

Electroless Ni–P/Ni–B duplex coatings: preparation and evaluation of microhardness, wear and corrosion resistance

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Abstract

The present work deals with the formation of Ni–P/Ni–B duplex coatings by electroless plating process and evaluation of their hardness, wear resistance and corrosion resistance. The Ni–P/Ni–B duplex coatings were prepared using dual baths (acidic hypophosphite- and alkaline borohydride-reduced electroless nickel baths) with both Ni–P and Ni–B as inner layers and with varying single layer thickness. Scanning electron microscopy (SEM) was used to assess the duplex interface. The microhardness, wear resistance and corrosion resistance of electroless nickel duplex coatings were compared with electroless Ni–P and Ni–B coatings of similar thickness. The study reveals that the Ni–P and Ni–B coatings are amorphous in their as-plated condition and upon heat-treatment at 450 °C for 1 h, both Ni–P and Ni–B coatings crystallize and produce nickel, nickel phosphide and nickel borides in the respective coatings. All the three phases are formed when Ni–P/Ni–B and Ni–B/Ni–P duplex coatings are heat-treated at 450 °C for 1 h. The duplex coatings are uniform and the compatibility between the layers is good. The microhardness, wear resistance and corrosion resistance of the duplex coating is higher than Ni–P and Ni–B coatings of similar thickness. Among the two types of duplex coatings studied, hardness and wear resistance is higher for coatings having Ni–B coating as the outer layer whereas better corrosion resistance is offered by coatings having Ni–P coating as the outer layer. © 2003 Elsevier B.V. All rights reserved.

Keywords: Amorphous materials; Electroless plating; Duplex coating; Microhardness; Wear resistance; Corrosion resistance

1. Introduction

Electroless deposition process experienced numerous modifications to meet the challenging needs of a variety of industrial applications since Brenner and Riddell invented the process in 1946 [1]. Among the various types of electroless plating, electroless nickel has gained immense popularity due to their ability to provide a hard, wear and corrosion resistant surface [2–4]. Hypophosphite-reduced electroless nickel plating has proved its supremacy in providing improved hardness, corrosion and wear resistance. Recently, much attention is being paid towards borohydride-reduced electroless nickel plating. The properties of sodium borohydride-reduced electroless nickel coatings are often superior to those of deposits reduced with other boron compounds or with sodium hypophosphite. The principal advantages of borohydride-reduced electroless nickel deposits are its hardness and superior wear resistance in the as-deposited condition [5]. Elec-

troless Ni–B coatings are more wear resistant than tool steel and hard chromium coatings and it can replace gold in electronic industries. The columnar structure of Ni–B coatings is useful in retaining lubricants under conditions of adhesive wear. The rapid changing needs of engineering industries warrant the development of coatings that possess high hardness and good wear and abrasion resistance and in this respect one such coating which seems promising is the borohydride-reduced electroless nickel deposit. The major limitation of Ni–B coating is its relatively poor corrosion resistance compared to electroless Ni–P deposits. The corrosion resistance of electroless Ni–P and Ni–B deposits is found to increase with the incorporation of an additional alloying element such as Cu, Zn, W, Mo, etc. or with the incorporation of second phase particles, such as silicon nitride, ceria and titania in the metal matrix [6–9]. Ni–P–B alloy deposits are prepared using both the reducing agents in the same plating bath [10]. As borohydride is stable only under alkaline condition, Ni–P–B alloy deposits are generally prepared by the addition of hypophosphite in the borohydride-reduced electroless nickel bath. Since borohydride is a powerful reducing agent than hypophosphite and the plating bath is alkaline, the amount of phosphorous in

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the resultant alloy deposit becomes low. Similar is the case with alloy deposits, namely, Ni–Cu–P, Ni–W–P, etc. where the incorporation of copper, tungsten, etc. decreases the phosphorous content of the deposit [11–14]. Ultimately, the improvement in corrosion resistance is not fully realized. In recent years, multilayer coatings obtained from single and dual baths have received considerable attention. The present work aims to prepare Ni–P/Ni–B duplex coating using dual bath technique and to evaluate its hardness, wear resistance and corrosion resistance.

2. Experimental details

Mild steel was used as the substrate material for the preparation of electroless Ni–P/Ni–B duplex coatings. The bath composition and operating conditions used for preparing Ni–P and Ni–B coatings were given in Tables 1 and 2, respectively. The mild steel substrates were pickled in dilute hydrochloric acid, rinsed with deionized water and electrolytically cleaned using an alkaline solution containing sodium carbonate, sodium hydroxide and sodium dodecyl sulfate. The electrolytically cleaned substrates were subsequently given a nickel strike using Wood's nickel bath. The Ni–P, Ni–B coatings were prepared using their respective baths (Tables 1 and 2) whereas Ni–P/Ni–B duplex coatings having different thickness of Ni–P and Ni–B coatings, both as inner and outer layers were prepared using both the hypophosphite- and borohydride-reduced electroless nickel baths. The phosphorous and boron contents of the deposits were analyzed by atomic absorption spectrophotometer (GBC-Avanta). The nickel content was analyzed gravimetrically after precipitating nickel as Ni–DMG com-

plex. The plating rate was assessed by measuring the gain in weight after plating and using the density of the deposit. Using the plot of thickness of the deposit vs. time, Ni–P, Ni–B and Ni–P/Ni–B duplex coatings of varying thickness were prepared.

The structure of the Ni–P and Ni–B deposits, in as-plated and heat-treated (450 °C for 1 h) conditions was assessed by X-ray diffraction (XRD). Scanning electron microscope (SEM) was used to obtain the cross-sectional micrographs of Ni–P/Ni–B duplex layers. A Leitz microhardness tester with a Vickers indenter was used for determining the microhardness of the electroless Ni–P, Ni–B and Ni–P/Ni–B duplex coatings both in as-plated and heat-treated (450 °C for 1 h) conditions. All deposits used for microhardness measurement have a thickness of around 20 μm. A constant load of 100 g was applied to cause the indentations in all the deposits and the hardness values were averaged out of five such determinations.

The wear resistance of the coatings of the present study both in as-plated and heat-treated (450 °C for 1 h) conditions was evaluated using a pin-on-disc apparatus (DUCOM, India). In this method the pin and disc are arranged in such a way that the rotating disc served as the counterface material while the stationary pin served as the test specimen. Steel discs (composition conforming to EN 31 specification) of 10 cm diameter and 5 mm thickness were chosen as counterface materials to slide against the test specimens. These discs were fully hardened (R_c 63) and surface ground to a finish (R_a) of 0.02 μm. During the wear test, a constant load of 40 N was applied to the pin and the counter disc was rotated at a constant speed (0.5 m s⁻¹). The specific wear rate was calculated by the expression: $w_s = w/(lL)$, where w is the wear mass, L is the normal load and l is the sliding distance. In the present study, the sliding distance was calculated at the mean radius of the disc.

The corrosion resistance of Ni–P, Ni–B and Ni–P/Ni–B duplex coatings in 3.5% sodium chloride solution was assessed by polarization and electrochemical impedance studies performed using a potentiostat/galvanostat/frequency response analyzer (Gill AC) of ACM Instruments, UK. During these studies, the coated specimens were masked with lacquer so that only a 1 cm² area was exposed to the electrolyte solution. A saturated calomel electrode was used as the reference electrode whereas a platinum electrode served as the counter electrode. The corrosion potential (E_{corr}) and corrosion current density (i_{corr}) were determined using the Tafel extrapolation method. The charge transfer resistance (R_{ct}) and double layer capacitance (C_{dl}) were determined from the Nyquist plot by fitting the data as a semicircle using the built-in analysis software of ACM Instruments.

3. Results and discussion

The plating rate of the electroless Ni–P and Ni–B deposits is evaluated by measuring the gain in weight after

Table 1

Bath composition and operating conditions of hypophosphite-reduced electroless nickel bath

Bath composition	
Nickel sulfate hexahydrate	21 g l ⁻¹
Sodium hypophosphite monohydrate	24 g l ⁻¹
Lactic acid	28 g l ⁻¹
Propionic acid	2.2 g l ⁻¹
Operating conditions	
pH	4.5
Temperature	90 ± 1 °C

Table 2

Bath composition and operating conditions of borohydride-reduced electroless nickel bath

Bath composition	
Nickel chloride hexahydrate	30 g l ⁻¹
Ethylenediamine	90 g l ⁻¹
Sodium hydroxide	90 g l ⁻¹
Sodium borohydride	0.8 g l ⁻¹
Thallium acetate	14 mg l ⁻¹
Operating conditions	
pH	14.0
Temperature	95 ± 1 °C

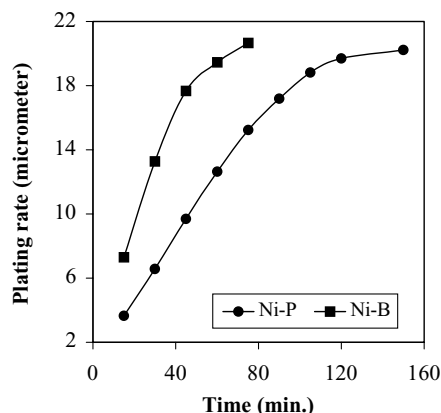
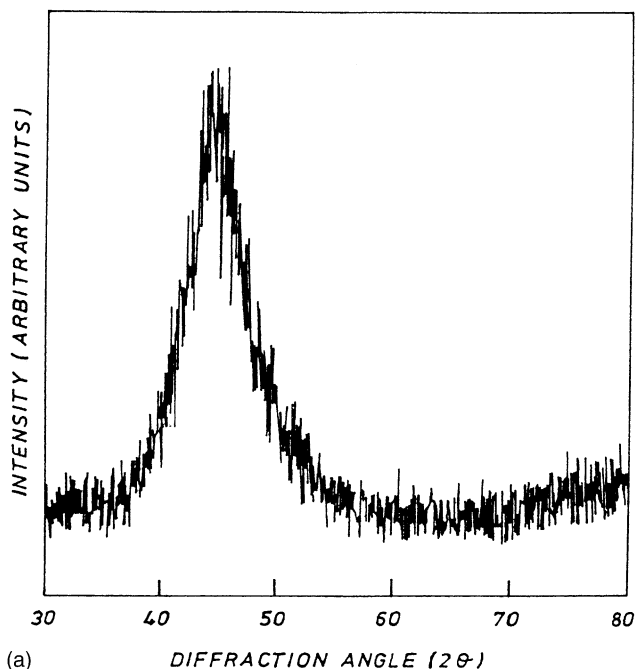


Fig. 1. Plating rate of electroless Ni-P and Ni-B deposits as a function of plating time.

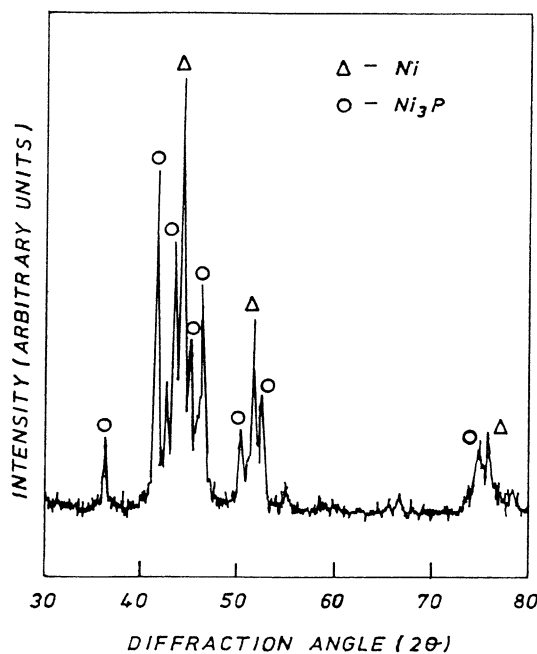
plating and using the density of the deposit. The thickness of the Ni-P and Ni-B deposits increases with increase in plating time. However, the extent of increase in thickness is not linear throughout the entire duration of plating and it saturates after some time. This is due to the accumulation of oxidation products of hypophosphite and borohydride in their respective baths. A plot of thickness of the deposit versus plating time is obtained (Fig. 1) to prepare Ni-P and Ni-B coatings having varying thickness so that they can be used for preparing Ni-P/Ni-B duplex coatings.

The chemical composition of the Ni-P and Ni-B deposits is given in Table 3. The Ni-P deposit contains 9 wt.% phosphorous and 91 wt.% nickel, whereas the Ni-B deposit, besides 6.5 wt.% boron and 93.2 wt.% nickel, contains 0.3 wt.% thallium. The incorporation of thallium in the Ni-B deposit is unavoidable since thallium acetate is used as the stabilizer and without the addition of thallium acetate it is not easy to prepare Ni-B deposits with higher film thickness.

The XRD patterns of Ni-P and Ni-B deposits, in as-plated and heat-treated (450 °C for 1 h) conditions are shown in Figs. 2 and 3, respectively. It is evident from Figs. 2 and 3 that both Ni-P and Ni-B deposits are amorphous in as-plated condition (Figs. 2(a) and 3(a)). Upon heat-treatment at 450 °C for 1 h, both Ni-P and Ni-B deposits crystallize and produce, nickel and nickel phosphide (Ni₃P) in Ni-P deposit (Fig. 2(b)), and, nickel and nickel borides (Ni₂B and Ni₃B) in Ni-B deposit (Fig. 3(b)). Obviously, one would expect that the duplex coating should possess Ni₃P and Ni₃B phases upon heat-treatment. The



(a)



(b)

Fig. 2. X-ray diffraction pattern of electroless Ni-P deposit in (a) as-plated and (b) heat-treated (450 °C for 1 h) conditions.

Table 3
Chemical composition of the Ni-P and Ni-B deposits

Type of deposit	Nickel content (wt.%)	Phosphorous content (wt.%)	Boron content (wt.%)	Thallium content (wt.%)
Ni-P	91.0	9.0	–	–
Ni-B	93.2	–	6.5	0.3

XRD pattern of Ni-P/Ni-B duplex coating heat-treated at 450 °C for 1 h confirms the presence of Ni, Ni₃P and Ni₃B phases (Fig. 4). Hence it is evident that in Ni-P/Ni-B or Ni-B/Ni-P duplex coatings it is possible to impart the qualities of both Ni-P and Ni-B coatings.

The scanning electron micrographs of the cross-section of electroless Ni-P/Ni-B and Ni-B/Ni-P duplex coatings in their as-plated conditions are shown in Figs. 5(a) and 6(a),

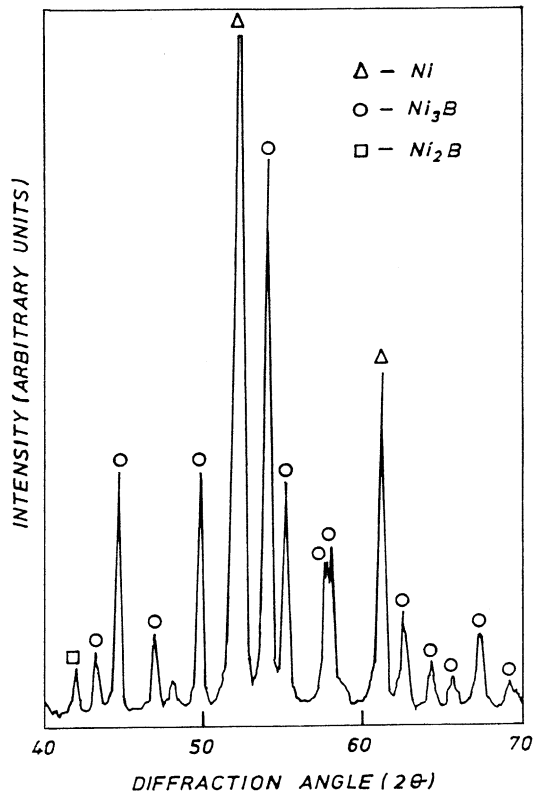
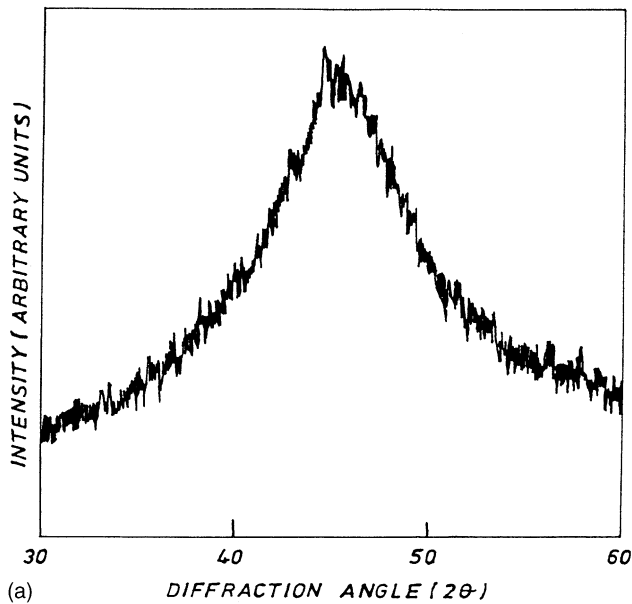


Fig. 3. X-ray diffraction pattern of electroless Ni-B deposit in (a) as-plated and (b) heat-treated (450 °C for 1 h) conditions.

respectively. It is evident from these figures that these duplex coatings are uniform and the compatibility between the Ni-P and Ni-B layers is good. The compatibility between these layers is found to be good even after heat-treatment at 450 °C for 1 h (Figs. 5(b) and 6(b)). However, some cracks are formed in heat-treated duplex coatings due to the brit-

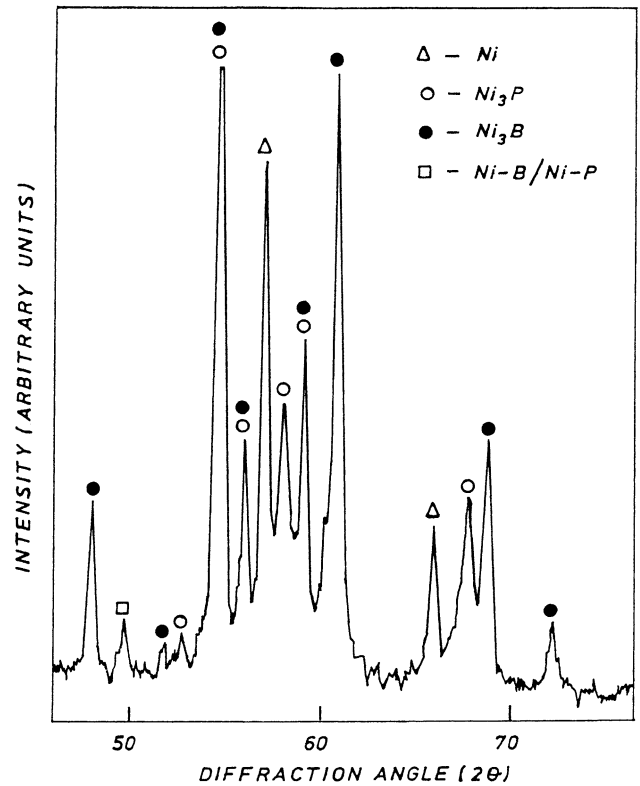


Fig. 4. X-ray diffraction pattern of Ni-P/Ni-B duplex coating heat-treated at 450 °C for 1 h.

tleness of electroless Ni-B coating (Fig. 5(b)).

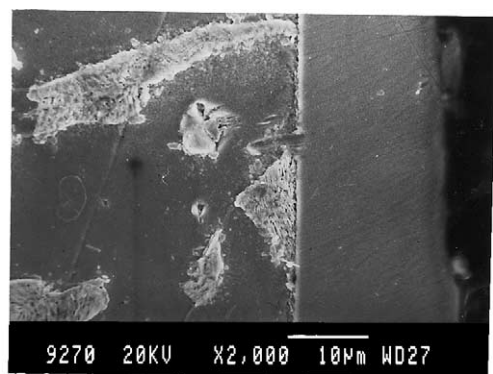
The microhardness of Ni-P, Ni-B and the duplex coatings, in as-plated and heat-treated (450 °C for 1 h) conditions, is given in Table 4. For all the coatings studied, the microhardness is higher for coatings subjected to heat-treatment (450 °C for 1 h) than those in as-plated condition. This is due to the formation of hard nickel phosphide phase (Ni₃P) in Ni-P coating, nickel boride phase (Ni₃B) in Ni-B coating and both nickel phosphide and nickel boride phases (Ni₃P and Ni₃B) in duplex coatings. The formation of such phases is confirmed by XRD measurements (Figs. 2(b), 3(b) and 4). The microhardness of duplex coatings is higher than that of Ni-P and Ni-B coatings of similar thickness, both

Table 4

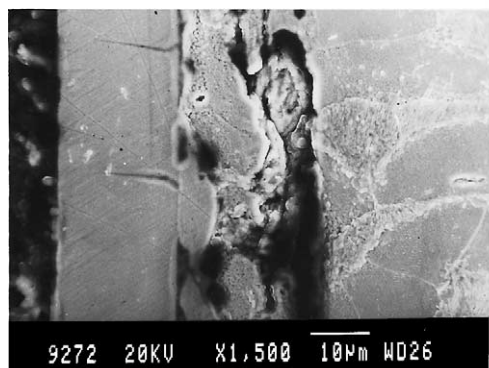
Microhardness of electroless Ni-P, Ni-B and duplex coatings in their as-plated and heat-treated conditions

Type of coating	Thickness (μm)	Treatment condition	Microhardness (HV ₁₀₀) ^a
Ni-P	20	As-plated	497 ± 22
Ni-B	20	As-plated	570 ± 18
Ni-B/Ni-P	10 + 10	As-plated	596 ± 24
Ni-P/Ni-B	10 + 10	As-plated	652 ± 27
Ni-P	20	Heat-treated 450 °C/1 h	770 ± 21
Ni-B	20	Heat-treated 450 °C/1 h	908 ± 19
Ni-B/Ni-P	10 + 10	Heat-treated 450 °C/1 h	945 ± 27
Ni-P/Ni-B	10 + 10	Heat-treated 450 °C/1 h	1062 ± 22

^a Average of five determinations.



(a)

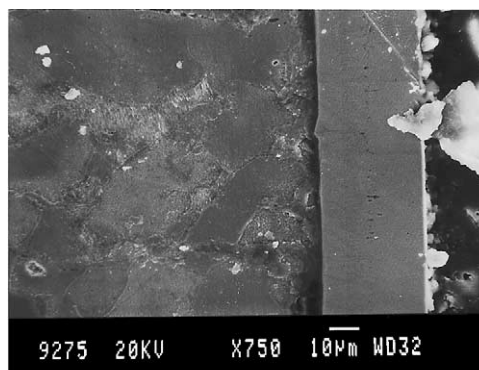


(b)

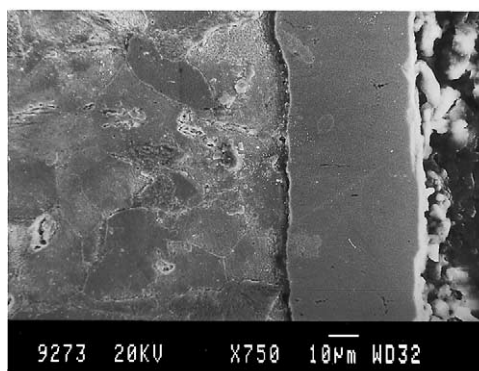
Fig. 5. Scanning electron micrographs of the cross-section of electroless Ni-P/Ni-B duplex coatings (a) as-plated and (b) heat-treated at 450 °C for 1 h.

in as-plated and heat-treated (450 °C for 1 h) conditions. Between the two types of duplex coatings, the coating having Ni-B outer layer exhibits a higher hardness. The difference in microhardness between these duplex coatings will have a definite impact on the wear resistance of these coatings.

The specific wear rate of electroless Ni-P, Ni-B and the duplex coatings, of similar thickness, at an applied load of 40 N, in as-plated and heat-treated (450 °C for 1 h) conditions, is given in Table 5. A comparison of the specific wear rate of all the coatings studied reveals that coatings that are heat-treated offer better wear resistance than the as-plated ones. The formation of hard Ni₃P and Ni₃B phases following heat-treatment, presents a virtually incompatible surface for the counterface material as there exists very little solubility between iron and these hard phases, leading to a decrease in specific wear rate. Besides, following heat-treatment, there is a considerable increase in the hardness of the coatings. Hence when the counterface material comes in contact with the matrix, because of the high hardness, the matrix experiences lesser wear. The specific wear rate of duplex coatings is lesser than that of Ni-P and Ni-B coatings of similar thickness, both in as-plated and heat-treated (450 °C for 1 h) conditions. Between the two types of duplex coatings, the coating having Ni-B outer layer exhibits a lower specific wear rate. This could be attributed to the higher hardness



(a)



(b)

Fig. 6. Scanning electron micrographs of the cross-section of electroless Ni-B/Ni-P duplex coatings (a) as-plated and (b) heat-treated at 450 °C for 1 h.

of Ni-B coating, which facilitates the coating to experience lesser wear.

The mechanism of wear of electroless Ni-P, Ni-B and the duplex coatings depends on the attractive force that operates between the atoms of nickel from the coating and iron from the counter disk (hardened steel of EN 31 specification). Adhesive wear is most likely to occur under the experimental

Table 5
Specific wear rate of electroless Ni-P, Ni-B and duplex coatings in their as-plated and heat-treated conditions at an applied load of 40 N

Type of coating	Thickness (µm)	Treatment condition	Specific wear rate (kg N ⁻¹ m ⁻¹ × 10 ⁻¹⁰) ^a
Ni-P	20	As-plated	4.60
Ni-B	20	As-plated	2.45
Ni-B/Ni-P	10 + 10	As-plated	1.93
Ni-P/Ni-B	10 + 10	As-plated	1.74
Ni-P	20	Heat-treated 450°C/1 h	1.62
Ni-B	20	Heat-treated 450°C/1 h	0.88
Ni-B/Ni-P	10 + 10	Heat-treated 450°C/1 h	0.58
Ni-P/Ni-B	10 + 10	Heat-treated 450°C/1 h	0.44

^a Average of two determinations.

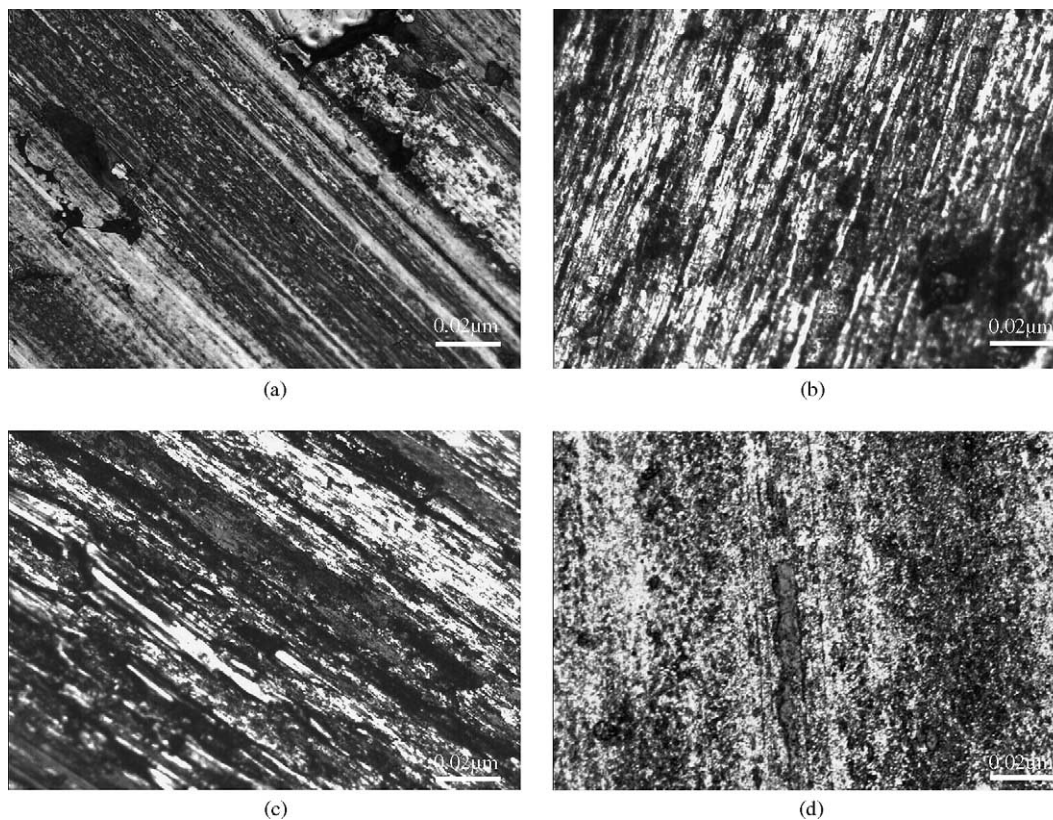


Fig. 7. Optical micrograph of the wear track pattern of coatings of the present study in their as-deposited condition (a) Ni-P coating; (b) Ni-B coating; (c) Ni-P/Ni-B coating; and (d) Ni-B/Ni-P coating.

conditions used, which induce a substantial attractive force between these mating surfaces, leading to a high mutual solubility of nickel and iron. The optical micrographs of electroless Ni-P, Ni-B and the two types of duplex coatings subjected to pin-on-disc wear test clearly indicate the presence of torn patches and, in some places even detachment of the coating, in their as-plated condition (Fig. 7(a)–(d)). This type of morphological feature, commonly called as “prows” is reported for adhesive wear failure of electroless Ni-P coatings, by several researchers [15–19]. Hence adhesive wear appears to be the most likely mechanism during the wear process of electroless Ni-P, Ni-B and the duplex coatings in their as-plated condition. Though the wear mechanism is the same, the adverse effects due to wear is observed to be less in the case of duplex coatings (Figs. 7(c) and (d)). Between the two types of duplex coatings, coating that has Ni-B as the outer layer exhibits lesser wear due to the higher microhardness of the Ni-B coating (Fig. 7(d)). In contrast to the as-deposited coatings, heat-treated coatings, after wear exhibit a bright and smooth finish with fine grooves along the sliding direction (Fig. 8(a)–(d)). Though this trend is common for electroless Ni-P, Ni-B and the duplex coatings, the extent of adhesive wear is less pronounced in the case of duplex coatings (Fig. 8(c) and (d)).

The electrochemical parameters derived from potentiodynamic polarization and electrochemical impedance studies,

such as, corrosion potential (E_{corr}), corrosion current density (i_{corr}), charge transfer resistance (R_{ct}) and double layer capacitance (C_{dl}), for all the coatings systems studied, both in as-plated and heat-treated conditions, are presented in Table 6. There observed to be a significant decrease in corrosion current density and increase in charge transfer resistance for electroless Ni-P/Ni-B and Ni-B/Ni-P duplex coatings, compared to those obtained for electroless Ni-P and Ni-B coatings. The loss in protective ability of the coatings upon heat-treatment at 450 °C for 1 h is clearly evident from the low values of charge transfer resistance, higher corrosion current densities and the cathodic shift in the corrosion potential.

The polarization curve obtained for electroless Ni-P/Ni-B duplex coating that is heat-treated at 450 °C for 1 h and, the Nyquist plot obtained for electroless Ni-B/Ni-P duplex coating in as-plated condition, at its open circuit potential, are given in Figs. 9 and 10, respectively. The Nyquist plots obtained for electroless Ni-P, Ni-B and, Ni-P/Ni-B and Ni-B/Ni-P duplex coatings, both in as-plated and heat-treated conditions, at their respective open circuit potentials, in 3.5% sodium chloride solution, exhibit a single semicircle in the high frequency region. However, these curves differ considerably in their size. This indicates that the same fundamental process is occurring on all these coatings but over a different effective area in each case. To

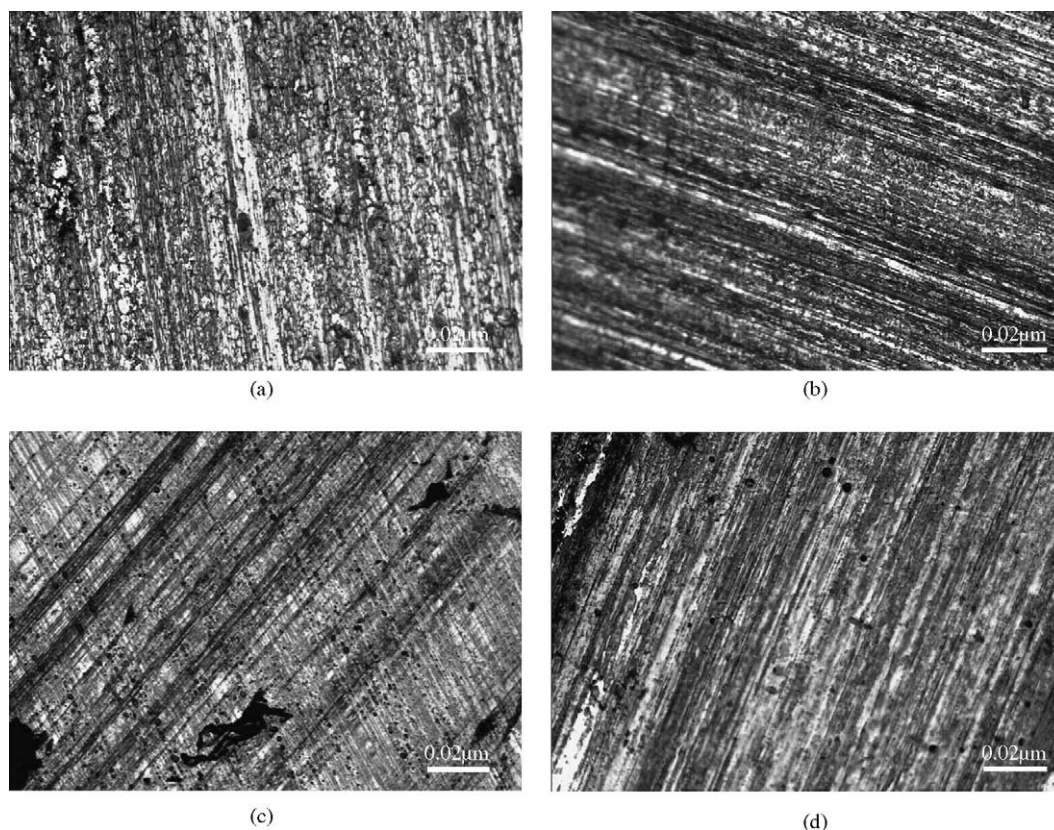


Fig. 8. Optical micrograph of the wear track pattern of coatings of the present study in their heat-treated condition (a) Ni-P coating; (b) Ni-B coating; (c) Ni-P/Ni-B coating; and (d) Ni-B/Ni-P coating.

account for the corrosion behavior of these coatings, at their respective open circuit potentials, an equivalent electrical circuit model consists of solution resistance, double layer capacitance and charge transfer resistance, in which the C_{dl} and R_{ct} are parallel to each other, is proposed. Lo et al. [20] and Balaraju et al. [8] have also used a similar model to study the electrochemical impedance behavior of electroless Ni-P coatings in 1 M NaOH at -1.2 V and in 3.5% NaCl solution at -0.32 V, respectively. The occurrence of a single semicircle in the Nyquist plots indicates that the corrosion process of electroless Ni-P, Ni-B and, Ni-P/Ni-B and Ni-B/Ni-P duplex coatings involves a single time constant.

The appearance of a single inflection point in the plot of $\log f$ versus $\log Z$ and a single phase angle maximum in the plot of $\log f$ versus phase angle (figure not shown), further confirm that the process involves only a single time constant. Hence it is evident that the coating-solution interface of electroless Ni-P, Ni-B and, Ni-P/Ni-B and Ni-B/Ni-P deposits exhibit charge transfer behavior.

In general, the corrosion resistance of borohydride-reduced electroless nickel coatings is less than that of electroless nickel coatings reduced with sodium hypophosphite. The results obtained in the present study also confirm this fact (Table 6). The difference in corrosion resistance between

Table 6

Corrosion resistance of electroless Ni-P, Ni-B, Ni-P/Ni-B and Ni-B/Ni-P duplex coatings in as-plated and heat-treated conditions in 3.5% sodium chloride solution evaluated by potentiodynamic polarization and electrochemical impedance studies

System studied	Thickness (μm)	E_{corr} (mV vs. SCE)	i_{corr} ($\mu\text{A cm}^{-2}$)	R_{ct} (Ωcm^2)	C_{dl} (F) ($\times 10^{-4}$)
Ni-P as-plated	20	-354	3.62	7960	1.85
Ni-P heat-treated	20	-492	6.89	6498	2.36
Ni-B as-plated	20	-508	9.15	3844	3.53
Ni-B heat-treated	20	-519	14.60	1232	4.22
Ni-P/Ni-B as-plated	10 + 10	-386	3.86	7638	1.89
Ni-P/Ni-B heat-treated	10 + 10	-432	4.93	5339	2.44
Ni-B/Ni-P as-plated	10 + 10	-311	2.46	10130	1.61
Ni-B/Ni-P heat-treated	10 + 10	-356	3.24	7024	1.96

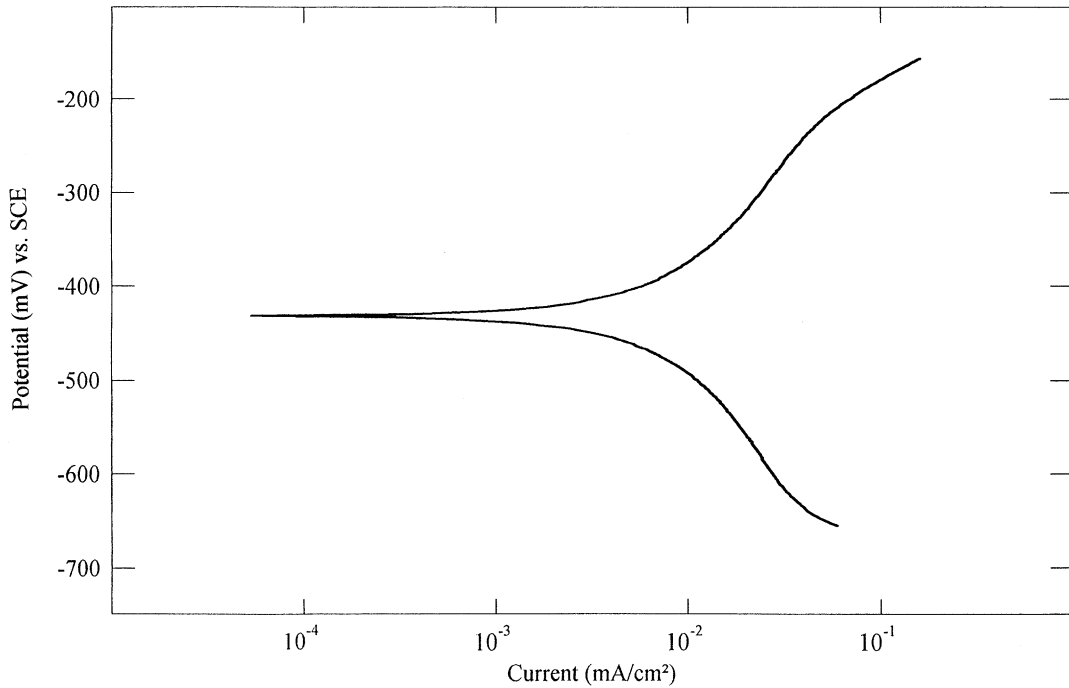


Fig. 9. Polarization curve obtained for electroless Ni-P/Ni-B duplex coating heat-treated at 450 °C for 1 h, in 3.5% sodium chloride solution.

Ni-P and Ni-B coatings is due to the difference in their structure. Since borohydride-reduced electroless nickel deposit is not totally amorphous, the passivation films that form on its surface are not as glassy or protective as those that form on high-phosphorous coatings. The phase boundaries present in these deposits also produce passivation

film discontinuities, which are preferred sites for corrosion attack to begin. Also, boron and thallium are not homogeneously distributed throughout the coating, areas of different corrosion potential are produced on the surface, leading to the formation of minute active/passive corrosion cells and accelerated attack. Hence in duplex coating systems, when

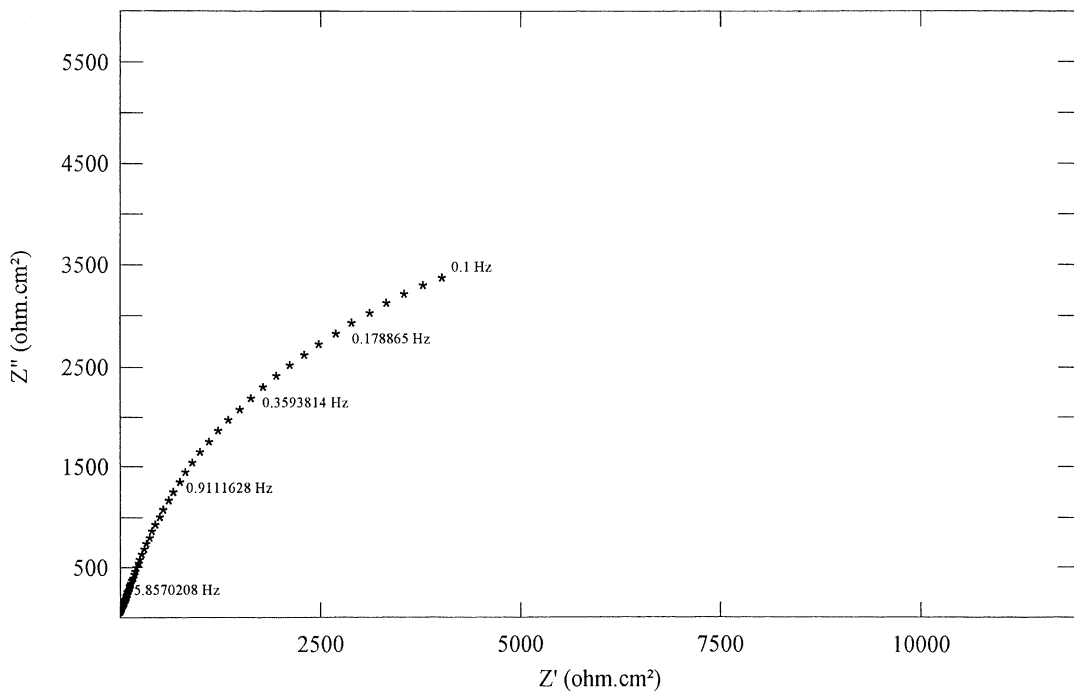


Fig. 10. Nyquist plot obtained for electroless Ni-B/Ni-P duplex coating in as-plated condition, in 3.5% sodium chloride solution.

Ni–B coating is used as the outer layer, the corrosion resistance is decreased (Table 6). On the other hand, when Ni–P coating is used as the outer layer, the ability of the Ni–P coating to impart passivity helps to increase the corrosion resistance significantly (Table 6).

4. Conclusions

The study reveals that electroless Ni–P/Ni–B duplex coatings could be prepared using dual baths (acidic hypophosphite- and alkaline borohydride-reduced electroless nickel baths). The Ni–P and Ni–B coatings are amorphous in their as-plated condition. Upon heat-treatment at 450 °C for 1 h, both Ni–P and Ni–B coatings crystallize and produce nickel, nickel phosphide and nickel borides in the respective coatings. All the three phases are formed when Ni–P/Ni–B and Ni–B/Ni–P duplex coatings are heat-treated at 450 °C for 1 h. SEM of the cross-sectional view of the electroless nickel duplex coatings reveals that the coatings are uniform and the compatibility between the layers are good. The microhardness of electroless nickel duplex coatings is higher than Ni–P and Ni–B coatings and between the two types of duplex coatings the coating that has Ni–B as the outer layer exhibit a higher microhardness, both in as-plated and heat-treated conditions. The specific wear rate is less for duplex coatings compared to Ni–P and Ni–B coatings of similar thickness, both in as-plated and heat-treated conditions. Among the coatings studied, the specific wear rate is less for electroless nickel duplex coatings that has Ni–B coating as the outer layer. The wear process of duplex coatings is governed by adhesive wear mechanism, which is confirmed by the presence of torn patches and detachment of coatings. The two types of electroless nickel duplex coatings offer better corrosion resistance than electroless Ni–P and Ni–B coatings of similar thickness. The corrosion resistance of the coatings studied is decreased when they are heat-treated at 450 °C for 1 h. Hence it can be concluded that electroless nickel duplex coatings will be a useful replacement for Ni–B and Ni–P coating, as they could provide the desirable qualities of both types of coatings. If higher hardness and wear resistance are desired, then the duplex coating having Ni–B as the outer layer will be the ideal choice whereas the duplex coating having

Ni–P as the outer layer is the preferred option where higher corrosion resistance is sought.

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