Composite Electroless Nickel Coatings For the Aerospace & Airline Industries

By Michael D. Feldstein

This paper discusses in depth the variety of composite electroless coatings used in the aerospace and airline industry. Included are (1) Composites with wear-resistant particles, including diamond, aluminum oxide, tungsten carbide, silicon carbide and boron carbide for hardness, wear and impact resistance; (2) composites with self-lubricating particles, including PTFE, as well as harder inorganic materials that provide greater wear resistance with a low coefficient of friction and are capable of withstanding high temperatures; and (3) composites with light-emitting particles for wear-indicating layers, as well as product authentication. Test results, a cross sectional photomicrograph and patent references are also included.

Electroless plating has grown to be a mature segment of the metal finishing industry. Its characteristics and distinction from other coating methods, including electroplating, are well known and widely utilized. Numerous metals and alloys are capable of electroless deposition. Electroless nickel (EN) processes, discovered by accident in 1946,[1] are the most commercialized in this field and are used widely by the aerospace and airline industries.

The primary reasons for the growth of EN in aerospace and aircraft applications are its properties of corrosion and wear resistance, lubricity, uniformity, and its ability to replace toxic chromium and cadmium plating processes. Typical gas turbine aircraft engine components benefiting from EN are stator assemblies, high pressure compressor spacers, fan blade retainers, fuel and oil line fittings, and bearing housing supports. Airframe components commonly coated with various types of EN include rotor head components, ramp locking devices, landing gear components, and flap and activator components.[2]

Composite EN coatings are still a developing and promising area of metal finishing with extensive potential in the aerospace and airline industries. The potential advantages extend to actual aircraft parts as well as the manufacturing equipment used in aircraft production. The safety benefits of longer lasting, more durable aircraft parts are self evident. This paper discusses the nature and types of composite EN coatings available today, including recent advanced developments.

Electroless nickel is frequently deposited as an alloy of 88 to 99 percent nickel, with the balance phosphorus, boron, or a few other possible elements. EN coatings, therefore, can be tailored to meet the specific requirements of an application through proper selection of the alloying element(s) and their respective percentages in the plated layer. EN is commonly produced in one of four alloy ranges: low (1-4 pct P), medium (6-8 pct P), or high (10-12 pct P) phosphorus, and electroless nickel-boron with 0.5-3 percent B. Each variety of EN thus provides coatings with varying degrees of hardness, corrosion resistance, magnetism, solderability, brightness, internal stress and lubricity. All varieties of EN can be applied to numerous substrates, including metals, alloys, and nonconductors, with outstanding uniformity of coating thickness on complex geometries. It is this last characteristic that most commonly distinguishes electroless from electrolytic plating.

Electroless nickel is produced by the chemical reaction of a nickel salt solution and a reducing agent. Typical EN baths also include one or more complexing agents, buffers, brighteners when desirable, and various stabilizers to regulate the speed of metal deposition and to avoid decomposition of the solution, which is inherently unstable. Diligent control of the solution's stabilizer content, pH, temperature, tank maintenance, loading, and freedom from contamination are essential to its reliable operation.

EN solutions are highly surface-area-dependent. Surfaces come into contact with the solution from the tank itself, in-tank equipment, immersed substrates, and by contaminants. Continuous filtration of the solution, often at submicron level, at a rate of at least ten turnovers per hr, is always recommended to avoid particle contamination that could lead to solution decomposition or imperfections in the plated layer.[3]

Composite EN is intriguing, therefore, as it intentionally introduces insoluble particulate matter into the solution for subsequent codeposition within the coating. The stability ramifications for the plating bath are significant. One gram of 1-μm-sized diamond particles, for instance, contains approximately 310 billion particles.[4] This creates a surface area loading near 100,000 cm^2/L, approximately 800 times the preferred loading of a conventional EN bath.[5] This natural incompatibility between an inherently unstable, surface-area-dependent plating bath and an extraordinary loading of insoluble particles has been overcome by the precise addition of particulate matter stabilizers, or PMSs, as taught in U.S. patents 4,997,686, 5,145,517, and 5,300,330. The methods disclosed therein have made composite EN plating reliable and commercially viable.

Early work on composite electroless coatings was attempted in 1966 by W. Metzger *et al.*[6] Composite EN is currently a growing and exciting segment of the metal finishing industry. Codeposition of particles within EN coatings can dramatically enhance existing characteristics and even add entirely new properties. These capabilities are making composite EN coatings increasingly advantageous for:

1. Facilitating the use of new substrate materials, such as titanium, aluminum, lower-cost steel alloys, ceramics and plastics. The benefits of this capability are of special interest to aerospace and airline applications where lighter, more durable, or less expensive materials are desirable and are made practical with such a surface treatment.
2. Replacing environmentally problematic coatings, such as electroplated chromium.

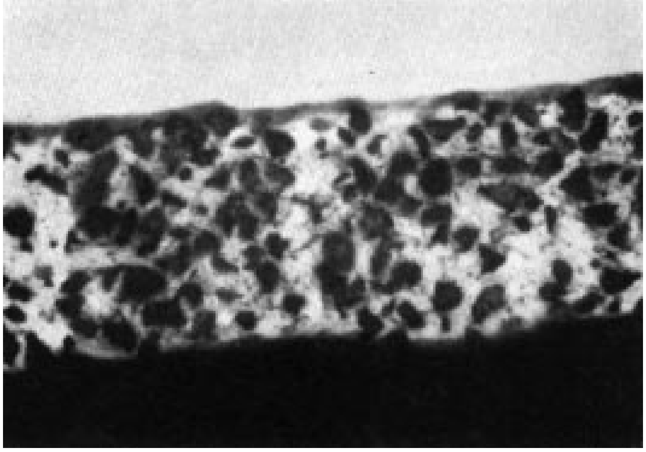
3. Allowing higher productivity of manufacturing equipment with greater speeds, less wear, and less maintenance-related downtime.
4. Ever more demanding usage conditions requiring less wear, lower friction, etc.

Composite EN coatings are regenerative, meaning that their properties are maintained even as portions of the coating are removed during use. This feature results from the uniform manner with which the particles are dispersed throughout the entire plated layer, as observable in the cross sectional photomicrograph. The particles are not merely a topical treatment as with other processes. Particles suitable for practical composite EN incorporation can be up to approximately 10 µm in size. Promising work with nano-sized particles has even been achieved. Narrow particle size distributions are specified for the various categories of composite EN coatings, as discussed below. Certain performance benefits have been discovered (U.S. patents 4,547,407 and 4,906,532) when a composite coating is generated, simultaneously utilizing two distinct particle sizes. It is theorized that the smaller particles fill the spaces between the larger particles.

Depending on the particle sizes and the plating conditions, coatings can be produced with a particle density up to 40 percent by volume. Particle densities of 15-25 percent are optimal for most commercial applications. Lesser densities may not provide the maximum benefits available from the particulate matter, and significantly higher densities risk premature wear of the coating since there may not be enough of the metal "glue" to prevent the particles from being removed. This observation indicates that the typical wear mechanism of composite EN coatings is not wear to the particles themselves when the particles are harder than the EN alloy, but rather wear to the surrounding metal matrix, which eventually allows the particles to be removed.

Coating thicknesses of 12 to 25 µm (0.0005" to 0.001") are typical for most applications. Again, even tighter ranges of coating thicknesses are identifiable for each of the various categories of composite EN coatings. As with conventional EN, composite EN coatings can be heat treated after plating to further enhance their hardness and their adhesion to the substrate. Most composite EN coatings can operate at continuous temperatures of 400 °C (750 °F).

All key parameters of composite EN coatings, such as coating thickness, particle size, particle density, hardness, surface finish, adhesion and corrosion resistance are readily measurable prior to use to comply with the strictest aerospace and airline quality assurance requirements.



Cross sectional photomicrograph showing dispersion of diamond particles within EN deposit. 1000X.

Table 1
Major Uses of Electroless Nickel in the Aerospace Industry

Component	Basis metal	Phosphorus* %	Property of interest**
Bearing journals	Al	L, M	WR, U
Servo valves	Steel	M, H	CR, LU, U
Compressor blades	Alloy steels	M, H	CR, WR
Hot zone hardware	Alloy steels	M, H	WR
Piston heads	Al	M, H	WR
Engine shafts	Steel	L, M	WR, Build-up
Hydraulic actuator splines	Steel	L, M	WR
Seal snaps & spacers	Steel	M, H	WR, CR
Landing gear components	Al	M, H	WR, Build-up
Struts	SS	M, H	WR, Build-up
Pitot tubes	Brass/SS	M, H	CR, WR
Gyro components	Steel	L, M	WR, LU
Engine mounts	Alloy steels	M, H	WR, CR
Oil nozzles	Steel	M, H	CR, U
Optics	Al	H	

* Phosphorus content: H = 9 to 12; M = 5 to 8; L = 1 to 2
** CR = corrosion resistance; WR = wear resistance; U = uniformity; LU = Lubricity

A wide variety of particulate matter is capable of codeposition in EN coatings. In each instance, the plating bath must be modified to accept the specific particles and produce an optimal coating. The three general categories of composite EN coatings that have been developed and commercialized are for wear resistance, lubricity and indication.

Table 1 lists the most common applications of EN in the aerospace industry.[7] Included in this table are the specific properties of EN essential to each application. This table serves as a useful guide for selection of the category of composite EN that would most benefit each application. Certain advanced combinations of composites and deposition techniques have recently been developed and are also discussed below. These advanced combinations are of particular interest to those aerospace applications requiring multiple enhanced properties, as in Table 1.

Wear Resistance

Coatings designed for increased wear resistance have proven, to date, to be the most widely utilized composite EN coatings. Within this category, an extensive array of suitable particles can be used, including diamond, silicon carbide, aluminum oxide, tungsten carbide, boron carbide, and chromium carbide. These materials differ not only in hardness and wear resistance, but also in their shape. Any of these factors can affect surface and performance characteristics. These particles are typically used in nominal size ranges of 1 to 4 µm, with a few applications benefiting from 6-µm-sized particles. Such coatings generally have particle densities of 18-25 percent by volume, and coating thicknesses of 20 to 25 µm (0.0008" to 0.001"), although 50-µm (0.002") coatings have proven advantageous in certain high wear applications.

Proper selection of the optimal particulate material specifications, including size, shape, density, and material for specific wear resistance applications, depends on many factors, including the specific wear mechanism involved. For this reason, standardized wear testing methods are instruc-

Table 2
Taber Wear Test Data

Wear-Resistant Coating or Material	Wear Rate per 1000 cycles (10^4 mil^3)	Wear Rate vs. diamond
Composite EN-diamond*	1.159	1.00
Cemented tungsten carbide	2.746	2.37
Grace C-9 (88WC, 12Co)		
Electroplated hard chromium	4.699	4.05
Tool steel, hardened Rc 62	12.815	13.25

* Composite EN containing 20-30% of 3-µm-grade diamond.

tive, but cannot substitute for controlled testing of various composites under the actual intended use conditions.

Various test methods have been employed to evaluate wear resistance of different materials and coatings. The Taber wear test is the most common. It evaluates the resistance of surfaces to abrasive rubbing produced by the sliding rotation of two unlubricated, abrading wheels against a rotating sample. This test measures the worn weight or volume. The Taber results in Table 2[8] demonstrate the wear resistance of a composite EN-diamond coating vs. other surface treatments and a common tool steel by the Taber test method.

Lubricity

Certain particles can be incorporated into EN to produce a coating with all the properties of EN as well as a low coefficient of friction.[9] Although these composite coatings also provide wear resistance benefits, they are considered in a separate category based on the additional characteristics they embody: dry lubrication, improved release properties, and repellency of contaminants, such as water and oil.

Most applications employing composite coatings with lubricating particles utilize coating thicknesses of 6 to 25 µm (0.00025" to 0.001"). Because these thicknesses are less than those typical of the wear-resistant composite coatings discussed above, an underlayer of conventional (often high-phosphorus) EN is applied to insure maximum corrosion resistance when required.

Most commercial interest in composite lubricating coatings has focused on the incorporation of PTFE into EN deposits. The properties of PTFE are widely recognized.

Table 4
Friction Coefficients for Various Composites & Materials

Coating	Load, kg/cm^2	Friction Coefficient
EN-PTFE	0.1	0.12
EN-BN	0.1	0.13
EN (no particles)	0.1	0.18
Chromium	0.1	0.25
EN-BN	0.3	0.09
EN-PTFE	0.3	0.13
EN (no particles)	0.3	0.16
Chromium	0.3	0.40
EN-BN	0.5	0.08
EN-PTFE	0.5	0.13
EN (no particles)	0.5	0.15
Chromium	0.5	150.00

Table 3
Friction Coefficient & Wear Data for Electroless Nickel-PTFE Composite

Coating on Pin	Coating on Ring	Coefficient Friction Relative	Relative Wear Rate
EN	Cr steel	0.6-0.7	35
EN + PTFE	Cr steel	0.2-0.3	40
EN + PTFE	EN + PTFE	0.1-0.2	1
EN + PTFE	Cr steel	0.2-0.5	20
EN + PTFE[a]	EN + PTFE	0.1-0.7	2

[a] Heated 4 hr at 400 °C

Composite PTFE-EN is commonly available in two density ranges: 10-15 percent and 25-30 percent by volume. The desired density depends on the specific usage conditions of the individual application. PTFE particles in such composite coatings are 1 µm in size or smaller.

The coefficients of friction for EN and composites with PTFE have been measured by a rotating ring apparatus. The results of these measurements, summarized in Table 3,[10] suggest that the lowest coefficient of friction is achievable when both the pin and the ring in the test apparatus are coated with a composite PTFE-EN.

As with wear-resistant particles, there is a variety of particles that produce self-lubricating properties when codeposited with EN. Materials other than PTFE have become an area of increasing interest in the plating field, especially inorganic materials, such as boron nitride, molybdenum disulfide and graphite. PTFE is organic and decomposes at temperatures above 300 °C. This distinction results in significant performance differences. Many inorganic lubricating materials are harder than PTFE and withstand higher temperatures. Because PTFE is a very soft material, its inclusion in EN makes the composite coating comparatively softer, especially as the percentage of PTFE increases.[11] Higher temperature resistance permits higher post-plating heat treatment temperatures, yielding greater hardness of the EN matrix. Moreover, temperature resistance above 300 °C is a common requirement in many aerospace and airline applications. These factors make the composite inorganic lubricant coatings harder and more wear resistant than PTFE-EN in many applications.

Table 4[12] documents the coefficients of friction for a variety of coatings under different load conditions. Boron nitride is one such inorganic material with lubricating properties. It has the ability to withstand temperatures up to 3000 °C, depending on the atmosphere and, as demonstrated in Table 4, composite EN with boron nitride has a lower coefficient of friction than composite EN-PTFE under higher load conditions. There are numerous other materials like boron nitride that provide similar benefits in composite EN coatings. Experience and testing can determine which incorporated material is the most suitable and economical for a given application.

Indication

This category of composite EN coatings, developed with an eye toward the aerospace and airline industries, is one of the most recent and novel developments in the field. These coatings have all the inherent features of EN, and appear normal under typical lighting, but when these phosphorescent coatings are viewed under an ultraviolet (UV) light, they emit a distinct, brightly colored light. Particles of a number of different materials, each emitting light of a different color, have been successfully codeposited in EN. This unique property has been developed for two main uses, as taught in U.S. patents 5,514,479 and 5,516,591.

First, the presence of a colored light emission from the coating can be valuable in authenticating parts from a distinct source. This is especially promising for the identification of genuine OEM parts which otherwise can be routinely counterfeited. A technician or mechanic of an airline, for example, could verify the authenticity of a replacement part before installation on an aircraft. Thereafter, inspection by airline personnel or regulatory agencies is made easier. Its value also extends to the identification of specific manufacturing lots where conventional methods of marking are not sufficient or durable. For these purposes, the indicator layer needs to be only 6 to 12 µm (0.00025" to 0.0005") thick, with a density dependent on the particles used. Any mandatory periodic replacement of aircraft parts is facilitated by this clear method of indication.

Second, the light can serve as an indicator layer, warning when the coating has worn off and replacement, or recoating, is necessary. In this case, it is the disappearance of the light which signals wear. This feature permits the avoidance of wear into the part itself which may cause serious aircraft complications, or irreparable damage to a potentially costly part. When utilized in aircraft component manufacturing, the light-indicating layer serves to prevent the production of inconsistent aircraft components by a worn part, such as a mold, die, press, etc. A light-emitting indicator layer can even be applied prior to, or under, another functional coating to signal when the functional coating has worn through, exposing the indicator layer. In this case, it is the appearance of light which signals wear. As with any other EN coating, these composite coatings can be chemically stripped, leaving the substrate ready for recoating. Hand-held, battery-operated UV lights are readily available, and make inspection for the indicator layer at the operating site fast and convenient.

Advanced Composite Variations

Combination Composite

For certain applications requiring enhancement of multiple properties, hybrid combination composite coatings have been developed to satisfy unique requirements (See Table 1). These coatings incorporate particles of two or more materials into the same plated layer. When significant wear resistance and a low coefficient of friction are necessary, for instance, wear resistant particles can be combined with lubricating particles in the EN bath to produce a coating with both characteristics. Such a coating was recently provided to a manufacturer of internal engine components for small airplanes. Light-emitting particles can also be combined with particles of the other categories to create a more wear-resistant or lubricious coating that also emits light to identify the origin of the part or to indicate when the layer is worn from use. Thicknesses, materials, particle sizes, and densities for these combination composites all depend on the specific application.

Overcoating

Overcoating is a procedure often utilized for composite wear-resistant coatings. Composites containing particles (as discussed above) are smooth to the touch, and sufficient as-is for most applications. There may be, however, some particles on the surface of the coating that are only partially entrapped in the coating. When the coating is intended to contact certain delicate materials, these protruding particles may be deleterious or require a break-in period to smooth the surface. Instead of employing mechanical means to smooth the surface, and instead of operating a coated part for a less productive break-in period; an overcoat can be applied. For a composite EN coating, a conventional EN overcoat layer of only about 5 µm is sufficient to cover the composite surface and provide a new surface which will be smoother and more easily leveled by use. U.S. patents 4,358,922 and 4,358,923, which disclose this method, teach that the smoothness provided by the overcoat layer persists even after it has worn and the composite layer is contacted.

Composite Gradients

U.S. patent 5,707,725 discloses a method for accomplishing the physical benefits of an overcoated composite coating without requiring immersion of a substrate in two separate plating baths. The new method involves plating a substrate in a composite plating bath for a period of time sufficient to deposit the desired thickness of a composite layer, then altering certain parameters of the plating conditions to continue depositing the metal, but with fewer or no particles being codeposited. This, in effect, replicates the dual layer overcoat structure.

Selective Codeposition

In a subsequent refinement to the composite gradient development described above, another novel method has recently been developed. Instead of generating a gradient in particle density across the thickness of a composite layer (from substrate to top surface), the invention disclosed in U.S. patent 5,674,631 provides for different particle densities in different areas of the plated article. This invention is useful for an article where only a certain area(s) needs the beneficial properties of a codeposited particulate material, or if the particles are costly, if codeposited particles would be problematic in certain areas, or if conventional methods of masking are impractical.

Summary

The aerospace and airline industry has utilized electroless nickel (EN) plating for a diverse array of applications. EN coatings can be produced with a variety of properties to serve the needs of specific applications. Composite EN coatings (EN coatings containing fine particulate matter throughout the plated layer) have been developed to enhance certain characteristics of conventional EN such as wear resistance, hardness and lubricity. As demonstrated by the test results included in this paper, these composites surpass the performance of conventional EN and other surface treatments to offer greater productivity, lifetime, economy and safety benefits to the aerospace and airline industry. Other more recent composites have been produced to provide entirely novel properties to the EN coating, such as light emission for part authentication and wear indication critical to the aerospace and airline industries.

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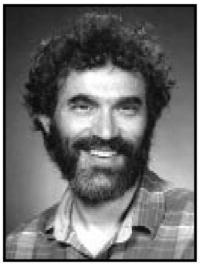

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