Properties and applications of electroless nickel

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The information contained in this publication has been compiled from the literature and through communication with recognized experts within the metal finishing industry. It is presented as a guide to the use of electroless nickel for engineers, metallurgists, designers and others involved in materials selection.

The important properties of electroless nickel deposits are described and examples given of how these properties have been used successfully to solve materials problems in various industries. Through presentation of this information, it is anticipated that new opportunities for the use of electroless nickel coatings will become apparent to those not already familiar with their broad range of properties, thereby promoting growth within the industry.

Introduction

Electroless nickel plating is a process for depositing a nickel alloy from aqueous solutions onto a substrate without the use of electric current. It differs, therefore, from electroplating which depends on an external source of direct current to reduce nickel ions in the electrolyte to nickel metal on the substrate. Electroless nickel plating is a chemical process which reduces nickel ions in solution to nickel metal by chemical reduction. The most common reducing agent used is sodium hypophosphite. Alternatives are sodium borohydride and dimethylamine borane but they are used much less frequently. It is estimated that sodium hypophosphite is used in more then 99% of all electroless nickel plating[1] and this publication refers only to the use of this reducing agent.

It is not the intention of this publication to provide details of the electroless nickel process but rather to review the properties of the deposits and describe successful applications. Some of the unique properties of electroless nickel, such as thickness uniformity, hardness, corrosion resistance and magnetic response have resulted in its use in many different industries. In spite of this, not all designers, engineers, metallurgists and others responsible for materials selection are aware of the value of electroless nickel as an engineering or functional coating. However, it is firmly established as a functional coating in the electronics, oil and gas, chemical, aerospace and automotive industries, for instance. It is also recognized and used effectively in many others and the number of applications continues to grow.

In the following pages, the engineering properties of electroless nickel are described and applications have been selected to demonstrate how these properties have been used to resolve materials problems. The information presented should provide those involved in materials selection, with sufficient background to enable cost effective decisions to be made. Some of these decisions will favour electroless nickel, thereby benefitting the industry and ensuring continued growth.

Properties of Electroless Nickel

Composition and Structure

There are major differences between electrodeposited nickel and electroless nickel that are associated with their purity and structure. For instance, the purity of electrodeposited nickel is typically greater than 99% but when sodium hypophosphite is used as a reducing agent in electroless nickel plating, a typical composition for the deposit is 92% nickel and 8% phosphorus. The phosphorus content has a great effect on deposit properties and it can be varied over a wide range, typically 3 to 12%. The industry normally identifies electroless nickel coatings according to their phosphorus content, e.g.

Low phosphorus	2 - 5% P.
Medium phosphorus	6 - 9% P.
High Phosphorus	10 - 13% P.

Consequently, once the performance requirements for the coating have been defined, it is essential that the appropriate type of electroless nickel be specified. For instance, there are distinct differences in the corrosion resistance and hardness properties of low and high phosphorus deposits, as described later.

The structure of electroless nickel is responsible for some of its unique properties. It differs greatly from the crystalline structure of electrodeposited nickel and it can normally be described as having an amorphous structure or one consisting of ultra fine crystallites.[2] The amorphous nature of the deposits becomes more dominant with increasing phosphorus content and above 10.5%, deposits are considered truly amorphous. The absence of a well-defined crystal structure eliminates the possibility of intergranular corrosion that can be a problem with crystalline deposits, such as electrolytic nickel. Electroless nickel, therefore, provides a more effective barrier coating in protecting a substrate from corrosive attack.

Heat treatment of nickel-phosphorus deposits can cause significant changes in properties and structure. X-ray diffraction examination shows substantial crystallinity and segregation of the deposit into small crystallites of two distinct phases, nickel metal and nickel phosphide (Ni_3P). Some volume shrinkage is associated with the recrystallization and this can result in cracking in high and medium phosphorus deposits.

Physical Properties

Density

The density of pure nickel is 8.9g/cm3. The density of electroless nickel is not constant and decreases appreciably with increasing phosphorus content. For instance, a deposit containing 3% phosphorus has a density of 8.52 g/ cm3 while at 11 %, the density is only 7.75g/cm^3.[3] The relationship between phosphorus content and density is shown in Figure 1.[4]

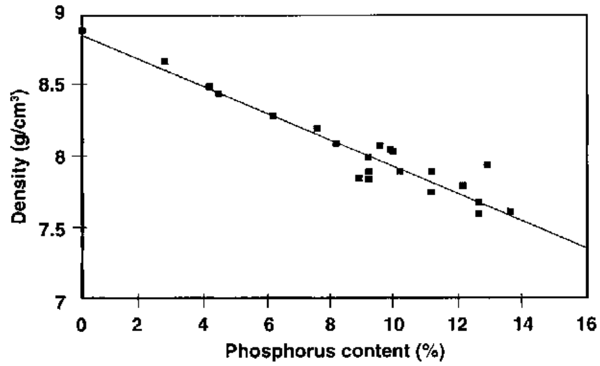

Figure 1 Effect of composition on deposit density.

Melting Point

Electroless nickel does not have the high temperature properties of pure nickel, e.g. high temperature oxidation resistance. Pure nickel has a melting point of 1455°C but the phosphorus content of electroless nickel has a very significant effect on its melting point, as shown in Figure 2. The final melting point curve declines almost linearly from 1455°C to 880°C for an alloy containing 11% phosphorus. This is the lowest melting point (eutectic) for the nickel/ phosphorus system and some melting will occur at this temperature, regardless of the phosphorus content, provided it is greater than 0.2%.[4]

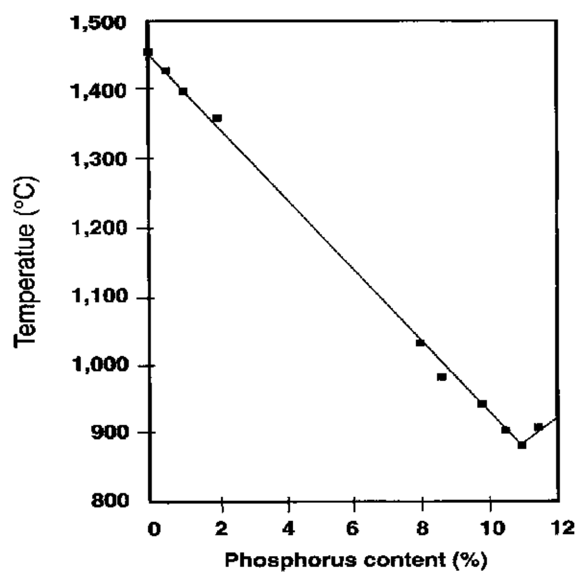

Figure 2 Effect of composition on melting point.

Thickness Uniformity

A feature of great importance in all applications for electroless nickel is the ability to produce deposits with a very high degree of thickness uniformity. It is obviously beneficial when coating complex parts with critical dimensions, such as ball valves or threaded components. This huge advantage over electrodeposited nickel is due to the fact that no current is involved and the associated problems of current distribution do not exist. Uniform thickness of electrodeposits is not easy to obtain and becomes more difficult with increasing complexity of the part. Improved current distribution can be obtained by a suitable choice of electrolyte, the use of auxiliary anodes and shields and by optimizing rack design. However, it is almost certain that the thickness uniformity available by electroless plating will not be achieved on complex parts by electroplating. As electroless nickel plating is a chemical process with no current flow involved, the rate of nickel deposition on all areas should be equal, provided uniform solution conditions are maintained. Temperature, pH, agitation and solution composition are the parameters that control deposition rates and uniform thickness will be obtained unless these are allowed to vary across the surface of the part. The wide acceptance and growth of electroless nickel plating can be attributed in part to this outstanding feature of deposit uniformity, even on complex components. Figure 3 provides an example of the difference in thickness uniformity of nickel deposited electrolytically and by the electroless process.

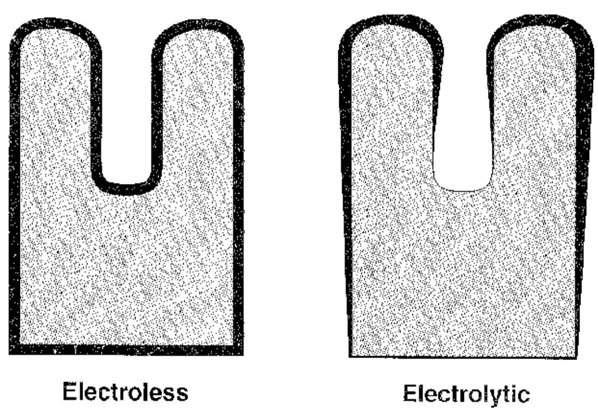

Figure 3 Comparison of deposit uniformity.

Electrical Properties

The resistivity of high purity nickel is 7.8×10^{-6} ohmcm, but that of electroless nickel can be as much as ten times greater. This results from the disruption of the regular lattice structure of high purity nickel by the codeposition of phosphorus and consequently resistivity of electroless nickel increases with increasing phosphorous content. Typically, values are in the range of 30 to 100 x 10^{-6} ohm-cm, as shown for low, medium and high phosphorus deposits in Figure 4.[4]

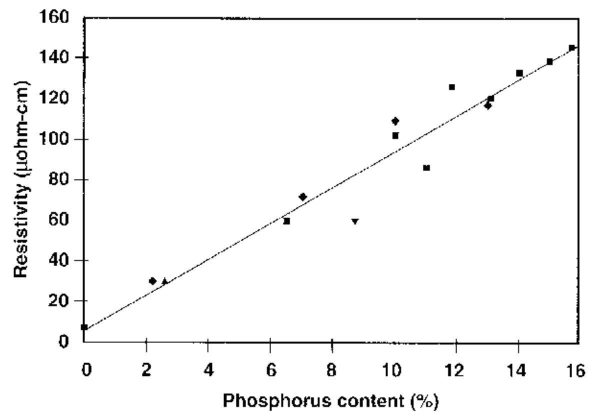

Figure 4 Effect of composition on electrical resistivity.

Heat treating of electroless nickel decreases the resistivity. This can occur at temperatures as low as 150°C but the most significant changes occur at temperatures which cause a structural change by precipitation of nickel phosphide, i.e. typically 260 to 280°C.

Magnetic Properties

The magnetic properties of electroless nickel are of extreme importance as they have been responsible for one of the single largest applications for high phosphorus deposits, i.e. as an underlayer for magnetic coatings in the production of memory discs.

The magnetic response of electroless nickel varies greatly with phosphorus content, as shown in Figure 5.[4] The ferromagnetism associated with high purity nickel decreases dramatically with increasing phosphorus content and deposits with over 11% phosphorus are described essentially as non-magnetic.[3] This condition can be maintained even after heat treatment at 260°C for a short time but once the precipitation of nickel phosphide and the associated structural change occur, ferromagnetism will increase.

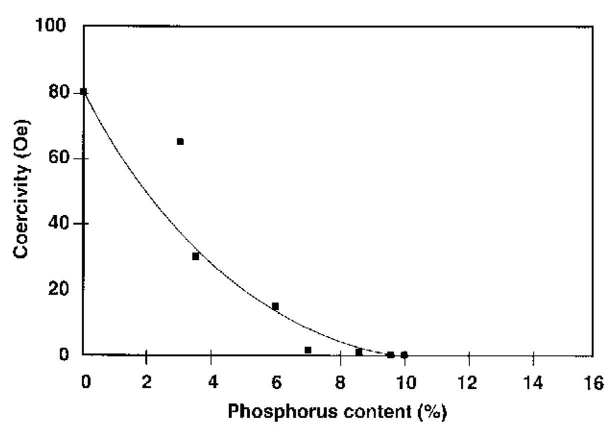

Figure 5 Effect of composition on magnetic properties.

Thermal Properties

The coefficient of thermal expansion of electroless nickel coatings varies from 22.3 µm/m/°C at 3% phosphorus to 11.1 at 11% phosphorus.[4] For comparison, the value for high purity electrodeposited nickel is in the range 14 to 17 pm/m/°C.

Mechanical Properties

Hardness

Note: Hardness values in this publication are presented in units used in the reference literature. No conversions have been made.

Hardness of electroless nickel is a very important factor in many successful applications. In the 'as-deposited' condition it is strongly influenced by the phosphorus content as shown in Figure 6[2]- but all deposits have greater hardness values than electrodeposited nickel e.g. typical Knoop microhardness values range from 500 to 720 compared to only 150 - 400 HK_{100}.

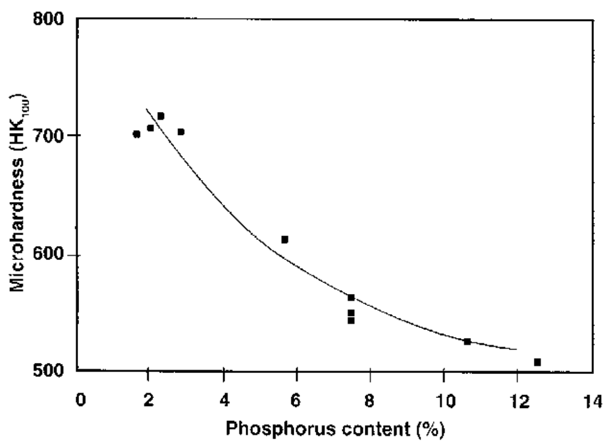

Figure 6 Effect of composition on the microhardness of as plated deposits.

Furthermore, of very special interest is the effect of heat treatment. The hardness of electrodeposited nickel decreases significantly on heat treatment due to recrystallization and grain growth. However, heat treatment of electroless nickel results in a dramatic increase in hardness to levels similar to those of chromium plate. It is for this reason that electroless nickel is used increasingly to replace chromium plate in applications requiring a coating with hard, wear-resistant properties. The case for electroless nickel is greatly enhanced by the vastly superior thickness uniformity of the deposits and the serious environmental issues associated with chromium plating.

The optimum temperature range for heat treatment is 345 to 400°C. The effect of heat treatment for one hour at these temperatures is shown in Figure 7[6] for electroless nickel deposits containing from 1 to > 10% phosphorus.

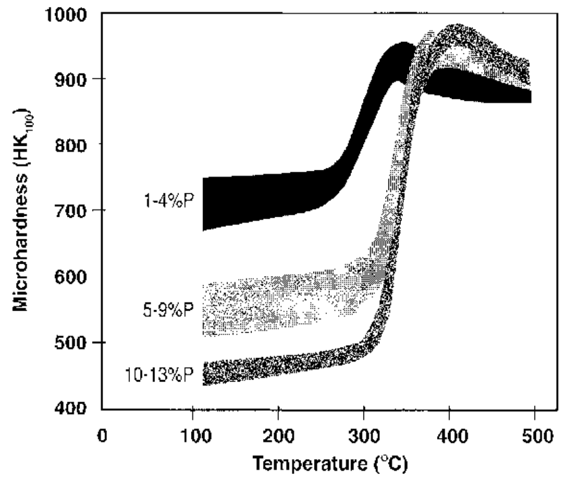

Figure 7 Effect of one hour heat treatment and phosphorus content on hardness.

It can be seen that 'as-deposited' hardness is greater for low phosphorus deposits but the hardness of all types increases dramatically to a range of approximately 850 to 950 HK_{100}.

Increased hardness can be obtained at lower temperatures but longer times are required. Phosphorus content is also a factor in the hardening rate. Prolonged exposure of high phosphorus deposits to heat treatment temperatures has very little effect on hardness, as the major phase present is the inherently hard nickel phosphide. The effect is shown in Figure 8.[2]

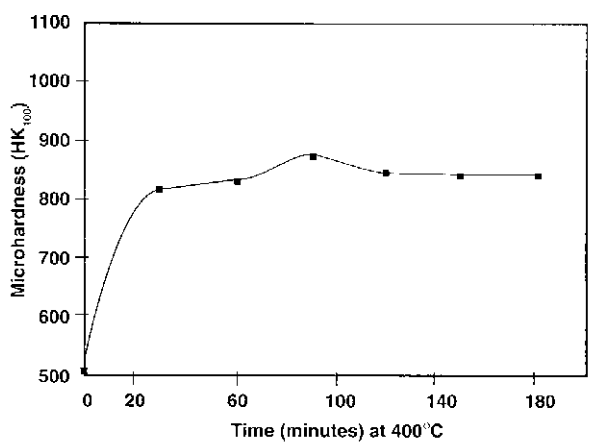

Figure 8 Heat treatment behavior of high phosphorus deposits.

Low phosphorus deposits behave differently and prolonged exposure to heat treatment temperatures results in a decrease in hardness from the maximum attainable. An example of this is shown in Figure 9 for a deposit containing 2% phosphorus.[2] This effect is attributed to the presence of two distinct crystalline phases-nickel metal and nickel phosphide and some associated grain growth.

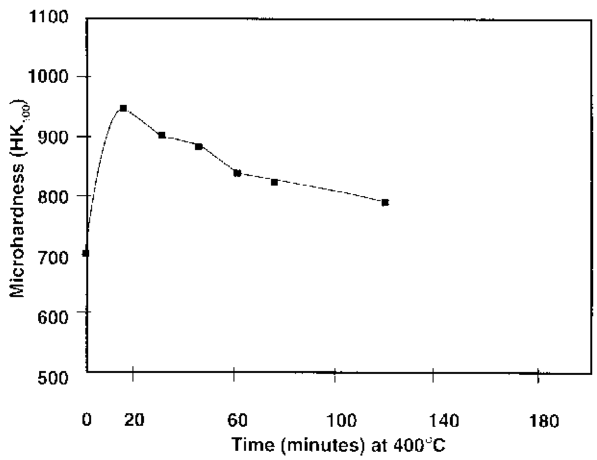

Figure 9 Heat treatment behavior of low phosphorus deposits.

It is shown that the hardness of electroless nickel can be controlled over a wide range. Figure 7 shows this range to be approximately 450 to 950 HK_{100}, which is dependent on phosphorus content and heat treatment time and temperature. The process has proven to be capable of producing deposits with consistent composition and hardness, which can be heat treated to provide increased hardness when required. Recommended heat treatments for the three types of electroless nickel to obtain maximum hardness are shown in Table I.

Table I Heat Treatment to Obtain Maximum Hardness

Phosphorus Content (%)	**Heat Treatment**
2 - 5	1 hour at 400° - 425°C
6 - 9	1 hour at 375° - 400°C
10 - 13	1 hour at 375° - 400°C

It must be emphasized that although heat treatment can be used to increase hardness, other property requirements must be considered. For instance, it can reduce corrosion resistance, especially with high phosphorus deposits.

Wear Resistance

Electroless nickel coatings have good wear resistance because of their high hardness and good, natural lubricity. Wear resistance can be enhanced by heat treatment and, if necessary, by the codeposition of particulate matter such as silicon carbide, diamond, alumina, fluorinated carbon and polytetrafluoroethylene.

Wear can be defined as the loss of material from a surface as a result of mechanical action. It can be caused by abrasion or erosion, for instance, and because it is a complex process, it is necessary to select the optimum method of protection based on the specific conditions involved. There is not one best protective coating against wear but because of the great versatility of electroless nickel, it can be used to resolve many different wear problems.

Hardness is certainly not the only factor in assessing wear-resistant coatings but it is a very important one in many cases. Electroless nickel coatings in the as-plated condition have good resistance to abrasion and erosion, although they are not as hard as some other coatings such as electroplated chromium. However, hardness and wear resistance can be increased by heat treatment to values similar to those of chromium and this, plus the environmental concerns with chromium, has resulted in some substitutional opportunities.

In situations involving wear, in which two metallic surfaces are in contact, galling may occur, particularly if the hardness of the two surfaces are similar. The ability to change the hardness of electroless nickel by heat treatment or by control of the phosphorus content, can be used to advantage to prevent galling, especially if both contact surfaces are electroless nickel.

There are various methods of investigating wear resistance. Abrasive wear resistance is often determined by applying abrasive media to a test piece and measuring the weight or dimensional loss of material under standard conditions. The Taber Abrader is most commonly used. Wear conditions are produced on the test piece by a rotating abrasive wheel and the weight loss is determined after each 1000 rotations. From these values, the Taber Wear Index (TWI) is calculated and typical results for as-deposited and heat-treated electroless nickel deposits with a range of phosphorus contents are shown in Figure 10.[2]

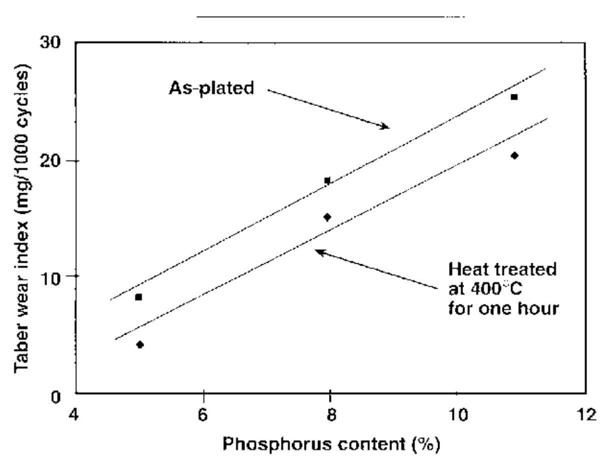

Figure 10 Effect of composition on Taber wear resistance.

It is clear that the low phosphorus deposits provide better wear properties in the as-deposited condition and this would naturally be attributed to greater hardness. However, the fact that the results obtained with the heat-treated deposits follow a similar trend suggests that hardness is not the only factor, as heat treatment produces similar hardness values throughout the range of phosphorus contents shown. Phosphorus content in the heat-treated samples is of greater significance than hardness with this test method.

The results of Taber Abrader tests have shown that high and low phosphorus deposits in the as-deposited and heat-treated conditions are much superior to electrodeposited nickel from a Watts solution. In addition, heat treated low phosphorus deposits gave similar results to electroplated chromium.[7]

Ductility

Electroless nickel deposits have low ductility and phosphorus content within the normal operating range has very little effect, as shown in Figure 11.[7] They are hard, brittle coatings and elongation to fracture is typically only 1 to 2.5%. Normal heat-treatment procedures for electroless nickel increase hardness and reduce ductility.

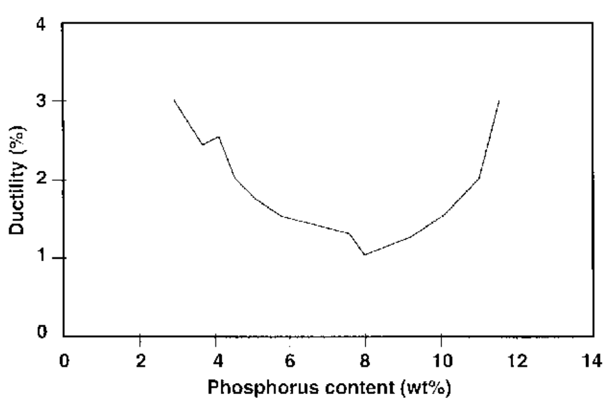

Figure 11 Effect of composition on ductility.

Internal Stress

Internal stress refers to a force, free from external forces that is created within the deposit that tends to change the shape of the deposit in order to relieve the force. When the stress is tensile, it is in a contractile state in which the deposit tends to contract in order to relieve the stress. When the stress is compressive, it is in an expansive state in which the deposit will tend to expand to relieve the stress. Stress can be sufficiently high to influence the properties of some substrates. For instance, the fatigue life of some high strength steels can be reduced when deposits are in a state of high internal stress but this can occur with other stressed coatings, not only electroless nickel.

Internal stress is rarely, if ever, measured on a deposit actually applied to a part. It is conveniently measured on a Brenner-Senderoff spiral contractometer, which provides a stress value that indicates the condition of the plating solution at that time. Electroless nickel deposited at the same time should have the same stress.

Stress is dependent on the substrate being plated,' the formulation and condition of the bath and in some cases, on its age. Organic and metallic impurities in solution can also significantly effect stress.

High phosphorus deposits are compressively stressed when plated from a new bath but generally the stress becomes progressively more tensile as the bath ages. Low phosphorus deposits are in a state of compressive stress from new or aged baths and those with medium phosphorus contents are in a state of tensile stress.[4] The relationship between composition and internal stress is shown in Figure 12.[4]

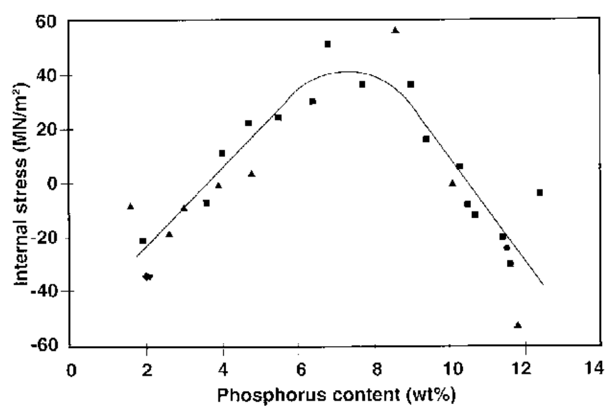

Figure 12 Effect of composition on internal stress.

Corrosion Resistance

The corrosion resistance of electroless nickel is one of the major reasons for its widespread use as a protective coating. However, it must be emphasized that all electroless nickel deposits do not perform in the same way and that the type must be selected to meet the requirements of the specific exposure conditions. For instance, high phosphorus deposits are inferior to low phosphorus deposits in elevated temperature, strongly alkaline media but superior in neutral or acidic media. Other factors that must be considered to optimize corrosion protection include the nature and surface condition of the substrate, the thickness of the deposit and any postplating requirements such as heat treatment.

Electroless nickel does not perform as a sacrificial coating in the same way that zinc or cadmium perform on steel substrates to provide protection against corrosion. It behaves as a true barrier coating between the corrosive environment and the substrate. Consequently, the thickness of the deposit and the absence of porosity are of great importance. Generally, electroless nickel deposits have very uniform thickness and very low porosity. Porosity decreases with increasing thickness and any tendency towards the formation of porous coatings is greatly reduced in deposits containing over 10% phosphorus.[2] The amorphous nature of these high phosphorus deposits is advantageous in corrosive environments for two reasons.[5] Firstly, unlike polycrystalline materials, amorphous alloys do not have grain boundaries at which corrosion sites can be initiated. Secondly, they form passive, glassy surface films, which provide added protection.

The surface condition of the substrate can have a significant effect on porosity in electroless nickel and generally thicker deposits are recommended for rougher substrates to ensure low porosity and optimum corrosion resistance. For instance, to obtain minimum porosity in coatings on relatively smooth substrates, a thickness of 25 microns has been recommended.[5] For rough or sandblasted substrates, a thickness of 50 to 75 microns has been suggested. These thicknesses are derived from porosity studies only and are not necessarily optimum values for maximum corrosion protection. Required thickness must be based on the severity of the environmental conditions.

Electroless nickel is frequently required to provide corrosion protection and wear resistance. Heat treatment is often used to increase hardness and improve wear properties. However, at the temperatures used, an increase in the porosity of the coating generally occurs with a corresponding decrease in corrosion resistance. This is probably due to the formation of microcracks[2] and is of most concern with high phosphorus deposits. Additional comments on corrosion resistance are made in the Chemical Process Industry section.

Applications

Chemical Process Industry

Electroless nickel is widely used in the chemical process industry. Innovative and less expensive substrate materials have found applications when used in conjunction with electroless nickel coatings, as alternatives to some high cost, traditional materials that have not always provided consistent and reliable performance. To ensure continued growth, the industry has actively sought methods of reducing the cost of storage, manufacture and transportation of chemical products. In turn, the search has resulted in increased demand for electroless nickel and the implementation of standards, which have improved the reliability of the performance of construction materials.

Requirements for materials used in the chemical process industry include a need to maintain product purity, to prevent corrosion/erosion problems that may effect the environment and to optimize cost and service life of equipment. Electroless nickel has excellent corrosion resistance, is not susceptible to stress corrosion cracking and can be deposited with a range of composition for use in acidic, neutral or alkaline conditions. It has therefore been evaluated extensively by the chemical process industry to determine its performance as a function of phosphorus content and to establish relative economic information and performance capabilities. The result has been acceptance of the coating for use in a broad range of applications.

It is important to realise that it is insufficient to simply specify electroless nickel for coating components as the composition of the deposit can have a dramatic effect on performance. Examples of this have been reported[8] for a variety of chemicals including thionyl chloride, orthochlorobenzyl chloride, phosphorus oxychloride, benzotrichloride and benzoyl chloride. However, the effect of the composition of electroless nickel coatings is clearly evident from the results of corrosion tests made in two more commonly used and very important chemicals in this industry i.e. phosphoric acid and sodium hydroxide. Figures 13 and 14 show corrosion rates for low, medium and high phosphorus deposits on mild steel in phosphoric acid and sodium hydroxide respectively. The phosphorus contents of the deposits were 1-2%, 6-8% and 10-11%. The superior performance of high phosphorus deposits in phosphoric acid and of low phosphorus deposits in sodium hydroxide clearly demonstrates the importance of composition.

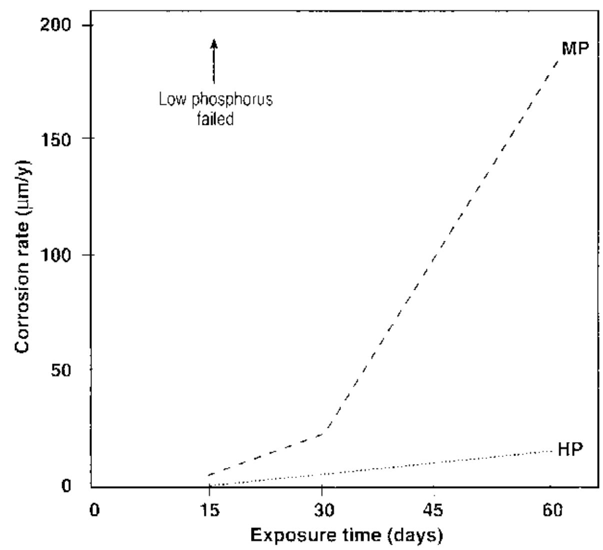

Figure 13 Effect of Composition of Electroless Nickel on Corrosion Resistance in Phosphoric Acid (75 Wt %) at 40°C.

The importance of specifying the type of electroless nickel is further demonstrated in Table II. It compares the performance of low, medium and high phosphorus deposits with alternative materials, in various sodium hydroxide solutions frequently encountered in the chlor-alkali industry[8].

Low phosphorus deposits are shown to be superior to higher phosphorus deposits, N02200 (Nickel 200) and S31600 stainless steel (316S.S.) but in making comparisons, there is some need for caution. It must be emphasized that electroless nickel is used as a coating deposited on a substrate material and under inadequately controlled con-

Table II Comparison of the corrosion rates of electroless nickel coatings in caustic solutions with other commonly used materials. All corrosion rates in microns/year, 100 days exposure.

Caustic Solution	N02200 (Nickel 200)	EN Coatings LP	MP	HP	Mild Steel	S31600 (316 SS)
45%Na0H+5%NaCI@40°C	2.5	0.3	0.3	0.8	35.6	6.4
45%Na0H+5%NaCI@140°C	80.0	5.3	11.9	Failed	No data	27.9
35%NaOH@930C	5.1	5.3	17.8	13.2	94	52.0
50%NaOH@930C	5.1	6.1	4.8	9.4	533.4	83.8
73%NaOH@1200C	5.1	2.3	7.4	Failed	1448	332.7

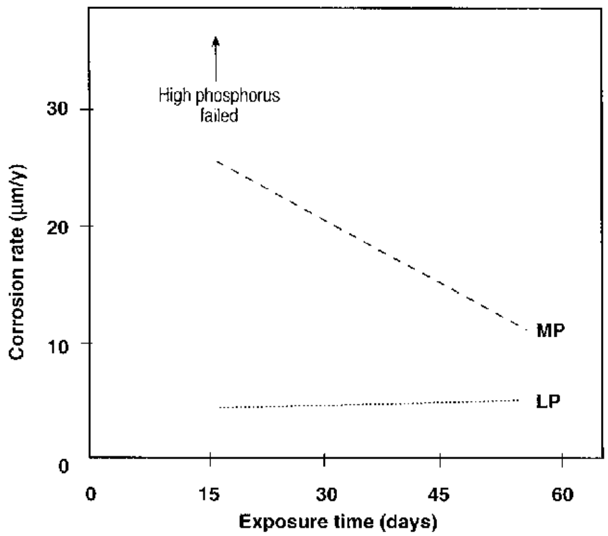

Figure 14 Effect of Composition of Electroless Nickel on Corrosion Resistance in Sodium Hydroxide (45%) at 40°C.

ditions can be susceptible to the formation of imperfections such as porosity or pitting. Satisfactory performance is dependent on the absence of such imperfections as exposure to the substrate material could lead to rapid failure of the parts. The alternative materials shown are uncoated metals and alloys, whose performance is dependant mainly on composition and metallurgical condition, rather than quality and adhesion of a protective coating.

In the chemical process industry, electroless nickel is frequently in competition with fibreglass reinforced plastics, mild steel, S31600 stainless steel, N02200, glass-lined steel and teflon-lined steel. Cost comparisons, for using these materials in the construction of closed vessels and piping systems were made in 1986 and are shown in Appendix 1 and 2 respectively[8]. A similar comparison for bolting applications is given in Appendix 3[8].

There are many applications in the chemical process industry where electroless nickel has been used successfully. In general terms low phosphorus electroless nickel has better corrosion resistance in strong alkaline environments than does high phosphorus electroless nickel. On the other hand, high phosphorus deposits have better resistance to chemicals that may hydrolize to produce weak acid environments. In addition, electroless nickel can provide protection to substrates that are susceptible to stress corrosion cracking. The phosphorus content of these deposits is therefore obviously of great importance but many other properties are also important in the industry, e.g. hardness, wear resistance and galling resistance. In addition, the importance of the adhesion of the deposit to the substrate and the continuity of the coating i.e. the absence of pitting or porosity, cannot be over-emphasized. Electroless nickel coatings provide corrosion resistance by preventing contact between the substrate and the environment. They are cathodic or non-sacrificial coatings when applied over steel and therefore continuous pore free deposits are mandatory. Minimum thickness recommendations are typically 40 microns but in severe corrosive environments 75 microns may be preferred. The ferroxyl test described in ASTM B733 and the salt fog test in ASTM B117 are valuable in determining if coatings are free from porosity. However, results are not always reproducible and the latter is destructive to the coating and requires 24 to 48 hours for completion. An alternative method has recently been reported9 that is based on measuring the mixed potential of a metal surface, consisting of the electroless nickel coating and a ferrous substrate exposed by pores to a corrosive electrolyte. The method is reported to be more sensitive than the ferroxyl test and comparable to the salt fog test. However, it has the advantage of being fast and non-destructive.

It has been reported[10] that the surface finish of the substrate can significantly influence the protective value of electroless nickel deposits. Generally, smoother substrate surfaces provide better quality electroless deposits and mechanical surface treatments and fabrication procedures can result in surface imperfections. These include grit blasting, casting, rolling, stamping, shearing, lapping, drawing, machining and others. Surface imperfections can result in entrapment of solutions which in turn can cause service failure. Improvements to the electroless nickel process are continuously being made and reliable preparation techniques are now available for most substrate materials.

Applications for electroless nickel have been found in the processing, storage and transportation of chemicals. The following are examples of successful applications.

Electroless nickel has been used extensively in the **chloralkali industry,** in which the two main products are chlorine and sodium hydroxide obtained by the electrolysis of sodium chloride, i.e. brine. As produced, chlorine has a temperature of 80°C, is wet and contains some hydrogen, air, carbon dioxide and nitrogen. It must be cooled, dried, purified and compressed to about 0.4MPa (60psi) for liquefaction. **Steel compressors**[10] at a chlor-alkali plant in the U.S. Gulf coast area provided less than one year of service and failure was attributed to build up of sodium sulphate and ferric chloride resulting in corrosion and erosion problems. Although ferric chloride is aggressive to electroless nickel, the good wear and abrasion resistance of high phosphorus deposits have proved beneficial in increasing the compressor life. In one example, six diaphragms in a compressor required repairs annually and the total life cycle of the diaphragms was about eight years. Replacement cost was approximately $200,000 but coating with high phosphorus electroless nickel every four years cost only $15,000. The use of electroless nickel almost

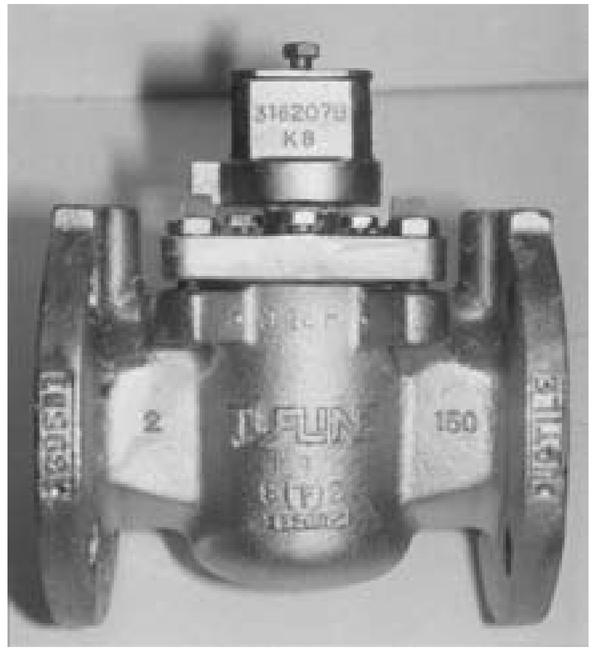

Figure 15 A variety of control valves are protected from corrosion by brine and sodium hydroxide.

doubled the life cycle to fifteen years with significant cost and production savings.

The uniform thickness of electroless nickel deposits combined with the good corrosion resistance has proven very beneficial in many valve applications. For example, the life of **a control valve**[10] used in the concentration of sodium hydroxide from a chlor-alkali cell was greatly increased by electroless nickel plating. The process solution controlled by the valve contained approximately 34% sodium hydroxide, and 7% sodium chloride in water. Solution temperature was 95°C and the flow through the 75mm diameter butterfly control valve was approximately 380L/min. at a rate of 1.75 m/sec.

The original S31600 stainless steel process control valve had a service life of only about two weeks and a change to N08020 (Alloy 20) extended this to about three months. However a laboratory evaluation of 50 microns of low phosphorus electroless nickel over mild steel suggested this as a suitable alternative. Cost was a significant factor and the cost of an electroless nickel coated steel valve was less than one fifth of that of a N02200 valve. The latter material has been widely used in the industry yet is reported to have suffered from corrosion and erosion problems over the years. Performance has been heavily dependent on solution velocity and temperature in sodium hydroxide environments. Tests showed that the corrosion rate of low phosphorus electroless nickel was only half that of the N02200 under static or high velocity flow conditions. They also showed that there was no advantage in heat treating the electroless nickel to increase hardness and in fact the hardness of 59 R_c of the as-plated deposit gave better results than the heat treated hardness of 68 R_c.

An economic study ruled out the use of S31600 stainless steel or N08020 material due to their short lives. In addition, based on an estimated ten year service for a N02200 valve, it was shown that the use of an electroless nickel coated steel valve would be economically attractive if it could provide satisfactory service for a two year period. Such a valve has operated for well over 5.5 years without any signs of corrosion and based on additional laboratory testing it is theoretically possible that it will survive for up to 50 years.

The feed solution to chlor-alkali plants is usually **saturated brine,** typically with a pH of 5.6 and a temperature of about 70°C. Under these conditions[11] austenitic stainless steels such as S31600 have acceptable corrosion rates but are susceptible to pitting and stress corrosion cracking. N02200 is not usually suitable for use with rapidly flowing brine and mild steel corrosion rates are unacceptably high. High phosphorous electroless nickel has been shown to have superior corrosion resistance in this environment and has been used extensively for **transporting brine in chlor-alkali plants.** Rubber lined equipment is a competitor but typically has a design life of about eight years, compared with an expected life of fifteen years for 75 microns of high phosphorus electroless nickel on mild steel.

Also in the chlor-alkali industry, **cooling towers** are used to reduce the temperature of the 50% sodium hydroxide solution produced, to simplify handling and minimize corrosion. Typically[12], cooling tower water would have a temperature of 35°C and contain air, sodium carbonate and sodium chloride at a pH of about 8.5. Within two years of service, steel pumps and process lines failed due to corrosion/erosion and cavitation. Controlled tests made under the solution conditions described and at a flow rate of 1.83m/sec. indicated the excellent performance of high phosphorus electroless nickel. This is attributed in part, to the hardness of the deposit and the resulting beneficial effect on erosion. The test results and economics warranted the plating of **cooling tower water pumps** with 75 microns of high phosphorus electroless nickel. After three years, no corrosion or service problems had occurred.

In the transportation of chemicals, electroless nickel plating has been successful in protecting **nuts and bolts** used to hold down protective steel covers over loading valves on tank cars used for shipping 50% by weight sodium hydroxide. The original material of construction for these fasteners was 641400 (ASTM A 193-7) alloy steel but within a short time the bolts would corrode, become difficult to remove and create a risk of failure in transit. Electroless nickel plated nuts and bolts was an obvious alternative to other fastener materials.[10] Not only is the corrosion rate of low phosphorus electroless nickel extremely attractive but it also offers increased lubricity in addition to outstanding wear and abrasion resistance. The durability of the fasteners was therefore greatly enhanced and installation and removal simplified. Furthermore, the economics supported the use of electroless nickel. Consequently bolts coated with 25 microns of low phosphorus electroless nickel were installed on over 100 railcars and after 3 years of service there were no failures and after 5 years of service 70% of the bolts were still in satisfactory condition.

For such applications, it is essential that fastener dimensions be designed to account for the coating thickness so that no binding will occur. It is equally important that all burrs be removed from threaded areas before coating, as during installation of the fasteners, a nickel coated burr can easily be detached leaving behind a prime, uncoated site at which corrosion can begin. As in all applications in which coated materials are being considered as alternatives to uncoated materials, such as stainless steels and N02200, it must be remembered that a single defect in the coating can lead to premature failure of the part.

Figure 16 Rail car components such as safety vents, valve assemblies and cover plates are plated with electroless nickel.

Other components on **rail cars** used for transporting sodium hydroxide have provided excellent service after coating with electroless nickel". For instance, **safety vents, unloading connections, air connection valves and bottom outer valve assemblies** coated with low phosphorus electroless nickel have shown excellent corrosion resistance and prevented discolouration of the product due to iron contamination. Similarly, 50 microns of electroless nickel on mild steel unloading pumps on barges transporting high purity sodium hydroxide" have been technically and economically successful.

The corrosion resistance and lubricity of electroless nickel has resulted in its satisfactory application in a **monochlorotoluene distillation column.** The column was about 4.9 m high with a diameter of about 1.06 m. Within the column were forty trays, fabricated from 1 cm thick mild steel plate, with each tray containing over five hundred uniquely designed valves which provide an exit for the product after reaching a preset head pressure. The system experienced severe plugging due to the build-up of corrosion products and it was essential to prevent this to avoid frequent shutdowns. Following laboratory testing of various materials, electroless nickel-coated steel was selected as the best alternative based on performance and cost. The selection was justified by the results obtained in production, as no plugging or shutdown of the system occurred for over four years after plating the trays with 75 microns of high phosphorus electroless nickel.

Some sectors of the chemical industry have taken advantage of the excellent wear resistance that can be provided by electroless nickel deposits. **Grinding screens** are used in producing phenolic resin molding compounds '° and various filler materials are added to obtain required physical and mechanical properties. The screens were made from an abrasion resistant steel plate and were typically 35 cm x 76 cm x 0.5 cm thick. When using a certain mineral - type filler in the formulation, screen life was less than one day but by coating with 50 microns of low phosphorus electroless nickel, the life was extended to over four days. The economics were especially attractive, as coating cost was very low and each screen could be re-coated several times before being discarded. Although the process is no longer used in producing phenolic molding compounds, the example clearly demonstrates the wear resistant properties of electroless nickel.

Protection against wear and erosion has also been provided in **pelletizing equipment** for polyethylene.' On discharge from the reactor, product is separated into individual pellets in an impeller-type unit that operates with a rotary cutter and water ejection. The unit is shown in Figure 17 It is a lightweight component, made from aluminum for easy handling and the first one used was worn through in only three weeks. The erosion was so severe in that time that the weight of the unit was reduced from 40Kg to 25Kg. A replacement aluminum casing, coated with 125 microns of high phosphorus electroless nickel, showed no measurable attack after several years.

Sea water cooling is frequently used in chemical plants. It is efficient and inexpensive but does contain chloride ions and therefore can be aggressive towards some construction materials. When expanding cooling capacity, tapping into an existing line while continuing to operate can prevent down time and therefore be very cost effective. '° **"Hot taps"** are used to accomplish this but the design of standard units created some concern amongst materials engineers. This was related to the possibility of severe crevice corrosion occurring due to the presence of stagnant sea water between the existing ductile iron line and the hot tap. '4 After laboratory testing had proven the excellent corrosion resistance of high

Figure 17 The excessive wear of this aluminum pelletizer for polyethylene was overcome by electroless nickel plating.

phosphorus electroless nickel in sea water, 75 microns were plated onto hot taps and no corrosion or leakage occurred in over three years of service.

Flow metres for handling aqueous solutions containing 31% **potassium hydroxide** plus 19% potassium carbonate at 105°C have been manufactured from S31600 stainless steel[11]. However, there have been concerns about the possibility of stress corrosion cracking and in corrosion tests, low phosphorus electroless nickel was shown to have very much lower corrosion rates in this environment than S31600. The combination of low phosphorus electroless nickel over S31600 has proved to be very successful for these flow meters.

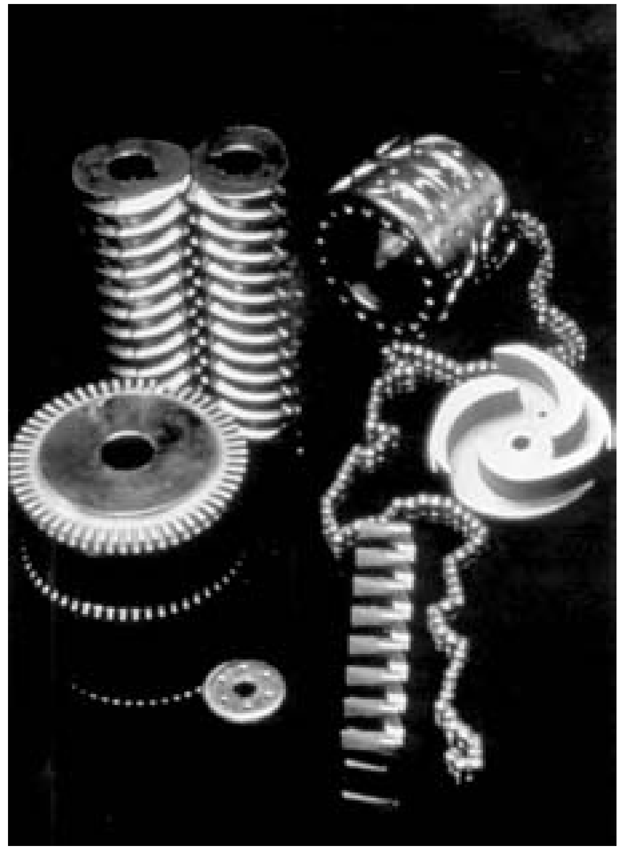

Figure 18 Typical plated components used in processing and packaging of food.

Food Industry

Electroless nickel coatings have found many applications in the food industry. However, no coating systems have blanket approval by The Food and Drug Administration (FDA). Only stainless steel has such approval and is used extensively in food processing equipment. In fact, materials and articles that are used in contact with food and where there is a possibility that components of the article will migrate into the food are treated by FDA[15] in the same way as food additives i.e. approval for their use is required on an individual basis.

When alternative materials to stainless steel are used because of cost, fabrication problems etc., manufacturers may consider aluminum alloys, carbon steel or low grade stainless steels. In this case, it is frequently necessary to coat these materials to provide suitable corrosion resistance, wear resistance and cleanability, for example. Electroless nickel has gained wide acceptance as a protective coating for many different components which do not make direct contact with food. For instance, typical **packaging equipment** applications include bearings, rollers, conveyer systems, hydraulics and gears in meat processing, grain processing, bakeries, fast food restaurants, breweries and poultry processing etc.

The preferred electroless nickel coating for most applications in the food industry is the high phosphorus type containing 10 to 12% phosphorus. These amorphous, glasslike coatings have excellent corrosion resistance and the absence of grain boundaries essentially eliminates concerns of stress corrosion cracking that may exist with stainless steels in certain environments. As-deposited hardness values of about 45 R_c are typical and so wear resistance is good. If necessary, hardness can be increased up to about 68 R_c by heat treatment and lubricity can by improved by codeposition of fluorinated carbon (CF_x) or polytetrafluoroethylene (PTFE) particles. These coatings offer great benefits when good wear and release properties are required on such items as **molds and rolls.** For instance, the dog bone mold shown in Figure 19 is coated with an electroless nickel/fluorinated carbon composite to provide excellent abrasion resistance and lubricity.[16] This composite was chosen due to the ability of the fluorinated carbon to withstand temperatures in excess of 540°C. This allows maximum hardness to be obtained in the nickel by heat treatment without adversely effecting the lubricity of the fluorinated carbon.

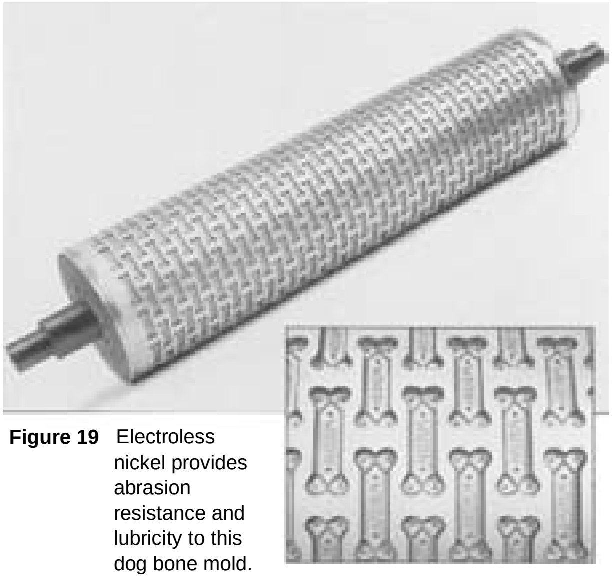

Figure 19 Electroless nickel provides abrasion resistance and lubricity to this dog bone mold.

Other features that are used to advantage in all applications for electroless nickel are also beneficial in the food industry, i.e. the thickness uniformity of the deposits and their pore-free characteristics. An additional benefit provided by the excellent release properties is the ease of cleaning components such as rolls and mixers.

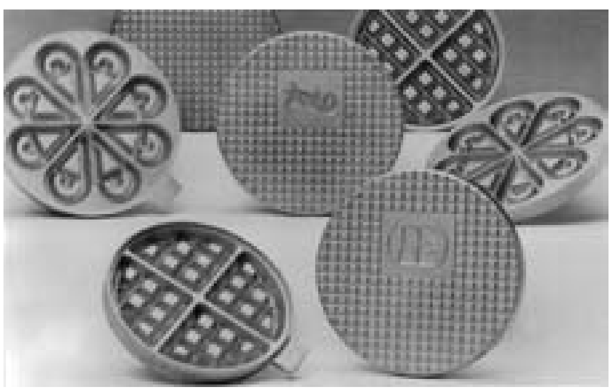

Figure 20 Plated waffle molds have excellent release and cleaning characteristics.

Some of the most successful applications involving food contact have been in the **meat processing industry**, which frequently uses sodium chloride, nitrites, citric and acetic acid in their processes. Natural wood smoke, very humid atmospheres and temperatures up to 200°C are also typical conditions associated with meat processing and electroless nickel has been successfully used to prevent corrosion, stress corrosion cracking and fatigue failure of process equipment." In addition, electroless nickel has been used as a cost effective alternative to chromium plate in applications requiring good abrasion and corrosion resistance, e.g. on extruders for meat products. It has also been used successfully as a replacement for chromium in the **bakery industry.** The equipment used for kneading dough is complex in shape for chromium plating but it presents no problem in applying uniform electroless nickel deposits. The excellent wear and release properties of the deposits combined with the thickness uniformity have all contributed to the success.

Figure 21 Wear on meat grinding equipment is greatly reduced by electroless nickel.

In a series of tests made by the National Sanitation Foundation for Occidental Chemical Corp.[18] the advantage of the high phosphorus over lower phosphorus coatings has also been demonstrated. This was in standard impact testing using a 2.5 cm steel ball, which resulted in visible cracks in electroless nickel coatings containing less than 10% phosphorus. This observation plus the superior corrosion resistance clearly demonstrates why electroless nickel containing 10-12% phosphorus is usually the preferred choice in the food industry.

Oil and Gas Industry

The oil and gas industry was a proving ground for electroless nickel for many years. The coating has provided excellent service in a wide range of applications and this industry is now reported[19] to account for about 15% of all electroless nickel plating in North America. The properties of most value to the industry have proven to be the thickness uniformity of the deposits, the excellent corrosion resistance - particularly of the high phosphorus type - and the abrasion/erosion resistance. The performance of many of the base materials traditionally used in the industry has been greatly enhanced by application of electroless nickel and lower fabrication costs and extended service life have been realised. The latter is of particular value as the cost of shutdowns in this industry to replace components can be extremely high.

Operations in the oil and gas industry can be divided into three major areas - surface operations, subsurface or downhole operations and offshore operations. Equipment is often exposed to severe environmental conditions which can include chlorides, hydrogen sulphide, carbon dioxide, brines, sea water and reef water. The latter usually contains high levels of sulphur compounds. Exposure may also be combined with abrasion problems associated with the ingestion of sand and mud and in some cases, temperatures as high as 250°C. Typical components, whose performance has been enhanced by electroless nickel include the following[19]:

Surface - blowout preventors, brake assemblies, chokes, compressors, gas turbines, pump housings, pumps, connection manifolds and valves.

SubsurfacelDownhole - couplings, logging tools, plungers, packers, pumps, safety valve units and tubing.

Offshore - blowout preventors, gas turbines/compressors, heat exchangers, pumps, riser connectors and valves.

There are many specific examples of the use of electroless nickel in this industry and exposure conditions may vary greatly, as can be seen in the applications described below.

The thickness uniformity, corrosion resistance and wear resistance of electroless nickel have resulted in its widespread use in **valves and flow control devices.** These are obviously critical components in the operation of a well where good performance and long life are major economic factors. The properties of electroless nickel that were first recognized as potentially useful in these applications were the corrosion resistance, smoothness and thickness uniformity of the deposits. It was considered that these properties would provide the required surface condition for ball plugs and improve the sealing at the seat areas. Initially regarded as a possible alternative to hard chromium, electroless nickel now dominates this market. The application of 75 microns of electroless nickel to mild steel ball valves is now typical in this industry. Typical ball valve plugs and bodies are shown in Figures 22 and 23 respectively.

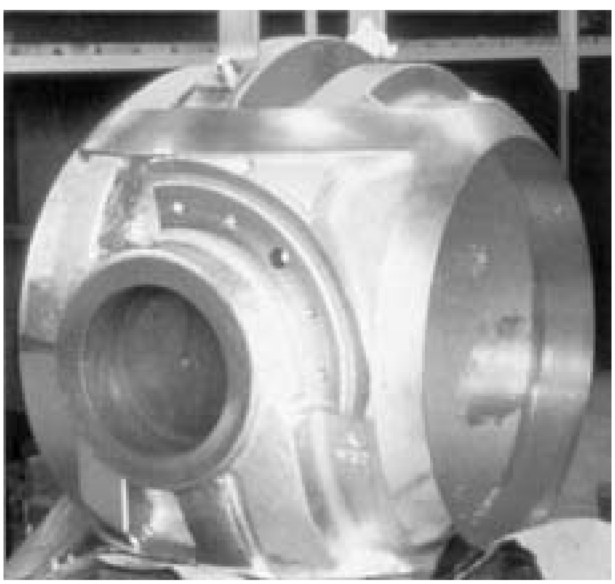

Figure 22 Plated 105cm ball valve plug. Thickness uniformity and corrosion resistance are major requirements of the deposit.

Successful applications have been observed in all areas of the oil and gas industry.[19] For instance, in crude oil production at a plant in the Middle East, the associated gas contains 55% hydrogen sulphide and is processed at 80°C and a pressure of 20MN/m^2 (3000 psi.). Under these conditions, mild steel **ball valves** had a maximum life of three months, with failure occurring as a result of corrosion, surface cracking and erosion. Electroless plating of the valve components with 75 microns of nickel extended the life of the assemblies enormously and no surface deterioration was evident after two years of continuous service.

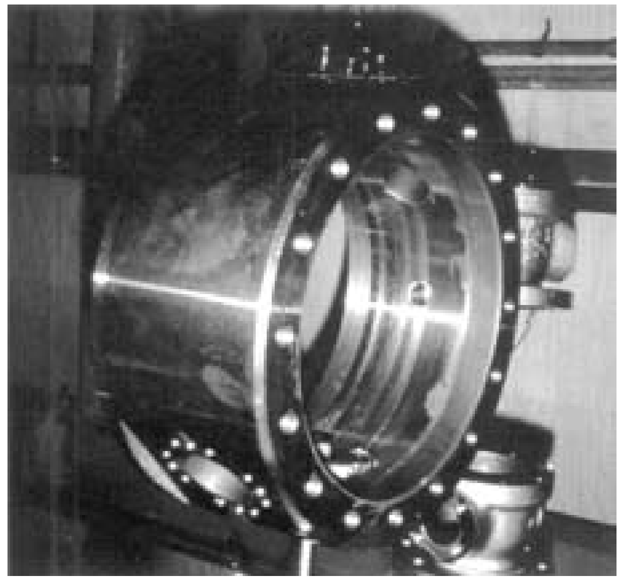

Figure 23 Electroless nickel plated body for large ball valve.

Similar benefits have been realized on ball valves at plants using the sea water injection system.[19] This involves pumping sea water under high pressure to force the oil to the surface. At the Ghawar oil field in Saudi Arabia, 75 microns of electroless nickel on the valves had satisfactorily withstood the operating conditions to such an extent that no degradation of the coating was detectable after four years of operation.

It should be recognized that although electroless nickel has been used successfully on ball valves in the oil and gas industry, it has been equally successful on valve components in other engineering applications. For instance, it has been used on the upper and lower stems of huge ball valves manufactured for the Aswan High Dam project in Egypt[4]. It is essential that valves can be opened and closed easily and reliably whenever necessary, even though no movement from a set position may have occurred over a long period of time. Protection of the stems from corrosion and abrasion by coating with 75 microns of electroless nickel, provided the reliability. The huge 106T valves had a 260cm bore and the upper stem alone weighed over 6T.

The performance of **valves, chokes** and other components plated with electroless nickel has been equally impressive in **Khuff gas wells.** Khuff gas is a lean natural gas, produced from a dolomite and limestone formation that typically contains about 6 mole % carbon dioxide and 0.1 mole % hydrogen sulphide'°. It also contains approximately 28L/Mm3 of condensate, predominantly hexane, and 7L/Mm' of water. At the wellhead, the gas pressure is typically 35MN/mz (5000psi) and the temperature 90°C. Gas velocities are normally greater than 6m/sec. and under these conditions, the damage to steel components by corrosion/ erosion was very severe. Pitting and erosion resulted in metal loss rates of 3 to 5 mm/year on carbon steel chokes and this was successfully eliminated by the application of 25 microns of electroless nickel on all wetted surfaces. Problems with ball valves in this environment have also been overcome by use of electroless nickel and typically 75 microns applied to valve plugs has prevented corrosion for at least six years.

The corrosion resistance, hardness, surface finish and lubricity of electroless nickel have been very beneficial in the manufacture and performance of **fire-flow valves.**[19]

Figure 24 Typical butterfly valve plated to provide corrosion resistance, hardness and lubricity.

These valves are required to provide a bubble-tight seal during normal operations and to act as shut-off valves after inadvertent exposure to 650°C. They are also required to remain operable in the event of a fire. A typical butterfly valve of this type is shown in Figure 24.

Electroless nickel is also used on some critical **safety valve** applications.' 9 For instance, **blowout preventors** are safety valves used to shut down oil and gas wells in emergency situations. A unit consists of a hydraulically operated ram, capable of cutting through the tubing carrying the oil and gas to seal the flow. After testing, a unit is only required to operate once in an emergency but to ensure satisfactory performance, it is mandatory that no corrosion or physical damage occurs on the ram or sealing surfaces. Electroless nickel coatings, approximately 100 microns thick, are frequently used to provide the hardness and corrosion resistance required. Typical rams are shown in Figure 25.

Figure 25 Rams on blowout preventors are plated to prevent corrosion and physical damage.

The oil and gas industry has an enormous demand for **tubular components**[19,4,17] and mild steel is most frequently used. However, in many applications it does not have the corrosion resistance or abrasion/erosion resistance to provide acceptable service life. Consequently, although the initial cost may be low, mild steel alone is not always cost effective but when coated with 50 to 100 microns of high phosphorus electroless nickel, the cost/performance factor can be very positive. High maintenance costs and production losses can be greatly reduced. As an example of the scale of this application, 30,000m of tubing coated with 50 microns of electroless nickel were installed down hole in the Permian Basin area of Texas over a four year period.4

Tubular components are frequently exposed to severe, corrosive conditions. For instance, the environment may contain hydrogen sulphide, carbon dioxide and chloride ions at temperatures as high as 260°C. In such environments, high phosphorus electroless nickel has been shown to have similar corrosion resistance to N06985 (Hastalloy G-3) at 65°C but to be inferior at 260°C. Nevertheless on a cost/performance basis, etectroless nickel is often superior."

Stainless steel tubulars can provide very effective performance in many applications but they are often susceptible to chloride attack and galling problems. Cost is also significantly higher than electroless nickel plated mild steel. Plastic coatings such as phenolics and epoxies can also be used to prevent corrosion but they are markedly inferior to electroless nickel under abrasive conditions. On threaded components, the thickness uniformity of electroless nickel is an additional advantage.

Electroless nickel is widely used to protect various components in **pumping systems,** such as housings, impellers and discharge barrels.[17] Typical deposit thickness is 25 to 75 microns depending on the environmental conditions. For instance, 75 microns of electroless nickel has greatly extended the service life of **mud pumps**[19]**.** Drilling mud is a mixture of various clays in water, which is used to lubricate and cool the bits during well drilling operations. It is abrasive and can be very corrosive in combination with oxygen and acidic gases such as hydrogen sulphide. The pumps used to circulate the mud are reciprocating units often fabricated from G86300 (AISI 8630) steel. This is a high strength alloy capable of withstanding the high pressures associated with drilling but pump failures due to corrosion fatigue or stress corrosion in the seal areas have been reported after only three months operation[19]. Electroless nickel plating has been effective in extending pump life to greater than eighteen months. Typical mud pumps are shown in Figure 26.

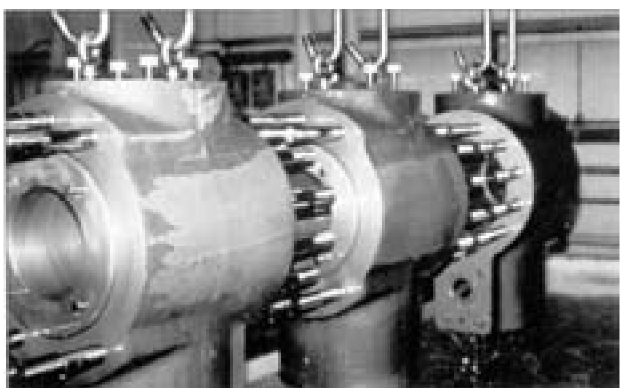

Figure 26 Electroless nickel plated mud pump bodies.

Historically, hard chromium electrodeposits have been used very successfully to protect **down hole drill motor rotors**[19] from wear. Down hole motors are installed adjacent to the **drill bit** and so operate at depth. This is in contrast to large surface mounted motors that operate bits at great depths through connections made by drill pipe strings. Down hole motors function as a result of power generated by the passage of drilling mud over a rotor. The value of electroless nickel first became apparent in North Sea oil operations, where sea water is used to make up drilling mud. Although chromium was capable of providing good wear resistance, it was unable to provide satisfactory corrosion resistance in the sea water environment. A duplex coating of high phosphorus electroless nickel with a hard chromium topcoat has resolved the corrosion and wear problems. Typical rotors are shown in Figure 27.

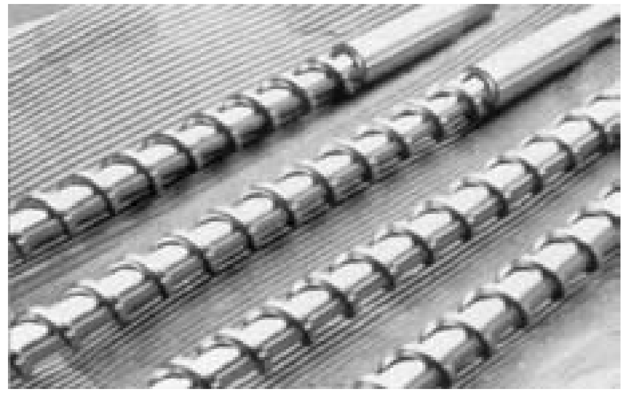

Figure 27 Corrosion and wear of down hole drill motor rotors are resolved by electroless nickel plus chromium plating.

There are many other steel components and tools used in the oil and gas industry that are routinely plated with electroless nickel. These are surface and submersible parts that require protection from corrosive and abrasive environments. Before specifying any heat treatment of parts, consideration must be given to the effect this may have on their performance under aggressive, corrosive conditions. Typical thicknesses of electroless nickel deposits are 25 to 75 microns but this range can be extended if demanded by exposure conditions. This industry has used the thickness uniformity of coatings to great advantage, especially for tubulars, threaded components and ball valves.

Automotive Industry

For many years now, automotive companies have been focussing on quality, performance, efficiency and extended warranties. Consequently electroless nickel properties such as corrosion resistance, wear resistance, lubricity and uniform deposit thickness have been used to great advantage in this industry. The performance of steel and aluminum components, for instance, has been enhanced by the use of electroless nickel and typical applications[21,17] are on heat sinks, pistons, engine bearings, hose couplings, gear assemblies, carburetor parts, fuel injectors, shock absorbers and exhaust system components. Automotive companies have recognized the benefits of electroless nickel in all these and other applications and have their own specifications for its use. However, recognition and acceptance of the value of the coating has generally been greater in Europe and Japan than in North America.

The interest in **alternate fuels** for automobiles generated an enormous amount of work on electroless nickel and the focus was on South America, especially Brazil, where a decision was made in 1976 to switch from gasoline to alcohol (ethanol) as fuel.[22] Enormous cost advantages were correctly predicted in Brazil, as alcohol fuel could be produced from local sugar cane whereas gasoline required imported oil. A major problem occurred during the introduction of alcohol fuel. Hydrated alcohol, passing through the **carburetor** at high temperatures, produced corrosive conditions that severely corroded the zinc diecast components. Corrosion products quickly plugged the narrow channels and orifices in the carburetor but electroless nickel was able to resolve the problem. The deposit, typically 5 to 9 microns thick, had excellent corrosion resistance in this environment and of equal importance was the thickness uniformity, which was mandatory for simplifying assembly and optimising carburetor performance.

Fuel injection systems, aluminum fuel filters and other components in contact with the alcohol also require the corrosion protection provided by electroless nickel to meet operational requirements. The conversion from gasoline to alcohol in millions of automobiles in Brazil has resulted in dramatic savings on imported oil and electroless nickel has been an important factor in the success of the programme. The complex shape of a typical carburetor, plated with electroless nickel is shown in Figure 28.

Figure 28 Electroless nickel resolved corrosion problems on carburetors using ethanol fuel.

In North America, 'alternate fuels' have normally been used to describe gasoline/methanol mixtures with a broad range of composition. These fuels are also very aggressive and can cause accelerated corrosion of some metallic, fuel system components.[23] High phosphorus electroless nickel has been shown to provide excellent corrosion resistance even in the most aggressive fuel mixtures. An added advantage is the excellent wear resistance of the coating in areas of rapid fuel flow.

The lubricity, wear resistance and anti-galling properties of electroless nickel have been used to good advantage in the automotive industry.[24] The coating should always be considered as an alternative to chromium plating or nitriding when wear is a factor. For instance, excessive wear can occur on **differential pinion shafts** as a result of contact with the uncoated teeth on the two gears that ride along them. Heat treated, low to medium phosphorus electroless nickel typically 25 microns thick, has been very successful in reducing this wear. The plating process competes with nitriding in this application but has an advantage at the higher loads exerted on the differential on new car models. Concerns exist about the embrittlement and possible fracture of nitrided shafts, a situation that does not arise with electroless nickel plating of these parts.

Figure 29 Plated pinion shafts in this differential have excellent wear and anti-galling properties.

Electroless nickel has competed with nitriding in other wear applications, such as on **viscous coupling plates** contained in vehicle transfer boxes.[24] These are discs that spin and rub together during the positive traction process and a typical four wheel drive vehicle would contain fifty such discs. It has been possible to maximise wear resistance by alternating electroless nickel plated discs with different hardness. For instance, by heat treating medium phosphorus deposits at two different temperatures, hardness values of $62R_c$ and $65R_c$ can be obtained and excellent performance has been achieved by alternating discs with these hardness levels. However, although this application has been technically successful, the economics of the nitriding process has resulted in this process taking preference in North America but electroless nickel continues to be used in some European plants.

A noise in the U-joint of the **cast iron slip yokes** used in vehicle power trains has usually been attributed to a galling problem.[24] Deposition of medium phosphorus electroless nickel on the slip yokes has been used to overcome this. Electroless nickel has also greatly improved the wear resistance between the mating surfaces without the need for a lubricant, such as oil. The uniform thickness of the nickel is an extremely important factor in the success of this application, as the dimensional requirements on the yokes are critical. A typical slip yoke is shown in Figure 30.

Figure 30 Thickness uniformity and lubricity are important properties of deposits on cast iron slip yokes.

Although the hardness, wear resistance and lubricity of electroless nickel are inherently good, these properties can be enhanced by the codeposition of particulate matter with the nickel. These particles are often ceramic materials. For instance, silicon carbide particles are reported to increase hardness and silicon nitride or boron nitride to improve self-lubricating properties.[25] These features have been used successfully in improving engine performance by electrodeposition of nickel phosphorus/silicon carbide composites on pistons and cylinder bores but electroless nickel/silicon carbide deposits have not produced similar results. However applications for composite coatings are not limited to nickel/ceramics. Other very important composites that have been used successfully in many applications involving various types of wear are electroless nickel with polytetrafluoroethylene (PTFE) or fluorinated carbon (CF_x). Both provide an excellent non-stick, low friction, dry lubricant surface with the latter having the advantage of superior temperature resistance. These composites have been used on **carburetor and clutch parts, engine valves, bearings and gears.** Deposition on brass carburetor parts for a European producer, resulted in an increase in the life of pneumatic cylinders from 30,000 to more than 8,000,000 cycles and an associated increase in pump rotor life of 100%.[26]

Aerospace Industry

There has been great interest in the use of electroless nickel in this industry for many years. The combination of excellent functional properties, such as wear, corrosion and erosion resistance, with the ability to obtain thickness uniformity on complex components has always been very attractive to engineers and designers. However, the obvious need for thorough, long-term evaluation of new systems in this industry made for slow progress but there is now wide acceptance of electroless nickel for many applications.

Initially, the main interest was in the use of electroless nickel during engine overhaul and maintenance programmes. Engine components are often in need of refurbishing and following several years of cooperation between processors and aircraft engineers, electroless nickel was eventually included in engine repair manuals. Subsequently, great improvements in the reliability and consistency of the plating process resulted in its acceptance not only for refurbishing used parts but also for enhancing the performance of original ones. The application of electroless nickel coatings now provides improved performance of many components used in engine assemblies and airframe structures. The coatings have been used[17,27] on bearing journals, servo valves, compressor blades, turbine blades, pistons, engine shafts, engine mounts, landing gear, hydraulic and manifold systems, gyroscope components and optics. On jet engines, it has also been used on fuel control assemblies and bellows and in the space programme, it has been used effectively on the docking, cargo bay and rudder mechanisms of the space shuttle.

Some of the earliest applications for electroless nickel were in the **compressor section of gas turbine engines.** In some commercial and military aircraft, S41000 stainless steel (410S.S.) compressor components are required to be protected from corrosive atmospheres and erosive particles[28] at temperatures of 425°C. For many years, two coating systems have been used extensively. The first was a nickel/cadmium alloy produced by diffusion of separate layers of electrodeposited nickel and cadmium. This system was generally successful but suffered from the problem of non-uniform thickness of deposits, associated with electroplating on complex parts. This, in turn, resulted in non-uniform composition of the diffused alloy and in the worst cases, cadmium embrittlement of the base material.[29] The second was an aluminide coating. This also had a thickness uniformity problem, especially at the leading and trailing edges of airfoils. The uniform thickness, corrosion resistance and erosion resistance of electroless nickel offered an alternative to these two traditional processes and it has been used very successfully in engine compressor components.

For instance, a number of major U.S. airlines have been applying a high-phosphorus (9-11 %), compressively stressed electroless nickel coating in the refurbishing of high pressure **compressor stator assemblies** in the Pratt and Whitney JT 8D engine.[30] Protection is provided for the gas path surfaces of the fourth, fifth and seventh to thirteenth stage stators. These 541000 stainless steel stator assemblies are burnished to a high quality finish by vibratory polishing before deposition of 8 to 16 microns of electroless nickel. The finish is retained by the nickel surface to provide excellent gas path flow in addition to greatly enhancing the corrosion and erosion resistance of these components. Electroless nickel has outperformed other coating systems in this application with little or no loss of the deposits being observed in JT 8D engines after more than 5,800 take-offs and landings.

High phosphorus electroless nickel has also been used in the overhaul and repair of **high pressure compressor spacers** on some of the early models of the Pratt and Whitney JT-8D engine.[30] The K 14675 (AMS 6304) alloy spacers serve to separate the stages of the compressor rotors and include seals to prevent leakage of the compressed air between the rotating and stationary parts. Typical stator assemblies and a spacer are shown in Figure 31 In this design, the tubes used to contain the tie bolts, which hold the stages together, are an integral feature of the spacer. High phosphorus electroless nickel has provided the uniform coverage and protection on these parts that was not possible with other coating systems.

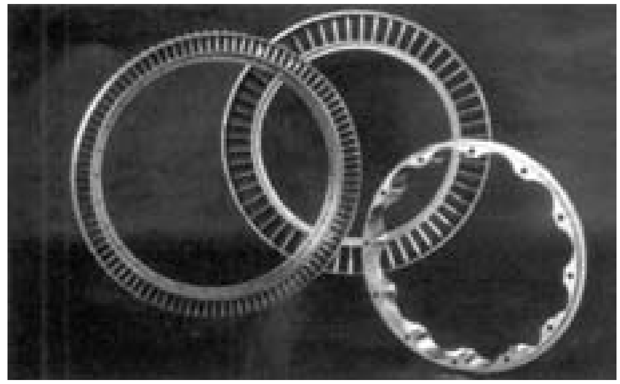

Figure 31 Electroless nickel is used in the overhaul and repair of stator assemblies and spacers.

Similar protection against corrosion and erosion at 425°C is also provided for various **compressor case components** on commercial and military aircraft engines.[30] These are martensitic and ferritic iron base alloys and wrought alloy steels plated with 8 to 25 microns of high phosphorus electroless nickel.

The performance of electroless nickel applied to components during engine overhaul and repair has sometimes resulted in the coating being specified for new versions of the same components. An example is in the overhaul and repair of the sixth to ninth stage HPC (high pressure compressor) **variable vanes** on the Pratt and Whitney 2037/ F117 engine.[30] The use of electroless nickel to provide corrosion and erosion protection to the airfoil surfaces and wear resistance to the trunions was jointly investigated by the engine manufacturer and a major U.S. airline. The vanes and trunnions shown in Figure 32 are fabricated from S41000 alloy. In test engines, high phosphorus electroless nickel outperformed both nickel/cadmium and a thermally sprayed aluminide coating. Furthermore, the simplicity of the electroless process permitted coating of the airfoil sur-

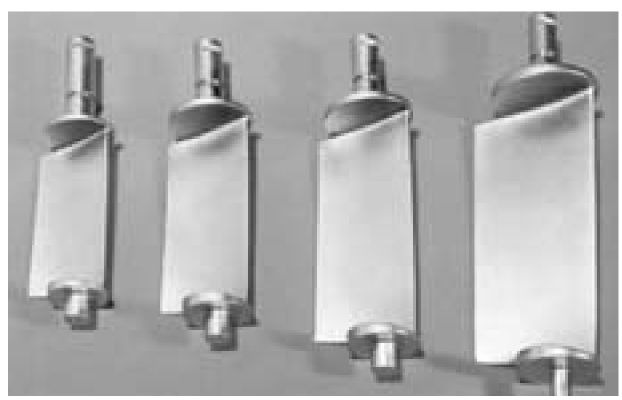

Figure 32 High phosphorus deposits on variable vanes and trunnions have provided performance and cost advantages.

faces and trunions to dimensional tolerances in a single operation, thereby contributing to a major cost saving for this repair procedure. The total benefits for this application were sufficient to warrant the use of electroless nickel on variable vanes for all new engines.

There are other examples in which the success of electroless nickel in a repair application is expected to result in its use on new components, e.g. on engine bearing housings.[30] The coating is specified for use in the overhaul and repair of the **number five bearing housing** of Pratt and Whitney JT-8D-200 engines. It is required to be deposited on the carbon seal support, manufactured from martensitic S41000 stainless steel, to protect it from hot oil corrosion and "coking". An 8 to 16 micron thick deposit of high phosphorus electroless nickel has provided outstanding service for this application.

Electroless nickel is used on some critical load-bearing parts. For instance, the **flexible bearing support** for the Allison TF41 engine is subject to heavy bearing loads at temperatures up to 480°C. It is also required to have good abrasion and fretting resistance. Electroless nickel plating during overhaul and repair operations has been very effective in extending the service life of this component.[30] Heavy deposits of 250-400 microns are often required to bring the dimensions of the part back within acceptable tolerances.

Figure 33 The service life of this flexible bearing support has been extended by electroless nickel plating.

The service life of **oil and fuel lines,**[30] along with associated components, on both military and commercial aircraft engines has been extended through the use of electroless nickel. For instance, fretting wear in O-ring locations and on threaded connections has been virtually eliminated. Components such as cam assemblies on the Pratt and Whitney TF-30A/B fuel control and bellows assemblies on the G.E. J-75 engines are typical components protected from abrasion by high phosphorus electroless nickel. Also, in a redesign of the G.E. TF-34-400 fuel injector tip, electroless nickel replaced the tungsten carbide plasma spray coating, used previously for protection against wear. In laboratory and engine tests, a low-phosphorus electroless nickel coating was shown to significantly reduce wear on the N06625 (Inconel 625) fuel tubes.

Applications in the aerospace industry are not limited to engine components. Electroless nickel is used on many **airframe assemblies**[30] such as landing gear components, ramp locking systems and flap and actuator components. Several parts of the main **landing gear** of the Boeing 727 are protected from corrosion and erosion by electroless nickel. These are mostly high strength steel parts that previously were coated with cadmium and now have extended service life since a change to electroless nickel was made. Typically a high phosphorus coating is used at a thickness of 8 to 16 microns. In addition, electroless nickel satisfies the wear resistance requirements of the trim cylinder barrel of the main landing gear of the McDonnell Douglas DC 10-10 and of the inner piston of the nose landing gear of the MD-80. The same aircraft manufacturer also uses a high phosphorus deposit on the high pressure pneumatic shock absorbers on the F-18 main landing gear. This demanding application requires a non-porous, crackfree coating to provide excellent wear resistance and corrosion protection.

In addition, electroless nickel is used on some critical and advanced aircraft **navigational systems.**[31] For instance, it is used on the pod of the Lantrin navigational and targeting systems for the F-15 Eagle fighter. This system is required to display all information for flight and combat and the pod shown in Figure 34 is the main housing component for all hardware and camera systems. It is a A03560 cast aluminum part (Alloy A356) and the critical mounting flange area is protected with electroless nickel.

The expanding use of **metallic optics**[17] in the aerospace industry has resulted in another successful application for electroless nickel. The requirement is for a high strength coating to be applied to a strong, light metal such as aluminum or beryllium. A deposit, contain-

Figure 34 Electroless nickel is used to protect the pod of the Lantrin navigational and targeting system.

ing 12.2 to 12.7% phosphorus, polished to an extremely fine finish has provided outstanding performance in space applications where high G forces are present and low inertia is required. The deposit thickness is typically 75 to 125 microns and stress is controlled within a range of 48 to 70 MN/m^2 (7,000 to 10,000 psi) compressive. Subsequent heat treatment to reduce stress as close as possible to zero, results in a very stable optical system for long time periods.

Coating uniformity and low coefficient of friction has enabled electroless nickel to be used to enhance the performance of several **flap and actuator components** on all Boeing 727 models.[30] These include the flap track carriage, the trunnion assembly for the ground speed brake control actuator and the outboard flap gimbal. The coating is also used successfully on the Boeing 767 high pressure shut off actuator and the inboard flap assembly barrel of the McDonnell Douglas DC10-10.

During overhaul and repair, refurbishment of the auxiliary **manual locking system** on the forward and aft ramps of the Lockheed C-5 aircraft is required.[30] These high strength steel parts, are restored to original dimensions with up to 250 microns of high phosphorus electroless nickel. The coating also provides excellent corrosion resistance for future service.

Electroless nickel plating has demonstrated a significant cost advantage over chromium in the refurbishment of the **connecting link** for the rotor head of the Boeing CH-46 helicopter.[30] Severe wear occurs on the horizontal bore of this hardened 641300 steel (4130) component and although chromium plate is used on original parts, electroless nickel is used for repair. It is typically required to reduce the diameter of the bore by 300 to 375 microns. The cost advantage over chromium results from the fact that the nickel deposit is so uniform that no grinding or lapping is required before the part is returned to service. In service, the performance of the refurbished part compares favourably with that of the original.

Electroless nickel has also found successful application in aircraft support equipment. For instance, when not protected, failure of **catapult covers and tracks**[17] used in the launching of planes from aircraft carriers can be expected within 6 to 12 months. Failure occurs from wear and corrosion as the operating conditions are very severe. During launch, tracks are exposed to steam at 230°C and a force of 4.45MN (1,000,000 lbs) is applied to the track, which creates high pressure and wear on the keyway. As the plane becomes airborne, the track is thrust upwards creating additional wear. The corrosion problem is due mainly to salt water, which is usually present in the keyway and this establishes a galvanic cell between the dissimilar metals of the track and the covers. The most effective method of overcoming these severe wear and corrosion problems was to plate the covers with 100 microns of electroless nickel and 12 microns of cadmium, subsequently chromated The service life was dramatically increased to 14 to 18 years and this has enabled carriers to remain operational for

Figure 35 Steel missile directional canisters are plated with electroless nickel for corrosion protection.

up to 5 years without the need to return to base for a four month overhaul.

Missile guidance systems also use electroless nickel to provide corrosion protection.[31] For instance, the missile directional canisters shown in Figure 35 are fabricated from 641400 steel (4140) and are plated for corrosion protection and appearance. In service, they are charged with a solid propellant and assist in controlling the missile flight path.

Many components used in the space programme are plated with electroless nickel to provide corrosion protection, wear protection and excellent lubricity as required. These include components on the **space shuttle**[31] used in fuel systems, gear systems and fluid transfer systems for example. Composite coatings of electroless nickel and fluorinated carbon are also used for various applications, including battery components and satellite systems.

Electronics Industry

The use of electroless nickel in the electronics industry has experienced continuous growth since the outstanding properties of the deposits became fully recognized. Magnetic properties, corrosion resistance, wear resistance, solderability and appearance have all contributed in making this industry the single largest user of electroless nickel coatings[32]. A major factor has been the phenomenal growth in demand for rigid memory discs and disc drives due to the increasing use of personal computers. For instance, 32.5 million disc drives were produced worldwide in 1991 and this was forecast to increase to over 44 million[33] by 1993. This was achieved and by 1995, the number had increased to almost 150 million with over half the production being in Japan[34]. During this period it was estimated that this application accounted for 20-25% of electroless nickel usage in the U.S.[32] - impressive statistics demonstrating the importance of this industry to electroless nickel plating.

The application of electroless nickel coatings for **memory disc** technology has become universally accepted and it is the standard barrier coating for media manufacturers. The continuing growth in the use of personal computers, the increased use of the Internet and the availability of more sophisticated software has resulted in an enormous demand for increased computer memory.[35] Typical memory discs, shown in Figure 36, consist of an aluminum substrate plated with non-magnetic, hard, high phosphorus electroless nickel to a thickness of 10 to 15 microns. This provides a protective barrier between the substrate and the magnetic data storage surface, thereby preventing ‘cross talk’ between opposite sides of the disc. The magnetic coating is a sputtered iron/cobalt alloy, deposited on the polished electroless nickel and is subsequently coated with a protective carbon overcoat to complete the disc manufacturing process.

The diameter and thickness of aluminum substrates for memory disc applications have consistently decreased due

Figure 36 Memory discs present a huge and demanding market for electroless nickel.

to the size restrictions imposed by present day portable computers and other electronic devices. The increased requirements for higher storage densities on smaller media has placed a huge demand on the quality of the aluminum substrate and the electroless nickel coating. The challenge has been met successfully.

The aluminum substrates are usually alloyed with magnesium, iron, copper, silicon, zinc and manganese to provide excellent polishing characteristics, high strength, low density and good corrosion resistance. The surface preparation of these alloys to ensure the smoothest possible substrate for the deposition of the electroless nickel is extremely important. Microdefects in the electroless nickel such as pits, nodules, residual magnetism and deposit stress must be minimized to meet present demands. In fact, defect free coatings are now required, as defects such as micropits and microbumps that may have been previously undetected, are now a source of head crash and data storage failures. This major application for electroless nickel is also one of the most critical. Advancements in aluminum pretreatment technology and electroless nickel bath chemistry have been instrumental in ensuring the success of this application.

Heat sinks are devices used to cool **semiconductor components** during operation. They are required to have good thermal conductivity and so copper or aluminum are usually materials of choice. They are also required to dissipate heat efficiently and this is achieved by maximising surface area by the use of fins as shown in Figure 37. The design entails deep recesses and to protect such parts from corrosion and to provide them with a hard, durable coating, capable of being soldered or brazed, they are often plated with electroless nickel.[17]

Probably the largest demand for any single **semiconductor** component plated with electroless nickel is the TO-3, a part developed in the late 1950's as the original power transistor device.[35] It allows a small package to act as a voltage regulator for any electronic device from rec-

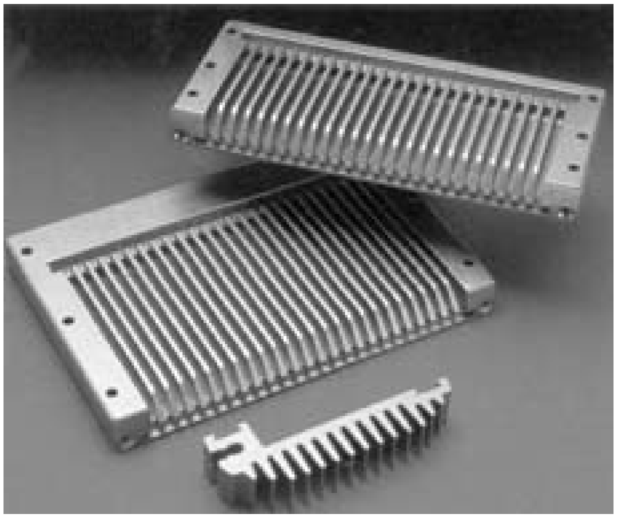

Figure 37 Electroless nickel provides a hard, durable coating with good solderability on heat sinks.

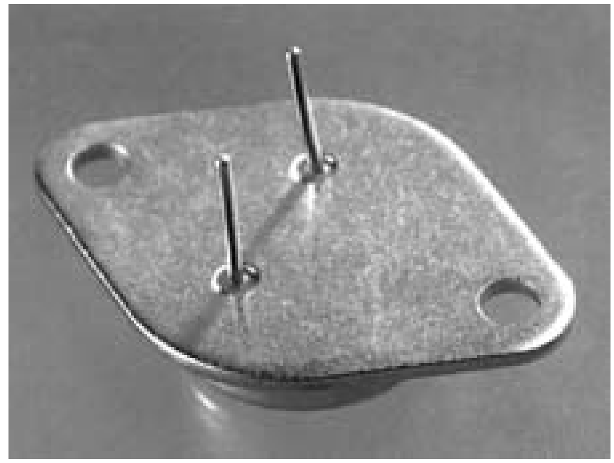

Figure 38 The plated TO- 3 power transistor device is still in large demand by the semicondutor industry.

tifiers to toasters. This well accepted package has experienced very little in the way of design change since its introduction and industry usage is now well in excess of one million per week.

The part, shown in Figure 38, consists of a diamond shaped steel base onto which is brazed a copper heat sink. During the furnace brazing cycle, two 52 alloy leads are mounted in glass seals of varying composition. Initially the devices were electroplated with sulphamate nickel, which required them to be racked and electrical contact made to each lead. The inconvenience of this and the thickness uniformity problems associated with electrodeposition resulted in inconsistent quality. The development and acceptance of electroless nickel coatings, however, has overcome quality problems while greatly improving productivity and reliability. A high phosphorus coating is used as it provides good ductility and excellent sealing and resistance welding properties. Good corrosion resistance allows use in external applications and its resistance to tarnishing and staining allows it to be used in automated production systems in which aggressive fluxing is utilized and the plated component can be cleaned without discolouration. The use of electroless nickel in this application has contributed to the continuing huge demand for this part.

There are other examples where the requirement for thin, uniform nickel deposits has resulted in electroless nickel replacing electroplated nickel in the electronics industry. The situation often occurs as a result of the ongoing trend towards smaller components and the associated demand for greater precision. A typical example is in the production of **surface mount components,** specifically a spring socket plug for low profile surface mount packages.[36] The spring plug was a four leaf socket with a height of 0.89mm and an outer diameter of 0.38mm. The original plating requirements were for 2.5 microns of electrolytic nickel to be deposited on a hardened copper beryllium substrate, followed by 0.5 micron of palladium and 0.05 micron of gold. The performance of the gold contact in the inner diameter of the part was of critical importance and the plating processes were required to provide 100% coverage of the area without excessive build-up that could cause soldering problems. Electroplated nickel produced by barrel plating in a sulphamate electrolyte, was unable to produce the required uniformity and continuity and a process using a low phosphorus electroless nickel was subsequently developed. The process not only provided the uniformity required and eliminated any distortion associated with non-uniform thickness but other benefits were realized. These included improved barrier layer characteristics and a nickel deposit hardness of 56 R_c, which significantly enhanced the wear properties of the palladium and gold.

Over 80% of the **printed circuit boards** currently produced in the U.S. are solder mask over bare copper (SMOBC)[35]. The hot air solder levelling process (HASL) is often used, whereby after application of the solder mask, the panel is fluxed and dipped into molten solder at about 230°C. Air knives using hot air, are then used to blow solder from the holes in the printed circuit board and smooth the solder surfaces. However, HASL has several disadvantages such as poor levelling of the solder, thermal shock to resins and solder mask, contamination caused by flux residues and design limitations in fine pitch and ultra fine pitch technologies.

One alternative to HASL is an electroless nickel/immersion gold process that is rapidly becoming the process of choice for several reasons. It offers improved shelf life in hot, humid conditions and solderability remains excel-

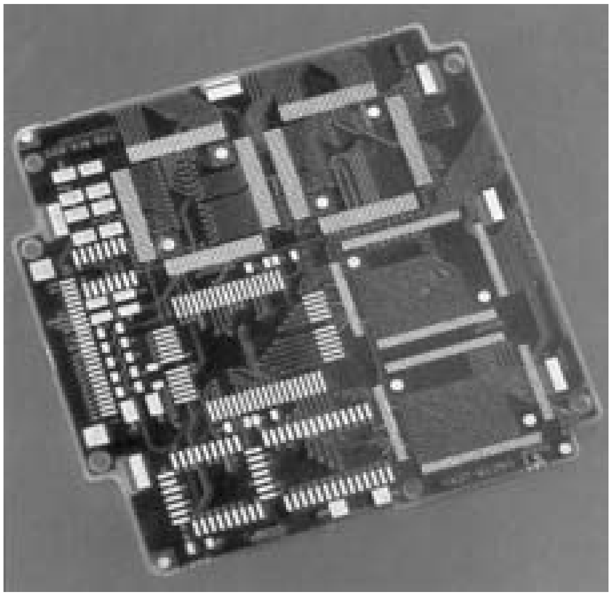

Figure 39 Electroless nickel/immersion gold deposits now being used on printed circuit boards.

lent after long term storage. It is compatible with all assembly solder pastes, fluxes and cleaning procedures and easily withstands multiple reflow cycles during assembly. In addition, it offers excellent planarity for ultra fine pitch technologies and control of thickness ensures joint reliability by preventing embrittlement. A typical board is shown in Figure 39. For this growing application, low or mid phosphorus electroless nickel deposits are preferred as they enable better gold coverage and denser coatings to be obtained. Typical thickness for the nickel deposits is 5 microns.

A large variety of **connectors** are plated with electroless nickel to enhance corrosion resistance and wear resistance. Other useful properties are lubricity, hardness, solderability, electrical conductivity and appearance. Aluminum alloys are commonly used for both military and commercial connectors, especially the 2000 and 6000 series of wrought alloys and the 380 cast alloys. Most specifications call for approximately 15 microns of electroless nickel as a base for cadmium plate or zinc alloy plate, which is subsequently chromated. This combination has provided excellent service in the most severe naval applications. High phosphorus electroless nickel at greater thicknesses is preferred if there is a risk of porosity in the aluminum.

Zinc diecast connectors have replaced aluminum in many applications. They are less expensive, easy to fabricate and generally offer good resistance to attack in corrosive environments such as sea water. For connectors, corrosion resistance is enhanced by copper plating prior to electroless nickel.

Figure 40 Wear and corrosion resistance of aluminum connectors are enhanced by electroless nickel plating.

The coating uniformity of electroless nickel is used to advantage in plating **microwave components.**[35] These are often complex shapes with deeply recessed areas. Many substrates are aluminum and some are copper. The electroless nickel coatings are usually applied as a barrier coating providing some hardness and corrosion protection for a subsequent coating of tin.

The good soldering properties of electroless nickel are of great value in the electronics industry. For instance, **transistor chips**[17] made from silicon wafers often use electroless nickel to provide easily solderable surfaces. The coating is applied in a two stage process to produce an adherent, solderable contact on the back side of the wafer and this is used as a common ground. Typical phosphorus content of the very thin deposits is 1 to 5%. The two stage process involves deposition of 0.1 to 0.2 micron initially, which is diffused thermally into the wafer to establish good adhesion. This is followed by activation of the diffused coating and deposition of another 0.25 to 0.35 micron of electroless nickel, which provides the surface for easy soldering.

Plating of plastic housings for **EMI shielding** requires very large areas to be covered. Electroless nickel is used in many cases to provide protection against corrosion and tarnishing for electroless copper, which is deposited directly on the plastic housings. Nickel thickness is typically 0.25 to 0.50 micron. Another new application involving large surface areas is the coating of **aluminum floor grates** in semiconductor manufacturing facilities[35]. Electroless nickel has replaced epoxy paints and some electrolytic nickel coatings, due to its high hardness, abrasion resistance and chemical resistance to many of the materials encountered in a clean room environment.

Other Applications

There are many other industries that are benefiting from the use of electroless nickel. Improvements in process technology and a greater awareness of the properties of these nickel-phosphorus coatings continue to create a growing demand for their use. The following general comments explain how electroless nickel is being used in these industries to improve product performance, productivity and cost savings.

Foundry Tooling - The properties of electroless nickel have proven to be very useful in protecting foundry tooling.[37] Cast iron, stainless steel, aluminum and plastic tooling is frequently used and the performance of all can be enhanced by plating with electroless nickel. The coating can provide excellent protection of the tooling from the harsh conditions imposed by the sand and additives used in mold production. Abrasion by the sand, particularly at high pressures, is a major concern as dimensional accuracy of the tooling can be quickly lost. The hardness and abrasion resistance of electroless nickel is therefore of great advantage but there are also other benefits to be considered.

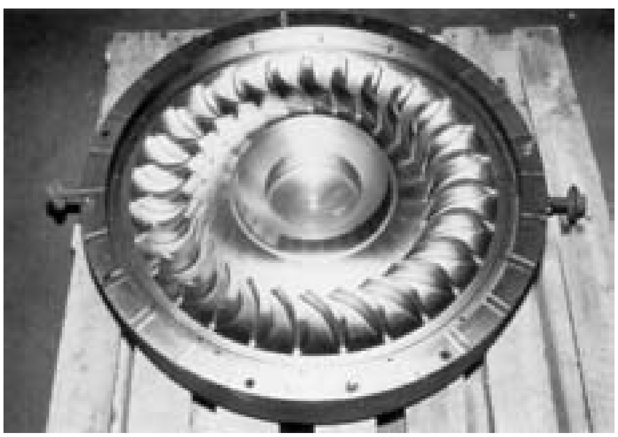

Figure 41 Electroless nickel is frequently used to protect foundry tooling such as this turbine core box.

The nickel-phosphorus coating has a low coefficient of friction. If required this can be enhanced by the codeposition of polytetrafluoroethylene (PTFE) or fluorinated carbon particles (CF_x). This provides an excellent surface for improved sand compaction, draw and release. The smooth, pore-free properties of electroless nickel are well suited to protect the tooling from the warm, moist conditions experienced during mold preparation. In addition, it has been shown that the carbonized resins and release agents used in conjunction with the sand do not bond to the smooth, electroless nickel surfaces and so good release, less mold scrap and higher productivity are all possible.

Although the abrasion resistance of electroless nickel is a very positive feature for this application, it can only reduce the rate of wear and not eliminate it. The high phosphorus deposits used are usually in the thickness range 75 to 125 microns[17]. As the wear progresses, it is usually easy to observe areas where the substrate material is exposed and this is very beneficial in maintaining control of dimensional tolerances. Wear of uncoated tooling is much less obvious and greater loss of accuracy can result. However, when areas of the nickel are worn through, the remaining deposit can be chemically stripped and the tooling re-plated to original tolerances, thereby greatly extending tool life.

Mold Protection - Increased awareness by mold producers of the properties of electroless nickel has led to a growing demand for its use in protecting mold surfaces. The properties have been compared with those of chromium electroplate, traditionally used on moulds for many industries and consequently many conversions have been made. The uniform deposit thicknesses obtainable have been an obvious advantage in this particular application because problems associated with current distribution in chromium electroplating have always been a major disadvantage. However, the fact that electroless nickel properties can be selected to meet a range of operating conditions has also been a contributing factor in the successful applications in this industry.

The protection of molds by electroplating with chromium becomes more difficult and more expensive within increasing complexity of mold design. The process usually requires complicated anode fixtures to be used to obtain chromium coverage in recessed areas and the time involved in set-up plus that required for the inefficient plating operation increase cost. To this must be added the additional cost of post-plating machining to obtain thickness uniformity and the required dimensional accuracy of the mold[17]. In comparison, the thickness uniformity of electroless nickel deposits requires no special fixturing and machining is usually unnecessary. Dimensional tolerances can usually be maintained within 1.25 to 2.5 microns[38]. However, the molding surfaces are not the only areas susceptible to damage in use. Heating or cooling channels, for instance, can rust and these can be easily protected with electroless nickel during the same plating cycle.

Damage to molding surfaces results mostly from wear and less frequently from corrosion. In the glass industry, abrasion and wear of molds is a serious problem and traditionally steel molds have been chromium plated to enhance their performance. Operating conditions are extremely severe. Molds are typically preheated to about 500°C and the molten glass temperature on contacting the mold is usually is the range of 550 to 650°C. The coating is required to be very well bonded to the mold and to have sufficient ductility to withstand the heating and cooling cycles. It must also have excellent release properties to allow easy separation of the cast glass. Due to the severe abrasive characteristics of silica, the coating must be able to provide protection against wear especially at areas where the molten glass impacts the mold. Low phosphorus electroless nickel with an 'as plated' hardness of 57 to 59 R_c, a high melting point and excellent abrasion resistance has become a viable alternative to chromium in this application[38].

Casting of ceramics can also be very aggressive on mold materials. For instance, the mold shown in Figure 42 was subjected to severe erosion and abrasion during the injection of ceramic slurry. Initially, protection was provided by chromium plate and a production rate of 900 parts per day was achieved. When chromium was replaced by electroless nickel, this was increased to 1400 per day due to greatly improved release properties and the life of the mold was increased by 50% due to the excellent wear resistance.[4]

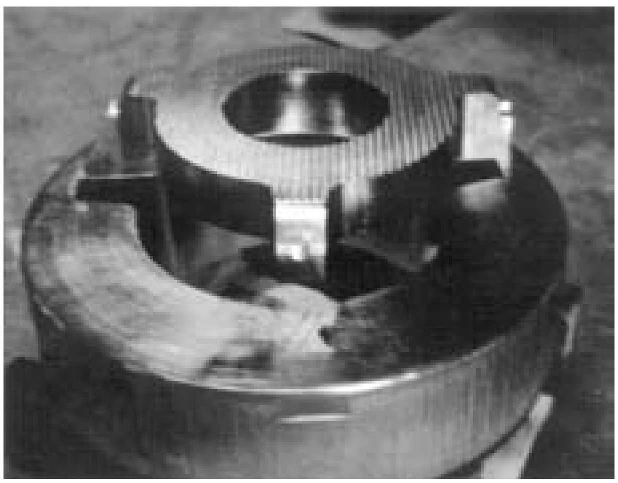

Figure 42 Wear resistance of electroless nickel has greatly improved productivity of molds for ceramic parts.

Electroless nickel is now widely used for the protection of molds in the plastic industry. Due to the many types of plastic molding operations, the requirements vary. Abrasion resistance is again important as mineral or glass filled resins can be very aggressive during compression molding. In transfer and injection molding, wear usually occurs on most of the high flow areas. Release properties are of great importance and the natural lubricity of electroless nickel has been very beneficial. In this regard, composite coatings incorporating polytetrafluorethylene (PTFE) have provided such good release properties that in some cases, mold release agents have not been required.

Molds for plastic components frequently require corrosion protection. Corrosive environments can be created by moisture condensing on mold surfaces or by acids produced by overheating of certain thermoplastics. Small amounts of hydrochloric acid are produced during the molding of poly-

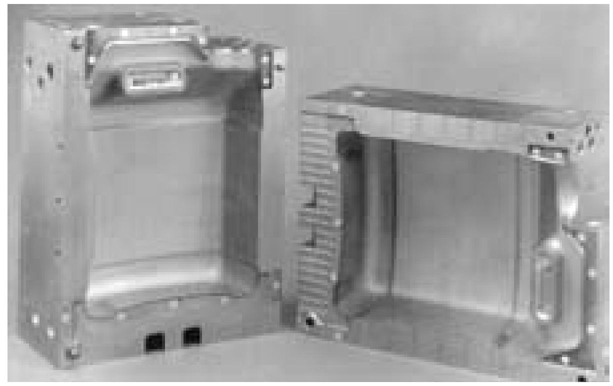

Figure 43 Electroless nickel prevents wear and corrosion of aluminum blow molds.

vinyl chloride and this is a well known cause of mold corrosion[38]. A similar condition arises with certain grades of rubber, notably epichlorohydrin - containing formulations.[39] Corrosive fumes are also produced during molding of acrylonitrilebutadiene styrene (ABS), polycarbonates, acrylics and polymers with thermoplastic additives.[32] When optimum corrosion resistance is required to protect mold surfaces, a high phosphorus deposit, containing 10-12% phosphorus and with a minimum thickness of 50 microns, is preferred. Alternatively a composite coating with polytetrafluoroethylene (PTFE) has been used very successfully.[38]

Printing Industry - Since the 1980s, electroless nickel has been steadily replacing chromium as a protective coating for printing rolls.[32] Once again, the major advantages are corrosion resistance and thickness uniformity. The rolls are generally made of steel or cast iron and need to have an excellent surface finish and be protected from corrosive inks. During chromium plating, non-uniform coating thickness will be obtained, especially at the ends of the rolls and some surface roughness is always possible due to the tendency of chromium to produce nodular deposits. The end result is that the plated rolls must be ground and polished before use.[40] In addition, the corrosion resistance of chromium is not always adequate due to its micro-cracked structure, although it can be greatly enhanced when used in conjunction with an undercoating of nickel.

The advantages of electroless nickel are therefore obvious. The use of a high phosphorus deposit provides outstanding corrosion resistance and an extremely smooth surface finish with uniform thickness on all areas of the roll. A deposit thickness of 25-50 microns[17] is typical for this application and the grinding and polishing operations after plating are usually unnecessary.

Textile Industry[41] **-** Electroless nickel has contributed to significant cost reductions and improved quality in practically all areas of the textile industry. With a single machine being capable of producing over ten million metres of yarn per week on a continuous basis, it is clear that equipment used in textile production and packaging is involved in the movement of fibres at extremely high speeds. This high speed transfer of fibres creates the most serious problem associated with textile machinery - very aggressive wear on a large number of components. Traditionally, hard chromium plate has been used to provide wear and corrosion resistance but only with limited success. Electroless nickel is now the coating of choice to provide the smooth, abrasion and corrosion resistant finishes on most components in contact with textile fibres. These include thread guides, fibre feeds, bobbins, shuttles, rapiers, ratchets, needles and picks.[32] The industry has several applications for the use of nickel composites in areas experiencing very aggressive wear. For instance, in producing yarns from cotton or cotton-polyester blends, an aerosol of fibres is directed into a steel cup, rotating at speeds approaching 100,000 r.p.m.. An electroless nickel/diamond composite coating is used to protect the steel in this highly abrasive environment. Similarly, a nickel/silicon carbide composite is used to protect the drive shafts to the cup and the contact areas between the shafts and the drive wheels. Nickel/PTFE coatings are used in the ‘texturing’ process for polyester yarns, which reduces their natural rigidity and provides them with the stretch required in such textiles. The process requires the yarn to be heated under tension and this can be done by passing through an externally heated tube. A concern with this procedure is the inadvertent contact of the yarn with the hot tube, which causes melting, sticking and shut-down. An electroless nickel/PTFE composite coating on the inside of the tube has been successful in minimizing the sticking problem.

The textile industry also requires corrosion resistant coatings. For instance, in the weaving process various chemicals are applied to the fabric to assist its progress through the loom. Some of these chemicals are corrosive to certain steel components of the loom e.g. the drop wires and needles and if rusting occurs, the fabric can be stained. High phosphorous electroless nickel provides the necessary protection.

Summary

This publication does not assume to cover all industries in which electroless nickel has been used successfully. However, it does include applications in many major industries and the successful performance of the coating has been described in relationship to specific properties.

Electroless nickel has a range of properties that is quite unique. Some of the properties that have contributed to the success of electroless nickel include corrosion and wear resistance, hardness, magnetic response, solderability, lubricity and thickness uniformity. Most of these can be modified to meet specification requirements by varying phosphorus content, heat treatment and deposition conditions, for instance. Properties can be further modified by codeposition of particulate matter such as silicon carbide and polytetrafluorethylene (PTFE). This broad range of properties is of enormous value when used appropriately but it is absolutely essential that materials selectors be fully aware that it is normally insufficient to simply specify `electroless nickel' as the coating required.[42] There must be close communication between the plater and materials selector in order to ensure that the coating will have the properties required for each application. For instance, if 'electroless nickel' is specified for a part that will be exposed to concentrated sodium hydroxide, it could be disastrous if a high phosphorus deposit is applied. "Low phosphorus electroless nickel" would normally be specified in this case. The applications described in this publication were successful because performance requirements were established and technical expertise was available to ensure that an electroless nickel deposit with suitable properties was selected. There is a wealth of technical expertise within the industry to assist designers, engineers and metallurgists in the appropriate use of this unique coating.

The many useful properties of these deposits should lead to continued growth in the industry. Of significant interest has been the opportunity presented as a result of the environmental concerns associated with chromium and cadmium plating. The successful replacement of chromium by electroless nickel has frequently been reported and cost savings described.[42] In these applications, thickness uniformity, hardness, corrosion resistance and wear resistance have been major factors. In addition, corrosion resistance enables electroless nickel to compete with other alternatives to cadmium plate.

The information contained in Appendix 4[3] provides an indication of the widespread use of electroless nickel in various industries. It also shows the properties that are of importance in these applications and the versatility of the coating is clearly evident. Through a greater knowledge of the properties of electroless nickel it is hoped that engineers, designers, metallurgists and others involved in materials selection will become more familiar with the many ways in which it can be used to resolve materials problems.

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Appendix 1

Economics of Electroless Nickel (EN) Coatings
Cost ratio of standard wall vessels designed for liquid with a density of 1.2g/cm^3 and containing two nozzles (top and bottom), closed top and vented.

Capacity (m^3)	FRP	Mild Steel	Stee1, EN Lined (50µm)	S31600 (316S.S.)	N02200 (Nickel 200)	Steel, Glass Lined (1270µm)	Steel Teflon Lined (1000µm)
0.32	1.0	1.2	1.6	1.7	4.5	5.5	7.0
0.76	1.5	1.6	2.4	2.3	7.1	6.5	9.0
1.9	2.0	2.0	3.4	3.0	9.0	10.5	13.3
3.8	3.0	2.9	5.5	4.1	14.0	13.0	18.7
18.9	5.0	4.5	10.6	8.0	30.0	35.7	42.5
37.9	10.0	8.5	21.3	15.0	56.0	59.0	64.0
60.0	16.0	12.0	32.1	22.0	78.0	81.0	75.3

Appendix 2

Economics of Electroless Nickel (EN) Coatings
Cost ratio for piping systems based on 3m long sections with flanges

Size of piping system	Steel, Schedule 40	Steel, EN Lined (50 µm)	S31600 (316SS) Schedule 40	*Steel, Polyprolined	Steel, Glass Lined (1270 µm)	**Steel, Teflon (PTFE) Lined	N02200 (Nickel 200) Schedule 40
2"(5.08cm)	1.00	4.00	5.00	7.05	14.35	14.45	24.00
3"(7.62cm)	1.75	6.45	9.00	11.80	19.40	22.75	42.00
6"(15.24cm)	3.75	13.35	18.75	27.75	43.30	63.25	112.50

* 0.4 - 0.6 cm thick
** 0.3 - 0.36 cm thick

Appendix 3

Economics of Electroless Nickel (EN) Coatings
Cost comparison for corrosion resistant bolting applications based on 5/8"(1.59cm) x 3½"(8.9cm) hex bolt with nut in 500 piece quantity

Bolt Material	Cost Ratio
(ASTM A 307) Low Carbon Steel	1.0
G41400 (ASTM A 193 B-7) Steel	1.8
G41400 (ASTM A 193-B7) *Fluorocarbon Coated	3.2
G41400 (ASTM A 193-B7) **EN Coated	2.3
G41400 (ASTM A320-L7)	6.3
G41400 (ASTM A320-L7) *Fluorocarbon Coated	7.2
G41400 (ASTM A320-L7) **EN Coated	6.8
S31600 (ASTM A193-B8M)	7.0
N02200 (Nickel 200) 40.5	

** 15-20 gm coating, as plated high phosphorus
* 20-25 pm coating not recommended for immersion, DuPont developed coating system.

Appendix 4

Applications for Electroless Nickel

	Corrosion	Adhesive Wear	Fretting Wear	Hardness/Abrasion	Repair & Salvage	Lubricity	Weldability	Solderability	Uniformity	Magnetics
Automotive										
Heat Sinks	X							X	X	
Pistons	X	X		X					X	
Engine Bearings	X	X	X	X						
Hose Couplings	X		X	X					X	
Gears		X							X	
Bushings		X								
Brake Cylinders	X	X								
Brake Pad Holders		X								
Shock Absorbers	X	X				X			X	
Exhaust Manifolds	X								X	
Cams		X	X							
Carburetors	X								X	
Aircraft										
Engine Overhaul	X	X	X	X	X				X	
Landing Gear	X	X							X	
Hydraulics	X	X				X			X	
Propellers	X	X	X						X	
Engine Mounts	X		X							
Turbine Parts	X			X					X	
Gyro Parts	X	X	X						X	
Compressor Stators	X			X					X	
Compressor Spaces	X			X					X	
Compressor Blades	X			X					X	
Compressor Case	X			X					X	
Laser Mirrors									X	
Engine Pistons	X	X		X		X			X	
Fuel Lines	X		X						X	
Chemical										
Tanks, Vessels	X				X				X	
Pumps	X	X	X	X	X				X	
Filters	X	X	X						X	
Heat Exchangers	X	X							X	
Control Valves	X	X	X	X					X	
Spray Nozzles	X	X	X	X					X	
Centrifugal Screens	X	X	X	X					X	
Stirrers/Blenders	X	X		X					X	
Extruders	X	X		X					X	
Railroad										
Diesel Shafts		X	X	X	X	X			X	
Trunions		X	X	X						
Electric Motors										
Motor Shafts		X	X	X	X				X	
Rotor Blades	X	X	X	X	X				X	
Starter Rings	X	X	X	X	X				X	

	Corrosion	Adhesive Wear	Fretting Wear	Hardness/Abrasion	Repair & Salvage	Lubricity	Weldability	Solderability	Uniformity	Magnetics
Printing										
Printing Rolls	X	X	X	X		X			X	
Impact Print Cylinders	X	X	X	X		X			X	
Rollers (copiers)	X	X	X	X		X			X	
Mining										
Drills	X	X	X	X		X			X	
Hydraulics	X	X		X	X				X	
Bearings	X	X	X	X					X	
Rollers	X	X		X		X				
Textile										
Feed Rolls	X	X		X		X			X	
Drop Wires	X	X		X		X			X	
Heddles	X	X		X		X			X	
Spinneretts	X	X		X		X			X	
Bobbins		X		X		X			X	
Thread Guides		X		X		X			X	
Spools		X		X		X			X	
Combs		X		X		X			X	
Electronics										
Heat sinks	X							X		
Connector Housings	X	X	X							
Chassis	X									
Lead Frames								X	X	
Transistors	X				X	X	X	X	X	
Headers	X									
Printed Circuit Boards						X			X	
Memory Disks	X			X					X	X
Disk Heads	X	X		X					X	
Head Cover	X	X		X					X	
Lead Wires							X	X		
Terminals							X	X		
Packaging IC's	X						X	X	X	
Filters	X						X	X	X	
Hermetic Seals							X	X	X	
Power Generation										
Reactor Head(nuclear)	X			X					X	
Steam Turbine Parts	X	X		X	X				X	
Gas turbine parts	X	X		X	X				X	
Pulp and Paper										
Rollers	X	X	X	X	X	X			X	
Oil and Gas										
Safety Valves	X									
Tubulars	X									
Separators, Fire Tubes	X									
Packers	X									
Mud Pumps	X									
Chokes	X									
Collars	X									
Couplings	X									
Flow Control Valves	X									
Pump Impellers	X									