Materials Research Express

PAPER

Surface roughness, wear and thermal conductivity of ternary electroless Ni–Ag–P coating on copper substrate

Nur Ariffah M S¹, Nurulakmal M S¹,² @, Anasyida A S⁰ and Shiu E K³

¹ School of Materials and Mineral Resources Engineering, Universiti Sains Malaysia, 14300 Nibong Tebal, Pulau Pinang, Malaysia
² Intel Product (M) Sdn. Bhd, Kulim Kedah, Malaysia
³ Author to whom any correspondence should be addressed.

E-mail: ariffah.sani@gmail.com, srmurul@usm.my, anasyida@usm.my and eng.keong.shiu@intel.com

Abstract

Thermal testing tool used in electronic industries requires a high thermal conductivity and wear resistant coating to ensure efficient thermal transfer over some period of testing cycles. A study on ternary nickel–silver–phosphorus (Ni–Ag–P) coating was carried out by adding silver sulphate into electroless nickel–phosphorus (Ni–P) bath solution with a target to improve thermal conductivity. The results showed that silver can be co-deposited into Ni–P coating but in limited concentration without causing bath decomposition. Cetyltrimethyl ammonium bromide (CTAB) were added into the bath solution as surfactant to improve the coating surface morphology and roughness. Characterization of coatings were done using atomic force microscope (AFM), scanning electron microscope (SEM), energy dispersive x-ray (EDX), optical microscope, Knoop microhardness tester, pin–on–disc wear tester and hot disk thermal analyser. When the concentration of silver sulphate added was low, coating produced have smoother surface with improved thickness, hardness and wear resistance. Higher concentration of silver sulphate led to bath decomposition thus coatings have rougher surface with reduced thickness, hardness and wear resistance. Thermal conductivity test showed increment in the thermal conductivity value of Ni–P coating from 445.7 W m⁻¹ K to 466.9 W m⁻¹ K with addition of 10 mg l⁻¹ silver sulphate. It is found that co-deposition of silver at low concentration can improve the hardness, wear resistance and thermal conductivity, and as comparable thickness value is possible, ternary Ni–Ag–P showed interesting potential to replace current NiP coating used in thermal testing tool.

1. Introduction

Development of ternary electroless Ni–P coating is considered as the most effective method to alter the chemical and physical properties of binary Ni–P alloy coating (Balaraju et al 2010). Certain metals that cannot themselves be deposited by the autocatalytic mechanism can be induced to co-deposit with an electroless depositing metal such as nickel (Sahoo and Das 2011). Co-deposition of metallic elements like tungsten, cobalt, molybdenum, rhenium, copper, zinc, and tin can further enhance the properties of Ni–P coating. By combining the metallic element advantageous properties with the existing Ni–P coating properties, the newly developed ternary coating possess their own chemical and physical properties which differ from those of the parent alloy, Ni–P. The choice of metallic elements to be co-deposited depends on the property that is desired.

Previous studies on ternary nickel-tungsten-phosphorus (Ni–W–P) (Balaraju et al 2006, Kundu et al 2019) have indicated that the characteristics of electroless Ni–W–P coating such as hardness, wear resistance and thermal stability are superior to properties of binary Ni–P. The incorporation of cobalt in Ni–P matrix has been reported to enhance corrosion resistance of the basis metal (Seifzadeh and Hollagh 2014). Although the corrosion resistance of Ni–P coating are found to be better in nickel-molybdenum-phosphorus (Ni–Mo–P) coating (Balaraju et al 2006, Lu and Zangari 2002), it is also noteworthy that coating with 11wt% molybdenum...
was non-ferromagnetic even with only 2 wt% of phosphorus within it. Addition of potassium perhenate to Ni–P bath produced ternary nickel-rhenium-phosphorus (Ni–Re–P) coating with double melting point compared to Ni–P coating (Balaraju et al 2006). Co-deposition of copper into binary electroless nickel had positive effect on coating characteristic such as smoothness, brightness, corrosion resistance and hardness (Georgieva and Armanyov 2007) while ternary nickel-zinc-phosphorus (Ni–Zn–P) coating offers sacrificial protection to steel substrate and therefore has been considered as possible replacement for cadmium coating (Veeraraghavan et al 2004, Constantin 2014). On the other hand, ternary nickel-tin-phosphorus (Ni–Sn–P) alloy with low-Sn content possessed a high corrosion resistance and the thermal stability was improved in comparison with Ni–P alloys having the same phosphorus content (Georgieva and Armanyov 2007, Popoola et al 2016).

Due to the high electrical and thermal conductivity of silver, the introduction of silver into Ni–P is expected to improve electrical and thermal conductivity of the coating making it attractive for electrical or thermal testing tool. However, to the best of our knowledge, very limited studies have been reported on the ternary electroless Ni–Ag–P coating. The work of Ma et al (2009) and Alirezaei et al (2013) reported on nano-composite Ni–P/Ag where nano-particles of Ag was added into electroless Ni–P coating to improve coating properties, focusing on contribution of Ag as lubricant metallic particles. In this study, we are able to co-deposit Ag into Ni–P coating whereby the Ag is added as an alloying element forming into ternary Ni–Ag–P coating on a copper substrate. The primary objective is to produce ternary Ni–Ag–P with sufficient thickness and hardness, relatively low surface roughness and at the same time, aim to improve on the thermal conductivity of the coating to be used as thermal testing tool. For this application, surface roughness is significant as lower surface roughness provide better contact, which would increase thermal transfer efficiency.

Thus, special attention was given to minimize surface roughness as it is also important for coating to possess lower roughness value to ensure better surface contact in electrical application (Pennece et al 2012)). Surfactant was added into Ni–Ag–P bath to improve the surface roughness. Hamid (2003) observed that the addition of surfactants to the electrolyte had a beneficial effect on the composition and microstructure of the coatings, leading to finer grain and more compact coatings compared to coating without the addition of surfactant. Surfactant acts as wetting agent which help reduce the surface tension of a liquid, allowing easier spreading and thus lower the interfacial tension between liquid and solid surface (Sahoo & Das 2011, Czagány & Baumli 2019). Previous research by Elansezhian et al (2009) showed positive result in morphology and roughness of Ni–P coating when CTAB as surfactant was added into Ni–P bath solution.

The aim of this current work is to develop ternary Ni–Ag–P coating from binary Ni–P plating bath. In this study, CTAB was added to improve the surface roughness of ternary Ni–Ag–P. The ternary Ni–Ag–P coating was characterized in terms of the surface roughness, morphology, elemental composition, thickness, hardness, wear resistance and thermal conductivity. Results were compared with that of the Ni–P coating and the effect of adding Ag was discussed.

2. Materials and methods

2.1. Substrate preparation

Copper sheet specimens (35 mm × 60 mm × 0.5 mm) were used as substrate for binary Ni–P and ternary Ni–Ag–P alloy deposition. The samples were ground with 600, 1000, and 2000 grit of silicon carbide (SiC) abrasive paper followed by polishing using alumina powders; 1.0, 0.3, and 0.05 μm to ensure complete removal of oxides and contaminants. Prior to coating, the specimens were first cleaned with alkaline solution to ensure sample surface are free from grease or polishing powder then followed by rinsing with distilled water. After that the degreased samples were dipped in acid etching containing 15% H2SO4 for 1 min Acid etching was used to remove undesirable contaminants but also to enhance coating adhesion. After rinsing with distilled water, the sheets were then dipped in palladium chloride activation solution (0.1 g l−1 palladium chloride and 0.1 ml l−1 hydrochloric acid, room temperature) for 1 min to initiate and prepare nucleation sites for electroless deposition. The copper sheets were rinsed 3 times prior to coating to ensure Ni–P solution is not contaminated with palladium.

2.2. Bath Composition

The composition of Ni–P and Ni–Ag–P bath solutions with and without CTAB are given in table 1. Binary Ni–P coating was also prepared using similar bath composition for comparison with ternary Ni–Ag–P coatings. The bath composition was developed based on the deposition bath used by Huang and Cui (2007). Silver sulphate (Ag2SO4) was used as the source of Ag in Ni–Ag–P coating solution. Ternary Ni–Ag–P coatings were prepared by varying silver sulphate concentration (5, 10, 20, 30 & 40 mg l−1) added into Ni–P plating bath. It was found that when the bath contains more than 30 mg l−1 of silver sulphate, the coating solution turned cloudy after 1 hr of coating process but the coating process was continued until 2 hr deposition time for solution containing 30 and 40 mg l−1 silver sulphate. The coating produced from bath solution with 40 mg l−1 silver sulphate had black
The average roughness value of Ni–Ag–P coating was measured by performing a simulation of wear using DUCOM TR-20 pin-on-disc test machine. The sample was attached on a pin which was held stationary against a rotating disc. The test was conducted at a load of 30 N with 0.5 m s\(^{-1}\) speed and sliding distance of 1000 m. The coefficient of friction (COF) was measured automatically by the wear test machine while the coating specific wear rate was calculated by the expression:

\[
\text{Specific wear rate, } kg/N.m = \frac{W}{DL}
\]

where 'W' is the loss of sample weight, 'D' is the sliding distance and 'L' is the load applied.

3. Results and discussion

3.1. Surface roughness

The average roughness value of Ni–Ag–P coating was measured using AFM (atomic force microscopy) and compared with those of binary Ni–P coating. The AFM results were used to evaluate the surface roughness, microstructure, and composition of the coatings. The surface roughness was characterized using SEM (scanning electron microscopy) equipped with energy dispersive x-ray (EDX) analysis. The thickness and hardness of the coatings were determined using LECO microhardness test machine. The average hardness values were calculated from five different locations on each sample.

CTAB was added as surfactant, at 0.6 g l\(^{-1}\) following a research done by Elansezhian et al. (2009). The pH of all plating solutions were adjusted and maintained at pH5 using ammonium hydroxide (Yuan et al. 2017). The bath was heated and maintained at a temperature of 88 ± 2 °C. Once the solution was ready, the palladium activated samples were immersed in the electroless plating solution for 2 h at loading 1.5 dm\(^2\) l\(^{-1}\). By using magnetic stirrer, the bath was continuously stirred during deposition at speed 300 rpm. After the deposition, the plated samples were cleaned with distilled water and dried.

2.3. Coating characterization

After deposition, samples were cut to smaller pieces for characterization of coatings. Atomic force microscopy (AFM) was employed to evaluate the surface roughness. The results presented here is an average for 5 different locations on each samples, in 10 \(\mu\)m \(\times\) 10 \(\mu\)m area for each locations. The surface morphology and elemental composition of the coating was analysed using scanning electron microscope (SEM) equipped with energy dispersive x-ray (EDX) analysis. In order to measure thickness and hardness of the coating, cross section of samples were carefully mounted. Polished cross section of samples were observed using optical microscope to measure thickness and LECO microhardness test machine was used to determine hardness. The Knoop microhardness indentation load was 100 g with 20 s dwell time. All hardness values were an average of five readings.

The friction and wear resistance of Ni–Ag–P coating was measured by performing a simulation of wear using DUCOM TR-20 pin-on-disc test machine. The sample was attached on a pin which was held stationary against a rotating disc. The test was conducted at a load of 30 N with 0.5 m s\(^{-1}\) speed and sliding distance of 1000 m. The coefficient of friction (COF) was measured automatically by the wear test machine while the coating specific wear rate was calculated by the expression:

\[
\text{Specific wear rate, } kg/N.m = \frac{W}{DL}
\]

where 'W' is the loss of sample weight, 'D' is the sliding distance and 'L' is the load applied.

Thermal conductivity is determined by measuring the average transient temperature increase of the sensor when sample was supplied with a constant electrical current for a short of time. The hot disk thermal constant analyser TPS 2500 was used to measure the thermal conductivity of coating. For this test, two pieces of each sample was prepared by coating copper rod having 5 cm diameter and 2 cm thickness. The sensor was sandwiched between the samples as in figure 1. The power and time setting used are 4.4 W and 3 s respectively.

Table 1. Composition of electroless binary and ternary Ni–Ag–P bath without and with surfactant.

| Chemical               | Ni–P Without surfactant | Ni–P With surfactant | Ni–Ag–P Without surfactant | Ni–Ag–P With surfactant |
|------------------------|-------------------------|----------------------|----------------------------|-------------------------|
| Nickel sulphate        | 30                      | 30                   | 30                         | 30                      |
| Sodium hypophosphite   | 25                      | 25                   | 25                         | 25                      |
| Sodium acetate         | 20                      | 20                   | 20                         | 20                      |
| Glycine                | 20                      | 20                   | 20                         | 20                      |
| Lead nitrate           | 0.002                   | 0.002                | 0.002                      | 0.002                   |
| Silver sulphate        | —                       | —                    | 5, 10, 20, 30 & 40 mg l\(^{-1}\) | 5, 10, 20, 30 & 40 mg l\(^{-1}\) |
| CTAB                   | —                       | 0.6                  | —                          | 0.6                     |

suspended solid embedded on its surface. It is believed that the presence of this colloidal solid nuclei would lead to bath decomposition (Elansezhan et al. 2008). And addition beyond 40 mg l\(^{-1}\) of silver sulphate in solution bath led to self-accelerating chain reaction where bath stability decreased and the solution spontaneously decomposed. Similar observation was reported by Balaraju et al. (2006) in their work on Ni-W-P coating. Thus, the addition of silver sulphate as the source for Ag is limited to 40 mg l\(^{-1}\).
Surfactant CTAB has also been widely used in composite coating research to improve particles dispersion (Rudnik et al 2010, Kilic et al 2013). Without CTAB, the average roughness in Ni–P is 36.61 nm and slightly decreased when 5 mg l$^{-1}$ of silver sulphate was added. Addition of more silver sulphate led to higher roughness value and at 20 mg l$^{-1}$ the roughness exceeded the roughness of Ni–P coating. It can also be seen from the graph that addition of CTAB improved the average roughness of Ni–Ag–P coating. Ni–P coating with CTAB has 11.64 nm average roughness and the value slightly increased but remain constantly low up to 20 mg l$^{-1}$ silver sulphate. At 30 mg l$^{-1}$ concentration, Ni–Ag–P coating with CTAB has 37.05 nm average roughness. This is just slightly higher than the Ni–Ag coating without CTAB.

During electroless deposition, nickel particles were produced from reduction of nickel salt at the electrolyte/substrate interface. At the same time during the electroless process, hydrogen gas was also generated as side reaction. Because of turbulence during generation of hydrogen gas, the nickel particles tend to float and attach themselves to the hydrogen gas. The hydrogen gas together with the attached nickel will rise to the bath surface and the hydrogen gas will escape leaving the attached particles to sink or scattered due to turbulence in the solution bath. The nickel eventually will either attach to sample surface or at other available surfaces. In the presence of critical amount of CTAB surfactant, the surface tension value is sufficient to counteract the buoyancy and the effect of turbulence. Hence the nickel particles will not leave the substrate and the flotation of these colloidal particles with the hydrogen bubbles is prevented (Elansezhian et al 2008). Also, surfactant molecules help facilitate the removal of hydrogen bubble form substrate surface (Guo et al 2008). As a consequence, the surface roughness is reduced with addition of surfactant.

In Ni–Ag–P coating, silver with atomic radius 165 pm is larger compared to nickel ($r = 149$ pm) and phosphorus ($r = 98$ pm). The addition of larger size atomic element to Ni–P matrix could potentially induce better geometrical filling of the space (Lu & Zangari 2002). So with a small space gap between atoms, the coating produced is compact and have smoother surface. This is the reason of decreasing average roughness value of coating when silver is co-deposited into Ni–P coating. In both solutions, without and with surfactant, low average surface roughness was found in bath with lower silver sulphate concentration but increased when silver sulphate concentration was increased. As discussed earlier, the increment of metal ion concentration in bath may lead to spontaneous decomposition of the
Ni–Ag–P solution. Based on the result of surface roughness, the solution without CTAB might have started to show sign of decomposition at concentration of silver sulphate more than 5 mg l$^{-1}$. Even though the solution has not completely decomposed, the formation of fine black particles throughout the solution as the bath decompose may lead to higher surface roughness as the particles attached themselves to the coating (Agarwal et al 2014). Foreign particles can be seen attached on the coating surface as shown in SEM image in figure 3(a). Addition of CTAB help stabilized the solution by reducing the rate of particles build-up and thus solution containing CTAB only started to decompose at higher silver sulphate concentration (more than 20 mg l$^{-1}$).

3.2. Morphology, thickness and hardness
The morphological feature of ternary Ni–Ag–P coatings was analysed by SEM. SEM photographs of the coating without and with addition of CTAB are shown in figure 3. At 30 mg l$^{-1}$ concentration of silver sulphate, both coatings have similar round nodular structure observed on the surface. Without CTAB, ternary Ni–Ag–P coating features rougher and more nodular structure compared to coating with CTAB, with a few solid particles embedded on the surface (figure 3(a)). Addition of surfactant CTAB produced comparatively a smoother coating surface (figure 3(b)). The observed morphology of coating supported the results of surface roughness.

Ternary Ni–Ag–P coating was prepared using different silver sulphate concentrations. It is expected that silver content in coating will increase as the concentration of silver sulphate increases from zero to 40 mg l$^{-1}$. Figure 4 presents the elemental composition of ternary Ni–Ag–P coating measured using EDX. An increase in
silver sulphate concentration in the solution increased the silver (Ag) content of Ni–Ag–P coatings from zero to 3.49 wt%. As silver content increased, nickel (Ni) and phosphorus (P) content decreased. The Ni/P ratio increased slightly from 7.5, 7.9, 8.1, 8.3 and 9.1 to 1 as the silver sulphate concentration is increased. A possible reason for this is that silver suppressed the cathodic reaction of hypophosphite ion in coating solution and thus, certain amount of hypophosphite ions which is able to produce elemental phosphorus is spent for silver reduction (Balaraju et al 2006). Previous ternary research have reported similar reduction of phosphorus as a third metallic element is added into electroless nickel solution (Seifzadeh & Hollagh 2013, Hamid 2003).

The reduction mechanism of metal ions by hypophosphite involves two reactions, i.e., hypophosphite ions are catalytically oxidized and nickel ions are reduced at the catalytic surface (Sudagar et al 2013). The anodic reaction of hypophosphite ions then released hydrogen which is absorbed onto the catalytic surface. The nickel ion at the surface of the catalyst is then reduced by the absorbed active hydrogen and this is the cathodic reaction. With the addition of Ag₂SO₄, Ag is simultaneously reduced along with nickel and co-deposited at the substrate surface. Although Ag has more positive potential value (+0.80) compared to nickel (−0.25) according to standard emf series, the priority of reduction is on the relative activity of nickel and Ag elements. The concentration of added Ag₂SO₄ is much lower (maximum of 40 mg l⁻¹) compared to nickel sulphate at 30 g l⁻¹. Thus, reduction of nickel would be the priority compared to reduction of Ag. Co-deposition of Ag however, seems to be limited at lower concentration of Ag₂SO₄. As explained earlier, higher addition of Ag₂SO₄ resulted in loss of bath stability and spontaneous decomposition of solution. This could be influenced by the relatively large potential difference between Ag and nickel.

The thickness of ternary Ni–Ag–P at different silver sulphate concentration is shown in table 2. Addition of low silver sulphate concentration slightly increased the coating thickness but the coating thickness reduced with addition of more than 5 mg l⁻¹ silver sulphate. At low silver sulphate concentration, slight increment of coating thickness is observed due to co-deposition of large atom silver into the Ni–P coating. At higher silver sulphate concentration, spontaneous decomposition of solution bath occurred and causing nickel and phosphorus that are needed to form coating layer precipitated in the solution. This led to the reduction of nickel ion concentration in the bath and hence, the Ni–Ag–P solution with signs of decomposition resulted in lower thickness coating.

The hardness of coatings were measured using Knoop Microhardness and all indentations were done at the cross-section of Ni–Ag–P coating to ensure hardness value is not influenced by the hardness of substrate. The results in table 2 show that addition of silver sulphate at low concentration improved the coating hardness but addition of more than 10 mg l⁻¹ silver sulphate reduced the coating hardness. The hardness however, were still higher than that of for Ni–P coating. This shows that co-deposition of silver into Ni–P coating produced a ternary coating with improved coating hardness. Silver by itself is a low hardness element. However, co-deposition of larger atomic size Ag into Ni–P coating resulted in significant lattice strain within the Ni structure and hardening occurs at low silver sulphate concentration. For higher concentration of silver sulphate in the solution, the amount of large silver atoms in Ni–P matrix have increased and this may have reduced the effectiveness of large solute atoms in blocking dislocation movements. This is shown in decreasing hardness of coating as the silver sulphate concentration is added beyond 10 mg l⁻¹.

### Table 2. Thickness and hardness value of ternary Ni–Ag–P coating at different silver sulphate concentrations.

| Characterization | 0     | 5     | 10    | 20    | 30    | 40    |
|------------------|-------|-------|-------|-------|-------|-------|
| Thickness (μm)   | 21.83 | 22.3  | 20.5  | 17    | 16.2  | 16    |
| Knoop hardness (HK) | 381  | 394   | 423   | 392   | 394   | 393   |
| Range of hardness values | 372–393 | 339–409 | 405–435 | 380–407 | 379–411 | 387–405 |

3.3. Wear behavior

The coefficient of friction (COF) result from pin-on-disc test of ternary Ni–Ag–P coating with various silver sulphate concentration in shown in figure 5. In all samples, the COF increased at the first 100 s due to the different surface topography and static force that holds back a stationary object. However, once static friction was overcome, the wear process reached a steady state condition and the COF became constant. At this stage, the kinetic force restricting the movement of a sliding object remain constant through the wear test. The oscillations of COF recorded through the test were due to the non-uniform surface features caused by wear debris along the wear track. During wear test, some of the wear debris may entrapped between the two sliding surfaces. These trapped particles generated during wear act as abrasive material that lead to more material loss as wear test proceed (Parthasarathi et al 2013).
Figure 6 shows the average value of COF and wear rate for ternary Ni–Ag–P coating at different silver sulphate concentration. The co-deposition of silver in Ni–P coating reduced the COF and coating wear rate. Ni–Ag–P coating containing 5 mg l\(^{-1}\) silver sulphate showed the lowest COF and wear rate. Higher addition of silver sulphate increased both COF and wear rate. At 40 mg l\(^{-1}\), the coating have the highest COF and wear rate.

Researchers have reported that surface roughness of coating could play an important role in wear behaviour (Sudagar et al 2013, Gheisari & Polycarpou 2018). They found that the wear rate of coating becomes higher if it has higher surface roughness. Thus low surface roughness of Ni–Ag–P coating have contributed to low COF and wear rate. At 40 mg l\(^{-1}\), the coating have the highest COF and wear rate. According to Alirezaei et al (2013) who have studied the wear behaviour of Ni–P–Ag composite coatings, silver particles that adhered on the wear surface help to lubricate the wear surface and hence reduced the wear rate. Thus, this explained the lower rate and less surface damage for ternary Ni–Ag–P coating.

3.4. Thermal conductivity

Based on the results shown previously, the coating with 10 mg l\(^{-1}\) concentration of silver sulphate has the best properties with low roughness, high thickness and hardness value, and relatively low wear rate. Hence, the
The thermal conductivity test was done for Ni–Ag–P coating with 10 mg l⁻¹ silver sulphate and compared with that of binary Ni–P coating. The thermal conductivity measured for Ni–P coating is 445.70 W m⁻¹ K and increased to 466.9 W m⁻¹ K with addition of 10 mg l⁻¹ silver sulphate. This is approximately 5% increment as a result of co-deposition of Ag into Ni–P coating, indicating good potential of ternary Ni–P–Ag for better thermal conductivity coating on Cu substrate required for testing tool of electronic packages. It is believed that co-deposition of silver with high thermal conductivity properties helped increase the thermal conductivity of binary Ni–P. However, further research has to be done to stabilize the bath solution in order to increase the percentage of Ag into the ternary coating at similar thickness and low surface roughness.

4. Conclusions

It has been demonstrated that silver can be co-deposited in Ni–P coating but at limited concentration of silver sulphate as the Ag source. Higher silver sulphate concentration produced coating with high surface roughness. Addition of surfactant CTAB helped improve the surface roughness and morphology of coating. It can be concluded that co-deposition of silver at low concentration can improve the hardness, wear resistance and thermal conductivity of Ni–P electrodeposited coating. Comparable thickness value is possible for the Ni–Ag–P with improved wear resistance and thermal conductivity indicating great potential for ternary Ni–Ag–P coating to replace current NiP coating used in thermal testing tool.

Acknowledgments

The authors acknowledge and appreciate financial funding provided by the Collaborative Research in Engineering, Science & Technology (CREST) research grant (geran304/PBAHAN/6050280).

ORCID iDs

Nurulakmal M S https://orcid.org/0000-0001-8953-9579
Anasyida A S https://orcid.org/0000-0002-5655-7997

References

Agarwal A, Pujari M, Uppaluri R and Verma A 2014 Efficacy of reducing agent and surfactant contacting pattern on the performance characteristics of nickel electroless plating baths coupled with and without ultrasound Ultrason. Sonochem. 21 1382–91
Alirezai S, Monir Vaghfei SM, Urgen M, Saatchi A and Kazmali A 2013 Novel investigation on tribological properties of Ni–P–Ag–Al₂O₃ hybrid nanocomposite coatings Tribol. Int. 62 110–6
Balaraju J N, Kalavati and Rajam K S 2010 Electroless ternary Ni-W-P alloys containing micron size Al₂O₃ particles Surf. Coat. Technol. 205 575–81
Balaraju J N, Selvi V E, Grips V K W and Rajam K S 2006 Electrochemical studies on electroless ternary and quaternary Ni–P based alloys Electrochim. Acta 52 1064–74
Constantin I 2014 Microstructural characterization and corrosion behavior of electroless Ni-Zn-P thin films J. Metall. 1–6
Czagány M and Baumli P 2019 Effect of surfactants on the behavior of the Ni–P bath and on the formation of electroless Ni–P–TiC composite coatings Surface & Coatings Technology 361 42–9

Elangsezhian R, Ramamoorthy B and Nair P K 2008 Effect of surfactants on the mechanical properties of electroless (Ni–P) coating Surf. Coatings Technol. 203 709–12

Elangsezhian R, Ramamoorthy B and Nair P K 2009 The influence of SDS and CTAB surfactants on the surface morphology and surface topography of electroless Ni—P J. Mater. Process. Technol. 209 233–40

Georgieva J and Armyanov S 2007 Electroless deposition and some properties of Ni-Cu-P and Ni-Sn-P coatings J. Solid State Electrochem. 11 869–76

Gheisari R and Polycarpou A A 2018 Three-body abrasive wear of hard coatings: Effects of hardness and roughness Thin Solid Films 666 66–75

Guo C, Zuo Y, Zhao X, Zhao J and Xiong J 2008 Effects of surfactants on electrodeposition of nickel-carbon nanotubes composite coatings Surf. Coat. Technol. 202 3385–90

Hamid Z A 2003 Mechanism of electroless deposition of Ni-W-P alloys by adding surfactants Surf. Interface Anal. 35 496–501

Huang Y S and Cui F Z 2007 Effect of complexing agent on the morphology and microstructure of electroless deposited Ni–P alloy Surface & Coating Technology 201 5416–5418

Kundu S, Das S K and Sahoo P 2019 Friction and wear behavior of electroless Ni–P–W coating exposed to elevated temperature Surfaces and Interfaces 14 192–207

Kılıç F, Gül H, Aslan S, Alp A and Akbulut H 2013 Effect of CTAB concentration in the electrolyte on the tribological properties of nanoparticle SiC reinforced Ni metal matrix composite (MMC) coatings produced by electrodeposition Colloids Surfaces A Physicochem. Eng. Asp. 419 53–60

Lu G and Zangari G 2002 Corrosion resistance of ternary Ni–P based alloys in sulfuric acid solutions Electrochim. Acta 47 2969–79

Ma H, Tian F, Li D and Guo Q 2009 Study on the nano-composite electroless coating of Ni–P/Ag J. Alloys Compd. 474 264–7

Parthasarathi N L, Borah U and Albert S K 2013 Correlation between coefficient of friction and surface roughness in dry sliding wear of AISI 316 L (N) stainless steel at elevated temperatures Comput. Model. New Technol. 17 51–63

Penne C, Peyrou D, Leray D, Pons P, Plana R and Courtade F 2012 Impact of the surface roughness description on the electrical contact resistance of ohmic switches under low actuation forces IEEE Trans. Components Packag. Technol. 285 85–94

Popoola A P I, Loto C A, Osifuye C O, Aigbodion V S and Popoola O M 2016 Corrosion and wear properties of Ni-Sn-P ternary deposits on mild steel via electroless method Alexandria Engineering Journal 55 2901–8

Rudnik E, Burzyńska L, Dolasański I and Misiaik M 2010 Electrodeposition of nickel, SiC composites in the presence of cetyltrimethylammonium bromide Appl. Surf. Sci. 256 7414–20

Sahoo P and Das S K 2011 Tribology of electroless nickel coatings—a review Mater. Des. 32 1769–75

Seiffzadeh D and Hollagh A R 2014 Corrosion resistance enhancement of AZ91D magnesium alloy by electroless Ni-Co-P coating and Ni-Co-P-SiO2 nanocomposite J. Mater. Eng. Perform. 23 4109–21

Sudagar J, Lian J and Sha W 2013 Electroless nickel, alloy, composite and nano coatings—A critical review J. Alloys Compd. 571 183–204

Sudagar J, Lian J S, Jiang Q, Jiang Z H, Li G Y and Elansezhian R 2012 The performance of surfactant on the surface characteristics of electroless nickel coating on magnesium alloy Prog. Org. Coatings. 74 788–93

Veeraraghavan B, Kim H and Popov B 2004 Optimization of electroless Ni-Zn-P deposition process : experimental study and mathematical modeling Electrochim. Acta 49 3143–54

Yuan J, Wang J, Gao Y, Mao J and Hu W 2017 Preparation and magnetic properties of Ni-Co-P-Ce coating by electroless plating on silicon substrate Thin Solid Films 632 1–9