Synthesis and Characterization of Electroless Ni–P/Ni–Mo–P Duplex Coating with Different Thickness Combinations

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Abstract In this work, a novel duplex Ni–P/Ni–Mo–P coating upon the aluminum (Al) substrate was synthesized via an electroless plating, i.e., the binary Ni–P coating as a transition layer and the ternary Ni–Mo–P coating on the top. It was found that the duplex coating was of a high hardness, large elastic modulus, low porosity and excellent corrosion resistance. In addition, experimental results revealed that for a total 20 μm coating thickness, the duplex coating with a 7 μm of the Ni–Mo–P coating exhibited the best corrosion resistance in 0.5 mol/L sulfuric acid solution, which was attributed to its compact structure and low porosity. This duplex Ni–P/Ni–Mo–P coating with a thin ternary Ni–Mo–P layer is expected to solve the problem of low deposition rate of ternary alloy coating and thereby may expand applications of Al and its alloys in the fields of machine manufacture and corrosion environment.

KEY WORDS: Electroless plating; Aluminum (Al); Porosity; Ni–P/Ni–Mo–P duplex coating; Corrosion resistance

1 Introduction

Aluminum (Al) and its alloys is widely used in mechanical industry, power transmission, medical and our daily life, because of their excellent properties, such as low density, good ductility, high specific strength, superior electrical conductivity and thermal conductivity, high reflective and

oxidation resistance [1–4]. However, the weaknesses involving low surface hardness, inferior corrosion and wear resistances also blocks Al and Al alloys' practical industrial applications.

As we all know, electroless binary nickel–phosphorus (Ni–P) plating has been widely applied in industry, due to its advantages of superior corrosion resistance, high surface hardness and wear resistance, simple operation and low cost. It also improves solderability and polishing property of the surface and prolongs the service life [5–8]. Currently, with the development of high industrial requirement, the binary Ni–P alloy cannot meet applications under special conditions, such as specific machine manufacture and the corrosion resistant components in seawater. Therefore, a large number of studies have concentrated upon the electroless ternary alloy, i.e., co-deposition a third metal, including Zn, Cu, Co, Fe, Sn, W and Mo into the electroless Ni–P coating [9–13]. The resultant ternary alloy exhibits improvements of the coating's physical and chemical properties by adjusting the microstructures and refining the grain size [14].

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In general, the electroless ternary Ni–Mo–P alloy coating is of higher hardness and corrosion resistance than those of the binary Ni–P coating and can also delay the crystallization temperature [15–17]. It has been demonstrated that the deposition rate of the electroless ternary Ni–Mo–P alloy coating is lower than that of the binary Ni–P coating, due to the Mo co-deposition. That is to say, when the sodium molybdate concentration is too high, the deposition process will stop, which prevents to form a desired coating [18]. In addition, the Mo–P co-deposition also increases the hardness and internal stress concentration of the coating, which makes the coating more brittle and prone to cracking and stripping when the coating reaches a large thickness [19].

Recently, most researches have focused mainly on certain constant thickness of duplex coatings, such as Ni–P/Ni–Mo–P [20], Ni–P/Ni–W–P [21], Ni–P/Ni–B [22] and Ni–P–ZrO₂/Ni–P [23]. However, a lot of electroless Ni-based coatings present variations of morphologies and chemical compositions with depth of the coating, and it is even more probable that the chemistry of Ni–Mo–P varies with the deposition time. And in addition, the generation of the internal stress varies with many factors, including deposition temperature, deposition time and during electroless process [24].

In this work, we synthesized the electroless Ni–P/Ni–Mo–P duplex coating on the Al surface, i.e., applying an electroless binary Ni–P coating as a transition layer and plating a ternary Ni–Mo–P coating on the top. And the effects of different thickness combinations of the Ni–P and Ni–Mo–P coatings on the coating's surface morphology, porosity, corrosion resistance and mechanical property were investigated. It was found that this duplex coating exhibited excellent characters, such as uniform and compact surface, low porosity, good corrosion resistance and high mechanical property. This duplex coating with a thin ternary Ni–Mo–P coating is expected to solve the problem of low deposition rate of ternary alloy coating, thereby expanding applications of Al and its alloys in the fields of machine manufacture and corrosion environment.

2 Experimental

Commercial pure aluminum (Al) sheets with 25 mm × 10 mm × 0.1 mm in size were used as the substrate. Table 1 lists the major elements of the Al substrate. The Al

Table 1 Chemical compositions of commercial pure aluminum (Al) substrate (wt%)

Si	Fe	Cu	N	Al
0.15	0.015	0.015	0.005	Bal.

sheets were totally subjected to the processing steps as follows: cleaning → alkaline degreasing → acid pickling → electroless nickel pre-plating → electroless binary Ni–P plating → electroless ternary Ni–Mo–P plating → rinsing → properties tests. Table 2 lists the detailed parameters for each step.

The morphologies, crystallization and chemical compositions of the samples were characterized by using a scanning electron microscope (SEM) (S-4800, Hitachi, Japan, and SIRON, FEI, the Netherlands) equipped with an energy-dispersive X-ray spectroscopy (EDS), X-ray diffraction spectrometer (XRD, D8 Advance, Bruker AXS, Germany) with Cu K_{α} radiation, X-ray photoelectron spectroscopy (XPS, ESCALAB 250Xi, Thermo Fisher, USA) with Al K_{α} radiation of 1486.6 eV as the excitation source. The hardness and elastic modulus of the samples were measured by using an instrumental nanoindenter (Agilent G200 Nanoindenter, Agilent Technologies, USA). The CSM (continuous stiffness measurement) standard hardness and modulus test program were used, in which the harmonic depth and frequency were 2 nm and 45 Hz, respectively. The maximum indentation depth was 2000 nm. For each sample, ten points were tested for getting an average value.

The porosity of the coatings was measured according to the Chinese Light Industry Standard QB/T3823-1999, i.e., a filter paper method. The solution compositions consisted 3.5 g/L aluminon and 150 g/L sodium chloride. The soak time was 10 min for each sample. The measurement was carried out according to the processes: (1) put a glass plate with square grids (square covers an area of 1 cm²) on the filter paper with the flecked pores; (2) count the number of the spots within a square grid; and (3) calculate the data of porosity (number of spots/cm²). The porosity calculation was made according to the rules: (1) when the spot diameter was less than 1 mm, one spot was regarded as one pore; (2) when the spot diameter was in a range of 1–3 mm, one spot was regarded as three pores; (3) when the spot diameter was in a range of 3–5 mm, one spot was regarded as ten pores; and (4) the final result was determined by the mean value of three measurements.

The corrosion resistance of the coatings was performed by using an electrochemical workstation (CHI604D, Chenhua Instrument Company, China) in 0.5 mol/L H₂SO₄ solution under the room temperature. A conventional three-electrode setup was used, i.e., the sample served as a working electrode, a saturated calomel electrode (SCE) as a reference electrode and a platinum net as an auxiliary electrode. For each sample, the open-circuit potential (OCP) was first measured for half hour. The polarization curve was obtained at a constant scan rate of 0.5 mV/s, and the voltage range was approximately ±150 mV versus the OCP.

Table 2 Parameters for every process

Process	Solution composition	pH	Temperature (°C)	Time (min)
Cleaning	Anhydrous ethanol		25	1
Alkaline degreasing	20 wt% sodium hydroxide solution		40	0.3
Acid pickling	20 vol% nitric acid		25	3
Electroless Ni pre-plating	13 g/L nickel sulfate 30 g/L sodium hypophosphite 40 g/L sodium citrate 30 g/L ammonium chloride	9–10	50	5
Electroless binary Ni–P plating	27 g/L nickel sulfate 30 g/L sodium hypophosphite 20 g/L sodium acetate 1.2 g/L sodium citrate 31 mL/L lactic acid 3.7 mL/L propionic acid 5 mg/L copper sulfate 5 mg/L sodium thiosulfate	5	91 ± 1	60
Electroless ternary Ni–Mo–P plating	31 g/L nickel sulfate 31 g/L sodium hypophosphite 20 g/L sodium pyrophosphate 40 g/L ammonium sulfate 0.8 g/L sodium molybdate 10 mL/L triethanol amine 1 mg/L thiourea 0.05 g/L sodium dodecyl sulfate 1 g/L saccharin	9	70 ± 1	60

3 Result and Discussion

In order to obtain a desired electroless Ni–P or Ni–Mo–P coating on the Al substrate, in our previous work, we introduced a novel environment friendly formulation of the electroless Ni pre-plating (also called nickel immersion) solution. That was, alkaline etch and acid pickling were used to remove thoroughly the alumina layer, and the pre-plating nickel solution contained 13 g/L nickel sulfate, 30 g/L sodium hypophosphite, 40 g/L sodium citrate, 30 g/L ammonium chloride. Experimental results revealed that 5-min pretreatment provided a homogeneous pre-plating layer on the Al surface, which was considered to be the best condition for the subsequent plating. The effect of the pre-plating time on the morphologies of the binary Ni–P and ternary Ni–Mo–P coatings, and bonding strength between the coating and substrate were also studied [25].

Figure 1 shows the SEM morphologies of the electroless binary Ni–P coating and the duplex Ni–P/Ni–Mo–P coating. We can see that there were many holes on the Ni–P coating and no hole on the duplex coating. The particles size of the Ni–P coating was smaller than that of the duplex coating, which was caused by co-deposition of element Mo.

Figure 2 illustrates the EDS chemical composition profiles of a single Ni–P coating and the 14 + 6 Mo duplex coating, respectively. 3.63 wt% phosphorus (P) content was measured from the single binary Ni–P coating, which belonged to a kind of low P coating. In the surface of the duplex coating, the elements of Mo and P were detected with data 1.03 wt% P and 2.05 wt% Mo, which showed that the upper layer was the ternary Ni–Mo–P coating. This result was also proved by element mapping analysis of the duplex coating, as shown in Fig. 3.

Figure 4 shows the XRD patterns of the electroless Ni–P alloys and the duplex Ni–P/Ni–Mo–P coatings. According to the patterns, it is evident that only a single peak was detected for the Ni–P coating, while extra two weak peaks were observed for the duplex coating. These revealed that the Ni–P coatings had an amorphous-like structure, and the duplex coating showed a more crystalline nature. In general, P content in the coating determines the crystal structure of the electroless Ni–P coating. That is to say, high P content in the coating leads to an amorphous structure, while low P content shows a crystalline structure. Therefore, if a third element (such as Mo) is added to the coating, it will influence the P content and causes changes of the coating microstructures. Many reports have indicated that

Fig. 1 SEM images of **a** Ni-P coating, **b** Ni-P/Ni-Mo-P duplex coating

Fig. 2 EDS analysis of **a** Ni-P coating, **b** Ni-P/Ni-Mo-P duplex coating

the Mo content exhibited a negative correlation with the P content in the coating [26, 27]. In the present work, the outer Ni-Mo-P coating contained low P (about 1.03 wt%) and consisted of the crystalline and microcrystalline nickel, which indicated that the number of P atoms was not sufficient to distort the Ni lattice to an extent to form the Ni amorphous. The diffraction peak was corresponded to the (111) plane of a face centered cubic phase of nickel [28].

Figure 5 shows the XPS spectra of the Ni-P coating and the duplex coating. The survey scan suggested that the duplex coating contained elements of Ni, Mo, P and O. C element was also detected on the surface of the outer Ni-Mo-P coating, possibly due to surface contamination by atmospheric hydrocarbon during storage. The constituent elements exhibited in various states. The Ni 2*p* spectrum in Fig. 5b indicated that Ni existed as element Ni and nickel hydroxide, corresponding to the peaks at binding energies of 852.6 and 855.8 eV, respectively. The Mo 3*d* spectrum in Fig. 5c showed different species of Mo in the coating. The peaks at 227.7 and 230.8 eV correspond to element Mo, and those at 235.3 eV indicated the presence of MoO_x, respectively. The peaks of element P appeared at 129.3 and

130.2 eV, as shown in Fig. 5d, and peak at 133.5 eV was due to existence of PO_x [29].

Figure 6 shows the SEM images of the surfaces and cross sections of the duplex Ni-P/Ni-Mo-P coating with different thicknesses of the outer Ni-Mo-P coating (total thickness was 20 μm). The results showed that with the increase in thickness of the Ni-Mo-P coating, the surface morphologies were changed significantly, i.e., from poriferous to compact and cracking. That is to say: (1) when the coating thickness was less than 7 μm, the surface was poriferous; (2) when the coating thickness reached 7 μm, the compact structure was formed; (3) at the arrange of 10–13 μm, the surface was somewhat uneven, because of the decrease in stability of the plating solution and effect of the impurity substances within the plating solution. The large cellular size in Fig. 6d was attributed to the aging of bath solution and consumption of the complex agent, i.e., production and agglomeration of impurity during electroless process and the weakened complexation increased the grain growth rate and therefore resulted in a higher growth rate than the nucleation rate. At last, the large cellular size was formed; (4) when the coating thickness was large

Fig. 3 EDS elemental mapping analysis of Ni-P/Ni-Mo-P duplex coating: **a** SEM image; **b** Ni element; **c** Mo element; **d** P element

Fig. 4 XRD patterns of Ni-P coating and Ni-P/Ni-Mo-P duplex coating with 7 μm of Ni-Mo-P coating

enough and reached 17 μm , the cracks were observed in the coating, due to a large internal stress concentration in the coating [30]. From the cross-section morphology, as shown in Fig. 6f, favorable homogeneity and approximate thickness of the duplex coating were observed distinctly,

which demonstrated a good adhesion strength at both the interface between the Al substrate and the Ni-P coating, and between the Ni-P coating and the Ni-Mo-P coating.

It has been known that, during electroless plating, the formation of porous coating is because of the H^+ aggregation adjacent to cathode and adsorption at the substrate. Generally, a small amount of hydrogen will remain with the coating and results in the pore formation. In addition, when the coating is too thin, there are not sufficient particles to cover in the surface and also form gaps in the surface. Obviously, once the corrosive medium seeps into the coating via the pores and gaps, a galvanic cell will be generated and accelerated the corrosion process. In a word, the size and the number of the porosity in the coating affect seriously on corrosion resistance of the coatings.

Figure 7a shows the porosity variations of the Ni-P coating and the duplex Ni-P/Ni-Mo-P coating with different thicknesses of the Ni-Mo-P coating. Clearly, when the Ni-Mo-P coating thickness was less than 7 μm , a number of pores were observed in the duplex coating. However, for the thickness in a range of 7–10 μm , no pores were observed, which was attributed to the compact structure of the duplex coating. When the thickness

Fig. 5 XPS spectra of Ni-P/Ni-Mo-P duplex coating **a–d** (**a** full scope spectrum, **b** Ni 2p spectrum, **c** Mo 3d spectrum, **d** P 2p spectrum) and Ni-P coating **e–g** (**e** full scope spectrum, **f** Ni 2p spectrum, **g** P 2p spectrum)

exceeded 17 μm , the coating began to strip from the substrate. For the binary Ni-P coating, even the thickness reached 20 μm , only few pores were observed on the surface.

Further, we studied the relationship between the thickness of the Ni-Mo-P coating and corrosion resistance of the duplex coating. Figure 7b and Table 3 give the potentiodynamic polarization curves and its fitting results of the duplex coatings with different thicknesses in a 0.5 mol/L sulfuric acid solution, respectively. It was revealed that, when the Ni-Mo-P coating thickness was around 7 μm , there existed the most positive corrosion potential and the minimum corrosion current, which demonstrated the best corrosion resistance of the duplex coatings, because of only few pores in the coating surface. Therefore, the duplex coating effectively improved the porosity and corrosion resistance of the binary Ni-P coating.

Figure 8 presents typical nanoindentation load–displacement curves of the coatings for comparison with the

Al substrate. Obviously, the coatings have a significant influence on the nanoindentation property, i.e., for the same 2000 nm penetration depth, the maximum load (P_{max}) was 39 mN for the Al substrate, while the P_{max} increased to 400 mN and 491 mN for the Ni-P and Ni-Mo-P coatings, respectively. According to these curves, the hardness (H) and elastic modulus (E) of the coatings could be calculated from the following equations by using the data including P_{max} , initial slope (or indentation stiffness) (S) of the unloading curve, and the projected contact area (A_c) [31]:

$$H = \frac{P_{\text{max}}}{A_c}, \quad (1)$$

where A_c can be further calculated as a function of the contact penetration depth (h_c). And h_c is related to the deformation behavior of the materials and the shape of the indenter. Therefore, h_c is estimated as:

$$h_c = h_{\text{max}} - \frac{\varepsilon P_{\text{max}}}{S}, \quad (2)$$

Fig. 6 SEM morphologies of duplex Ni-P/Ni-Mo-P coating with different thicknesses of outer Ni-Mo-P coating: **a** 4 μm , **b** 7 μm , **c** 10 μm , **d** 13 μm , **e** 17 μm , **f** cross-section morphology of Ni-Mo-P coating of 7 μm (total thickness was 20 μm)

Fig. 7 Porosity of Ni-P coating and Ni-P/Ni-Mo-P duplex coatings **a** and potentiodynamic polarization curves of bare Al, Ni-P coating and Ni-P/Ni-Mo-P duplex coatings with different thicknesses of outer Ni-Mo-P coating in 0.5 mol/L H_2SO_4 solution (total thickness was 20 μm ; E_{corr} : corrosion potential; I_{corr} : corrosion current density) **b**

where ε is a constant that depends on the geometry of the indenter. For the Berkovich indenter used in the present work, ε is equal to 0.75.

In general, from indentation testing, the elastic modulus (E) can be obtained by the following equations:

$$E = (1 - \nu^2) \left(\frac{1}{E^*} - \frac{1 - \nu_i^2}{E_i} \right)^{-1}, \quad (3)$$

$$E^* = \frac{\sqrt{\pi}}{2\beta} \frac{S}{\sqrt{A_c}}, \quad (4)$$

where E^* is the effective modulus of the indenter-sample system and E and E_i are the elastic modulus of the sample and the indenter, respectively. ν and ν_i are Poisson ratios of the sample and the indenter, respectively, where ν is 0.07 and ν_i is 0.31. β is a correction factor associated with the indenter shape, 1.034 for a Berkovich indenter.

According to Eqs. (1)–(4) and the instrumented indentation procedure, the results of the loading–unloading tests, as shown in Fig. 8, were converted into hardness values (H) and elastic modulus (E) for different coatings.

Table 3 Potentiodynamic polarization tests of bare Al, Ni-P coating and Ni-P/Ni-Mo-P duplex coatings with different thicknesses of Ni-Mo-P coating in 0.5 mol/L H₂SO₄ solution (E_{corr} : corrosion potential, I_{corr} : corrosion density)

Thickness of Ni-Mo-P coating (μm)	E_{corr} (V)	I_{corr} (A/cm ²)
Bare Al	-1.205	5.624×10^{-4}
0 (Ni-P coating)	-0.113	7.385×10^{-6}
4	-0.126	3.285×10^{-6}
7	-0.086	1.526×10^{-6}
10	-0.098	2.332×10^{-6}
13	-0.430	2.929×10^{-6}
17	-0.478	8.560×10^{-5}

Obviously, at the same depth (such as 1500 nm), loads on the Ni-P coating and the duplex Ni-P/Ni-Mo-P coating were much higher than that of the Al substrate, which indicated that the Ni-P coating and duplex Ni-P/Ni-Mo-P coating were of high hardness and elastic modulus. As shown in Fig. 8b, the hardness of the Ni-P coating and the duplex coating was five times and nine times higher than that of the Al substrate, and the elastic modulus was also increased by 94 and 167%, respectively. Obviously, the duplex Ni-P/Ni-Mo-P coating exhibited the highest H and largest E values, due to the co-deposition of Mo element and the compact microstructure [32].

In addition, as shown in Fig. 9, we found a jump point at the 900 nm penetration depth for the duplex Ni-P/Ni-Mo-P coating, i.e., the slope of the curve reduced suddenly at the point, which indicated that this point was the interface between the Ni-P coating and the Ni-P-Mo coating. Apparently, the former portion of the curve belonged to the

Fig. 9 Load-displacement curve showing jump point at interface between Ni-P coating and Ni-Mo-P coating of Ni-P/Ni-Mo-P duplex coating

top Ni-Mo-P coating with higher H and larger E , and the latter was the transition Ni-P coating [33].

4 Conclusions

The duplex Ni-P/Ni-Mo-P coating was successfully synthesized by dual bath electroless deposition on the Al substrate. The following conclusions could be drawn:

- (1) The duplex coating was of compact surface and favorable thickness homogeneity.
- (2) The duplex coating without holes was obtained when the Ni-P coating served as a transition layer under a

Fig. 8 Load-displacement curves **a** and fitted results of hardness and elastic modulus **b** of bare Al, Ni-P coating and Ni-P/Ni-Mo-P duplex coatings

relative thin Ni–Mo–P coating, which was attributed to the proper surface state of the Ni–P coating.

- (3) For a total 20 μm coating thickness, the duplex coating with a 7 μm of the Ni–Mo–P coating exhibited the best corrosion resistance in 0.5 mol/L sulfuric acid, because of its compact surface and low porosity.
- (4) Due to the co-deposition of Mo element, the hardness of the Ni–P coating and the duplex coating was five times and nine times higher than that of the Al substrate, and the elastic modulus was also increased by 94 and 167%, respectively.
- (5) The synthesis process of this duplex coating with advantages, such as simple, low cost, environmental friendly, desired controllability and repeatability, is suitable to industrial production, thereby expanding the applications of Al and its alloys in the fields of machine manufacture and corrosion environment.

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References

- [1] Y.B. Unigovski, A. Grinberg, E. Gerafi, E.M. Gutman, *Surf. Coat. Technol.* **232**, 695 (2013)
- [2] W.S. Miller, L. Zhuang, J. Bottema, A.J. Wittebrood, P. De Smet, A. Haszler, A. Vieregge, *Mater. Sci. Eng., A* **280**, 37 (2000)
- [3] W. Qin, *J. Coat. Technol. Res.* **8**, 135 (2010)
- [4] Y.S. Huang, *Adv. Mater. Res.* **189–193**, 265 (2011)
- [5] A.E. Fetohi, R.M.A. Hameed, K.M. El-Khatib, *J. Ind. Eng. Chem.* **30**, 239 (2015)
- [6] N. Nagata, T. Kanadani, K. Nakagawa, M. Fukuhara, K. Horikawa, K. Murakami, M. Hino, *J. Jpn. Inst. Met.* **79**, 151 (2015)
- [7] N. Nagata, T. Kanadani, K. Nakagawa, M. Fukuhara, K. Horikawa, K. Murakami, M. Hino, *J. Jpn. Inst. Met.* **79**, 146 (2015)
- [8] L.W. Ren, Z. Wang, M.M. Meng, H. Tian, H.J. Yang, J.W. Qiao, *J. Non-Cryst. Solids* **430**, 115 (2015)
- [9] A.E. Fetohi, R.M.A. Hameed, K.M. El-Khatib, E.R. Souaya, *Int. J. Hydrogen Energy* **37**, 10807 (2012)
- [10] M.L. Wang, Z.G. Yang, C. Zhang, D.L. Liu, *Trans Nonferrous Met. Soc.* **23**, 3629 (2013)
- [11] X. Shu, Y. Wang, X. Lu, C. Liu, W. Gao, *Surf. Coat. Technol.* **276**, 195 (2015)
- [12] E. Valova, S. Aramyanov, G. Hristova, T. Vassilev, O. Steenhaut, J. Dille, A. Hubin, I. Vandendael, *Surf. Coat. Technol.* **304**, 468 (2016)
- [13] X.L. Wang, Y.X. Zheng, M.L. Jia, L.S. Yuan, C. Peng, W.H. Yang, *Int. J. Hydrogen Energy* **41**, 8449 (2016)
- [14] J. Li, D. Wang, H. Cai, A. Wang, J. Zhang, *Surf. Coat. Technol.* **279**, 9 (2015)
- [15] G. Lu, G. Zangari, *J. Electrochem. Soc.* **150**, C777 (2003)
- [16] Y.H. Chou, C.Y. Bai, M.D. Ger, C.L. Chao, S.J. Lee, C.Y. Lee, in *Proceedings of the 35th International MATADOR Conference*, Springer, London, United Kingdom, 2007, pp. 21–24
- [17] A.E. Fetohi, R.M.A. Hameed, K.M. El-Khatib, *J. Power Sources* **240**, 58 (2013)
- [18] D.L. Liu, Z.G. Yang, C. Zhang, *Mater. Sci. Eng., B* **166**, 67 (2010)
- [19] R.C. Agarwala, V. Agarwala, *Sadhana* **28**, 475 (2003)
- [20] H. Liu, Y.Y. Lv, Z. Liu, H. Liu, G.E. Thompson, *Tribol. Int.* **103**, 343 (2016)
- [21] V.E. Selvi, P. Chatterji, S. Subramanian, J.N. Balaraju, *Surf. Coat. Technol.* **240**, 103 (2014)
- [22] C. Subramanian, K. Palaniradja, *Int. J. Metall. Eng.* **4**, 25 (2015)
- [23] Y. Wang, X. Shu, S. Wei, C. Liu, W. Gao, R.A. Shakoob, R. Kahraman, *J. Alloys Compd.* **630**, 189 (2015)
- [24] J. Sudagar, J. Lian, W. Sha, *J. Alloys Compd.* **571**, 183 (2013)
- [25] S. Sun, G.S. Song, Z. Ma, *Surf. Technol.* **45**, 49 (2016). (**In Chinese**)
- [26] L.M. Abrantes, A. Fundo, G. Jin, *J. Mater. Chem.* **11**, 201 (2001)
- [27] X.B. Xi, H. Miao, R.H. Zhang, J. Cheng, *Surf. Coat. Technol.* **297**, 27 (2016)
- [28] J.N. Balaraju, N. Raman, N.T. Manikandanath, *Trans. Inst. Met. Finish.* **92**, 169 (2013)
- [29] H.M. Lee, H. Chae, C.K. Kim, *Korean J. Chem. Eng.* **29**, 1259 (2012)
- [30] J.C. Hsu, K.L. Lin, *Thin Solid Films* **471**, 186 (2005)
- [31] M. Sribalaji, O.S. Asiq Rahman, T. Laha, A.K. Keshri, *Mater. Chem. Phys.* **177**, 220 (2016)
- [32] A.S. Hamada, P. Sahu, D.A. Porter, *Appl. Surf. Sci.* **356**, 1 (2015)
- [33] P. Wieceński, J. Smolik, H. Garbacz, J. Bonarski, A. Mazurkiewicz, K.J. Kurzydłowski, *Surf. Coat. Technol.* **309**, 709 (2017)