *metal ion cell* by which time blistering of the protective film and ‘bleeding’ of rusty water is very evident.

An anti-corrosion coating system that can effectively reduce or eliminate permeation of water will reduce or eliminate the establishment of initiating corrosion cells, which lead to blistering and more advanced manifestations of corrosion.^{11,12}

TIE COAT/TOPCOAT CORROSION RESISTANCE ON AN AUTOMOTIVE BRAKE DRUM TO PASS: 240 HRS.

Photographs Courtesy of M. Koons, UV Coatings, Ltd.

672 HOURS HUMIDITY RESISTANCE (ASTM D 2247)



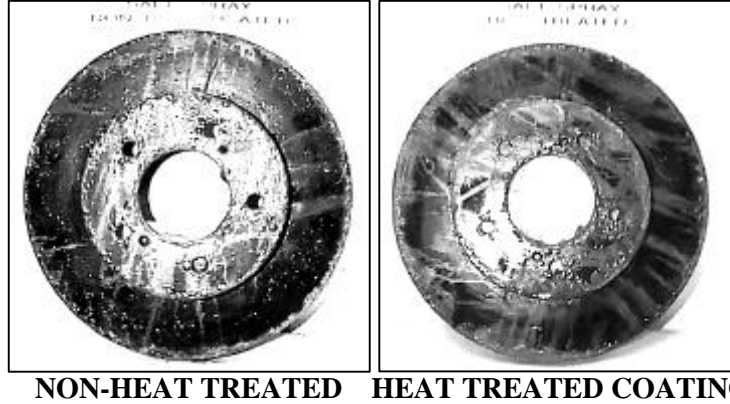
NON-HEAT TREATED HEAT TREATED COATING

Note the significant reduction of blistering and filiform corrosion between the regularly processed parts (above, left) and heat-treated tiecoat/topcoated parts (above, right).

TIE COAT/TOPCOAT CORROSION RESISTANCE
ON AN AUTOMOTIVE BRAKE DRUM
TO PASS: 240 HRS.

Photographs Courtesy of M. Koons, UV Coatings, Ltd.

696 HOURS SALT FOG RESISTANCE (ASTM B 117)



Note the significant reduction of blistering and filiform corrosion between the regularly processed parts (above, left) and heat-treated tiecoat/topcoated parts (above, right). Parts surpassed a required 240 hrs. of salt fog corrosion resistance by over a factor of 2.

Heating coated parts with a tie coat/topcoat system greatly enhances the coating system's ability to resist water permeation. Note the significant reduction of blistering in the heat-treated part above, right. After coating and curing, the coated part is heated for 2 hours at 350°F followed by a cold water quench. The part is then processed normally.

The enhancement of heat treating tie coat/topcoat systems is evident in salt fog corrosion resistance. The system's ability to retard the permeation of water (Humidity – ASTM D2247) to the metal surface to significantly reduce blistering translates into more effective corrosion resistance to salt water (ASTM B-117).

196 HOURS SALT FOG
RESISTANCE (ASTM B 117) ONE COAT

Photograph Courtesy of M. Koons, UV Coatings, Ltd.



The pulley, above, was coated with a single layer of coating and subjected to 196 Hrs of salt fog (ASTM B 117). Typically, single layers of coating ranging between 1-2 mils have difficulty in passing salt fog corrosion resistance testing of 150-200 hrs. (ASTM B 117).

UV technology is such a competitive advantage that its utilization is a closely guarded secret by manufacturers using it in their production. As such, case studies or photographs of operational UV production lines are rarely if ever released by manufacturers. In addition to superior corrosion resistance and other remarkable physical properties, the

authors have personally experienced the following competitive advantages that UV technology brought to manufacturing operations:

- ❖ UV Eliminated need for third party coating due to Title V EPA emission limitations;
- ❖ Bringing coating operations in-house eliminated out costs of third party processing.
 - Freight savings on parts to/from third party
 - Eliminates third party mark-up
- ❖ Low Initial Capital Investment with ROI of 1-5 years
- ❖ Elimination of large ovens made plant floor space available
- ❖ Energy usage decreased from elimination of large ovens
- ❖ Speed of processing facilitates quality assurance - parts can be inspected immediately. Risk of coating defects minimized with minimal drying time. Parts can be stacked or palletized immediately without a required post cure.
- ❖ Environmental savings are realized because hazardous waste disposal penalties and manifest are not required
- ❖ 100% solids, UV curable coatings are non-flammable; potentially insurance costs will be lowered
- ❖ Dunnage remains cleaner as no uncured coating comes off on dunnage.
- ❖ 100% solids, UV curable coatings are recoverable and reusable without affecting performance or composition
- ❖ 100% solids, UV curable coatings cover more square footage efficiently and effectively.

CONCLUSIONS

Though corrosion can not be completely and permanently inhibited, its effects can be significantly slowed. Understanding the root cause of corrosion provides insight by which the most effective, and appropriate anti-corrosive measure can be selected. The most common and versatile corrosion prevention measures are protective coating systems. Given the dynamics by which corrosion cells are established the most effective anti-corrosive coating system is a properly engineered tie coat/topcoat system. Such systems can be engineered to provide complementary and supplemental chemical and physical properties appropriate to the service environment that the coated part will be subjected to.

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