Corrosion Protection Options for Aluminum

Q. Can you provide an overview of corrosion and corrosion protection options for aluminum?

A. Corrosion is a destructive phenomenon that affects almost all metals and is the result of continued exposure to an environment containing moisture and oxygen or certain oxidizing agents. Therefore, corrosion protection is key for maintaining physical and mechanical properties for many industrially used metals and metal alloys.

Aluminum is the most abundant metallic element in the Earth's crust. It is the world's most broadly used nonferrous metal due to distinct advantages such as high thermal and electrical conductivity, low specific gravity, excellent mechanical properties and strong corrosion resistance. It is used in various industrial markets including automotive, packaging, electrical/electronics, building/construction materials, aerospace and general consumer goods.

Given the substantial volume of aluminum used and its overall market value in various industries, it is of great interest to enhance the lifespan of products made from this metal or its metal alloys. By enhancing the lifespan of products, it preserves mechanical integrity, object aesthetics and saves operational costs in replacing aluminum-based parts or objects. Thus, much effort and study have gone into understanding aluminum corrosion and developing ways to prevent corrosion through a variety of surface treatments.

Aluminum and its alloys, when in contact with the atmosphere, typically form a thin oxide layer less than 1-2 microns (µm) thick. This thin aluminum trioxide film is compact and strongly adhered to the underlying aluminum metal offering some natural corrosion resistance. However, due to its porosity and minimal thickness, corrosion eventually initiates and occurs. In the environment, corrosion typically localizes and starts in or around one of the aluminum oxide pores near an impurity, often an intermetallic particle, in the aluminum or aluminum alloy. The various forms of aluminum surface treatment seek to eliminate this by blocking or further limiting the exposure of these impurities, or intermetallic particle sites, to the atmospheric environment. These surface treatments include alclading, electroplating, anodizing and using chemical conversion coatings (passivates) dependening upon the end application.

Ultimately, the main goal of these various surface treatments is to create a surface that is more noble and corrosion resistant. For alclading, high-purity aluminum is used and layered over an aluminum alloy of lesser purity. In comparison, with electroplating or electroless plating, a more noble metal, such as nickel, is deposited onto the aluminum surface from a solution containing that particular metal's ions (whether using an electrical current or not). The two most commonly used forms to alter the surface of bare aluminum substrate are anodizing and passivation.

Anodizing uses an electrolytic process to increase the thickness of the natural oxide layer (20-50 um) on the surface of aluminum metal parts. The aluminum is used as the anode and is immersed into an acid bath with a cathode mounted inside the tank. Electrical current is passed through and the oxygen reacts with the surface of the aluminum to create an anodic layer. Stable to heat and the action of water vapor and other corrosive agents, these porous films can be impregnated with various substances further enhancing corrosion resistance and changing the aluminum aesthetic qualities. Substances often used to modify the surface of anodized aluminum are paraffins/waxes, insulating and noninsulating paints and polymers. One drawback to anodizing is that it cannot be used in applications such as aerospace that require minimal dimensional change. Those applications can often benefit from passivation.

Chromium passivates, originally referred to as chromium conversion coatings or chromates, have been used to enhance corrosion protection of metals and their alloys for over 70 years. Chromating involves chromium ions being applied to the surface of a metal or metal alloy which form a thin protective chromium oxide film (<1 µm) to enhance wear and corrosion resistance. Chromium passivates not only help to enhance corrosion resistance but also create a surface film involving no dimensional change and can be formulated with other reagents acting as a pretreatment for functional coatings such as painting. The chemistries involved are categorized based on the type of chromium cation employed: hexavalent chromium (Cr^{6+}) versus trivalent chromium (Cr^{3+}). Initially, many industries heavily relied on hexavalent chemistries for corrosion protection of certain metals and their alloys. However, over the years, concerns were raised regarding the toxicity of hexavalent chromium and its effects on human health and the environment so a push for safer alternatives was brought forth. This afforded many opportunities to further develop chemistries to fill technology gaps and performance requirements.

Therefore, a shift in focus occurred to further develop trivalent chromium passivates for aluminum that cost-effectively provide excellent corrosion protection. When developing a trivalent chromium passivate, a variety of studies are performed to assess the influence of different parameters of operation including how different components in the formula affect the performance of the passivate. Examining factors such as the components themselves, selection of auxiliary metal ions, chelators, sealers and surfactants, or the parameters used during the aluminum pretreatment are critical drivers to successful development.

Chromium passivation is a kinetically driven event. Thus, the rate at which the passivation layer builds is dictated via concentration, time and temperature. Keeping time and temperature the same while targeting a passivate layer on the surface, the passivate solution's concentration naturally affects the overall corrosion resistance. The more dilute, the lower the concentration of trivalent chromium ions in solution, the less there are to assemble on the surface to produce an effective protective passivate layer. Therefore, when optimizing a passivate formula, the minimum working solution concentration should be determined to maximize the number of salt spray hours to match those results achieved by the trivalent chromium passivate. After effective pretreatment of the aluminum, balancing the three parameters ensures that the maximum performance regarding corrosion resistance is being met cost-efficiently. Processing parameters, pretreatment and passivation, are highly dependent upon the aluminum alloy being used. When selecting a trivalent passivate for use on aluminum or aluminum alloys, it is important to work with a knowledgeable chemistry supplier whose R&D process considers and understands all the factors needed to develop and optimize the technology.

The sheer volume of the aluminum market across key manufacturing segments, coupled with aluminum's distinct advantages and mechanical properties, will continue to drive attention to the need for the development of coatings that can further enhance corrosion resistance and extend the life of this valuable material. With continued research and study, building a stronger understanding of composition and physical characteristics of aluminum alloys and the surface finishing chemistries employed will only help to further evolve the aluminum market.

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