

## Electroless Ni-P/PTFE Self-Lubricating Composite Thin Films Applied for Medium-carbon Steel Substrate

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Generally, the linear guide (made by medium-carbon steel) ways are operated under lubricated conditions. The external lubricants such as grease and oil will evaporate easily, thus, the re-lubrication is necessary. The electroless deposition technique is utilized to deposit a layer of self-lubricating Ni-P/PTFE composite coating with a uniform thickness about 5  $\mu\text{m}$  onto the medium-carbon steel substrate in this study. The effect of PTFE concentration in the plating bath on the deposition rate, corrosion resistance, hardness, hydrophobicity and wear behavior of the composite coatings are studied. The results show that the hardness as well as the friction coefficient of composite coatings decreases with the increase of incorporated PTFE content in the coating. It results in the wear rate of the Ni-P/PTFE composite coating first decreases with the increase of PTFE content in the coating and then increases with the PTFE content. Heat treatment at 400°C is found to have significant effect on the wear properties of Ni-P/PTFE coating. The friction coefficient of composite coatings increases after heat treatment at 400°C due to the decomposition of PTFE. The wear test result shows that the friction coefficient of medium-carbon steel substrate reduces from 0.07 to 0.035 after deposition a layer of Ni-P/PTFE composite coating on it.

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**Keywords:** self-lubrication; composite coatings; Ni-P/PTFE; medium-carbon steel substrate; electroless deposition

### 1. INTRODUCTION

The linear motion guides are widely used in many ultra-precise positioning devices to transport machine parts through a linear rails. The durability of the linear guides should be high enough to make

sure the reliability after long-term usage. The roller will direct contact with the shaft or rail material and resulting in galling and brinelling damage during the motion of the rolling or sliding element against the rails without sufficient lubrication. Generally, grease or oil is applied as a lubricant in the industry linear motion guides. Owing to the evaporation of these external lubricants, the re-lubrication is necessary. Recently, there has been a tendency to employ self-lubricating materials for bearing applications due to economical, ecological and even technical reasons. The external lubricants such oil or grease can be excluded and the design of machinery can be simplified by using self-lubricating materials [1]. Therefore, a prolongation of the service lifetime of guide rail can be achieved simply by coating of a thin film with excellent anti-wear characteristics and corrosion resistance. However, the thickness of the coating must keep as small as possible in order not to influence the precision of the guide way.

Due to their superior properties in corrosion and wear resistance, the electroless Ni-P coatings have been extensively used for various engineering applications [2, 3]. The incorporation of solid lubricants such as PTFE, graphite, MoS<sub>2</sub>, Si<sub>3</sub>N<sub>4</sub> and h-BN [4-10] into Ni-P matrix can further enhance the tribological properties of Ni-P composite coatings. Among these solid lubricant particles, PTFE has attracted tremendous interest due to its low friction coefficient, excellent dry-lubricity, and very good wear and corrosion resistance. It has been reported that the incorporation of PTFE nanoparticles into Ni-P matrix significantly enhanced wear resistance of the coatings, and this also improved the corrosion resistance of the resulting coatings [11-14]. Thus, it suggests that Ni-P/PTFE composite coatings are useful in any situation where wear under dry lubrication condition is vital and/or in applications where the materials may corrode easily.

Considerable works have been carried out to investigate the tribological and corrosion performances of electroless Ni-P/PTFE composite coatings. Their results all showed that composite coatings containing PTFE exhibited not only high wear resistance and corrosion resistance but also low friction coefficient compared with the Ni-P coatings, both in as plated and heat-treated conditions. However, their attentions were focused on thick Ni-P/PTFE coatings where the thicknesses of coatings are all greater than 10  $\mu\text{m}$ . Based on our knowledge, few literatures are available on the wear behaviors of the thin electroless Ni-P/PTFE composite coatings which are useful in medium-carbon steel substrate applications.

In this work, the Ni-P/PTFE electroless composite coatings with the thickness of 5  $\mu\text{m}$  on the medium-carbon steel substrate were prepared. The influences of PTFE incorporation on the friction coefficient, hardness and wear resistance of Ni-P/PTFE composite coatings were discussed. The heat treatment temperature effect on these properties was also investigated.

## **2. EXPERIMENTAL**

### *2.1. Specimens preparation*

A medium-carbon steel plate (chemical composition listed as Table 1) of 50 mm  $\times$  25 mm  $\times$  2 mm was used as the substrate in the laboratory testing phase. Prior to electroless plating Ni-P/PTFE

coating, the substrates were degreased with acetone for 30 minutes, activated by 10 wt.% NaOH aqueous solution at 40°C for 30 minute and pickled in a 50 vol. % hydrochloric acid solution for 3 minutes. Ni-P/PTFE composite coatings were deposited on the pretreated substrates by electroless plating. The bath compositions and conditions for electroless coatings are listed in Table. 2.

**Table 1.** Chemical compositions of medium-carbon steel (wt.%)

element	C	Si	Mn	Cr	P	S	Fe
medium-carbon steel	0.43	018	0.76	0.18	0.04	0.03	Bal.

**Table 2.** Electroless bath composition and parameters

Component	Concentration	Parameter	Value
Nickel sulfate	30 g/L	pH	4.8
Sodium lactate	40 ml/L	Temperature	90°C
Glycine	10 g/L	Agitation	100 rpm
Hypophosphite	30 g/L	Coating thickness	about 5 $\mu\text{m}$
KIO <sub>3</sub>	2 ml/L	Plating time	40 min
CO-890	1 ml/L		
PbNO <sub>3</sub>	0.15 ml/L		
PTFE	2.0, 3.0, 5.0, 7.5 g/L		

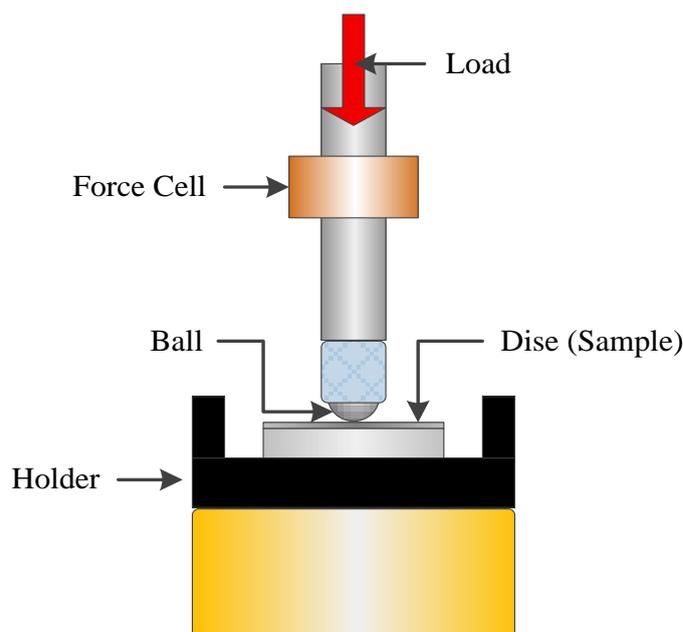
The average size of PTFE particles used in this experiment is 0.3  $\mu\text{m}$ . PTFE particles were suspended in bath solution by using surfactant CO-890. The electroless plating was carried out for 40 min. A magnetic stirrer was used to keep the PTFE dispersed in the bath.

## 2.2. Characterization of Ni-P/PTFE composite coatings

The phase structures of the Ni-P/PTFE composite coatings were examined using a Bruker D2 Phase X-ray diffractometer (XRD) with Cu  $k_{\alpha}$  radiation over a scanning range from 10° to 90°. The morphologies of the coatings were analyzed by a scanning electron microscopy (SEM, HITACHI-3000S). The distribution of Ni, P and F in the coatings was assessed with an electron probe X-ray micro-analyzer (EPMA, JEOL JXA-8200). The hardness of the composite coatings was measured by a Mitutoyo microhardness tester with a load of 100 g and a time of 10 s.

The potentiodynamic polarization analysis of various samples were carried out by an Autolab-PGSTAT30 potentiostat/galvanostat analyzed by a GPES (General Purpose Electrochemical system) software. A platinum sheet and Ag/AgCl electrode were used as the counter and reference electrodes in a saturated solution of 3.5% NaCl at room temperature. The measured potential range was from -0.3 to 0.5 V with a scanning rate at 0.5 mV/s.

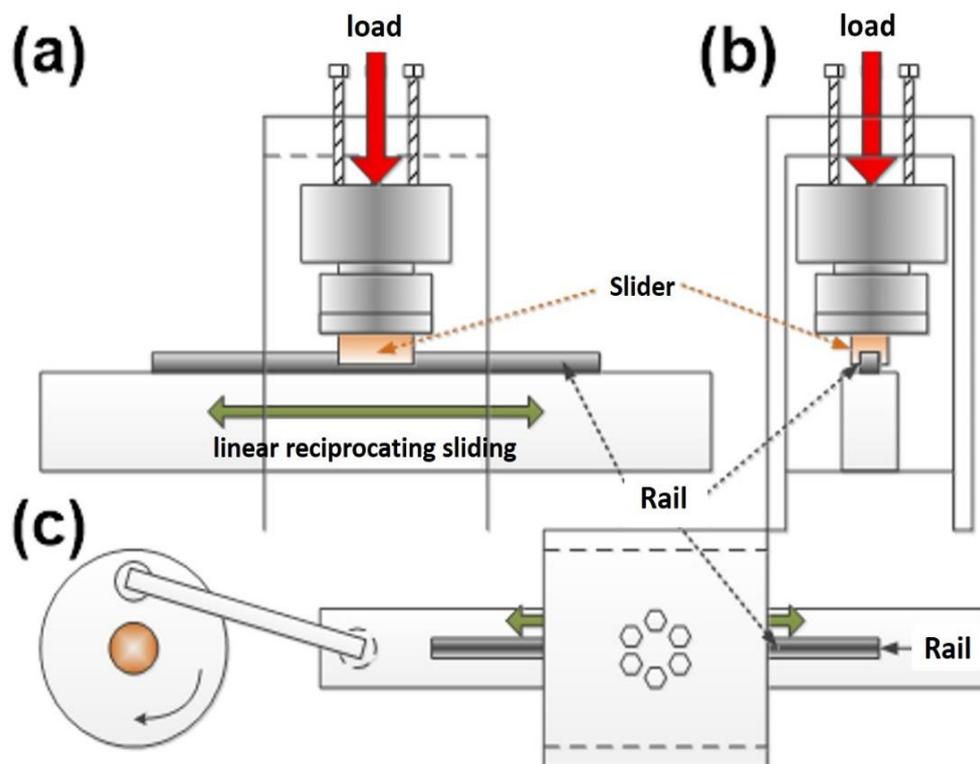
A ball-on-disk tribometer (SENSE-7) was employed to measure the tribological properties of the coatings. The schematic diagram of the apparatus is shown in Fig. 1 [15]. The commercially obtained steel balls ( $\varphi 6.25$  mm) were used as the counterpart. The friction tests were carried out at a reciprocating sliding velocity of 4m/s under a load 6 N for a distance of 60 m, and the sliding stroke was around 1.00 mm. Each of these tests was repeated three times. All the experiments were accomplished in ambient condition of temperature  $25\pm 1$  °C and  $50\%\pm 2\%$  relative humidity. No lubrication was used during wear tests. The volumetric wear rate ( $R_w$ ) of specimens was calculated by  $R_w = V/F \cdot S$ , where  $V$  is the wear volume ( $\text{mm}^3$ ),  $F$  is the applied load (N), and  $S$  is the sliding distance (m). The wear volume was obtained by a non-contact surface mapping profiler (ADE Corporation, USA).



**Figure 1.** Schematic diagram of ball on disk tribometer (SENSE-7) [15].

### 2.3. The wear test for real roller linear motion guides

The linear motion guide rails supplied by TBI motion technology Co., LTD, Taiwan were used as the substrate materials (medium-carbon steel) which chemical composition was listed at Table 1. The dimension of rail is 15 mm  $\times$  15 mm  $\times$  600 mm. Prior to electroless plating Ni-P/PTFE coating, the real roller linear motion guides were degreased with acetone for 30 minutes, activated by 10 wt.% NaOH aqueous solution at 40°C for 30 minute and pickled in a 50 vol. % hydrochloric acid solution for 3 minutes. Ni-P/PTFE composite coatings were deposited on the medium-carbon steel rails by electroless plating with the same conditions as described in section 2.1. The thickness of composite coatings deposited on medium-carbon steel rails was measured by X-Ray Fluorescence (XRF, Tech Max-SFT110), and the average of the results measured at five different positions are reported.



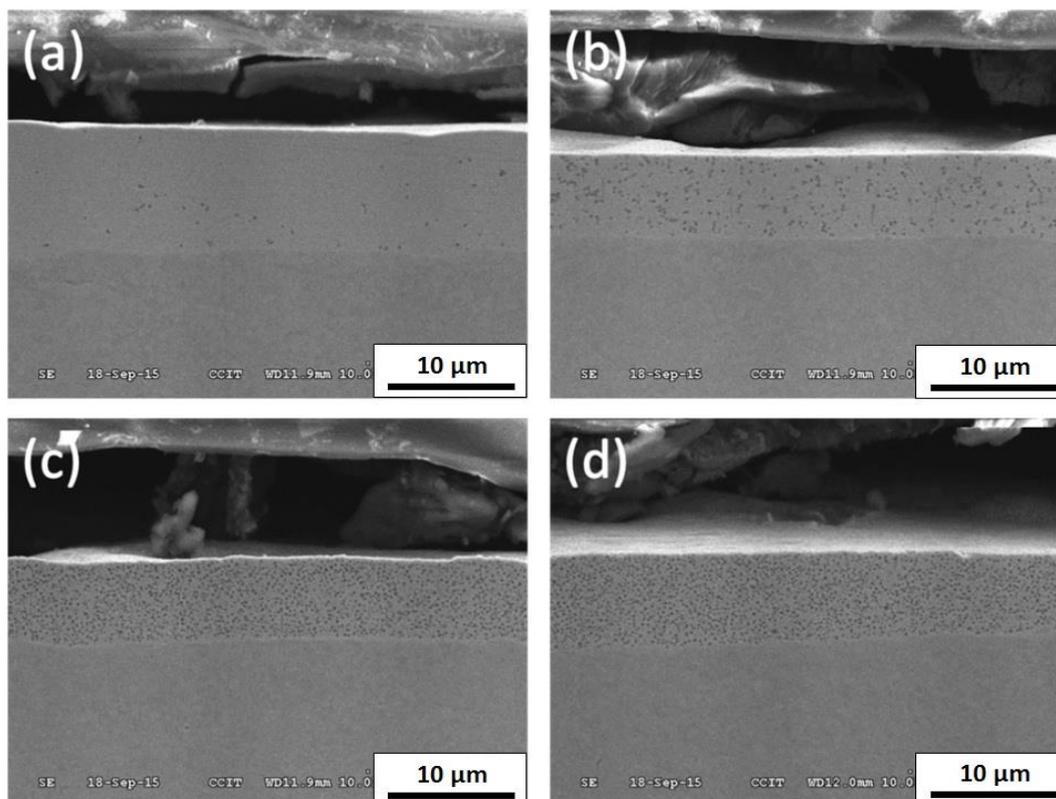
**Figure 2.** The schematic diagram of the roller linear guide tribometer setup (a) right side view, (b) positive side view, and (c) plan view.

The friction coefficient of the coated roller linear motion guides were measured by a linear guide tribometer with a load of 120 kg for a distance of 1000 m. The test system schematic diagram with a loading function for the roller linear motion guides were shown in Fig. 3. Dynamic wear test of the Ni-P/PTFE coating on the linear guideway was adopting the counter slider that has 40 balls which is 2.5 mm diameter set in each side within the slider. During the testing, the frictional coefficient were calculated by using the data acquisition system of eStrain (Chief SI Co., Ltd.) and biaxial load cell sensing device of JIHSENSE (Esense SI Co., Ltd.) to get friction force and load variation with one time per ten seconds. Test conditions was load of 120 kg, the frequency of 60 rpm (speed of 30 m/min), the stroke distance of 0.25 meters, and wear test time 60 minutes is equivalent total wear distances of 1,000 meters.

### 3. RESULTS AND DISCUSSION

#### 3.1. Characteristics of Ni-P-PTFE composite coatings

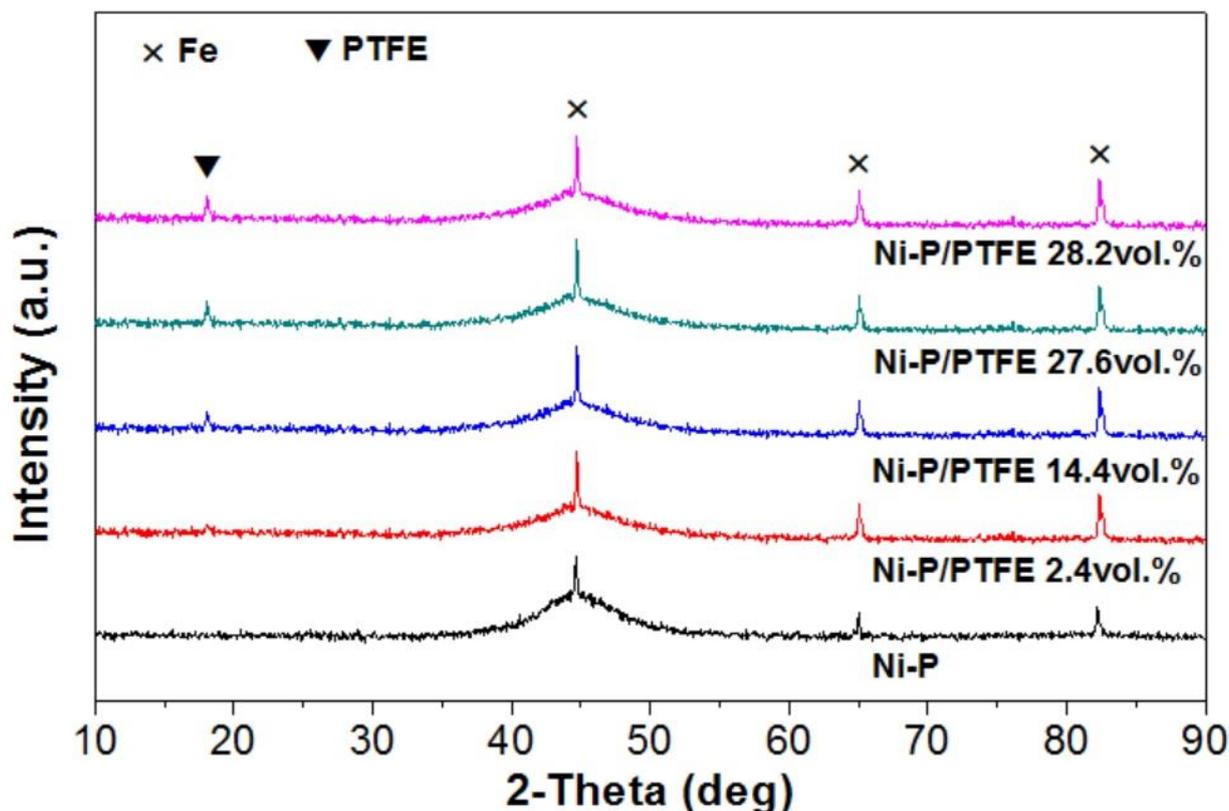
Fig. 3 shows the cross-sectional micrographs of the electroless Ni-P-PTFE coatings deposited from the bath containing different PTFE contents for 40 min.



**Figure 3.** SEM cross-sectional images of the electroless Ni-P/PTFE composite films deposited from the bath with different concentrations of PTFE particles: (a) 2.0 g/L, (b) 3.0 g/L, (c) 5.0 g/L, (d) 7.5 g/L.

It is observed from Fig. 3(a) that the thickness of Ni-P-PTFE coating is 9  $\mu\text{m}$  for the deposition plated from the bath containing 2.0 g/L PTFE. The thickness of the electroless plated composite coating decreased from 9  $\mu\text{m}$  to 5  $\mu\text{m}$  as the PTFE bath concentration was increased from 2.0 to 3.0 g/L (Fig. 3(b)). As the PTFE concentration in the plating bath surpasses 3.0 g/L, it shows from Fig. 3 (c) and (d) that the thickness of the coating remains almost constant (around 5  $\mu\text{m}$ ). The volume percentage of the co-deposited PTFE particles into the composite coatings deposited from different baths is presented in Table 2. The volume percentage of PTFE content in the composite coating is 2.4 vol. % at 2.0 g/L PTFE in the bath, and reaches a value 14.4 vol. % at 3.0 g/L PTFE in the bath. As the PTFE concentration in the plating bath surpasses 3.0 g/L, the volume percentage of PTFE content increases continuously to 27.6 vol. % and 28.2 vol. %, respectively, for deposit plated at 5.0 g/L and 7.5 g/L PTFE in the bath. It clear shows the amount of incorporated PTFE particles increases with increasing PTFE loading in the plating bath and the deposition rate of Ni-P decreases with increasing PTFE loading in the plating bath. On the other hand, the phosphorus content is 11.98 wt.% in the Ni-P coating and it only decreases slightly to 11.1 wt.% at 7.5 g/L PTFE in the bath. It implies that the nickel content in the coating reduces tremendously with the PTFE concentration in the bath. The presence of cationic surfactant CO-890 might be the cause for that. The surfactant adsorbed on the PTFE surface enhances PTFE particles embedded into the Ni-P matrix on the one hand. On the other hand, the cathode surface coverage by surfactant hinders the reduction of nickel ions [16]. It also can be seen

from the SEM images of the cross-section of Ni-P/PTFE composite coating (see Fig. 3) that the PTFE particles are uniformly distributed in the nickel-phosphorous matrix and the structure of coatings is very dense as well as crack-free.



**Figure 4.** XRD patterns of electroless Ni-P coatings deposited from the bath with and without PTFE particles.

Fig. 4 shows the XRD patterns of Ni-P coating and Ni-P/PTFE composite coatings. A broad peak around  $2\theta$  of  $40^\circ$ - $50^\circ$  with a sharp peak of  $45^\circ$  was observed. Due to the deposit thickness is thin, the diffraction peak ( $2\theta = 45^\circ$ ) related to the Fe atom from the substrate can be clearly seen. This rather broad peak indicates that the crystal microstructure of these electroless coatings is mainly amorphous. It is evident that incorporation of PTFE particles in electroless Ni-P matrix has not influenced the structure of the composite coating, which is consistent with the literature reports [17, 18]. The small peak around  $2\theta$  of  $18^\circ$  in the XRD patterns for the Ni-P/PTFE composite coatings having a higher PTFE content also confirms the presence of the PTFE particles embedded into the Ni-P matrix. The content of PTFE in the coating plated from the bath with 2.0 % PTFE is very small (less than 3 vol.%). So, PTFE diffraction peak cannot be seen in its XRD pattern.

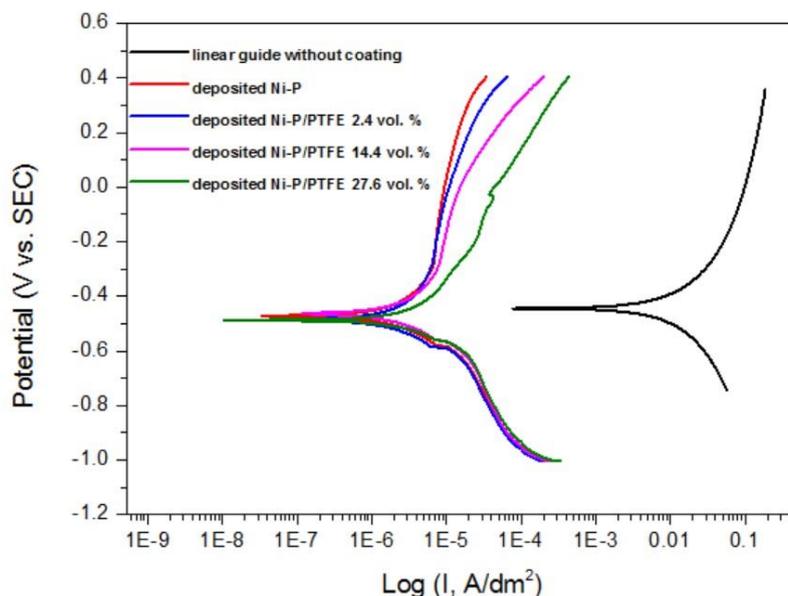
The contact angle and hardness of electroless Ni-P and Ni-P/PTFE composite coatings are also given in Table 3.

**Table 3.** The characteristics of Ni-P/PTFE composite coatings

Sample	Deposition rate (μm/h)	PTFE (vol.%)	Hardness (Hv)	Contact angle (degree)
PTFE 0.0 g/L	5.0	0.0	506	84
PTFE 2.0 g/L	5.0	2.4	472	94
PTFE 3.0 g/L	3.4	14.4	393	103
PTFE 5.0 g/L	3.3	27.6	325	113
PTFE 7.5 g/L	3.3	28.2	323	114

As expected, the contact angle increases and the hardness decreases with the content of PTFE particles in the coating. This can be attributed to the hyperphobic and soft nature of the lubricating particles.

3.2 Effect of Ni-P and Ni-P-PTFE composite coatings on the corrosion resistance



**Figure 5.** Polarization curves of medium-carbon steel substrate, deposited Ni–P coating and different PTFE contents within Ni–P/PTFE composite coatings in 3.5 wt.% NaCl solution.

In our previous study [19], the Ni-P coating and Ni–P/BN(h) composite coatings has an excellent corrosion resistance and can protect the iron substrate in 3.5wt.% NaCl solution. In order to enhance the self-lubrication of Ni-P coating, the different contents of PTFE particles were added into the bath to obtain the Ni-P-PTFE composite coatings in this study. Fig. 5 presents the deposited Ni-P coating and Ni–P/PTFE composite coatings have an excellent corrosion resistance and can effectively protect the medium-carbon steel substrates from the corrosive environment such as 3.5wt.% NaCl solution. Table 4 shows the corresponding corrosion parameters, including corrosion potential, corrosion current density, anodic Tafel slope  $\beta_a$  and cathodic Tafel slope  $\beta_c$  for medium-carbon steel

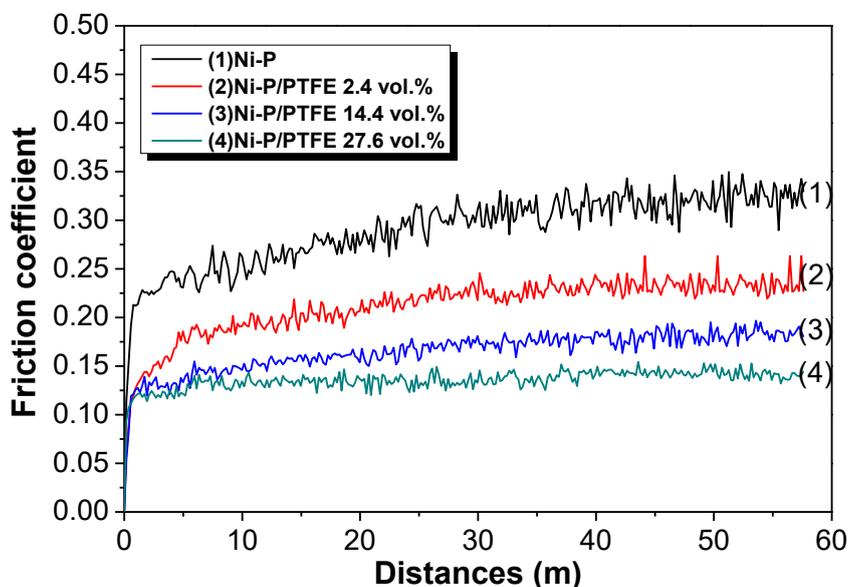
substrate, deposited Ni-P and different PTFE contents within Ni-P/PTFE composite coatings in 3.5 wt.% NaCl solution.

**Table 4.** Corrosion characteristics of medium-carbon steel substrate, deposited Ni-P and different PTFE contents within Ni-P/PTFE composite coatings in 3.5 wt.% NaCl solution.

Sample code	$\beta_a$ (V/ decade)	$\beta_c$ (V/ decade)	$I_{corr}$ (A/dm <sup>2</sup> )	$E_{corr}$ (V vs. SCE)
medium-carbon steel substrate	0.162	-0.148	$3.75 \times 10^{-3}$	-0.45
deposited Ni-P	0.152	-0.143	$1.86 \times 10^{-6}$	-0.49
deposited Ni-P/PTFE 2.4 vol.%	0.148	-0.144	$1.65 \times 10^{-6}$	-0.49
deposited Ni-P/PTFE 14.4 vol.%	0.131	-0.136	$1.52 \times 10^{-6}$	-0.49
deposited Ni-P/PTFE 27.6 vol.%	0.098	-0.114	$1.21 \times 10^{-6}$	-0.49

The adding PTFE particles will improve the corrosion resistance ( $i_{corr}$ ) of Ni-P and Ni-P composite coating from  $1.86 \times 10^{-6}$  to  $1.21 \times 10^{-6}$  A/dm<sup>2</sup>, due to PTFE particles enhance a barrier effect in Ni-P matrix such as the previous studies that incorporated BN(h) particles [19], SiC particles [20] and TiO<sub>2</sub> particles [21] into Ni-P matrix.

### 3.3 Wear property of Ni-P-PTFE composite coatings



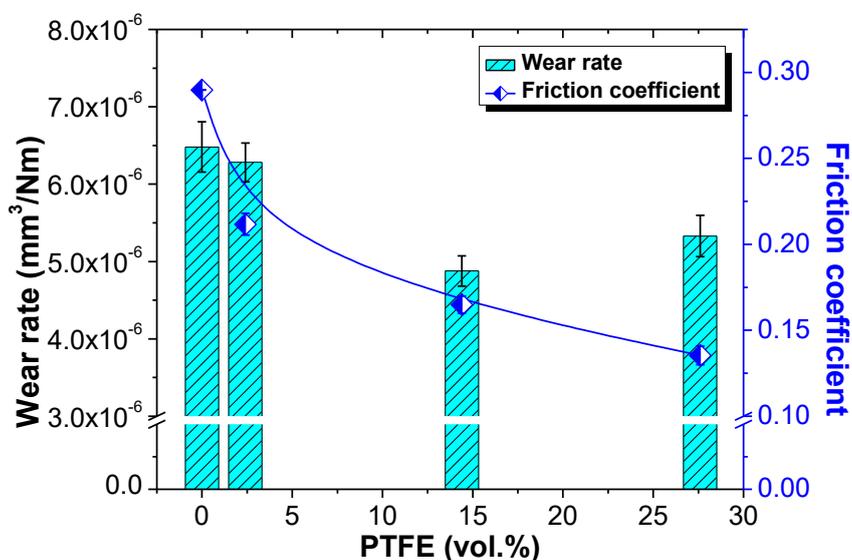
**Figure 6.** The friction curves of the various Ni-P/PTFE composite coatings deposited on medium-carbon steel substrates.

Fig. 6 shows the friction curves of coatings during the wear test. As seen from Fig. 6, the friction coefficient of Ni-P, Ni-P-PTFE 2.4 vol.%, Ni-P-PTFE 14.4 vol.%, and Ni-P-PTFE 27.6 vol.% is about 0.25 to 0.30, 0.2, 0.15 and 0.125, respectively. It is evident that the Ni-P coating has the higher value of friction coefficient than that of composite coating. As for the composite coatings, the friction coefficient decreases with the increase of PTFE contents. In Ni-P-PTFE composite coatings, the friction coefficient of composite coatings decreased with an increase of the incorporated volume percentage of PTFE particles within composite coatings can be ascribed to the PTFE particles would be thrust into the sliding surface by the shear force and formed a thin lubricated film led to increase the lubrication of sliding surface and reduce the friction coefficient of composite coatings during wear process [22].

In general, the wear resistance of coatings is affected by its hardness, strength and friction coefficient, etc. It is generally believed that the high hardness and low friction coefficient of coatings will improve its wear resistance [23, 24]. As mentioned above, the introduction of PTFE particles into the Ni-P matrix resulted in a decrease in both hardness and friction coefficient. It is, thus, interesting to investigate the effect of the incorporated PTFE content in the coating on the wear behaviors of Ni-P/PTFE composite coatings.

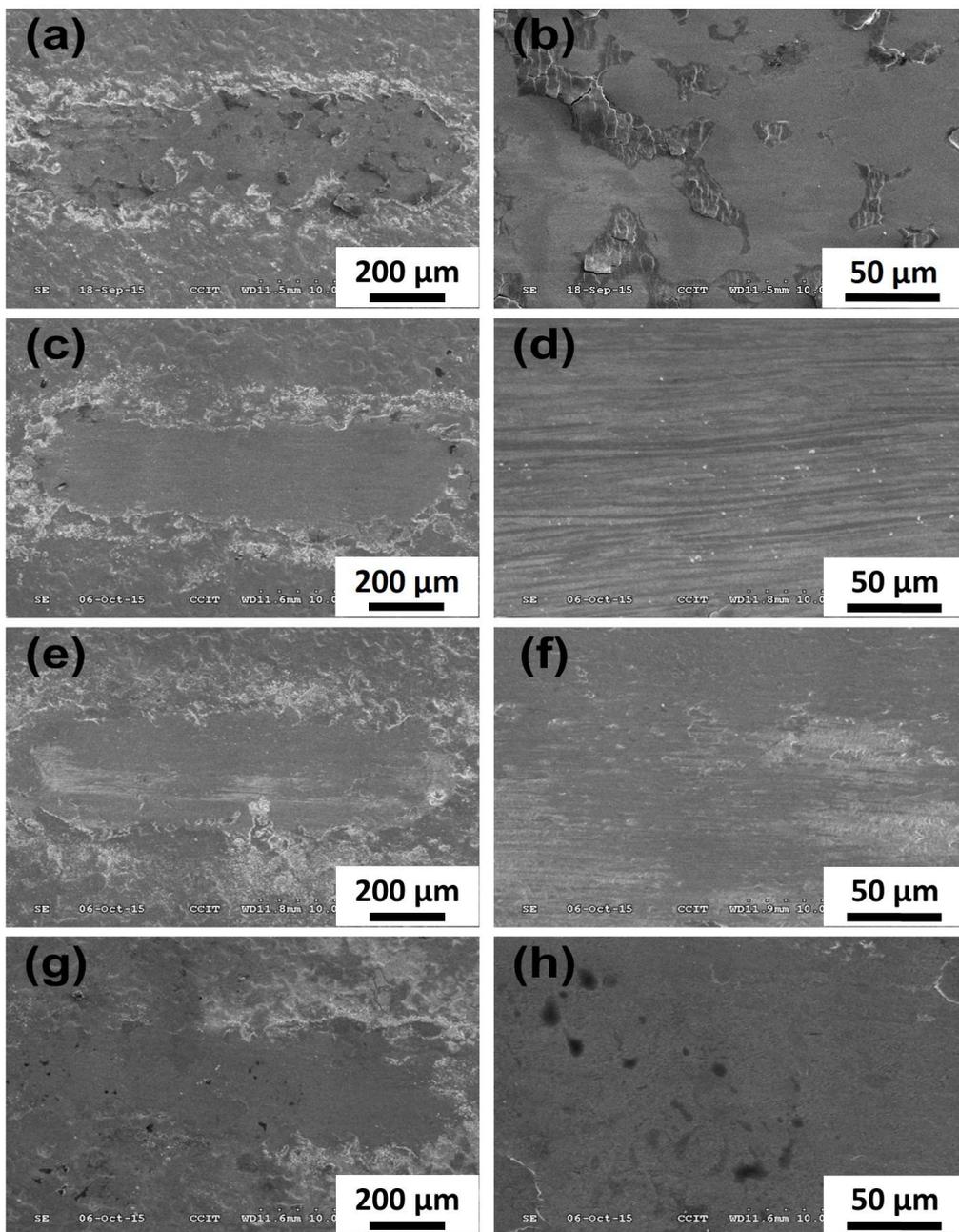
**Table 5.** The wear characteristics of various Ni-P/PTFE composite coatings

Sample	Average friction coefficient	Wear rate (mm <sup>3</sup> /Nm)
Ni-P	0.32	6.48E-06
Ni-P/PTFE 2.4vol.%	0.21	6.28E-06
Ni-P/PTFE 14.4vol.%	0.16	4.88E-06
Ni-P/PTFE 27.6vol.%	0.13	5.33E-06



**Figure 7.** The friction coefficient and wear rate of the various Ni-P/PTFE composite coatings deposited on medium-carbon steel substrates.

Fig. 7 and Table 5 show the wear rate and friction coefficient of composite coatings with different volume percentages of incorporated PTFE particles. It can be seen that the wear rate of Ni-P coating is  $6.48 \times 10^{-6} \text{ mm}^3/\text{Nm}$  and the wear rate of Ni-P/PTFE composite coating decreases from  $6.28 \times 10^{-6} \text{ mm}^3/\text{Nm}$  at incorporated PTFE particles of 2.4 vol.% to  $4.87 \times 10^{-6} \text{ mm}^3/\text{Nm}$  at incorporated PTFE particles of 14.4 vol.%, and then slightly increases to  $5.33 \times 10^{-6} \text{ mm}^3/\text{Nm}$  0.33 at incorporated PTFE particles of 27.6 vol.%.



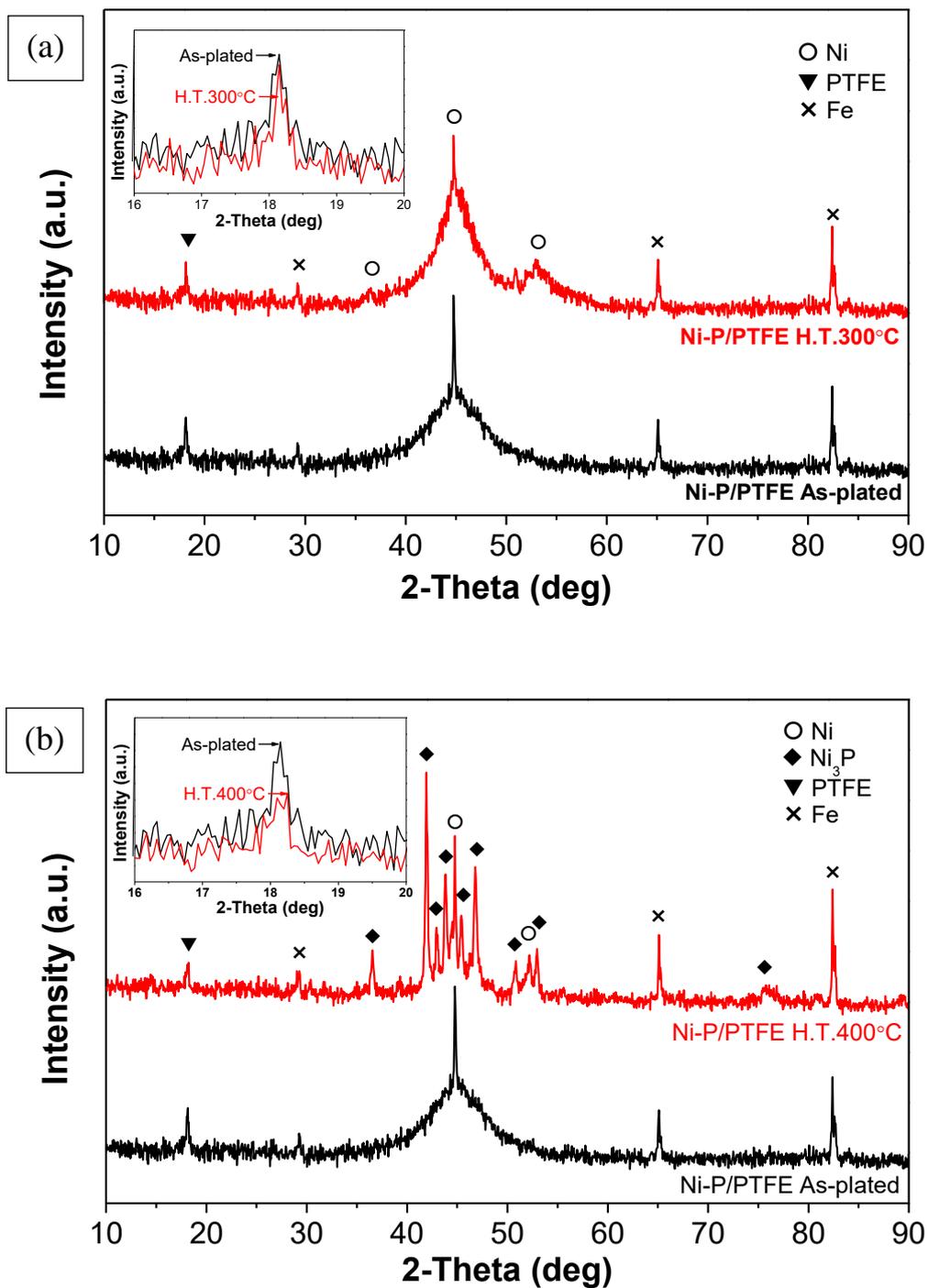
**Figure 8.** The worn morphology of the coatings with different volume percentage of PTFE particles within composite coatings: (a) 0 vol.%-100X, (b) 0 vol.%-500X, (c)2.4 vol.%-100X, (d)2.4 vol.%-500X, (e) 14.4 vol.%-100X, (f)14.4 vol.%-500X, (g)27.6 vol.%-100X, (h)27.6 vol.%-500X.

According to these results, it can be seen that there was an improvement in the wear resistance of the Ni-P/PTFE composite coating compared with the wear resistance of an electroless Ni-P coating and the Ni-P/PTFE 14.4 vol.% coating offers better wear properties. The Ni-P/PTFE 2.4 vol.% coating has a higher friction coefficient because of the lower incorporation of the PTFE lubricant nanoparticles in the coating. Therefore, the wear rate increases. In the case of Ni-P/PTFE 27.6 vol.% coating, despite the friction coefficient is lower than Ni-P/PTFE 14.4 vol.% coating, its wear resistance is inferior to that of Ni-P/PTFE 14.4 vol.% coating. The hardness of the Ni-P/PTFE 27.6 vol.% coating is less than that of the Ni-P/PTFE 14.4 vol.% coating (Table 3). As a result, the wear rate increases.

The SEM images of worn surfaces are shown in Fig. 8. The morphology of worn surface of Ni-P coating is shown in Fig. 8(a) and (b). It shows the coating flaked seriously, which is characterized as a typical adhesive wear. It results in the curve of friction coefficient gradually rising and shocking. The worn surface morphology of Ni-P/PTFE 2.4 vol.% PTFE coating shows moderate scratches which can be characterized as abrasive wear (Fig. 8(c) and (d)). Increasing the PTFE particles in the Ni-P matrix to 14.4 vol.%, the abrasive scratches decreases (Fig. 8(e) and (f)). The worn morphology presents a smooth surface when the Ni-P/PTFE incorporated with 27.6 vol.% of PTFE particles (Fig. 8(g) and (h)), the wear process runs smoothly and indicated the abrasive wear does not play a dominate role in this condition.

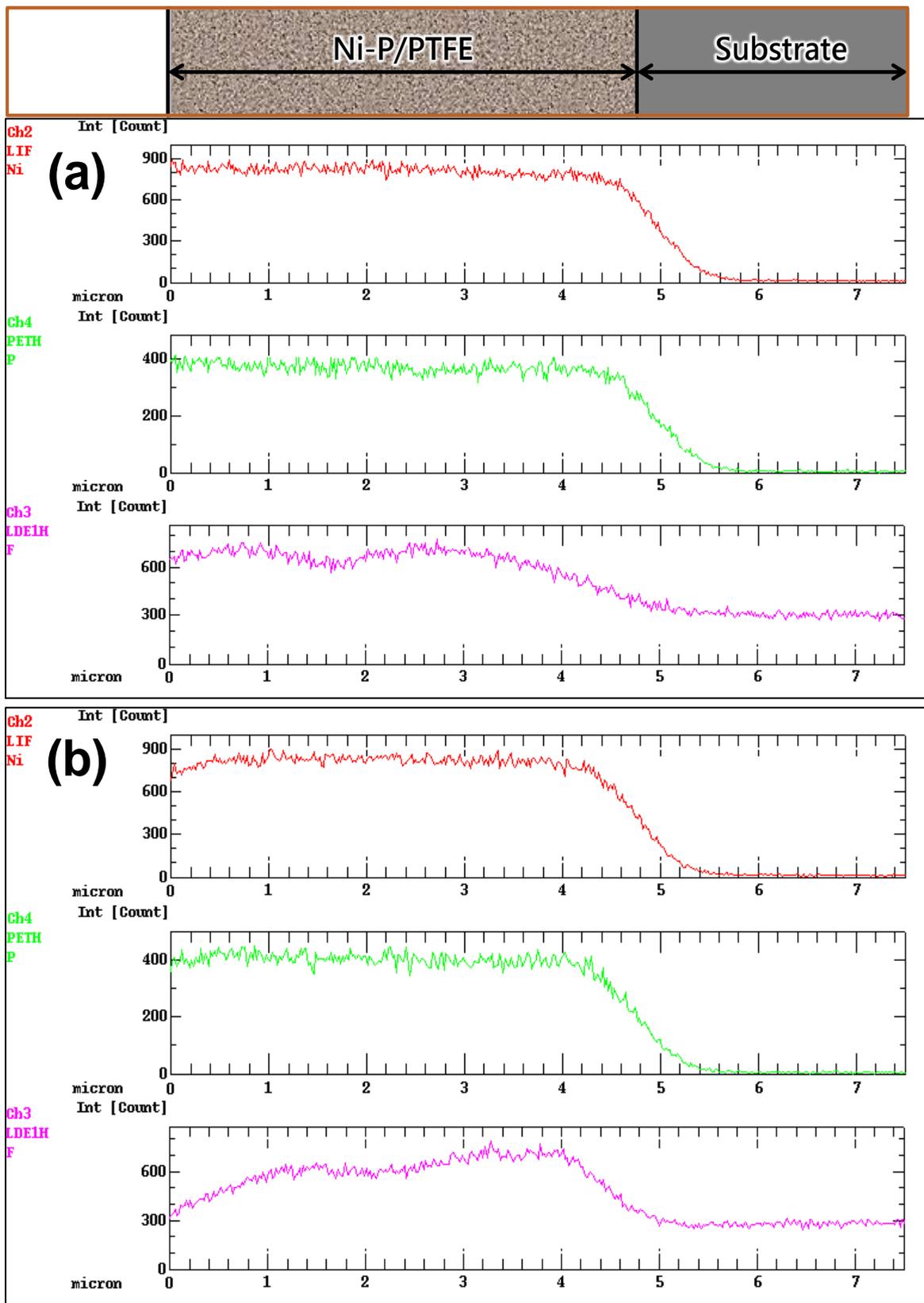
### 3.4 The heat treatment effect on mechanical properties of Ni-P-PTFE composite coatings

Wu et al. [4, 25] investigated the microhardness of Ni-P/PTFE composite coating and found that the hardness of Ni-P/PTFE composite coating increased after heat treatment and the coating annealed at 400°C had the maximum hardness. This was due to the formation of Ni<sub>3</sub>P compound resulting from the heat treatment. It leads to precipitation hardening of the coating. On the other hand, it has been reported that the decomposition of PTFE occurred at 320-350°C [26]. However, a controversial result can be observed in the literature. Yu et al. [14] reported that the Ni-P/PTFE composite coating after annealing at 400°C possessed the lowest friction and the highest wear resistance without any decomposition of PTFE. Therefore, the Ni-P/PTFE 14.4vol.% coating was heat-treated at 300 and 400°C, respectively, to examine the heat treatment temperature effect on the phase structure, composition, and the corresponding tribological properties. Fig. 9 shows the XRD patterns of Ni-P/PTFE coatings after heat treatment under different temperatures. It shows from Fig. 9(a) that there was no significant change in XRD pattern observed for the Ni-P/PTFE coating after annealing at 300°C. The inset of Fig. 9(a) compares the intensity of PTFE diffraction peak ( $2\theta = 18^\circ$ ) for the samples before and after heat treated at 300°C. It shows the intensity of PTFE diffraction peak for coating after heat treatment at 300°C was nearly unchanged as compared to as-deposited one. With a further increase annealing temperature to 400 °C, peaks of Ni and Ni<sub>3</sub>P appears in the XRD pattern for the heat-treated coating (Fig. 9(b)), suggesting the structure of the Ni-P matrix in the Ni-P/PTFE composite coating changed from amorphous Ni-P alloy to crystalline. Moreover, the intensity of PTFE diffraction peak for coating after heat treatment at 400°C reduces dramatically as shown in the inset of Fig. 9(b), indicated the decomposition of PTFE will occur at 400°C .



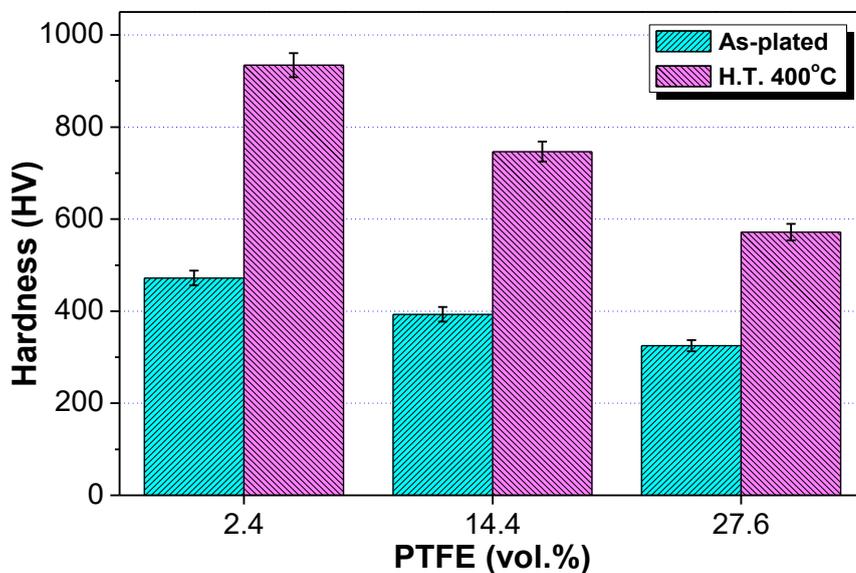
**Figure 9.** XRD patterns of Ni-P-PTFE composite coatings (a) as-plated and heat-treated at 300°C (b)as-plated and heat-treated at 400°C

To further confirm the decomposition of PTFE during the heat treatment at 300 and 400°C, the EPMA line scanning was carried out to detect the variation of bath elements (nickel, phosphorus and fluorine) in depth of Ni-P-PTFE composite coatings (see Fig. 10).

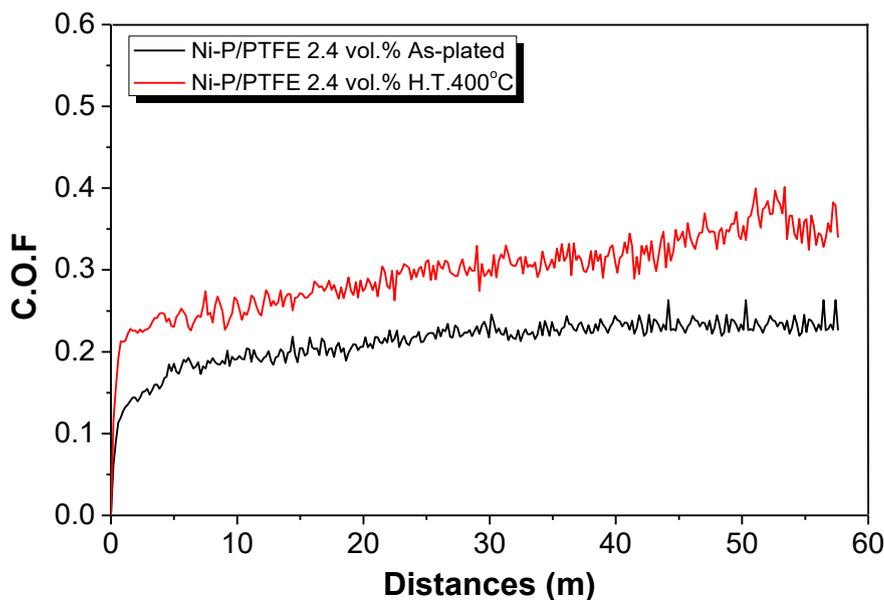


**Figure 10.** The profiles of EPMA line-scan analyzed for Ni, P and F in Ni-P-PTFE composite coatings (a) heat-treated at 300°C (b) heat-treated at 400°C.

Since PTFE molecules are composed of fluorine atoms, the distribution of fluorine atoms represents the distribution of the PTFE particles in the coating. Fig. 10(a) shows the EPMA line scanning of coating after annealing at 300°C. It can be clearly seen from Fig. 10(a) that the homogeneous distribution of the PTFE in the Ni-P matrix is still maintained even after heat treatment at 300°C.



**Figure 11.** The hardness of as-plated and heat-treated at 400°C of various Ni-P-PTFE composite coatings with different PTFE contents.



**Figure 12.** The friction curves of the as-plated and heat-treated at 400°C of Ni-P-PTFE 2.4 vol.% composite coatings.

However, Fig. 10(b) shows that a significant loss of fluorine element takes place within the area about 1  $\mu\text{m}$  from coating surface with higher heating temperature (400°C). This can be ascribed to the thermal decomposition of PTFE, which is consistent with the result found in the XRD pattern (Fig. 9(b)).

Fig. 11 shows the hardness of as-plated Ni-P/PTFE coatings and those annealed at 400°C (H.T. 400°C). It shows from Fig. 11 that the hardness for all Ni-P/PTFE composite coatings increase significantly after annealed at 400°C. The likely explanation to the enhancement of hardness of these Ni-P/PTFE coatings is the crystallization of Ni and the precipitation of Ni<sub>3</sub>P phase occurs at the annealing temperature of 400°C, which can be found clearly in the XRD patterns (see Fig. 9). However, the increase of hardness after heat treatment at 400°C depends on the corresponding PTFE content in the coating. It is worth to mention that the hardness of Ni-P-PTFE 2.4 vol.% composite coating is higher than that of Ni-P-PTFE 14.4 vol.% and Ni-P-PTFE 27.6 vol.%, both in as plated and heat-treated conditions. The reason for that might be ascribed to the less content of PTFE particles in the Ni-P matrix. The Ni-P/PTFE 2.4 vol.% composite coating exhibits the maximum hardness of 950 HV at the annealing temperature of 400°C. Since the hardness of the coatings increases after annealing, it is thus anticipated that the friction coefficient of heat-treated samples should be lower than those of as-deposited coatings. However, it shows from Fig. 12 that the friction coefficient of Ni-P/PTFE 2.4 vol.% composite coating heat-treated at 400°C increases to 0.3 in comparison to as-plated Ni-P/PTFE 2.4 vol.% composite coating, which the friction coefficient is about 0.21. It can also be attributed to lower PTFE content in the heat-treated coating owing to the decomposition of PTFE during the heat treatment process.

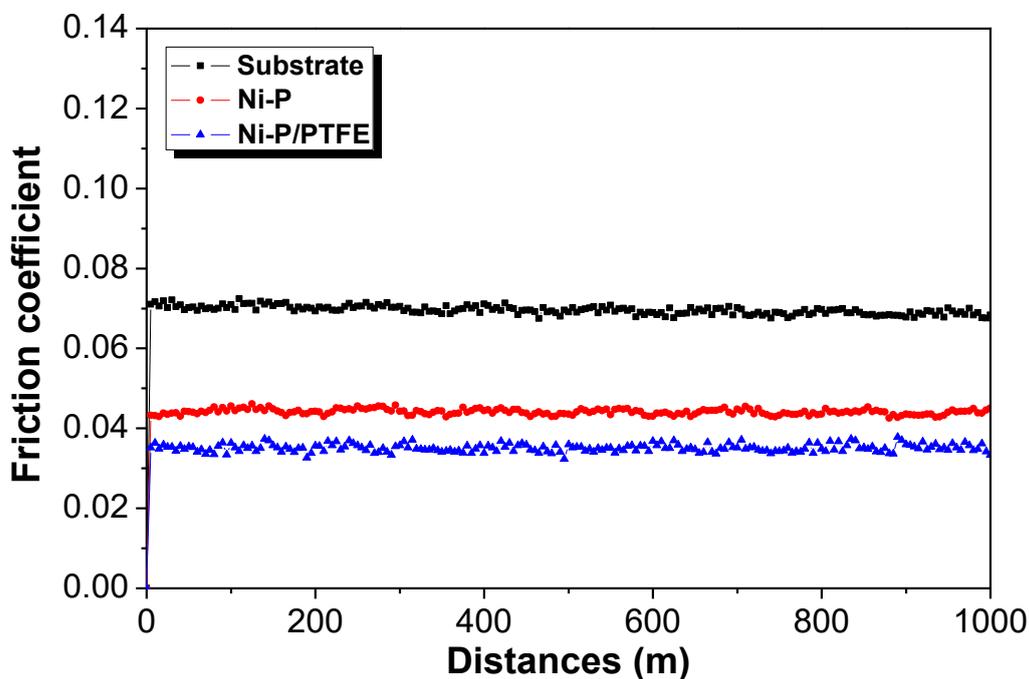
### 3.5 Wear test of real roller linear motion guides

**Table 6.** The thickness of Ni-P/PTFE 14.4 vol.% composite coating deposited at five different positions on real track of the linear motion guide

Measured position	A	B	C	D	E
Thickness ( $\mu\text{m}$ )	4.89	4.93	5.18	4.95	5.14

Table 6 presents the thickness of Ni-P/PTFE 14.4 vol.% composite coating deposited at five different positions on real track of the linear motion guide. It can be seen that a coating thickness of about 5  $\mu\text{m}$  is obtained on real track of the medium-carbon steel substrates. Then, the friction coefficient of bare substrate, Ni-P coated- and Ni-P/PTFE 14.4 vol.% coated-track of the medium-carbon steel substrates were measured with the linear motion guide tribometer. Fig. 13 shows the friction coefficient curves for these specimens. The bare medium-carbon steel substrate (linear motion guides) has the highest friction coefficient of about 0.07. The friction coefficient of the Ni-P coating is about 0.045. It can be also seen from Fig. 13 that Ni-P coating has the higher value of friction coefficient than that of Ni-P/PTFE composite coating (0.035). Thus, it is evident that the incorporation of the self-lubricant PTFE particles does play an important role in the friction reduction. By comparing Fig. 7 and Fig. 13, it is interesting to note that the friction coefficient of Ni-P/PTFE 14.4 vol.%

composite coating obtained from the linear motion guide tribometer (0.035) is four times less than that from the conventional ball on disk tribometer (0.15) despite the load used in the former (120 Kg) is much higher than that of the latter (6 N). This can be ascribed to the contact between load and test material for the linear motion guide tribometer is rolling contact and the load is distributed evenly to the balls. Consequently, the lower friction coefficient measured by this method is obtained as compared to friction coefficient measured by other methods.



**Figure 13.** The friction coefficient of Ni-P/PTFE and Ni-P coating deposited on tracks, respectively, measured by a linear motion guide tribometer.

Mohan et al. [27] developed an advanced linear reciprocating tribometer to investigate the oil flow pattern effect on the stick-slip behavior and dynamic coefficient of friction of the linear guide ways over a wide speed range from 0.1 to 6000 mm/min under lubricated conditions. The friction coefficient value reported in their study is in the range of 0.08-0.16. Based on our results, it is evident that this study does provide a possible route to develop the linear motion guideway that can be used under non-lubricated condition.

#### 4. CONCLUSIONS

In this study, the Ni-P/PTFE composite coating was deposited on medium-carbon steel substrates. The effects of the amount of incorporated PEFT particles in composite coatings and heat

treatment on hardness and self-lubrication properties of coatings were studied, the following conclusions can be drawn:

(1) The friction coefficient decreased with an increase of the incorporated amount of PTFE particles in composite coatings, the lowest friction coefficient of Ni-P/PTFE composite coating is about 0.125 when the amount of incorporated PEFT particles is about 27.6 vol. %, but the best wear rate of composite coating occurred at the amount of incorporated PTFE particles is 14.4 vol. % in the coating due to the effect of hardness decreases as the embedded PTFE content in the coating increases.

(2) Heat treatment at 400°C, on the one hand, promotes the hardness of Ni-P/PTFE composite coatings due to the precipitation of Ni<sub>3</sub>P phase. On the other hand, it deteriorates the friction property. The friction coefficient of composite coating will increase resulting from the decomposition of PTFE.

(3) An uniform thickness about 5 μm of Ni-P/PTFE composite coatings can be successfully deposited on medium-carbon steel substrates using electro-less plating process.

(4) The deposition of Ni-P coating on it can reduce the rolling friction coefficient of medium-carbon steel substrates from 0.07 to 0.045. The incorporation of 14.4 vol.% PTFE into Ni-P matrix can reduce the friction coefficient further to 0.035.

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