Surface Engineering & Process Feasibility Study of Anodically Treated Aluminum vs. Aluminum Applied with an Electroless Nickel Coating

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In today's finishing industry, many product and process engineers face the challenge of choosing the proper surface engineered coating for their aluminum substrates. Moreover, these personnel do not possess the knowledge of the diversity of coatings, processes, and characteristics provided by many of the coatings for aluminum. The purpose of this paper is to provide a comparison of anodically treated aluminum and aluminum applied with an electroless nickel coating. The comparison shall address the physical and chemical processes, the coating characteristics, environmental challenges, and associated costs for the applications.

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Surface engineering of aluminum substrates is a vital component to the product development, design, and manufacture of various parts used in many industries. The objective of surface engineering is to provide a treatment to a substrate, such as plating, coating, or painting, to achieve enhanced characteristics, such as improved corrosion resistance, wear resistance, surface hardness, or aesthetics. Anodizing and electroless nickel deposition are two processes used to provide aluminum alloys with a wide array of new properties over bare, untreated aluminum substrates. Several factors play a role in choosing which of these coatings to apply, including physical characteristics of the alloy, physical processing impacts on the alloy, chemical processes involved in the treatment, the desired characteristics of the coating, the environmental challenges and associated costs for the coating application. An examination of these factors is intended to assist the reader in the decision-making of which surface engineered coating to use.

Physical Characteristics

The physical characteristics of an aluminum substrate impact the application of coatings and the subsequent properties. Characteristics include alloy elements and percent composition, forming processes, and surface conditions. The aluminum alloy properties vary drastically in their metallurgical and physical conditions, which in turn have varying impacts on coating application.

Wrought Alloys

Wrought alloys are generally very easy for metal finishers to work with. The metal forming process aids the alloying elements in forming more intermetallic compounds. These compounds improve the consistency of the alloy. With improved adhesion to the base material and reduced pitting in the applied coating, the engineer experiences considerable benefit.

Extruded Alloys

Extruded alloys may also be easy for finishers to work with, however, difficult problems may arise. Extrusions are very similar to wrought alloys as the alloy elements form compounds consistently through the metal. Problems occur from the extruding process where the alloy is stretched and elongated, resulting in inconsistencies or imperfections in the surface of the material. This is sometimes seen as striations in the anodic coating. The extruding process also induces stress in the substrate which may be detrimental to the substrate or the applied coating.

Castings

Castings may be difficult for metal finishers to work with. The metallurgy of the alloying elements tends to form discrete particles in the alloy. This may require variations in the chemical pretreatment and coating application. Also, microscopic voids and cracks may be present in the alloy, which are enhanced by the applied coatings as pits or misplates.

Machined Surfaces

Machined surfaces on aluminum alloys provide favorable and unfavorable conditions for metal finishers. The surfaces are defined and usually smooth. To obtain the defined surface, the alloy is cut or machined to meet the required specifications. The machining imparts several unfavorable conditions. First, the use of dull cutting instruments tends to roll and push the alloy material versus cutting the material away. Second, the cutting instruments may embed foreign particles that are not within the alloy material elemental make-up. Another condition is the introduction of organic contaminants from machining coolants.

Physical Processes

Various physical processes are usually applied to the aluminum alloy prior to chemical processing and coating application. Machining, abrasive blasting, and welding are a few of the physical processes involved. Each treatment has varying effects on the alloy and surface condition prior to chemical processing. These effects must be addressed and accounted for by the process engineer and metal finisher.

Machining

Machining aluminum alloys imparts uniform surfaces with precise dimensions. To obtain these characteristics, several aspects of the alloy are affected. First, the mechanical interactions between the cutting tools and the alloy may lead to surface deformation, micro or macro cracking, and the addition of residual stress. The forces applied to the alloy during machining may generate significant temperatures, which in turn may cause changes in the microstructure of the alloy. These changes can have an effect on the hardness and phase structure of the alloy.

Abrasive Blasting

Abrasive blasting is one of the simplest and most efficient methods of physical treatments[1]. The treatment leaves the surface with a matte finish. The blasting is usually accomplished using silica or aluminum oxide abrasives, however steel and stainless steel abrasives can be used. The process is used to remove oxides and soils from the surface of the alloy, but chemical processes are also required for proper alloy preparation. The abrasive blasting induces compressive stresses in the surface of the material. The process also roughens the surface of the alloy, which can be favorable to adhesion in coating application. Abrasive blasting is generally not recommended for thin components as the process involves deformation and material removal that can be detrimental to the component. The final consideration is contamination of the abrasive media. If the media is used for various alloys or substrates, the process can imbed unwanted particles into the surface of the alloy, which may require special chemical treatments for removal.

Baking

Baking is specified to achieve various treatments to the alloy. Most commonly, the alloys are baked to relieve stresses that may have been induced into the alloy by physical processing. Alloys are also baked to change characteristics within the alloy itself to increase hardness or achieve phase transformation within the microstructure. Baking may impart detrimental characteristics to the alloy for the metal finisher. Baking may leave heat scale or oxide films on the surface of the aluminum. Evaluation of the baking environment must be considered, as contaminants in the environment may enter the alloy.

Welding, Brazing, and Soldering

Welding, brazing, and solder are three common methods of joining two or more pieces of aluminum together. These processes can impose very difficult problems for the metal finisher. Three common problems are the introduction of new metals, voids and cracks, and trapped gasses. New metals are introduced through the use of improper welding rods or wire, which contain metals not in the alloy. The introduction of these metals may cause the weld not to react the same as the alloy in chemical processing and coating application. The addition of voids and cracks can provide a source of contamination or pitting. Any gasses that may have been trapped from welding, brazing, or soldering can induce unwanted stresses or initial corrosion.

Chemical Processes

Chemical processes and their effect on aluminum alloys are the primary focus of this comparison. Several processes will be overviewed to provide an extensive look at the many processes available to provide anodic and electroless nickel coatings. Pretreatment of the alloy prior to processing will be addressed and post treatments as required for the applicable coating. Four types of anodizing will be covered: chromic acid, sulfuric, hardcoat, and special processes. Three types of electroless nickel coatings will be addressed: phosphorus based, boron based, and special processes.

Chemical Pretreatment

Chemical pretreatment is the sequences of operations required to clean, prepare, and activate the aluminum surface for subsequent coatings. The pretreatment steps required for anodizing and electroless nickel plating are very similar, with the exception that the electroless nickel requires a zincate application. The pretreatment steps that will be defined are for general reference only. Proprietary chemistries exist to perform one or more of the functions listed, and the chemical manufacturer's supplied data should always be consulted prior to processing. Typical processing steps for anodizing and electroless nickel plating are listed in Figures 1 and 2, respectively.

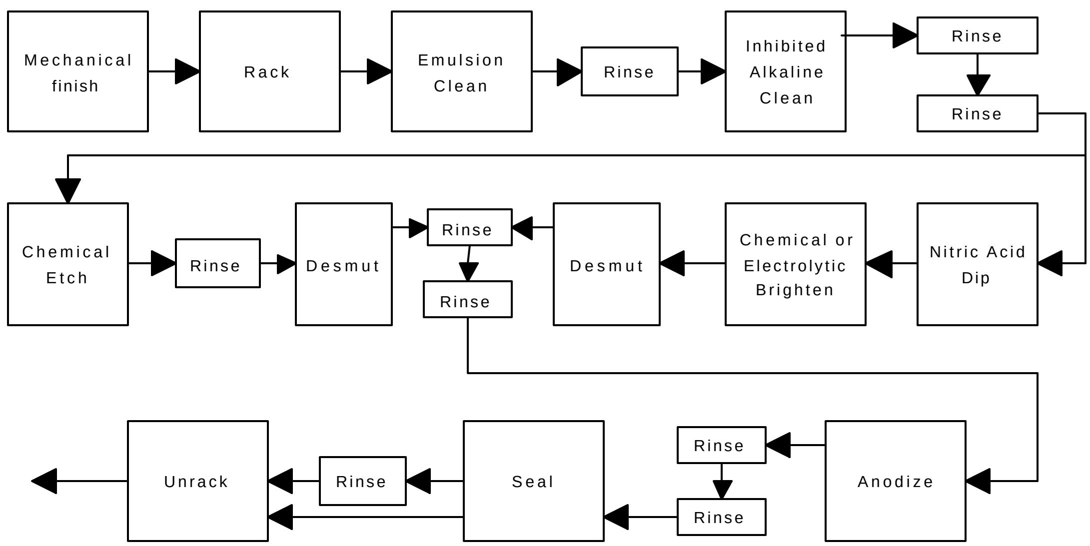

Fig. 1 Typical process sequence for anodizing operations[2].

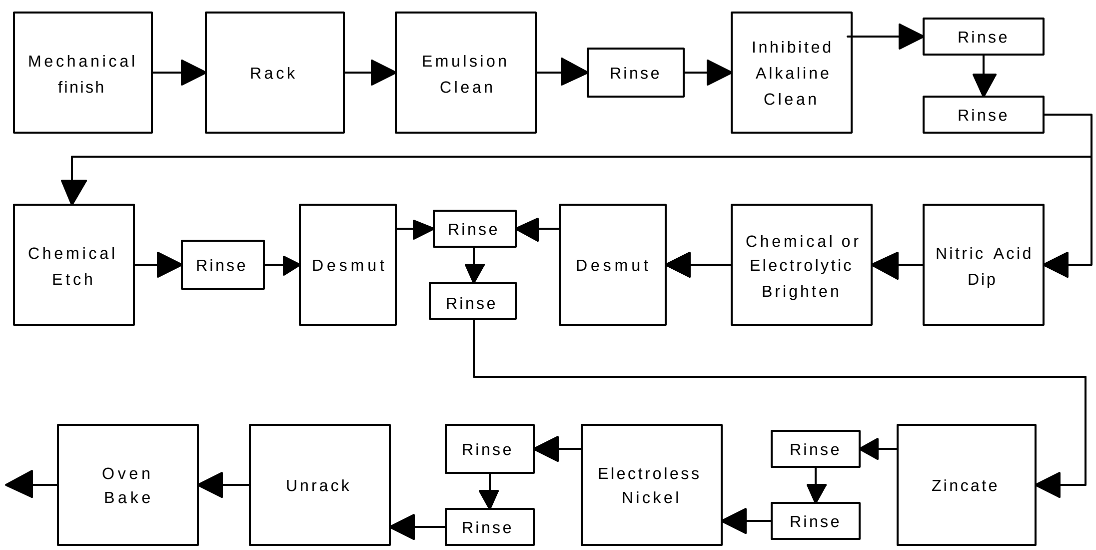

Fig. 2 Typical process sequence for electroless nickel on aluminum[2].

The purpose of the cleaning steps outlined in Figures 1 and 2 are defined below.

Emulsion Clean – Primarily used to remove oil and grease compounds from prior operations. Reduces soil loading in the subsequent alkaline cleaning step.
Inhibited Alkaline Clean – Primarily used to remove soil, oxides, and material from the substrate. Aluminum is readily attacked in alkaline solutions, and inhibitors are added to reduce the attack on the base material.
Chemical Etch – Used to remove large amounts of aluminum and soils. Also used to remove difficult alloy materials such as silicon.
Nitric Acid Dip – Used to remove copper from the surface of the alloy.
Chemical or Electrolytic Brighten – Process used to micro-etch and polish the surface of the alloy. Various chemical formulations exist for an array of alloys.
Desmut – Step used to remove any remaining oxides and alloying metal smut. Aluminum surface is chemically clean after this step.
Zincate – Process involving the application of thin zinc film over the surface of the substrate in preparation for plating. Some processes use a double zincate step, where the first coating is stripped off and new zinc film is applied.
Rinsing – Proper rinsing is as important as any chemical treatment. Parts should be clean with a water break free surface prior to entering any coating process.

Anodizing

Anodizing is an electrolytic process by which the part is made anodic in an electrolytic cell and a coating is formed as a result. For aluminum and its alloys, the resultant layer is a porous coating of aluminum oxide. Variations in current density, electrolytes, and temperature provide a wide diversity in the characteristics of the anodic coating. Anodizing is used to enhance the surface of the aluminum by increasing corrosion resistance, improving decorative appearance, increasing wear resistance, improving lubricity and adhesive bonding, and providing electrical insulation. Three common aluminum-anodizing processes are chromic acid, sulfuric acid, and hardcoat anodizing. Other processes have been developed for producing special characteristics.

Chromic Acid Anodizing – This process uses chromic acid as the electrolyte, typically at slightly elevated temperatures, to produce a thin, dense coating on the substrate. Chromic acid anodizing is primarily selected as an engineered coating for three reasons. First, it provides a good base for painting with increased corrosion resistance. Second, there is no appreciable dimension change from the coating. Finally, the residual electrolyte does not aggressively attack the newly formed coating, making the process suitable for parts with large recesses, assemblies, and blind holes. This anodic coating may be colored for decorative applications. Sealing is required to obtain maximum corrosion resistance. The common sealing solutions use deionized water, nickel acetate, or sodium dichromate at elevated temperatures for 5 to 30 minutes. Figure 3 outlines the typical operating parameters for chromic acid anodizing.

Chromic Acid Amount	5 to 10 % wt.	
Temperature °C (°F)	40 (105)	
Duration, min.	30 to 60	
Voltage (V)	0 to increasing limit controlled by amperage	
Current Density A/dm^2 (A/ft^2)	0.5 to 1.0 (5 to 10)	
Film Thickness µm (mils)	4 to 7 (0.2 to 0.3)	
Appearance	Gray to Iridescent	
Properties	Good chemical resistance, poor abrasion resistance, suitable for parts with narrow cavities, as residual electrolyte is not detrimental	
Sealing	Temp. °C (°F)	Time, min
- Deionized water	98-100 (208-212)	5-20
- Nickel Acetate	98-100 (208-212)	15-30
- Dichromate	90-95 (195-205)	20-30

Fig. 3 – Typical operating parameters for chromic acid anodizing[3,4].

Sulfuric Acid Anodizing – This process uses sulfuric acid as the electrolyte at room temperature. Sulfuric acid anodizing is the most common anodizing process. The anodic coating formed is very porous, making it ideal for coloring in decorative applications. Figure 4 lists the typical processing for sulfuric acid anodizing.

Sulfuric Acid Amount	12 to 20 % wt.	
Temperature °C (°F)	20 to 25 (68 to 77)	
Duration, min.	10 to 60	
Voltage (V)	12 to 18	
Current Density A/dm^2 (A/ft^2)	1 to 2 (10 to 20)	
Film Thickness µm (mils)	4 to 20 (0.1 to 0.8)	
Appearance	Colorless, transparent	
Properties	Good protection against corrosion, suitable for coloring prior to sealing.	
Sealing	Temp. °C (°F)	Time, min
- Deionized water	98-100 (208-212)	5-20
- Nickel Acetate	98-100 (208-212)	15-30
- Dichromate	90-95 (195-205)	20-30

Fig. 4 – Typical operating parameters for sulfuric acid anodizing[3,4].

Sulfuric acid anodizing is specified as the engineered coating to provide corrosion resistance, electrical insulation, and resistance to chemical attack. This process is also specified for architectural and decorative applications due to the process having excellent covering power and the ability to be colored. Sulfuric acid anodizing is not suited for aluminum assemblies or those parts with recesses or cracks. The residual electrolyte is corrosive to the anodic coating. Sealing is primarily accomplished with a nickel acetate solution or heated deionized water, however sodium or potassium dichromate is specified for particular applications.

Hardcoat Anodizing – Hardcoat anodizing, as stated in the name, is used to produce harder, denser coatings using sulfuric acid as an electrolyte. The sulfuric acid may be used independently or coupled with other acids or additives to produce the hard coating. This process is operated at lower temperatures than that of sulfuric anodizing, usually 25-50 °F. The coating produced is resistant to abrasion and wear, due to the increased density of the coating. Hardcoat anodizing uses higher voltages and current densities than sulfuric acid anodizing. As a result, a condition called "burning" due to localized overheating of the coating sometimes occurs. This burning renders the part useless and the part will need to be stripped and re-anodized. This condition is combated with proper agitation and cooling of the electrolyte. Figure 5 lists the typical operating parameters to produce this hard coating.

Sulfuric Acid Amount	1 to 20 % wt.	
Temperature °C (°F)	-4 to 10 (25 to 50)	
Duration, min.	20 to 45	
Voltage (V)	10 to 75	
Current Density A/dm^2 (A/ft^2)	2 to 3.6 (20 to 36)	
Film Thickness µm (mils)	25 to 50 (1 to 2)	
Appearance	Light to dark gray or bronze	
Properties	Very hard, wear resistant when sealing is not performed.	
Sealing	Temp. °C (°F)	Time, min
- Deionized water	98-100 (208-212)	5-20
- Nickel Acetate	98-100 (208-212)	15-30

Fig. 5 – Typical operating parameters for hardcoat anodizing[3,4].

Hardcoat anodizing is typically used as an engineered coating only, however certain applications specify coloring for decorative appearance. The sealing process is accomplished using deionized water or nickel acetate solutions, however this step significantly softens the coating and reduces wear resistance and hardness. For engineered coatings, sealing is not performed to retain the hardness and wear resistance of the anodic coating.

Special Anodizing Processes – Many special anodizing processes have been developed for specific applications and properties. One of these processes uses oxalic acid as an electrolyte or as an additive to an electrolyte. Oxalic acid has been used to produce thicker and harder coatings depending on the formulation. Another process uses phosphoric acid as the electrolyte for anodizing. Phosphoric acid anodizing produces a coating that is receptive to paint or adhesive bonding. Yet another process has been developed using sulfuric and boric acid as electrolytes[5]. This process produces coatings similar to that of conventional chromic acid anodizing. Due to strict environmental regulations and pollution prevention initiatives, the sulfuric-boric acid anodizing is being specified by the engineered coating of choice to replace chromic acid anodizing for the Navy[6]. Finally, there are various proprietary processes that have been developed by many manufacturers. These processes produce coatings that are harder, more wear resistant, and thicker that conventional anodizing processes. Self-coloring processes have also been developed to eliminate the need for dyes. Another process has been developed to produce conductive anodic coatings. If a proprietary process is being considered as an engineered coating, it is recommended that the process or product engineer contact the manufacturer of the process to determine the exact requirements of the process and the desired coating characteristics.

To summarize, many formulations and various processing environments can produce a wide variety of anodic coatings. The anodic coatings can impart electrical insulation, wear resistance, corrosion resistance, and decorative appearance to the surface of the aluminum alloy. Understanding the processing steps, the resultant coating, and the properties of the anodic coating will provide product and process engineers with the information to make an educated decision when selecting or specifying the engineered coating.

Electroless Nickel Plating

Electroless nickel plating is an autocatalytic process, by which nickel metal is deposited to a substrate through a chemical reduction process without the use of electrical current. The solutions used to produce the nickel coating contain an aqueous solution with metal ions, complexing and reducing agents. The metal ions, once in solution, are kept within the solution by complexing agents. Reducing agents added to the solution chemically reduce the metal ions to nickel metal once the reaction has started. Stabilizers may be added to the solution formulation to maintain pH, surface tension, and reaction rates. The reaction is autocatalytic, which means once the reaction has started, it will continue to reduce nickel metal onto the substrate as long as the solution parameters are maintained. Electroless nickel coatings are used on aluminum alloys to produce deposits that are uniform in thickness, corrosion resistant, wear resistant, and decorative in appearance. Some coatings are deposited for solderability and brazeability. Two common electroless nickel processes are phosphorus-based and boron-based depositions. Many special electroless nickel coatings have been developed for imparting specific characteristics to the deposit.

Phosphorus-Based Nickel – This process uses sodium hypophosphite as the reducing agent in the reaction. The coating produced is a nickel-phosphorus matrix which can range in phosphorus content from 3 to 12 percent. The phosphorus content of the deposited coating has a direct effect upon the characteristics of the coating. Internal stress, coefficient of thermal expansion, and coating density are just three properties affected by phosphorus content. Phosphorus content is a changed by variations in typical operating parameters and chemical concentrations within the electroless nickel bath. Temperature and pH are two operating parameters that have a direct effect on plating rate and phosphorus content of the deposition. Figure 6 illustrates typical acid hypophosphite reduced nickel bath chemistry and operating parameters.

Nickel sulfate	28 g/L	
Sodium Acetate	17 g/L	
Sodium Hypophosphite	24 g/L	
Lead Acetate	0.0015 g/L	
pH	4.4 to 4.6	
Temperature °C (°F)	82-88 (180-190)	
Plating Rate µm/hr (mils/hr)	12-25 (0.5-1.0)	
Film Thickness µm (mils)	2.5 to 250 (0.1 to 10)	
Phosphorus Content	3-12 %	
Appearance	Matte to Bright	
Properties	Hard, wear resistant, corrosion resistant.	
Post-Treatment Bake	Temp. °C (°F)	Time, min
- Precipitation Harden - Hydrogen Embrittlement Relief	400 (750) 190-210 (375-410)	60 120-1440

Fig. 6 – Typical operating parameters for an acid hypophosphite reduced nickel bath[7].

A unique property of the phosphorus based electroless nickel coating is that it can be precipitate hardened by baking at elevated temperatures. Nickel phosphorus coatings are 500-650 VHN as plated. Baking for 1 hour at 400ºC can increase the hardness to 1000 VHN. The phosphorus-based electroless nickel coating is primarily engineered for thickness uniformity, hardness, wear resistance and corrosion resistance.

Boron-Based Nickel – This process can be deposited from aminoborane or borohydride reduced solutions. The mechanism for deposition is similar to that of phosphorus-based nickel depositions. The aminoborane solution will deposit 0.4-5% boron in the coating. It operates at acidic to neutral pH. The borohydride solution will deposit 3-8% boron in the coating. This solution operates at a higher pH of 12-14. The boron in the coating enhances the hardness and wear resistance of the deposit. These characteristics make the coating ideal for some applications. The use of boron also decreases the corrosion resistance of the deposition when compared to the phosphorus-based nickel coatings. Typical operating parameters for these two types of boron-based nickel solution are listed in Figures 7 and 8.

Nickel Chloride	31 g/L	
Sodium Hydroxide	42 g/L	
Sodium Borohydride	1.2 g/L	
Ethylenediamine	52 g/L	
Thallium Nitrate	0.022 g/L	
pH	>13	
Temperature °C (°F)	93-95 (200-205)	
Plating Rate µm/hr (mils/hr)	15-20 (0.6-0.8)	
Film Thickness µm (mils)	2.5 to 250 (0.1 to 10)	
Boron Content	3-8 %	
Appearance	Matte to Semi-Bright	
Properties	Very hard, wear resistant.	
Post-Treatment Bake	Temp. °C (°F)	Time, min
- Precipitation Harden - Hydrogen Embrittlement Relief	400 (750) 190-210 (375-410)	60 120-1440

Fig. 7 – Typical operating parameters for a borohydride reduced nickel bath[7].

Nickel sulfate	25 g/L	
Sodium Acetate	15 g/L	
n-Dimethylamine Borane	4 g/L	
Lead Acetate	0.002 g/L	
pH	4.8 to 7.5	
Temperature °C (°F)	65-77 (149-171)	
Plating Rate µm/hr (mils/hr)	7-12- (0.5)	
Film Thickness µm (mils)	2.5 to 250 (0.1 to 10)	
Boron Content	0.5-5 %	
Appearance	Matte to Bright	
Properties	Hard, wear resistant, corrosion resistant.	
Post-Treatment Bake	Temp. °C (°F)	Time, min
- Precipitation Harden - Hydrogen Embrittlement Relief	400 (750) 190-210 (375-410)	60 120-1440

Fig. 8 – Typical operating parameters for an aminoborane reduced nickel bath[7].

Similar to phosphorus nickel, the boron-based nickel can also be hardened when baked at 400º C for an hour. The as-plated hardness of the boron nickel is 650 to 750 VHN. After baking, the hardness increases up to 1200 VHN. This post-treatment bake also increases the wear resistance of the coating. The boron-based nickel coatings, although similar in deposited coating, are slightly more labor intensive to control over the phosphorus-based nickel coatings. This also may play a factor in engineering an economical coating. *Special Electroless Nickel Coatings* – Many variations to typical electroless nickel processes have been made to produce specialized coatings with very unique attributes. These variations have been formulated by the addition of additives which can be co-deposited with the nickel, creating entirely different and enhanced coatings. These variations have also been called electroless nickel composite coatings. One of the composites introduces silicon carbide into the electroless nickel matrix. The silicon carbide is added to the electroless nickel solution as a small discrete particle. As the electroless nickel is deposited, the silicon carbide particles become codeposited into the matrix. Silicon carbide increases the hardness and lubricity of the electroless nickel coating. This makes the composite coating ideal where abrasion and wear resistance is of interest to the engineer. Another composite coating is electroless nickel with Teflon or PTFE. This coating is also used for abrasion and wear resistance. The Teflon adds lubricity to the electroless nickel matrix. The last composite to be discussed is the diamond matrix. Diamonds add hardness and wear resistance to the composite. This is very desirable when the coating will be in contact with an abrasive surface. As the name of the composite may imply, this coating is usually quite expensive in comparison with the previously mentioned composites.

In summary, electroless nickel coatings can be deposited from various solutions. The matrix that is formed from the reducing agents or the additive materials provides this coating with many of its enhanced properties. The electroless nickel coating can also be baked to increase hardness and wear resistance. The product or process engineers should understand the full range of properties the electroless nickel coatings offer, prior to specifying the coating.

Coating Characteristics

Coating characteristics are one of the primary elements that product and process engineers evaluate to determine proper application of the part for use in service. Each coating has positive and negative characteristics, which may make it suitable for one environment and unsuitable for another environment. All of the properties of a coating should be considered when specifying an engineered coating. The substrate, physical processes and chemical processes all play a vital role in process selection, but the required performance of the applied coating is critical to coating selection and part service. Coating properties to be considered are hardness, decorative appearance, wear resistance, deposit thickness, abrasion resistance, uniformity of deposit, and corrosion resistance. Other properties may be of concern such as electrical conductance or resistance, mechanical properties, and electromagnetic interference qualities. The coatings discussed earlier will be compared to each other to display the variations in each case. Figure 9 provides a quick table reference of various properties of anodic and electroless nickel coatings applied to aluminum.

A quick look at Figure 9 shows that electroless nickel has greater hardness than hardcoat anodize. Both hardcoat anodize and electroless nickels have excellent wear resistance properties. The boron-based electroless nickel is superior over both hardcoat and phosphorus-based electroless nickel in hardness and wear resistance. Electroless nickel provides a conductive surface over aluminum, whereas the anodic coatings are electrically insulating. Hardcoat anodize is much more brittle than electroless nickel. Electroless nickel is much more uniform than hardcoat anodize, which can make it a better choice in particular wear resistance applications. Appearance, as a property of consideration, can be split between the nickel and anodize coatings. Electroless nickel provides a matte to bright metallic finish to the aluminum. Anodize coatings can be dyed with a wide variety of colors, making them superior when coloration is required. The thickness varies between all of the coatings. Chromic acid anodizing has the thinnest coating, however it provides good corrosion resistance. Sulfuric anodizing also provides good corrosion resistance, but the coating is thicker. Hardcoat anodizing is a thicker coating and not normally specified for corrosion resistance alone. However when sealed, hardcoat coatings can provide fair to good corrosion resistance. Electroless nickel provides good corrosion resistance, but the level of resistance is related to the thickness applied. Electroless nickel coatings can be plated thicker than anodic coatings, making the coating suitable for high-build or salvage operations.

Coating	Chromic Anodize	Sulfuric Anodize	Hardcoat Anodize	Electroless Nickel Phosphorus	Electroless Nickel Boron
Property (ND = No Data)					
Hardness, VHN (After Bake)	ND	ND	<350	500 (1100)	700 (1200)
Corrosion Resistance, Hrs.	>336	>336	ND	96-1000	24-250
Wear Resistance, mg/1000 cycles		ND	<3.5	18 (9)	9 (3)
Electrical Conductivity	ND	ND	ND	ND	ND
Electrical Resistivity	ND	ND	ND	90	89
Density, g/cm^3	0.858	0.429	1.853	7.75	8.25
Tensile Strength (ksi)	ND	ND	6-15	700	110
Stress (ksi)	Tensile	Tensile	Tensile	Nil	110
Electromagnetic Interference Properties	Non-Magnetic	Non-Magnetic	Non-Magnetic	Non-Magnetic	Very weakly ferromagnetic
Reflectance of IR radiation	60-80%	40-60%	40-60%	ND	ND
Specular Reference	ND	20-50%	ND	ND	ND
Uniformity	Very Uniform	± 10% Thickness	± 20% Thickness	Very Uniform	Very Uniform
Appearance	Gray - Iridescent	Colorless	Light-Dark Gray	Matte-Bright	Matte-Semi Bright
Thickness, μm (mils)	4 - 7 (0.1-0.3)	4 - 20 (0.2-0.8)	2.5 - 50 (1-2)	2.5 - 250 (0.1-10)	2.5 - 250 (0.1-10)

Fig. 9 Coating properties comparison of anodic and electroless nickel coatings[4,7-10].

Overall, anodic coatings and electroless nickel plating offer excellent characteristics for aluminum alloys. Consideration should be given to both types of coating when specifying an engineered coating. One coating may be superior to another in one environment and inferior in another environment. Service environment may be a limiting factor in selecting a coating. The alloy, physical characteristics, chemical processes, and coating properties all play a crucial role in selecting the properly engineered solution. Other factors to be considered are the environmental challenges and associated costs for applying the coating.

Environmental Challenges

The metal finishing industry has faced scrutiny for the environmental impacts of the chemicals used. Electroplating operations and chromic acid anodizing operations have been regulated for many years. The Environmental Protection Agency has recently released the proposed Metal Products and Machinery Rule (MP&M). If enacted, anodizers will face new regulations to comply with. It is important for product and process engineers to consider the impacts that selected coatings may impose on the environment, because the metal finisher will need to comply with all environmental regulations. As the cost for compliance increases, so does the cost for processing. If the cost of compliance is too great, the metal finisher will not be able to support the process and will be forced eliminate the process, or even worse eliminate the metal finishing shop. Anodizing and electroless nickel plating both pose similar, yet different impacts to the environment. These processes will be evaluated for the environmental challenges they face.

Anodizing

Different steps in the anodizing process pose an array of environmental challenges. The pretreatment of the aluminum alloys for subsequent anodizing introduces a variety of pollutants into the chemical baths and rinsewaters. Many of the pollutants are heavy metals removed from the alloy during etching and deoxidizing, and oils or greases from previous manufacturing processes, collected in the emulsion cleaners. These pollutants must be removed using wastewater treatment facilities. The pretreatment chemistries may also generate fugitive emissions that require removal through industrial ventilation and scrubbing devices.

The anodizing process also contains pollutants. Anodizing with chromic acid as the electrolyte, is one of the most heavily scrutinized processes. Chromic acid is a known carcinogen. The hexavalent chromium in the solution must be removed through reduction and precipitation in wastewater treatment facilities. The emissions from the anodizing process are regulated and must be removed from the air using the most achievable control technologies. These technologies are more expensive to purchase and operate over conventional industrial ventilation. This is vital to worker and environmental safety. Sulfuric and hardcoat anodizing will build up pollutants from the aluminum alloys processed in the solution. Heavy metals in the solution can be removed with conventional wastewater treatment facilities. These processes also generate emissions that need to be removed using industrial ventilation and scrubbing devices.

Post treatment of the anodized aluminum may contain pollutants. Several coloring dyes are formulated with chromium-containing compounds, which must be removed from solution. If nickel acetate or sodium dichromate is used in the sealing process, the solution will require treatment in wastewater facilities. Most dyes and many sealing solutions are operated at elevated temperatures. As such, the emissions from these tanks will need to be removed with industrial ventilation. Emissions from hot or boiling water seals should be removed from the workspace to prevent corrosion in facilities and provide processing environment control.

Electroless Nickel

Electroless nickel plating of aluminum alloys presents similar environmental challenges to that of anodizing. The pretreatment processes, being nearly identical to anodizing, require heavy metal and oil or grease removal from solutions. Since aluminum requires a zincating step prior to plating, the zinc in the solution and rinses will need to be removed using wastewater treatment facilities.

The electroless nickel plating solution contains pollutants that require special treatment processes. Due to the nature of the plating process, the nickel within the solution is heavily chelated. The removal of the nickel requires additional treatment processes and facilities to break chelation, in addition to the existing wastewater treatment facilities. Another option to the metal finisher is to have the solution hauled off site as waste, as opposed to treatment on site. Either method will increase the cost of disposal.

Electroless nickel coatings do not require any special post treatments, thus no solutions require treatment except the rinsewater.

In summary, many of the processing solutions and the emissions from those solutions must be treated for pollutants. The level of treatment necessary is dependent upon the pollutant or chemicals involved in processing. Any additional treatment or control technologies required will result in additional cost. These costs for technology, facilities, and equipment are paid by the metal finisher, and subsequently passed on to the customer.

Metal finishers must be cognizant of the environmental regulations and concerns involved with the processing of aluminum alloys. It is also necessary for the product and process engineers to be aware of the environmental challenges to ensure the proper application of a coating that is environmentally friendly and cost effective.

Associated Costs

There are many associated costs involved with the coating of aluminum alloys. These costs include equipment purchase, chemical bath make-up, wastewater treatment, hazardous waste disposal, operational costs, and utilities. Various agencies have conducted studies to examine the costs involved with metal finishing of aluminum alloys. This discussion will focus primarily on the description of these costs.

The equipment costs primarily come from the initial capital purchase. Extended costs for equipment are attributed to maintenance parts and consumables, such as filters. The capital equipment costs include the purchase of tanks, heating and cooling devices, rectification, industrial ventilation, material handling, and ancillary processing equipment. The initial equipment purchase may also include the purchase of facilities or floor space for expansion of existing operations. The initial cost of equipment is the highest cost for setting up a process to the metal finisher.

The chemical make-up cost is another major investment for the metal finisher. The cost is heavily dependent on the types of chemistry used. Proprietary chemicals are generally more expensive than the use of bulk raw chemicals. Most cleaning solutions can be formulated from raw chemicals, however, formulation time and chemical storage space may eliminate this as an option. Pre-mixed proprietary solutions may be used for convenience. Proprietary solutions may also be used for the proprietary additives that may enhance cleaner performance under certain situations. Anodizing solutions are almost always made from raw chemicals, such as chromic or sulfuric acid, due to the simple bath formulations. Nearly all electroless nickel solutions are proprietary, although solutions can be formulated from raw materials. The electroless nickel chemistry is more expensive than the raw materials required for anodizing. This is largely due to the research and the expertise in electroless nickel formulations. Also, post treatment chemicals for anodizing are usually made from bulk raw chemicals. The solution formulations for sealing are usually very simple and can be mixed by the average metal finisher. A final note is that if raw chemicals are to be used, then the metal finisher needs to ensure that the quality of raw chemical is acceptable for the process.

Most all metal finishers have some type of wastewater treatment or minimization equipment within their facilities. There are significant costs involved with the type of treatment or minimization equipment installed. Evaporators and water recycling equipment are used to minimize the amount of wastewater generated or discharged. Water treatment facilities to remove heavy metals and other pollutants range in price, dependent upon flow rates and pollutants to be removed. As stated earlier, certain chemistries containing chromium or the electroless nickel solutions will require additional specialized treatment facilities. The costs for these facilities again depend upon the flow rates and chemistry involved.

As a byproduct of water treatment and chemical usage, the cost of hazardous waste disposal may be an added cost. This cost varies with the location of the facility, the size of the processing line, and the method of disposal. Many facilities try to utilize waste recycling to reduce the cost of hazardous waste. Metal finishers also use wastewater treatment to minimize the amount of waste to be sent out as hazardous waste. Other facilities may simply have all of the used chemical materials removed as hazardous waste, to avoid the potential hassles involved with wastewater treatment and discharge. Whichever method is employed, the cost of disposal is significant and is often offset by higher costs to the customer.

Operational costs and utilities are yet another cost to be incurred by the metal finisher. Operational costs include labor wages, insurance, permits or licenses, and shipping and receiving fees. The size of the processing operation will have a large impact on the costs involved. Utility costs, such as water, gas, electricity, and sewer, are generally taken for granted by the product and process engineer, but are of constant concern to the metal finisher. The costs of utilities vary widely dependent upon the location of the facility.

In summary, the overall costs of producing coatings upon aluminum alloys involve many different aspects. Product and process engineers should at least be knowledgeable of these costs when considering the specification of an engineered coating. Concern should be given to getting the right coating at the right price. This will result in a better end product for the manufacturer, customer, and metal finisher in the long run.

Summary

In summary, this discussion is designed to be an informative tool for product and process engineers. It provides a bird's eye view of all aspects of the finishing of aluminum alloys from the perspective of the engineer, manufacturer, metal finisher, and customer. The processes that the aluminum alloy must go through to the end-cost and product should always be in the mind of the designer and engineer. Moreover, all factors involved with the product design should be questioned from the material selection to the desired result, in order to select the proper process. A re-cap of the factors involved is provided.

The product or process engineer first considers the physical characteristics of the aluminum alloy at the material selection phase of product design. The physical characteristics should also be considered by the metal finisher. These characteristics will play directly into the metal finisher's decision-making regarding the successful application of either an electroless nickel or anodized coating.

The engineer may specify physical processes to enhance various properties of the aluminum alloy, from metallurgical to mechanical. Again, the processes specified will have a direct impact on proper metal finishing and successful coating application. Although there is no one recipe for physically treating aluminum, knowledge of the subsequent processes can help the engineer select an appropriate recipe for manufacturing a successful product.

Chemical processing of aluminum alloys takes many shapes and forms. Product and process engineers should be aware of what and how chemical processes are performed. Anodizing and electroless nickel plating are two of these processes. These processes can be broken into three steps: chemical pretreatment, coating application, and post treatment. The pretreatment for electroless nickel plating and anodizing are very similar with the exception that electroless nickel plating requires a zincating step. The coating application step for anodizing and electroless nickel plating is completely different. Anodizing utilizes the passing of rectified current through an electrolytic cell where the aluminum alloy is made anodic in an electrolytic solution. This electrolytic process forms the aluminum oxide coating. Electroless nickel plating is accomplished by placing the activated aluminum alloy into a solution, in which an autocatalytic chemical reaction takes place. The process deposits nickel metal in a matrix with phosphorus or boron, dependent upon the reducing agent. Anodizing and electroless nickel may have post treatments to enhance various features of the coating. Anodizing can be dye colored and is typically sealed, with the exception of hardcoat anodize. Sealing is used to increase corrosion resistance and contain or seal in dyes. Electroless nickel coatings can be post treated by baking to increase hardness and wear resistance.

Coating characteristics are generally foremost in an engineer's thoughts when designing a product. It is imperative that the engineer know the characteristics of a coating, how they are achieved, and what factors affect these characteristics. Common characteristics sought are corrosion resistance, wear resistance, decorative appearance, electrical conductivity or resistivity, and hardness. Various elements of the coatings have a direct or indirect effect on the desired characteristics. One element, coating thickness, may increase corrosion resistance and decrease wear resistance. Another element, chemical formulation, can vary all of the characteristics of a coating.

The environmental challenges faced by metal finishers should be another consideration for the engineer. Due to the environmental challenges in the industry, the process that is designed may not be available or cost effective. This affects both the manufacturer and the customer. Metal finishers do their best to be environmentally friendly, however to accomplish this means the costs will be shared by all.

Finally, the associated costs to apply a coating may go relatively unseen by the engineer. The engineer desires a coating for his design, and the associated costs to apply the coating are not involved in the decision-making process. As a result, the manufacturer and customer are not satisfied as the price of the end product increases, directly impacting its success or failure in the world.

With careful forethought, the product or process engineer can make informed decisions that produce successful products of very high quality. In the process, the designer, manufacturer, metal finisher, and customer can all find satisfaction.

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