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REVIEW

# Electroless Nickel Plating – A Review

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**Abstract** The operating process, versatility and the increasing research interest in optimising the process and products technology in the electroless plating method of metal coating, particularly, the electroless nickel plating of metallic substrates such as mild steel, necessitates the writing of this review. It is also aimed at providing more literature information, both of the past and the present published research in this field. In this paper, electroless nickel plating is introduced. The various nickel plating solutions and baths' operating parameters; main types of electroless nickel plating; the mechanism involved in the plating process; application of the nickel plating process to iron powders; advantages and disadvantages and the process's other applications are reviewed. Electroless nickel plating produces an amorphous deposit in the as-plated condition. The deposit is not dependent on current distribution and hence it is almost uniform in thickness. Electroless nickel plating is far more difficult to remove chemically than conventional nickel deposits due to its superior corrosion resistance. The deposit has a good wettability and is generally hard. However, its bath control is more complex than with electroplating. The bath also has lower efficiency and higher operating costs, even without the use of electricity.

**Keywords** Electroless · Nickel · Plating · Solutions · Baths · Process parameters

## 1 Introduction

Electroless plating, also known as chemical or auto-catalytic plating, is a non-galvanic type of plating method that involves several simultaneous reactions in an aqueous solution, which occur without the use of external electrical power. The reaction is accomplished when hydrogen is released by a reducing agent, normally sodium hypophosphite, and oxidized thus producing a negative charge on the surface of the part. The most common electroless plating method is electroless nickel plating. Electroless nickel plating produces an amorphous deposit in the as-plated condition. Since the deposit is not dependent on current distribution, it is almost uniform in thickness, regardless of the size or shape of the plated surface [1–3].

Electroless nickel (EN) plating is a chemical reduction process which depends upon the catalytic reduction process of nickel ions in an aqueous solution (containing a chemical reducing agent) and the subsequent deposition of nickel metal without the use of electrical energy [4]. It is a technique used to deposit a layer of nickel-phosphorus alloy on a solid work piece, such as metals or plastic. Alloys with different percentage of phosphorus, ranging from 2-5 (low phosphorus) to up to 11-14 (high phosphorus) are possible [5]. The metallurgical properties of alloys depend on the percentage of phosphorus.

In the EN plating process, the driving force for the reduction of nickel metal ions and their deposition is supplied by a chemical reducing agent in solution. This driving potential is essentially constant at all points of the surface of the component, provided the agitation is sufficient to ensure a

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uniform concentration of metal ions and reducing agents [4]. Electroless deposits are therefore very uniform in thickness all over the part's shape and size. In fact, one of the major characteristics making its use more prevalent is the ability of the process to provide uniform deposits in valves, deep recesses, bores, internal surfaces, blind holes and threaded parts [6]. Other characteristics are: excellent corrosion, wear and abrasion resistance, ductility, lubricity, solderability, electrical conductivity and hardness [4–6].

Due to its exceptional corrosion resistance and high hardness, the process finds wide application on items such as valves, pump parts etc. to enhance the life of components exposed to severe conditions of service, particularly in the oil field and marine sector. Other typical uses are on aerospace hardware, automotive parts, food processing equipment, fluid power components, textile machinery, hydraulics, plastic moulds, electronic components, chemical processing equipment, and printed circuit boards. These are a small representative of the wide range of applications for which electroless nickel is well suited.

The uniformity, structure, metallurgical composition and low porosity of an electroless nickel alloy are known [6] to have contributed to its excellent corrosion resistance to most organic liquids, weak acids, and halogens, dry ammonia gas, neutral or alkaline aqueous salt solutions, hydrocarbons and ketones among other corrosives. Electroless nickel has also been described [6], to withstand salt water, hydrogen sulphide and other industry related corrosive elements. Such performance will further expand its use to pipelines for both the marine and non – marine applications. Included in petrochemical applications are rod pumps, packers, mud pumps, collars, couplings, safety values, fire tubes, extruders and blenders, tanks and vessels. The antigalling properties of the coating are also of great importance for chemical processes.

## 2 Main Categories of Electroless Plating

Electroless coatings can be divided into three main categories, viz:

(i) **Alloy coatings**. Electroless alloy plating involves the deposition of metal alloys on the substrate being studied. The formed alloy coating depends on the reductant. Metallic addition to the electroless binary bath produces ternary or quaternary alloy coats. This plating process has been used to produce homogeneous, consistent coats for several industrial applications. The rapid rate at which deposition occurs and its capability of providing the necessary product quality in a satisfactory process period at reasonably low principal and operating overheads are parts of the significant reasons for the application of this technique [7]. Electroless depositions are redox reactions with the key components as the oxidizer and reductant in the bath solution [8].

(ii) **Composite coatings**. Electroless composite plating is the co-deposition of composite materials in the alloy coating. Electroless composite coatings are normally prepared by adding solid particles to the regular electroless nickel phosphorous plating bath to accomplish co-deposition of the solid particles and Ni–P matrix [9]. This type of coating, in recent times, has gained immense recognition in preparing composite coatings. PTFE, $ZrO_2$, $Al_2O_3$, SiC, and C are among the commonly used solid particles.

(iii) **Metallic coatings**. Electroless metallic (pure nickel) coating is a robust coating method that can provide a feasible alternative to the usual electroplating in appropriate circumstances. Properties like low friction, hardness, corrosion and wear resistance have led to their various applications. These three types of electroless pating are presented in Fig. 1 [10].

Sahoo and Das [11] reported the benefits of improving the properties of electroless nickel plating by the use of proper surface treatments, and integration of a variety of elements and solid particles by different researchers to appraise the appropriateness of these plating for diverse purposes. This surface coating technique has gained use in nautical atmospheres, and protecting of small-arms weapons used in arid and dusty regions.

Several authors [12–14] have reported on the development of electroless Ni-P binary alloy deposited metal with fine improvement in corrosion resistance. As a result of the unique properties of its deposits, Ni–P binary alloy is a paradigm of electroless deposition and has extensive industrial uses. It has very good applications in machinery, electronics, automobile, valve and aerospace industries because of its uniform coating, corrosion resistance, hardness and good wear resistance [15]. In addition, electroless

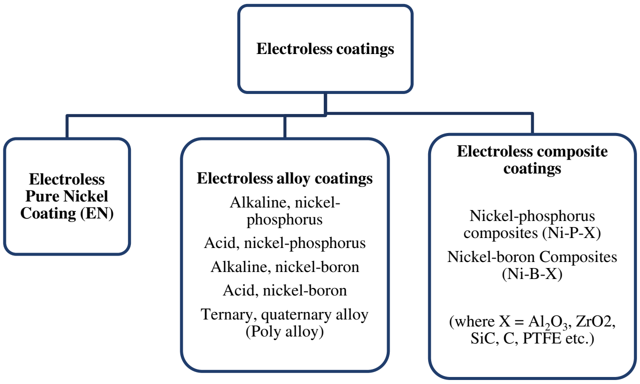


**Fig. 1** Types of electroless coatings [10]

Ni-P plating has the unique capability to be plated on a range of materials and irregular machine parts including ceramics, metals, glass, plastics and internal surfaces of valves, pipes and other parts [16].

By the controlled chemical reduction reaction, the electroless coating chemistry has emerged as one of the leading growth areas in surface engineering, metal finishing, etc. It is estimated to grow at a rate of beyond 15 percent per annum; certainly no other chemistry is growing at this rate. Electroless coatings have unique physiochemical and mechanical properties for which they are being used increasingly. Some of those properties, like uniformity; excellent corrosion resistance; and wear and abrasion resistant have been mentioned above.

The co-deposition of other materials with electroless nickel provides enhanced wear, abrasion resistance and/or lubricity of the surface of base substrates [6]. Among the composites deposited are those containing fluoropolymers (PTFE), natural and synthetic (polycrystalline) diamonds, ceramics, chromium carbide, silicon carbide and aluminium oxide. Co-deposition is employed on components for rubber and plastic moulds, fasteners, precision instrument parts, drills, gauge blocks, tape recording heads, guides for computers and food processing equipment.

Electroless nickel plating shows continuous growth in both technology and types of application.

### 2.1 Literature Review

The fact that all engineering metals and non-metals in a refined state of use and in interaction with the environment will want to or will revert to their original position as ore has made the issue of corrosion a perpetual struggle between man and nature. Metallic structures must be protected and corrosion has to be prevented and to avert the adverse economic, technological, health and safety consequences that such degradation causes to humanity. This issue has long elicited enormous interest in the research of corrosion and protection of engineering materials world-wide. Quite a large volume of literature has been generated in this regard that space will not permit to review here.

Electroless coating, since its inception by Brenner and Riddell [17], has been the subject of research interest and, in the past two decades, emphasis has shifted to the studies of its properties and applications. The co-deposition of particulate matter or substance within the growing film has led to a new generation of electroless composite coatings, many of which possess excellent wear and corrosion resistance. This valuable process can coat not only electrically conductive materials including graphite but also fabrics, insulators like plastics, rubber etc. Different characterisation studies have been conducted on various electroless nickel-based coatings with emphasis on wear and corrosion properties [18]. Coatings can be tailored for desired properties by selecting the composition of the coating alloy/composite metallic to suit specific requirements.

Electroless nickel coatings have gained a good deal of popularity and acceptance in recent years as they provide considerable improvement of desirable properties. The plating process enables deposition of a uniform coating regardless of the shape of surface irregularities [19]. Electroless nickel plating has been conducted in different baths to find optimum conditions for desirable properties, such as good corrosion and wear resistance, hardness and others [20–26]. The amount of phosphorus co-deposited with nickel can affect the strength and wear properties of coatings. The P content can be changed under certain conditions of plating, such as composition and pH of the plating bath used. An addition of some inhibitors may improve the stability of the plating bath and surface roughness.

It has been established that a certain quantity of $Cu^{2+}$ ions sufficiently stabilizes electroless nickel plating solutions containing glycine as a ligand for $Ni^{2+}$ ions, increases the Ni P plating rate and process coating appearance and ensures non-ferromagnetic stability [19, 27].

In electroless plating, difficulties of devising suitable solutions are such that a good deal of control over the plating process is sacrificed. The need to deposit on non-metals means that a reducing agent capable of reacting spontaneously is needed in solution [28]. However, to ensure that reduction occurs at the substrate surface a catalyst may be necessary although a metal substrate is often its own catalyst. The pH must be carefully controlled to obtain optimum reducing power and thence maximum deposition rates, while complexants may be required to prevent sludge formation and remove intermediate metal ions. For non-metals, surface preparation may include sealing, deglazing or etching, and sensitizing with a catalyst.

Electroless nickel has the advantage that the deposit thickness is completely even irrespective of the complexity of the surface geometry of the article being coated [29]. The incorporation of phosphorus or boron in the deposit increases hardness and brittleness, and alters the corrosion resistance compared with that of the electrodeposited metal. The adhesion of the deposits is dependent upon chemical bonding, assisted by mechanical keying to a roughened surface, and there is no alloying with the substrate metal unless diffusion is induced by heat-treatment after electroless plating. This report described the deposit as having a lamellate columnar structure in which the lamellae are parallel to the base metal. It has also been reported by some other researchers [17, 30] that in electron and X-ray diffraction studies the as-plated electroless nickel deposits consist of supersaturated solid solutions of phosphorus dissolved in crystalline nickel. Electroless nickel plate is semi-bright in appearance, the brightness increasing somewhat with increasing phosphorus content. Certain brighteners have been used to increase gloss [31].

### 2.2 Electroless Plating Baths

Spencer [32] has described the practical baths for nickel plating by catalytic chemical reduction as water solutions which consist primarily of:

(i) A source of nickel cations, such as nickel chloride or nickel sulphate, to supply metallic nickel.
(ii) Hypophosphite anions, normally sodium hypophosphite monohydrate, to supply the catalytic dehydrogenation active hydrogen atoms for reducing the nickel ions to the metal, and to supply the phosphorus portion of the deposited alloy.
(iii) An organic chelating agent to complex the nickel ions in order to prevent nickel phosphate precipitation, and to serve as a buffer to prevent a rapid decrease in the pH. Examples are the organic hydrocarboxylic acids such as hydroxyacetic, hydroxypropionic, citric or malic.
(iv) “Exaltant” to increase the rate of nickel deposition by activating the hypophosphite anions, and thus counteract the slowing effect of chelating agents and stabilizers. Examples include succinic anions adipic anions, and alkali fluorides.
(v) Stabilizers to prevent solution decomposition by “masking” active nuclei. Typical materials used include thiourea, sodium ethylxanthate, lead or tin sulphide.
(vi) pH regulators to adjust the pH of the solution and keep it constant during continuous operation. This would include acids ($H^+$ ions) such as sulphuric, and alkalizers ($OH^-$ions) such as caustic soda and sodium carbonate.
(vii) Wetting agents, such as sulphated alcohols, sulphonates of fatty acids, or sulphonated oil fractions, to promote wetting by the solution of the parts to be plated. The two general types of plating baths in commercial use are the alkaline type bath which operates in the pH range of 8 to 10, and the more popular acid bath, which operates in the pH range of 4 to 6. A large number of nickel plating baths have been suggested over the years, of which the more important are:

    (i) Sulphamate baths
    (ii) Watts type baths
    (iii) Fluoroborate baths
    (iv) Chloride or chloride – sulphate baths.

(i) ***Sulphamate baths*** - The basic constituent of this bath is nickel sulphamate, $Ni(NH_2SO_3)_2$, which has a very high solubility, Fig. 2.

Nickel sulphamate based plating solutions are employed wherever high speed, low stress, heavy nickel plating is required [34]. The concentration of boric acid is not very critical but Ericson [35] recommended a high concentration of boric acid (40g /1) in order to reduce hydrogen pitting which is frequently encountered with the use of sulphamate solutions. The concentrations of nickel chloride in sulphamate baths varies within the range of 5 to 30 g/1. Fanner and Hammond [36] recommend an addition of 3.3 g/1 of nickel chloride to ensure efficient anode corrosion.

(ii) ***Watts type baths***- Nickel sulphate is the major source of nickel ions in a Watts bath, and this is preferred [37] because of its cheapness, high solubility (570 g/1 at 50 °C), and its stable anion. But, however, in spite of the high solubility of nickel sulphate, commercial Watts type baths usually contain about 400 g/l. The bath also contains chloride ions in solution which function by increasing conductivity and throwing power of the solution. Boric acid is the third important constituent of the Watts bath and it acts as a weak buffering agent which controls the pH of the bath.

(iii) ***Fluoroborate baths*** - This is a very versatile system because of the high solubility of nickel fluoroborate. A bath composition of 300 g/l of nickel fluoroborate and 30 g/1 of boric acid may be operated at pH values between 2.7 and 3.5 (calorimetric) and at a temperature of 54 °C, as suggested by Roehl and Wesley [38]. The throwing power of fluoroborate barrel plating solution has been shown to be as good as the sulphate chloride bath [39]. The addition of ammonium fluoroborate reduces the resistivity of the bath and also improves its throwing power.

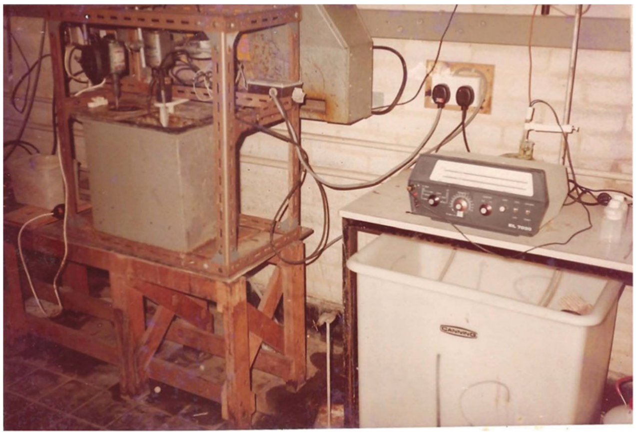


**Fig. 2** Plating bath and accessories [33]

(iv) ***Chloride baths*** - All solutions that contain a high chloride to sulphate ratio possess low resistivity, good throwing power and permit the use of high current densities in electrolytic plating [18, 40]. There are basically two constituents in this type of bath - nickel chloride and boric acid. They are used for high speed bright nickel plating and heavy nickel plating. All the above types of bath are what Spencer [32] described as alkaline and acid plating baths. For the electroless nickel plating baths, he summarised them into two tables.

The acid baths are more widely used in commercial installations than the alkaline baths. The acid bath is reputed to be more stable, easier to control with minimum loss of constituents by vaporization and has a higher deposition rate [32].

The rate of deposition which may be defined as the coating thickness produced in a given time depends primarily on the temperature of operation and the solution concentration. These plating baths have a narrow range of useful temperature for deposition (Tables 1 and 2).

The role of solution concentration, as well as the functions of the various constituents has been outlined by various investigators, [32] and these include:-

1. In both alkaline solutions and highly buffered acid baths with a high V/A (Volume/Area) ratio, at a substantially constant pH, the rate of deposition is primarily a function of the hypophosphite concentration.
2. The hypophosphite concentration is critical. Thus as cited by Brenner and Riddell, [40] a high hypophosphite concentration will result in a bulk deposition of the nickel ions, as opposed to a selective, catalytic deposition on the surface of the workpiece. In other words, bath stability decreases as a direct function of the hypophosphite concentration.
3. The rate of nickel deposition, as well as molecular hydrogen evolution, is a function of the pH of the bath and in addition, the phosphorus content of the deposit increases as the pH of the bath decreases.
4. Buffer agents, that retard the pH drop inherent in the reduction of the nickel, also serve as complexing agents for the nickel ions. Thus, they prevent the early precipitation of nickel orthophosphite.

**Table 1** Alkaline electrolese nickel plating baths [32]

| Constituent (g/I or conditions) | 1 | 2 | 3 |
|---|---|---|---|
| Nickel chloride | 30 | 45 | 30 |
| Sodium hypophosphite | 10 | 11 | 10 |
| Ammonium chloride | 50 | 50 | 50 |
| Sodium citrate | – | 100 | – |
| Ammonium citrate | – | – | – |
| pH (with ammonia) | 8 to 10 | 8.5 to 10 | 8 to 10 |
| Temperature °C | 90 – 96 | 90 – 96 | 90 – 96 |
| Plating rate, mil/hr. | 0.3 | 0.4 | 0.3 |

The mechanism of deposition, in both acid and alkaline baths [41] is not well established, but it is probable that the nickel, complexed as succinate or pyrophosphite, is reduced by nascent hydrogen produced by hypophosphite decomposition [28].

$$H_2PO_2^- = 2H + PO_2^-$$

$$\text{Anode reaction } 2H \longrightarrow 2H^+ + 2e$$

$$\text{Cathode reaction } Ni(P_20_7)_2^{6-} + 2e \longrightarrow Ni^0 + 2P_20_7^{4-} PH \sim 10.5$$

$$\text{or } Ni(C_40_4H_4)_2^{2-} + 2e \longrightarrow Ni^0 + 2C_40_4H_4^{2-} \quad PH \sim 5$$

Although, the mechanism involved in electroless plating has received considerable attention, there is a great controversy regarding the intermediate steps involved in the mechanism [41, 42].

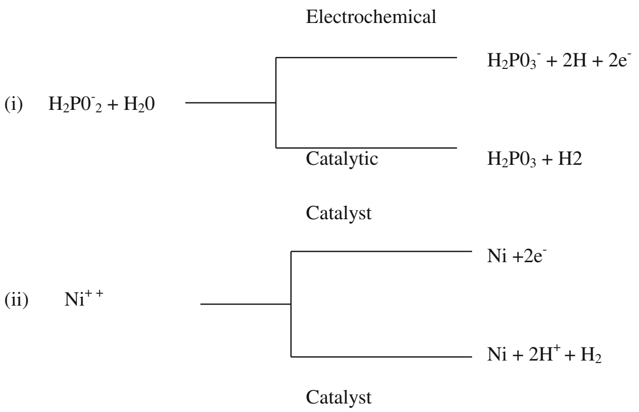
The basic reactions may be represented as follows:

$$NaH_2P0_2 + H_20 \longrightarrow NaH_2P0_3 + H_2$$

$$NiCl_2 + NaH_2P0_2 + H_20 \longrightarrow Ni + NaH_2P0_3 + 2HC1$$

$$3H_3P0 \longrightarrow H_3P0_3 + 3H_20 + 2P$$

In a review of the various mechanisms proposed, and on the basis of their own investigations, Gonda et al. [43] have put forward a mechanism involving both electrochemical and catalytic decomposition of the hypophosphite viz:-



Electroless nickel coatings are far more difficult to remove chemically than conventional nickel deposits, due to their superior corrosion resistance [32]. Thus a cyanide solution will take about four times as long to remove a chemical deposit than it does for the same thickness of electroplated nickel. The deposit has a good wettability and therefore tends to hold a lubricant film better than chromium [34]. Electroless nickel deposits are generally hard. The hardness values of electroless nickel deposits in the unheat-treated conditions, range between 300 – 600 kg/mm$^2$ depending upon the operating conditions, as compared to 190 kg/mm$^2$ for nickel electrodeposited, using the nickel sulphamate solution.

Various research studies have been and are now being undertaken to further develop and study the other various parameters vis-à-vis corrosion resistance and tribological characteristics of electroless nickel coating on metals/alloys both ferrous and non-ferrous [44–47].

A very good corrosion resistance performance was obtained when mild steel, coated with electroless nickel-phosphorous alloy from a bath containing sodium hypophosphite and glycine-citrate complexing agents in an aerated 3.5 % sodium chloride solution was investigated by polarization and immersion corrosion tests [38]. X-ray diffraction patterns showed that by changing the coating times, an amorphous or crystalline structure could be obtained. The corrosion resistance was found to increase with the increasing amorphous phosphorus content of the coating. In a different study, the corrosion resistance of electroless Ni-P-$ZrO_2$ composite coating on AZ91D magnesium alloys was found to be superior to Ni–P coatings due to the effect of the $ZrO_2$ nano-particle [44].

Lee [46] evaluated the corrosion and corrosive wear resistance of electroless nickel-phosphorous (ENP) coatings on glass fibre-reinforced plastic (GFRP) composites that are frequently used in wind turbine blades. A higher P content (P> 7 wt. %), lower micro-porosity, thickness and greater hardness of the ENP coatings on GFRP substrates were obtained as the surface roughness of the substrate increased over 0.3 $\mu$m, improving corrosion and corrosive wear resistance properties. The nano-composite electroless coating of Ni -P/Au was studied by Hongfang Ma, et al. [47]. The compositions, structures, morphologies and hardness of the nano-composite coating of Ni-P/Au, obtained by adding gold nano-particles to the Ni-P electroless plating solutions were characterized by a scanning electron microscope (SEM), energy dispersive spectrometer (EDS), X-ray diffractometer (XRD) and microsclerometer. The composite coatings, which contain gold nano-particles, were found to exhibit better properties of hardness, corrosion resistance and uniformity than the particle-free coatings. The coatings deposited from an electroless bath have the increased hardness after heat treatment due to the transformation of amorphous phase Ni -P to crystalline phase $Ni_3P$.

Studies on plain electroless Ni-P and submicron particles of silicon carbide (Ni-P-$Si_3N_4$) [48] and Ni–P coatings containing SiC particles [49] confirmed increased rate of plating, uniform particles incorporation throughout the thickness of coating, and improvement in microhardness, respectively for the composite co-deposition compared to the plain Ni–P coatings. The use of carbon nanotubes was also confirmed to improve significantly the tribological characteristics/properties of the coated alloys [49]. Electroless plating of Ni–P on aluminium alloys has been widely studied [50–53]. In each case, very good corrosion resistance results were obtained in various test media under different conditions.

### 2.3 Electroless Bath Parameters

Electroless bath operating parameters had been briefly reviewed [10]. Various factors affect the deposition and appearance of the metal on the plated substrate of an electroless plating process. These factors include but are not limited to: Bath age, Bath concentration, Operating temperature, Bath time, Bath volume, Operating pH and Bath Additives.

**Bath concentration** relates the quantity of each component of the electroless bath with the rate of deposition and the

**Table 2** Acid electroless nickel plating baths [32]

| Constituent (g/I) or conditions | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|
| Nickel chloride | 30 | – | 30 | – | 30 | 30 |
| Nickel sulphate | – | 20 | – | 15 | – | – |
| Sodium hypophosphite | 10 | 27 | 10 | 14 | 12 | 12 |
| Sodium acetate | – | – | – | 13 | – | – |
| Sodium hydroxyacetate | 50 | – | 10 | | – | – |
| Sodium succinate | – | 16 | – | | – | – |
| Lactic acid (80 %) | – | – | – | | – | – |
| Propionic acid (100 %) | – | – | – | | 10 | 10 |
| pH | 4–6 | 4.5–5.5 | 4–6 | 5–6 | 4.5–5.5 | 4.5–5.5 |
| Temperature °C | 88–99 | 93–99 | 88–99 | 88–99 | 88–99 | 88–99 |
| Plating rate, mil/hr. | 0.5 | 1.0 | 0.4 | 0.7 | 0.6 | 0.6 |

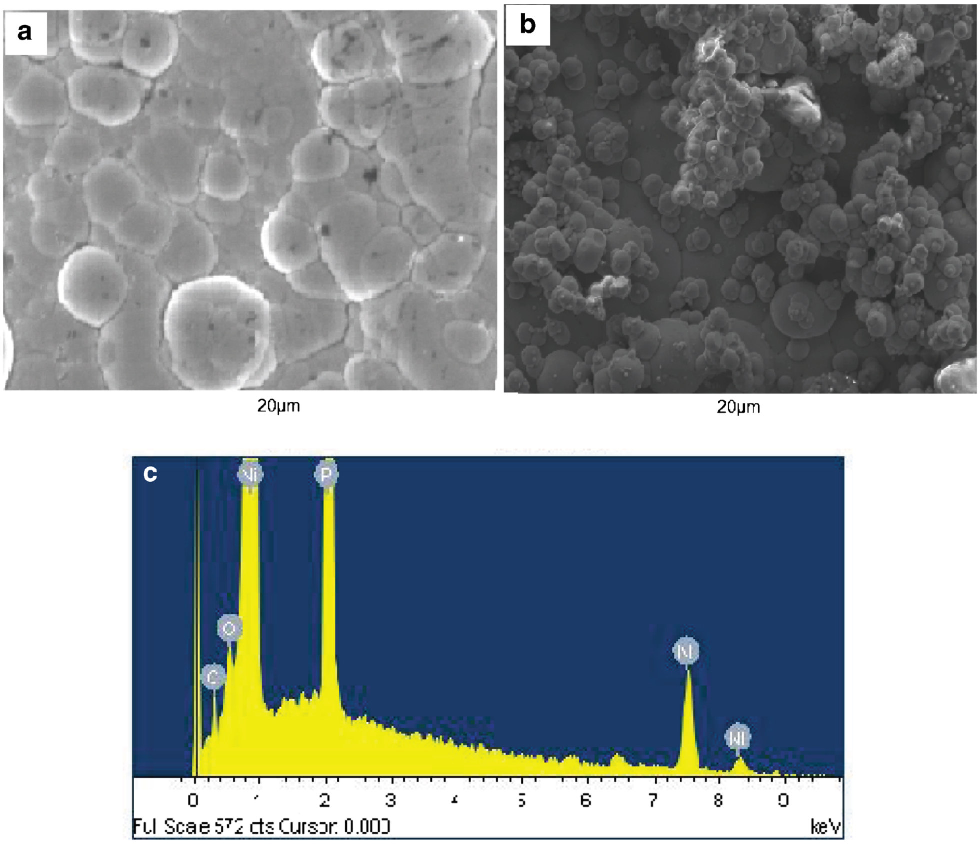


**Fig. 3** SEM micrographs of Ni alloy plated samples: **a**) Ni-P, **b**) Ni-Sn-P and (**c**) EDS analysis of Ni –P [10]

amount of the reduced metal deposited. It is generally evaluated by the analysis of the metal source. An increase in the metal source or the reducing agent yields an increase in the deposition rate and consequently, in the reduced metal. However, the depletion of the metal ion causes a decrease in the mass of the reduced metal as the equilibrium shifts and less metal ion is available compared to the electrons released by the reductant [54].

**Bath time** The time frame of an electroless bath depends a lot on the stability of the bath. A longer plating duration results in an increase in deposition of the metal, as long as the bath is stable [55]. Bath stability is achieved by controlling the production of metal particles in an electroless bath.

**Operating temperature** is a key parameter in evaluating the deposition rate of an electroless bath. Low temperatures offer a reduced amount of energy to the reaction which as well leads to poor deposition rates. Very high temperatures on the other hand could possibly make the bath excessively active, probably ensuing in plate-out and general bath

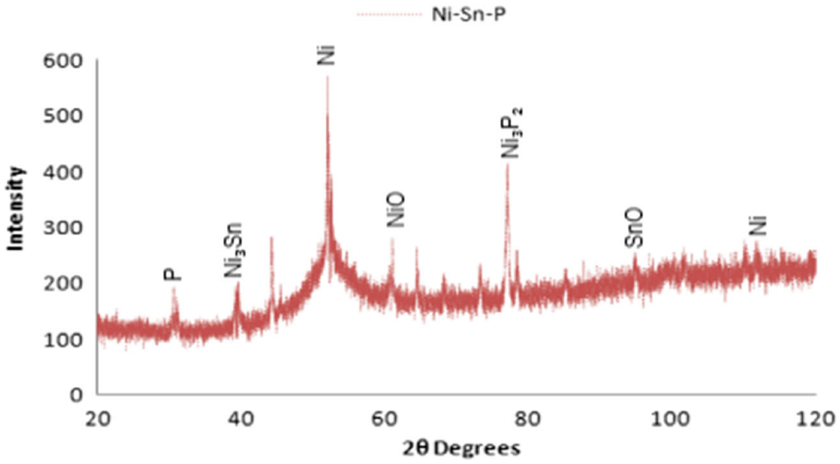


**Fig. 4** XRD spectrum for Ni-Sn-P plated sample [10]

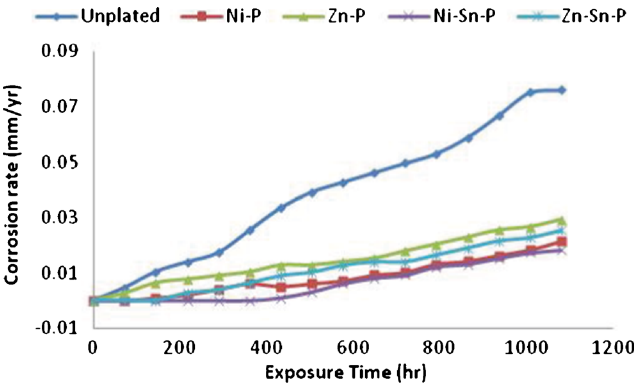


**Fig. 5** Corrosion rate versus exposure time for unplated and plated mild steel [10]

unsteadiness. Jothi et al. [56] stated that the metal deposition rate increases exponentially with increased temperature, everything else being equal. Low operating temperature can be applied depending on the metal to be deposited. All practical Ni-P baths needs operational temperatures of 60 °C and over. Nevertheless, a bath temperature exceeding 90 °C might lead to solution "plate-out" or bath decomposition [57].

**Operating pH** is an important parameter which influences phosphorus content in the deposit. Characteristically, higher pH values provide lesser phosphorus content in the deposit, at the same time lesser pH ranges produce high phosphorus deposits. Chen et al. [58] observed that an acidic bath with low bath pH values results in a film having an increased phosphorous content, up to 25 % at pH 4. At pH in the alkaline range less than 1 % phosphorous content is usually obtained. Deposits formed in acidic baths are inclined to exhibit tensile stress, while deposits from alkaline baths transfer the pressure in the compressive direction. Another property that is pH reliant is the good adhesion characteristics to steel exhibited by the films formed using acidic baths, and this probably explains its wide usage in industry [59].

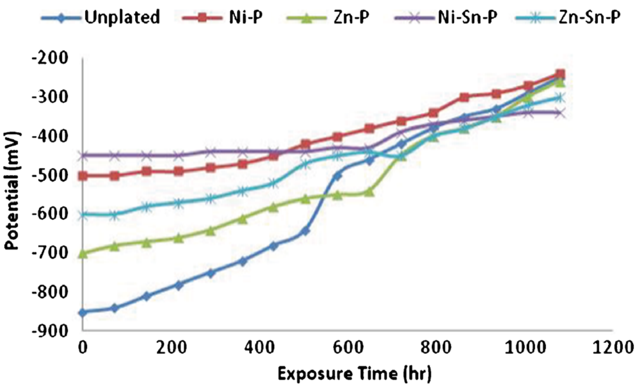


**Fig. 6** Potential measurement for the unplated and plated mild steel versus exposure time [10]

**Bath Volume** is an essential and frequently ignored control parameter needed for sustaining the operational level of the plating bath. For example, a plating tank is at a 50 inch depth level with the solution at 100 % activity and the bath chemically balanced. As plating occurs, it consumes at least 10 % of the bath chemistry. On analysis of the used-up bath, a substantial amount of nickel metal would have been deposited but the bath will not be stable. Particularly, the stabilizers would be low, and the relative amount of chelates in the bath would be higher than normal [14].

**Bath Additives** There are different additives used for electroless plating processes; one of these additives is called complexing agents. These are typically organic acids or their salts [8]. A case in point is the ammonium ion that is added for pH control, commonly used in alkaline baths, and the pyrophosphate ion. Their major responsibility is:

- To preserve the stability of pH
- To avert precipitation of the metal salts
- To decrease the amount of liberated metal ions

Stabilizers form another branch of additives. Increase in the quantity of the evolving hydrogen gas is trailed by the precipitation of fine black particles before solution breakdown. A bath can crumble abruptly with no trace of warning, hence the need of stabilizers.

Osifuye, [10] studied the effect of temperature, concentration, deposition time and the inclusion of Sn as a third addition to the electroless bath. Corrosion and wear behaviour of the electroless plated mild steel was also studied. It was found that temperature change had a considerable effect on the plating process and the Ni alloy coating displayed its best appearance with the highest amount deposited at 80 °C. Optimum conditions were observed at a concentration range of 0.60 - 0.65 g/L for Ni alloy coatings and 0.65 – 0.70 g/L for the Zn alloy coating. Deposition time depended strongly on the stability of the bath for both coatings. Surface characterization using Scanning Electron Microscopy of the plated and unplated substrates (Fig. 3) revealed finer and more evenly distributed particle orientation across the plated surfaces with the ternary deposits being the most evenly distributed. Identified phases by X-ray diffractometer include: NiO, $Ni_3Sn$, $Ni_3P$, ZnO and $Zn_3P_2$ (Fig. 4). Electrochemical tests indicated that the Ni-Sn-P ternary deposits on the mild steel displayed better corrosion resistance with the lowest corrosion rates values as compared with those of the Ni-P, Zn-P, Zn-Sn-P deposits and the substrate. Significant improvement in corrosion resistance was also indicated by a positive shift in potential E*corr*, higher polarization resistance value and lower current density. Sliding wear analysis demonstrates consistently enhanced wear resistance of the plated surfaces,

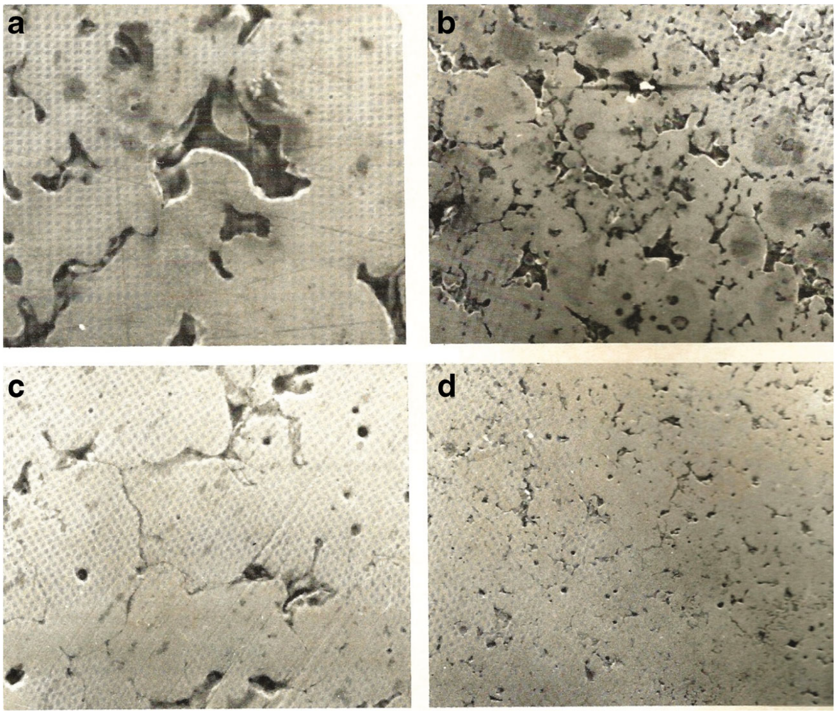


**Fig. 7** Electroless plated and sintered iron powders at 1120°, these compacts (x1000). **a** 100 mesh; (**b**) 150 mesh; (**c**) 200 mesh; (**d**) 325 mesh [26, 33]

with the ternary coating Ni-Sn-P showing better resistance to wear due to the presence of complex phases (Figs. 5 and 6).

## 3 Application of Electroless Nickel Plating to Iron Powders

Loto [33], applied the electroless method to the plating of iron powders using the nickel sulphamate solution. The coated powders exhibit a high level of homogeneity and the sintered compacts have good mechanical properties. Decreasing powder size increases the nickel concentration and improves diffusion by particle-to-particle contact. Alloying is promoted by reducing diffusion distances. Some selected results obtained in terms of powder size and porosity relationship are presented in Fig. 7.

Composite (coated) powders that improve homogeneity while retaining the good compressibility of elemental powders have been considered to alleviate the problems. Homogeneity of the sintered compacts results from proper alloying. The evolution of a homogeneous alloy structure for a completely solid-state sintering system is diffusion related. The degree of alloying increases greatly with a relatively small increase in sintering temperature. The increase in nickel content at smaller particle sizes improved the densification of the sintered compacts. It could be inferred that the intrinsic diffusivities of iron and nickel in Fe-Ni alloys increase with increasing nickel concentrations [60].

## 4 Uses and Advantages

To protect parts from wear, friction and corrosion, electroless nickel plating offers a range of advantages. An electroless nickel coating is often less porous than electroplated nickel and hard chrome, providing barrier corrosion protection to steel, and can also be applied with zero or little compressive stress making it gentle in application.

With no electricity required, electroless nickel plating can be completed in a more controlled environment with less equipment than traditional electroplating and the process requires fewer coats to produce a strong, high-quality coating. This reduction of equipment and time consumption results in an efficient, cost-effective process. Electroless Nickel (EN) plating can be applied to a multitude of base materials including aluminum, titanium, mild steels, stainless steel, hardened steel, copper, brass and zinc die-cast.

The electroless plating process provides a large flexibility of thickness and volume of the plating on metal surfaces, and can easily fill recesses or pits in the metal surface resulting in a uniform surface finish. This also allows for a wider variety of industrial parts to be plated such as: oil field valves, pumps, drive shafts, electrical/mechanical tools and engineering equipment to name a few.

## 5 Conclusion

The process of electroless nickel plating on a metal surface is an autocatalytic chemical reduction. Instead of using an outside source of electricity as in the similar electroplating process, the electroless nickel plating process uses a chemical bath to deposit a nickel / phosphorous layer onto the metallic surface. The electroless nickel technique has been successfully used in various corrosion protection and wear processes in other surface engineering applications. A surface coated in electroless nickel can even be used on non-conductive surfaces which allows for plating of a wider variety of base materials. This electroless process greatly improves the objects resistance to galling and leaves a predictable, uniform nickel coating for high-precision parts, which can be applied to both ferrous and non-ferrous surfaces of any geometry or intricate shape. The present review is expected to give a good fundamental background and provide a rich source of information especially of previous researchers to all those that have interest in this plating technique.

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