Improvement in The Working Life of A Micro Journal Bearings With An Electroless Ni-P Coating

Jin-Yih Kao (jykao@mail.lhu.edu.tw)
Lunghwa University of Science and Technology

Research Article

Keywords: electroless Ni-P, micro journal bearing, annealing, wear resistance, hardness

Posted Date: October 22nd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-993715/v1

Version of Record: A version of this preprint was published at The International Journal of Advanced Manufacturing Technology on January 26th, 2022. See the published version at https://doi.org/10.1007/s00170-022-08699-y.

Abstract

Wear is considered the main criterion to evaluate the mechanical performance of electroless Ni-P coating in a radial micro journal bearing (copper alloy, inner diameter 3 mm × outer diameter 5 mm × length 7 mm). The study was carried out using different coating parameter combinations, namely, solution pH values of (6, 7 and 8), deposition time (10, 20 and 30 min) and bath temperature (60, 80 and 95^{o}C). The structure, surface morphology, hardness and wear resistance of the electroless Ni-P coatings were measured and analyzed. The optimum combination of coating parameters for minimum wear is a pH value of 8, deposition time of 30 min and bath temperature of 95^{o}C. Further, the structural changes of the coatings before and after annealing treatment (100 ~ 700^{o}C) in a vacuum ambient were investigated by means of X-ray diffraction, while their elemental composition and surface morphology were analyzed using an energy dispersive spectrometer and a scanning electron microscope. The Ni-P films were subjected to annealing temperature at 400^{o}C for 1 hour, leading to recrystallization of the Ni matrix and the precipitation of Ni_3P. The hardness increases with increasing annealing temperature to a peak of 960 HV at 400^{o}C and then decreases monotonously.

1. Introduction

Electroless coatings, which utilize chemical catalysis and reduction reactions to solve the problems of surface treatment, are widely used in the aerospace, semiconductor, machinery, petroleum, electronic and chemical industries [1]. Electroless nickel coating, which does not require external current, is one kind of electroless coating process. The principle is to use the charge released by the reducing agent in the plating solution to supply the surrounding nickel ions. The reaction surface must have catalytic activity to reduce the nickel metal ions on the surface of the coated parts. The application and research of electroless coating are promoted with plating bath regeneration technology, adding additives and stabilizers to extend the working life of the plating solution and improve the quality of the coating products. Due to the development of high-tech and defense industries, the material properties and hardness requirements have been continuously improved. Thin film coatings meeting the properties required by high-tech and defense industries have been prepared to improve the wear resistance and corrosion resistance of materials [2], and new plating solution compositions, the performance and processing conditions, reduction of preparation costs and improvement of electroless coating technology are electroless coating technology research topics for the future.

Non-heat-treated electroless nickel coating film is metastable, and the structure of the metastable film is related to the phosphorus content. When the phosphorus content is high, the coating is amorphous, and the low phosphorus content can form microcrystalline. Gutzeit [3] reports the phosphorus content is less than 7 wt.%, and nickel-phosphorus alloy is a supersaturated solution of phosphorus in nickel crystals. Park and Lee [4] mentioned phosphorus content above 10 wt.% is completely amorphous. When Jones et al. [5] studied amorphous nickel-phosphorus alloys, they found the main effect of phosphorus in nickel-phosphorus alloys is the overpassive behavior shifts to low potential. This phenomenon also increases the current density in the passive and overpassive regions. Bai et al. [6] showed the adhesion strength between DLC films and nitrile-butadiene rubber first increases and then decreases along with the change in Ar plasma pretreatment time. Hsu et al. [7] found Ni-P films have greater hardness and fatigue life as the concentration of phosphorus gradually decreases from 17.07 to 16.83 at.%. Czagány et al. [8] found the microhardness increases with increased P content in Ni-P coating after annealing treatment. Many studies mention electroless nickel coating has better corrosion resistance because electroless nickel coating is an amorphous coating and has better corrosion resistance than the crystalline phase [9–11]. Following proper heat treatment of the phosphorus content of the coating film below 15 wt.%, the coating structure changes from amorphous to crystalline structures of Ni and Ni_3P. In Allen and Vander Sande research [12], the amorphous nickel phosphorus matrix was replaced by nickel FCC crystals at 247^{o}C, and Ni_3P was precipitated and grown above 367^{o}C.

Ever increasing demands of structures and components with regard to aerospace, military and transport industries require the development of advanced transmission mechanisms. The bearing, which controls the high accuracy and stability of machinery, is an indispensable key supporting component in the rotating or linear moving mechanism of machinery. In general, bearing operating modes can be divided into gas, magnetic levitation, hydrostatic pressure, hydrodynamic pressure, and rolling types. However, the efficiency requirements of industrial equipment are getting higher and higher, and the speed of the rotating mechanism is continuously increasing. When the speed increases, the micro-bearing operating inside the rotating mechanism will reduce the working life and increase the amount of vibration. The low working life of the bearing will lead to increased manufacturing costs and vibration in power transmission. Therefore, a metal nickel layer is prepared using the electroless coating method to achieve the effects of high hardness, corrosion resistance and wear resistance on the smaller copper bearing. However, the amount of phosphorus in the electroless nickel coating layer depends on the pH value of the plating solution, the deposition time, the temperature of the plating solution, the content of the nickel salt and the reducing agent and other supplemental liquid content factors. In this study, the electroless coating parameters (pH value, deposition time and bath temperature) were changed to find the optimal parameters with the smallest micro journal bearing wear. Nickel-coated micro-bearing are annealed under various temperatures (100, 200, 300, 400, 500, 600 and 700^{o}C) at the same time to analyze the effects of the film surface microstructure, crystal properties, microhardness, roughness and abrasion tests.

2. Experimental Procedures

2.1 Electroless coating process

To obtain high-quality micro journal bearing (copper alloy) working life, this study found the best pretreatment time through SEM morphological observation, and by changing the electroless coating parameters on the film (pH value of the plating solution, deposition time, bath temperature) to understand its surface structure, crystallization properties and microhardness. After the influence of roughness and the abrasion test, the nickel-coated bearing and the un-nickel-coated copper bearing are subjected to subsequent annealing treatment at the same time.

The material specification and dimensions of the micro journal bearing used in this experiment are C2600 copper alloy and 3 (inner diameter) ×5 (outer diameter) ×7 (length) mm^3. The copper alloy has good mechanical properties, such as hole expandability, bendability, stamping process ability and electroplating. The copper plate size is 20×20×1 mm^3 and is used for measuring mechanical properties. The surface of the copper plate is polished with water sandpaper (grain size #1000), and then further polished with a cloth wheel. In addition, pretreatment is a very important factor affecting the quality of the electroless nickel film. If the current treatment is not carried out, it will reduce the adhesion of the coating film, making the surface rough with many defects. The pretreatment in this study includes cleaning, roughening and activation. The purpose of cleaning is to remove oil, organic compounds, oxide layers and impurities on the surface of the workpiece, with isopropanol and deionized being utilized water to clean it by ultrasonic vibration for 10 minutes. The roughening treatment can obtain appropriate substrate surface roughness. The roughening formula is a mixed solution of chromic acid and sulfuric acid (H_2CrO_4+H_2SO_4). The activation treatment uses diluted hydrochloric acid (HCl) to make the surface of the substrate have catalytic activity. The surface energy of the active workpiece helps improve the quality of the electroless coated workpiece. The pretreatment solution for roughening and activation is shown in Table 1.

Table 1
Pretreatment solution for roughening and activation.

Pretreatment liquid	**Composition**	**Content (g/L)**
Roughening liquid	H_2CrO_4	120
	H_2SO_4	10
Activation liquid	HCl	100

The composition of the electroless coating solution used in this study is shown in Table 2. The pH value of the electroless coating solution is adjusted with diluted ammonia water, and the entire process of making the electroless coating solution is stirred and circulated with magnets. When the electroless coating solution is heated to the required temperature, the workpiece is placed in the bath for electroless coating. Fig. 1 is a schematic diagram of the electroless coating experiment.

Table 2
Composition of the electroless coating solution.

Process liquid	Composition	Content (g/L)
Chemical plating solution	$NiSO_4$	25
	$NaH_2PO_2 + H_2O$	25
	$Na_3C_6H_5O_7$	40
	NH_4Cl	30

Whether a good product quality is prepared or not depends on the deposition parameters of the pretreatment and electroless coating processes. Most of the pretreatment time specifications for roughening and activation are less than 5 minutes. Therefore, three changes of 1, 3 and 5 minutes are used to determine the surface morphology of pretreatment. The experimental parameters of the pretreatment are shown in Table 3. The electroless coating parameters, which include the pH value of the solution, deposition time, bath temperature and stirring, affect the coating results. The selected experimental parameters of the electroless nickel coating are shown in Table 4. Twenty-seven workpieces were prepared by electroless nickel coating, and the best chemical plating parameters were obtained after a bearing abrasion test. In addition, this study explores the effects of the vacuum annealing temperature (100, 200, 300, 400, 500, 600 and 700^{o}C) on the characteristics of electroless coating. The vacuum pressure is 1×10^{-1} torr, the heating rate is 20 ^{o}C/min, and the holding temperature is 1 hour. The furnace cooling method is used to cool to room temperature. The experimental parameters of the heat treatment are shown in Table 5.

Table 3
Experimental parameters of pretreatment.

Temperature	0^{o}C
Magnet stirring rate (fixed)	300 rpm
Roughening (min)	1, 3 and 5
Activation (min)	1, 3 and 5

Table 4
Experimental parameters of electroless nickel coating.

Magnet stirring rate (fixed)	300 rpm
pH of value	6, 7 and 8
Bath temperature	60, 80 and 95^{o}C
Deposition time	10, 20 and 30 min

Table 5
Experimental parameters of heat treatment.

Vacuum pressure	1×10^{-1} torr
Heating rate	20 ^{o}C/min
Cooling method	Furnace cold
Holding time	1 hr
Heat treatment temperature (1×10^{-1} torr)	100 ~ 700^{o}C

2.2 Experiment equipment

To obtain the data of micro journal bearing (copper alloy, Fig. 2a) working life, a self-developed testing machine was used to perform the abrasion test, as shown in Fig. 2 (b). The life testing machine includes: motor control timer (1), support base (2), ball sliding rod (3), working area (4), three-jaw chuck (5) and variable frequency motor (6). The test parameters are set to 2000 rpm of the bearing, wear time of 3 min and tested bearing load of 1 kg (shorten the life test time). The bearing wear amount is the weight of the bearing before wear minus the weight of the bearing after wear. The high-speed steel bars and bearings are subjected to wear tests in the working area. The high-speed steel bars are 2.8 mm in diameter and 200 mm in length. The nickel-coated micro journal bearing is 3 mm in inner diameter, 5 mm in outer diameter and 7 mm in length.

The structure of the thin film was analyzed using an X-ray diffractometer (Rigaku-2000 X-ray generator), and the XRD diffraction peak pattern obtained was compared with the JCPDS Card to determine the structure of the thin film. A field emission scanning electron microscope (SEM, JEOL JSM-6500F) was used to observe the surface morphology of the electroless nickel coating film. A surface profiler (α-step; ET-4000A) is used to measure the surface roughness. The α-step measurement is a mechanical transmission method. A rapid thermal processing (RTP) system is used to perform vacuum annealing treatment. A micro-nano hardness tester (HM 2000 series) is used for the indentation test, with the load being ≤ 200 gf. The indentation depth was set to 1/10 of the film thickness, the fixed load was 20 μN, and the indentation duration was 20 s. The average of each indentation was 5 times. The Vickers hardness test uses the stress of the indentation area as a hardness measurement. It uses a regular quadrangular pyramid diamond to press, and the indentation depth is shallow (the workpiece damage is small). The calculation formula of Vickers hardness is as follows:

$$HV = 0.204F\sin(\alpha/2)/d^2 \approx 0.1891F/d^2 \quad (1)$$

where F is the load of Vickers hardness (N), d is the indentation diagonal length (mm) and α is the angle between the opposite side of the indenter (136^{o}).

3. Experimental Results And Discussion

3.1 Effect of pretreatment on surface morphology

The quality of the pretreatment (roughening and activation) greatly influences the surface mechanical properties of the electroless coated parts. This preliminary experiment was carried out to understand the influence of the surface morphology of the workpiece and to determine the optimal pretreatment time. Fig. 3 shows the surface morphologies of without and with roughened substrates. Fig. 3(b) shows less corrosion, while Fig. 3(c) or Fig. 3(d) clearly display more corrosion. As the roughening time increases, the large surface roughness improves the nickel layer's adhesion. However, excessive corrosion will reduce the mechanical performance of the substrate. Therefore, roughening of 1 minute was selected as the benchmark before activation. Fig. 4 shows the surface morphologies of the activated substrates. The activating solution is a dilute solution of hydrochloric acid. Corrosion will also occur, and the corrosion pores will be coarser. From Fig. 4, activation of 5 minutes was selected to make the benchmark before electroless nickel coating.

3.2 Abrasion test

Fig. 5 shows the experimental results of micro journal bearing wear at different deposition parameters (6-8 pH values, 60-95 ^{o}C bath temperatures and 10-30 min deposition times). The bearing wear of 60^{o}C bath temperature is greater than that of the copper bearing substrate. It may be speculated the nickel layer is not attached to the bearing due to the low temperature of the plating solution and the pretreatment erosion. At a bath temperature of 80^{o}C and 95^{o}C, the pH value of 8 has lower abrasion than the other pH values of 6 and 7, indicating the chemical nickel plating of the alkaline plating solution has better wear resistance. At 95^{o}C, the abrasion is lower than 80^{o}C (pH value of 8). It is possible the higher bath temperature of the plating solution makes the deposition speed faster, the thickness of the nickel coating thicker, and the abrasion resistance increase. Therefore, a pH value of 8, bath temperature of 95^{o}C, and deposition time of 30 minutes are the selected deposition parameters in this study. Fig. 6 is a comparison diagram of wear with and without heat treatment for electroless nickel coating. The with heat treatment nickel-coated bearings have less wear than subtrates (copper bearings) and without heat treatment nickel-coated bearings, and the minimum wear of 400 ^{o}C annealing temperature for electroless nickel coating is 0.1 mg. Fig. 7 shows the surface morphology of wear for the copper bearings, chemical nickel-coated bearings (pH value of 8, bath temperature of 95^{o}C, deposition time of 30 min) and heat treatment nickel-coated bearings (100 ~ 700^{o}C). The wear of copper bearings is more serious than that of the nickel-coated bearings. The abrasion situation of the nickel-coated bearing at 400^{o}C is slight, the abrasion crack is large at 600^{o}C, and the surface products still exist after the heat treatment at 700^{o}C.

3.3 Surface morphology and composition analysis

Fig. 8 shows the top and side views of the different deposition times of the electroless nickel coating film (pH value of 8 and bath temperature of 95^{o}C). It can be seen the longer the deposition time, the better the nickel grain size and denseness. The film thickness was approximated by an average of three position point rulers. The film thickness values following deposition for 10, 20 and 30 minutes were 1.43, 2.42 and 3.58 μm, respectively. Fig. 9 shows the surface morphology of electroless nickel coating (pH value of 8, bath temperature of 95^oC and deposition time of 30 min) at different heat treatment temperatures. There are cracks at 600^oC and the obviousness of grains at 700^oC is worse than others. Fig. 10 shows the elemental analysis of electroless nickel coating film (pH value of 8 and bath temperature of 95^oC) at different deposition times. It is confirmed for the composition of nickel and phosphorus elements, the longer the deposition time, the more the phosphorus element will increase. Fig.11 shows the elemental analysis of heat treatment temperature (100 ~ 700^oC). Zinc is precipitated at 600^oC; oxides are generated at 700^oC. It is estimated the reason for the sudden increase in wear at 600 ^oC and 700^oC is related to the surface products.

3.4 Roughness measurement

Fig. 12 shows the surface roughness for the substrate, pretreatment and electroless nickel coating (pH value of 8, bath temperature of 95^oC) at different deposition times. The surface roughness values are averaged after measured three different positions. The surface roughness of the substrate slightly increases after pretreatment. Electroless nickel coatings (pH value of 8, bath temperature of 95^oC for 10, 20 and 30 minutes) show the longer the deposition time, the greater the surface roughness. It was found the surface roughness was directly proportional to the deposition time of the electroless nickel coating. Fig. 13 shows the correlation between surface roughness and annealing temperature for electroless nickel coating film after a heat treatment time of 30 min. Compared with heat treatment abrasion (Fig. 6), it can be seen the higher the surface roughness is, the higher the wear amount is. The minimum surface roughness (0.177 μm) is at 400^oC.

3.5 Structural analysis of deposition film

Fig. 14 shows the diffraction XRD patterns for substrate and electroless coating times of 10, 20 and 30 minutes (pH value of 8, bath temperature of 95^oC). It can be seen the electroless Ni-P thin film is an amorphous structure. However, there is a strong camel peak ($2θ=45^o$) at an electroless coating time of 30 min. Fig. 15 shows the diffraction XRD patterns of the Ni-P thin film after annealing (100^oC~700^oC). It can be seen the Ni-P thin film is still amorphous at a lower annealing temperature (200^oC). When the annealing temperature is 300^oC, Ni-P films have Ni_3P diffraction peaks at $2θ = 48^o$. When the annealing temperature reaches 400^oC, the Ni-P films have crystalline Ni and Ni_3P structures [13]. Due to the precipitation hardening effect of Ni_3P, the hardness of the coating is increased. Allen and Vander Sande [12] found a heat treatment temperature for Ni-P films of above 367^oC will create Ni_3P precipitates. Ni is dissolved in Ni_3P during high phosphorus content coatings, and Ni_3P is dissolved in Ni during low phosphorus content coatings. When the annealing temperature is higher than 400^oC, the Ni-P film has no obvious diffraction peak.

3.6 Hardness test

Table 6 shows the hardness values of substrate and chemical nickel plating film for different deposition times under a pH of 8 and bath temperature of 95°C. In Table 6, the hardness values of substrate are clearly smaller than the chemical nickel plating film for different deposition times. However, the hardness values of chemical nickel plating film for different deposition times are not much different from one another. Table 7 shows the hardness values of as-deposited (deposition time of 30 min) and chemical nickel plating film following heat treatment. The experimental results show the hardness value of chemical nickel plating film after heat treatment is significantly better than as-deposited. The maximum hardness reached 960 HV at an annealing temperature of 400°C. The hardness value slightly increases at an annealing temperature of 100°C to 300°C, but did not reach the indentation hardness of 400°C. It is presumed no Ni_3P crystal phase was generated. Besides, there is no precipitation hardening effect to make the hardness drop greatly change. Comparing the diffraction XRD patterns of the Ni-P thin film after annealing treatment, the diffraction peak at an annealing temperature of 500°C becomes lower and it becomes inconspicuous, and it is known zinc is precipitated above 600°C. When the annealing temperature reaches 700°C, oxides are generated. As the annealing temperature is higher than 400°C, it is speculated the softening tendency of the indentation hardness is caused by the above reasons. Table 8 shows the hardness values without and with heat treatment (without Ni-P coated). It can be observed the higher the heat treatment temperature, the lower the hardness is. The main reason is the surface has no coating layer. There are differences in hardness obtained by heat treatment of different components.

Table 6
Hardness values of substrate and chemical nickel plating film for different deposition times under a pH value of 8 and bath temperature of 95°C.

Deposition time (min)	HV1	HV2	HV3	HV4	HV5	Avg.
Substrate (none)	117.9	150.2	143.3	123.7	129.1	132.8
10	465.3	473.7	466.4	430.5	446.8	456.5
20	470.5	425.3	455.0	460.3	443.1	450.8
30	471.1	462.2	467.5	442.9	453.0	459.3

Table 7
Hardness values of as-deposited (deposition time of 30 min) and chemical nickel plating film following heat treatment.

Annealing temperature (°C)	HV1	HV2	HV3	HV4	HV5	Avg.
As-deposited (none)	471.1	462.2	467.5	442.9	453.0	459.3
100	483.0	478.1	496.7	512.5	491.2	492.3
200	506.4	511.0	493.9	487.2	518.3	503.4
300	515.9	510.1	536.0	528.4	527.5	523.6
400	923.6	954.4	980.7	965.0	978.1	960.4
500	834.0	843.6	849.0	810.3	814.2	830.2
600	691.3	713.8	699.2	704.7	711.0	704.0
700	697.7	661.4	680.8	653.0	675.6	673.7

Table 8
Hardness values without and with heat treatment (without Ni-P coated).

Annealing temperature (°C)	HV1	HV2	HV3	HV4	HV5	Avg.
Substrates (none)	117.9	150.2	143.3	123.7	129.1	132.8
100	128.8	123.7	125.6	130	127.3	127.1
200	120	125.3	121.4	117.8	119.2	120.7
300	120.4	115	113.1	119.4	116.5	116.9
400	108.7	109.1	110.8	113.5	115	111.4
500	105.6	101.4	108.8	103.6	109.6	105.8
600	101.7	99.8	97.3	103.1	95.6	99.5
700	98.1	90.5	89.3	96.1	92.4	93.3

4. Conclusions

This study used electroless coating to prepare a metal nickel layer on a radial micro journal bearing (copper alloy, inner diameter 3 mm × outer diameter 5 mm × length 7 mm). The parameters of the electroless coating process (pH value of the solution, deposition time and bath temperature) were changed to prepare nickel-coated bearings with a nickel-coated workpiece, and then vacuum annealing treatment (100~700°C). The experimental results are summarized as follows:

1. The amount of pretreatment time will affect the quality of subsequent processing. The corrosion pores are less slightly corroded for 1 minute, and the corrosion is more obvious for 3 or 5 minutes. The

roughening improves the surface roughness of the substrate and increases the adhesion of the coating layer. However, excessive corrosion reduces the performance of the substrate. Roughening for 1 min was selected as the baseline before activation. The purpose of activation is to make the surface of the substrate catalytically active, causing the corrosion pores to shrink and the surface oxides to be removed by the reaction. An activation time of 5 minutes is used as the benchmark prior to electroless nickel coating.

2. The minimum wear of chemical nickel plating on micro journal bearing with optimal parameters (pH value of 8, bath temperature of 95^{o}C and deposition time of 30 minutes) was 0.5 mg. Electroless nickel-coated bearings are prepared with the best parameters and uncoated bearings are subjected to vacuum annealing heat treatment (100 ~ 700^{o}C) together. It is known the wear of the coated bearings is less than the uncoated wear, and the heat treatment at 400^{o}C has the best resistance of 0.1 mg.

3. According to the surface morphology of the electroless nickel coating film, it is known the longer the deposition time, the more uniform the grain size and the better the nickel density. The surface morphology of 600^{o}C heat treatment has cracks. The elemental analysis chart shows zinc is precipitated. The surface morphology of 700^{o}C is significantly worse than other grains and oxides are generated. The reason for the sudden increase in bearing wear during heat treatment at 600 and 700^{o}C is presumed to be related to surface precipitation.

4. After the micro journal bearing is pretreated by the process of electroless nickel coating, the roughness increases, and the roughness of the deposition time is higher than that of the deposition time. The surface roughness is directly proportional to the deposition time of the electroless nickel coating. Comparison of the roughness values at different heat treatment times with the heat treatment wear diagram shows the higher the surface roughness, the higher the wear amount. The surface roughness is also proportional to the bearing wear amount. The minimum roughness at a heat treatment of 400^{o}C is 0.177 μm.

5. It is shown the electroless coating Ni-P thin film is an amorphous structure, and there is a strong camel wave peak (2θ = 45^{o}) during the deposition time of 30 min. When the annealing temperature reaches 400^{o}C, Ni-P films have crystalline structures of Ni and Ni_3P. Due to the precipitation hardening effect of Ni_3P, the hardness of the coating is increased. When the annealing temperature is higher than 400^{o}C, the Ni-P films have no obvious diffraction peaks.

6. The experimental results show the hardness of the nickel-coated film is significantly increased on the substrate, and the hardness values are similar at different deposition times. When the temperature is 100~300^{o}C, the hardness value is slightly increased, but not higher than the indentation hardness of 400^{o}C, and the maximum hardness is 960 HV when the annealing heat treatment is 400^{o}C. The reason is the hardness of the coating is improved by the precipitation hardening effect of Ni_3P, and the XRD diffraction peak at 500^{o}C becomes lower. However, it is not obvious at first, and it is known zinc is

precipitated above 600^{o}C; oxides at 700^{o}C are generated. An indentation hardness above 400^{o}C shows a softening trend, which is presumed to be caused by the above reasons.

Declarations

Acknowledgements The authors gratefully acknowledge the support of the Ministry of Science and Technology of the Republic of China, through Grant nos. MOST 109-2221-E-262-003.

Code availability Not applicable.

Author contribution JinYi Kao: conceptualization, experimentation, characterization, validation, analysis, writing - original draft.

Funding The authors appreciate the financial support of the Ministry of Science and Technology of the Republic of China (MOST 109-2221-E-262-003).

Data availability All necessary data is shown in the figures and Tables within the document. The raw data can be made available upon request

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent to publish Not applicable.

Conflict of interest The authors declare no competing interests.

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Figures

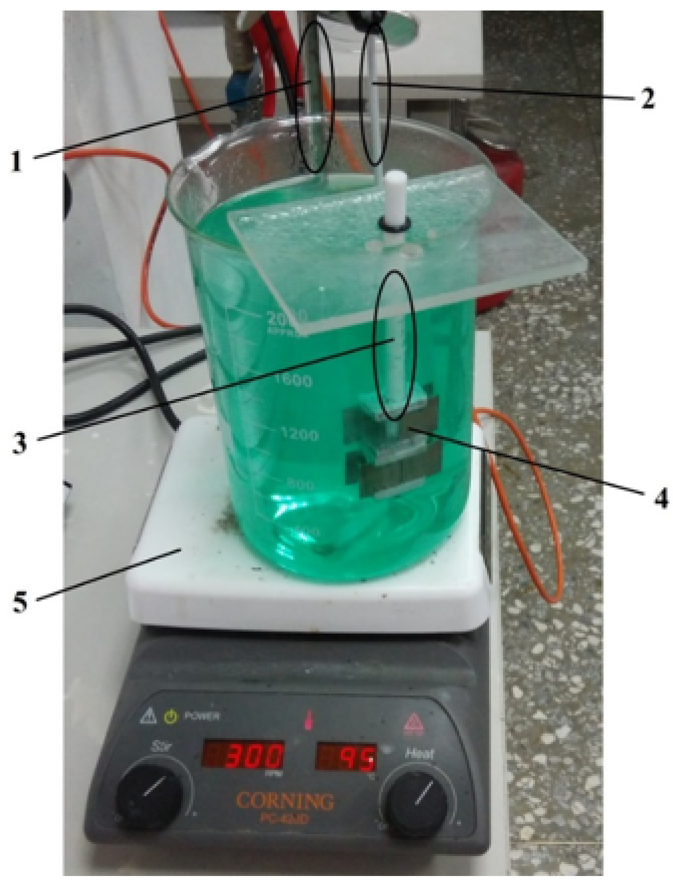
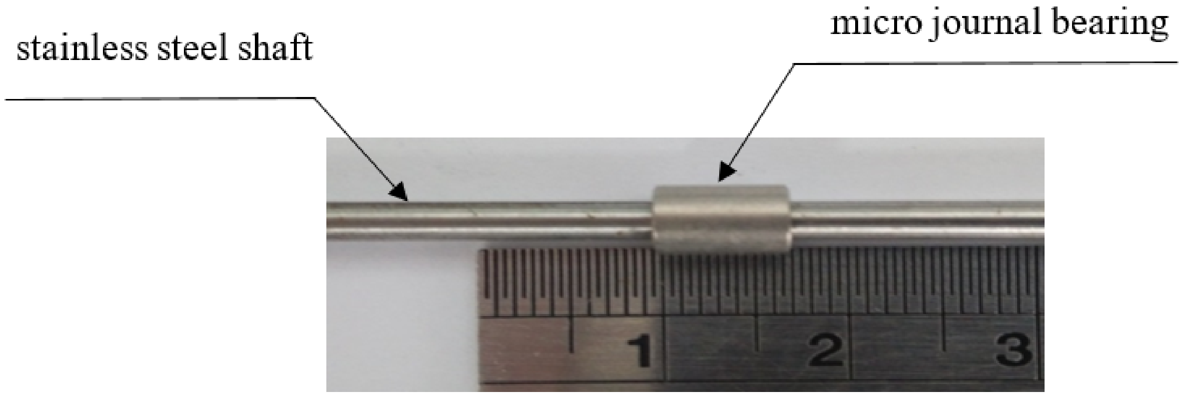
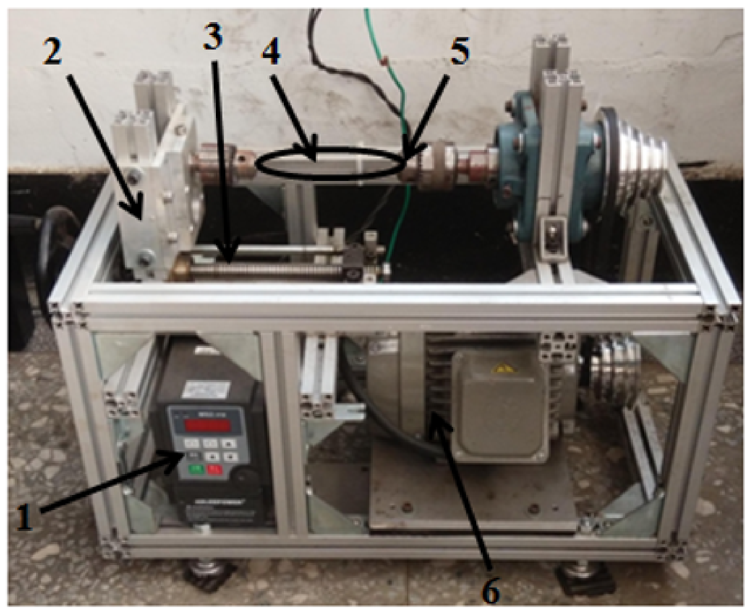


Figure 1

Schematic diagram of the electroless coating experiment: (1) Support frame, (2) Temperature sensor, (3) Workpiece carrier (Teflon), (4) Plated Workpieces and (5) Heating plate.



(a) Micro journal bearing (inner diameter 3 mm × outer diameter 5 mm × length 7 mm)



(b) Micro journal bearing life tester

Figure 2

Micro journal bearing and life tester.

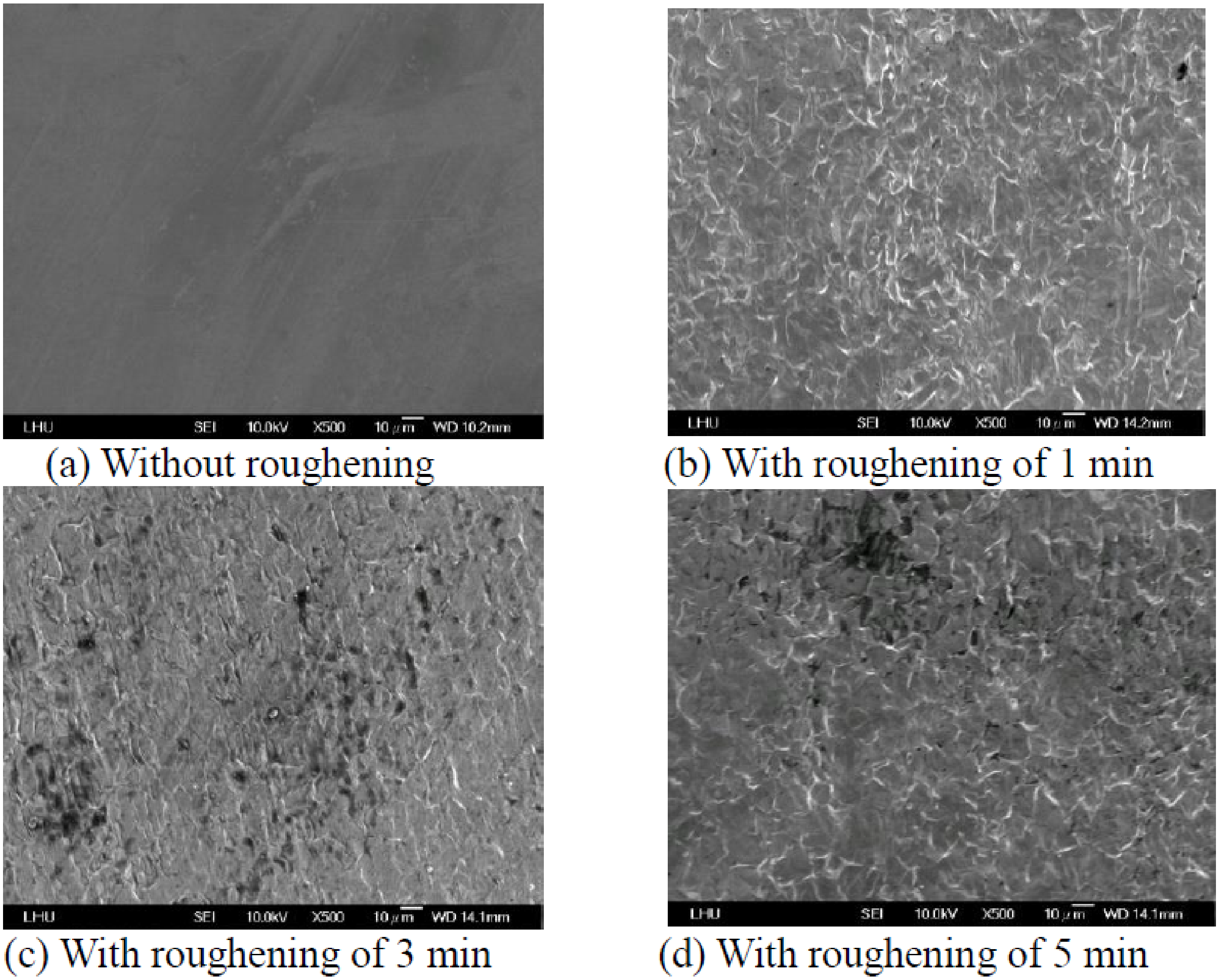


Figure 3

Surface morphology of without and with roughening substrates.

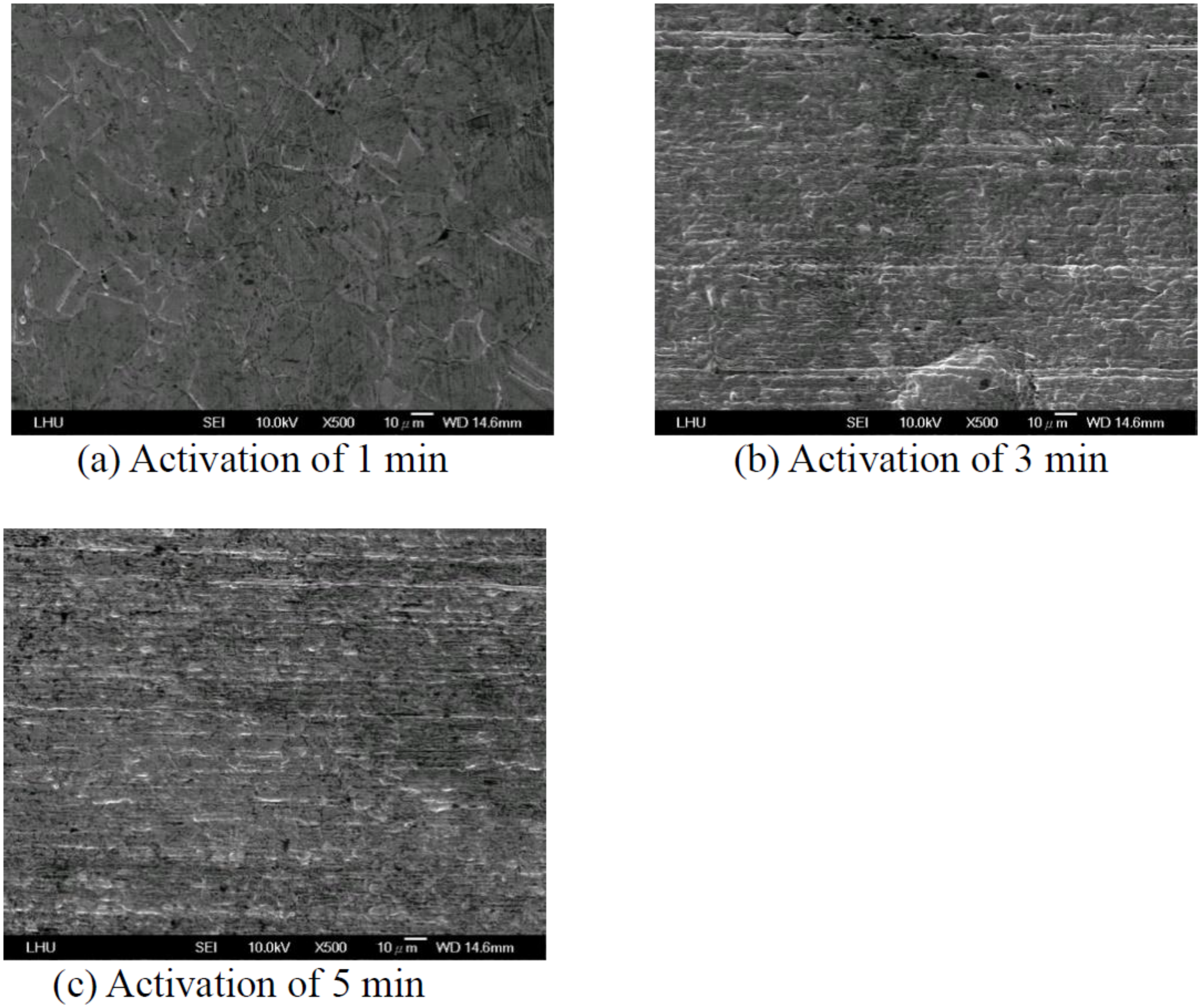


Figure 4

Surface morphology of substrates after different activation times.

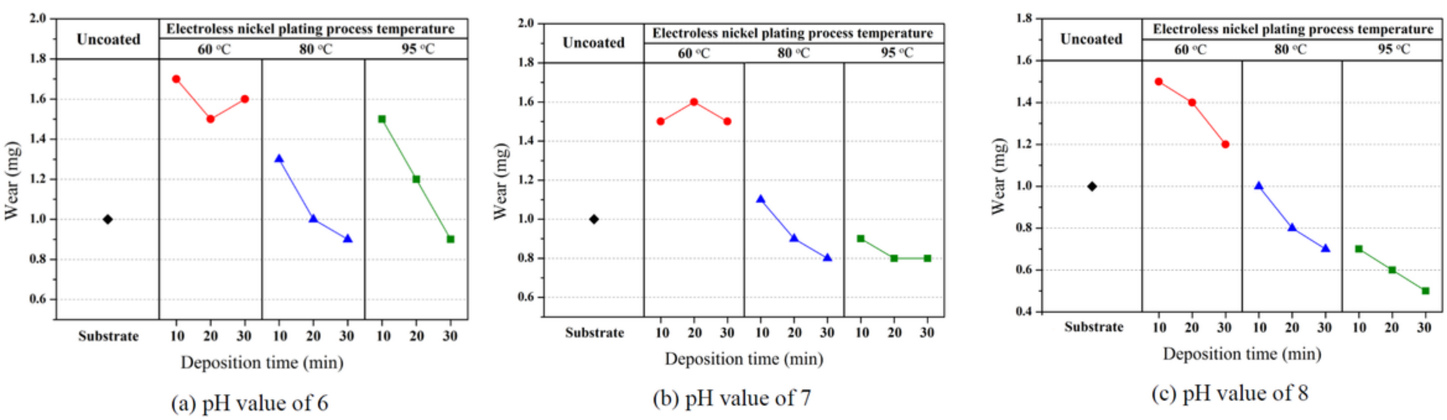


Figure 5

Wear diagram of micro journal bearing at different pH values and deposition times.

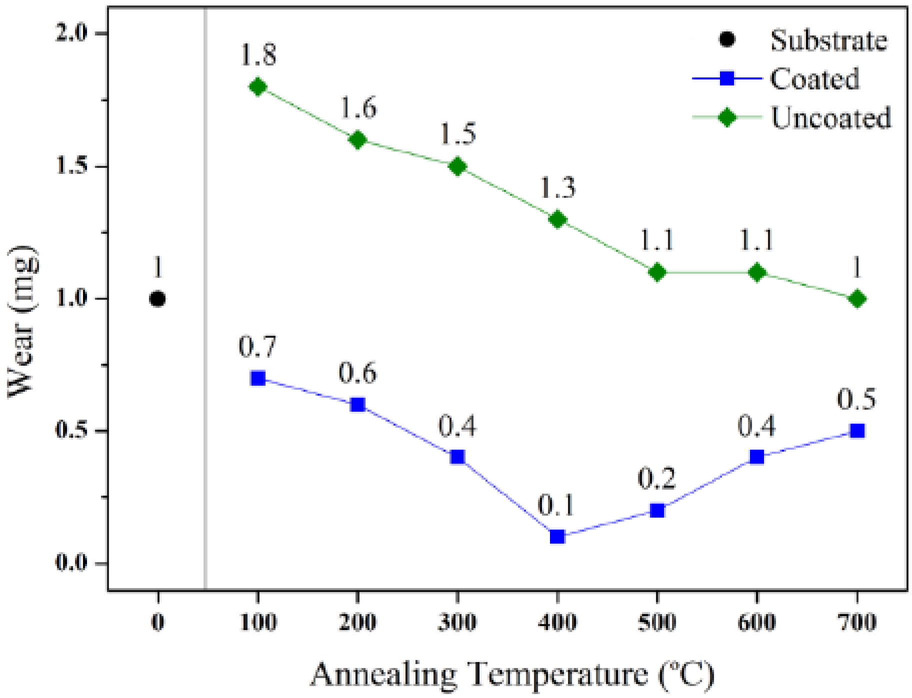


Figure 6

Comparison diagram of wear with and without heat treatment for electroless nickel coating.

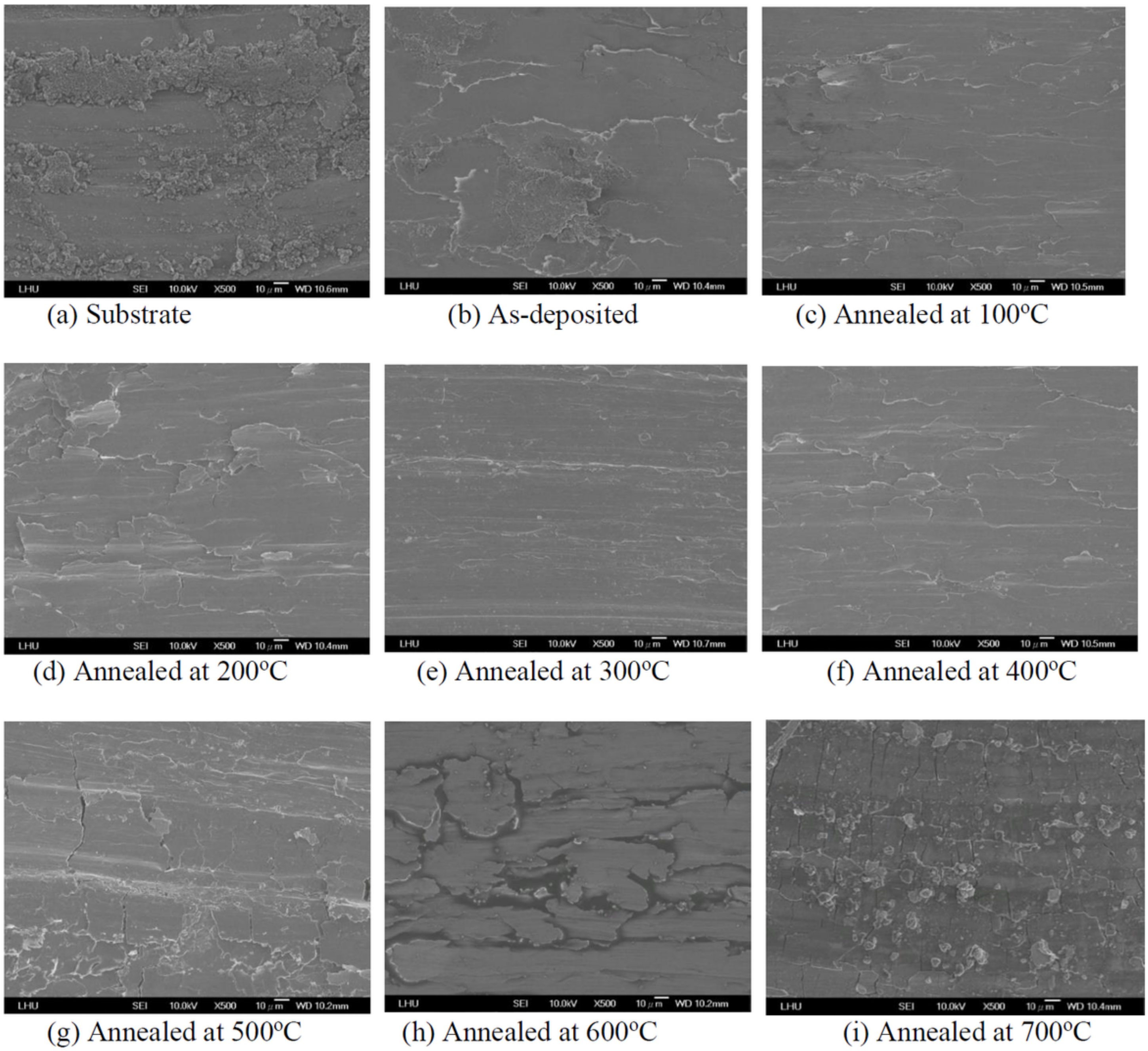
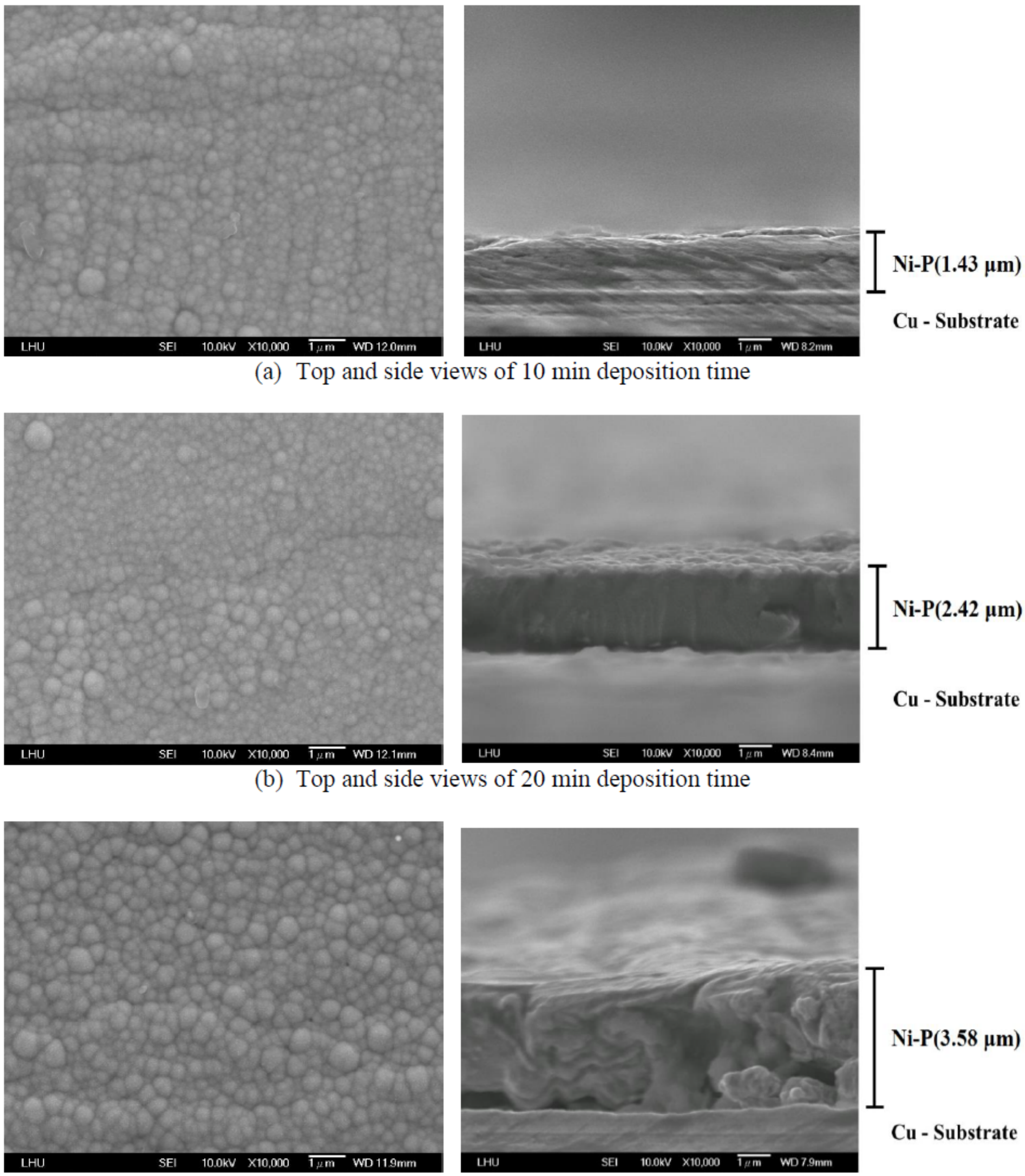


Figure 7

The surface morphology of wear for the micro journal bearings, chemical nickel-coated bearings (pH value of 8, bath temperature 95oC and deposition time 30 min) and heat treatment nickel-coated bearings (100 ~ 700oC).



(a) Top and side views of 10 min deposition time

(b) Top and side views of 20 min deposition time

(c) Top and side views of 30 min deposition time

Figure 8

Electroless nickel coating (pH value of 8 and bath temperature of 95oC) at different deposition times.

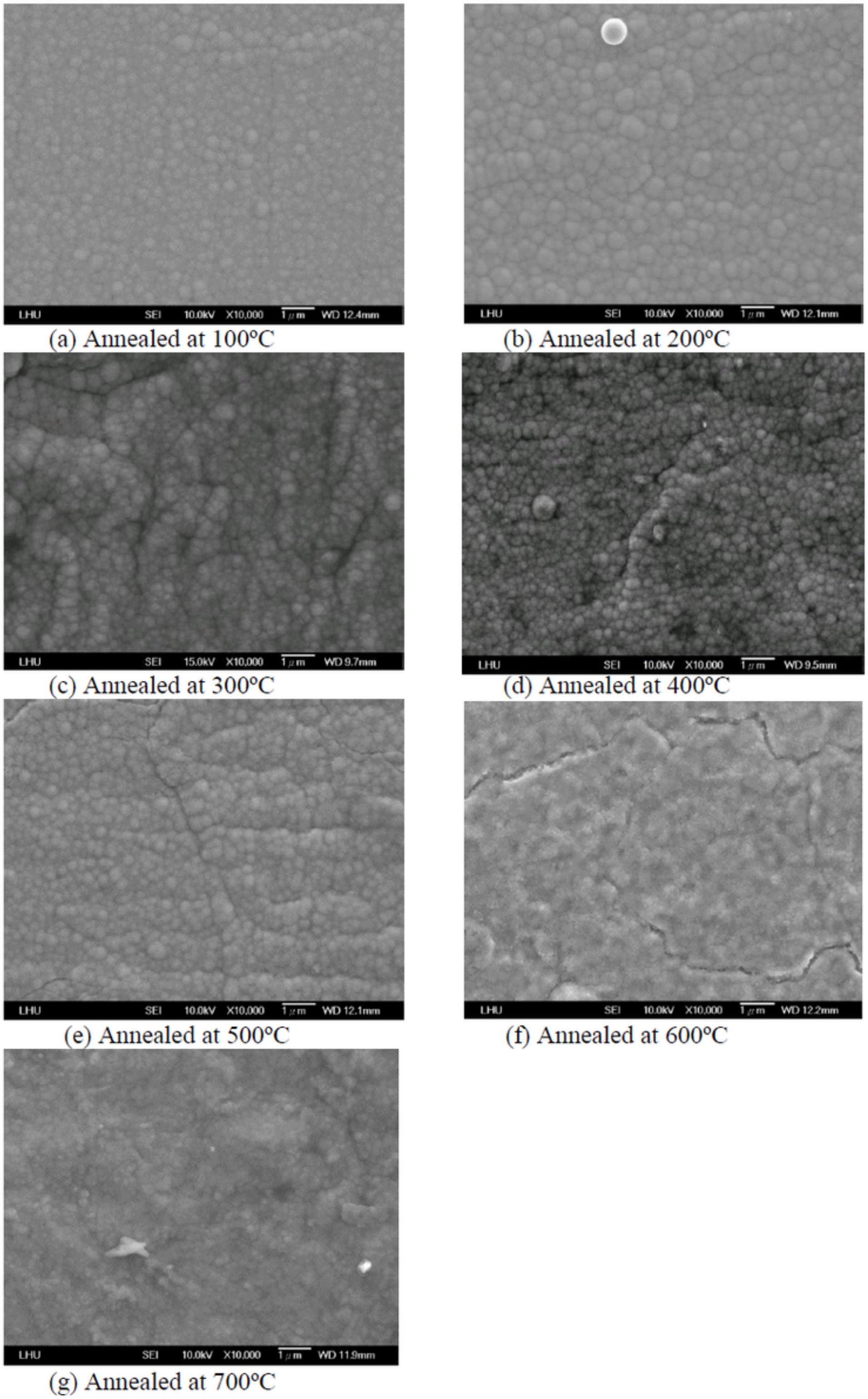
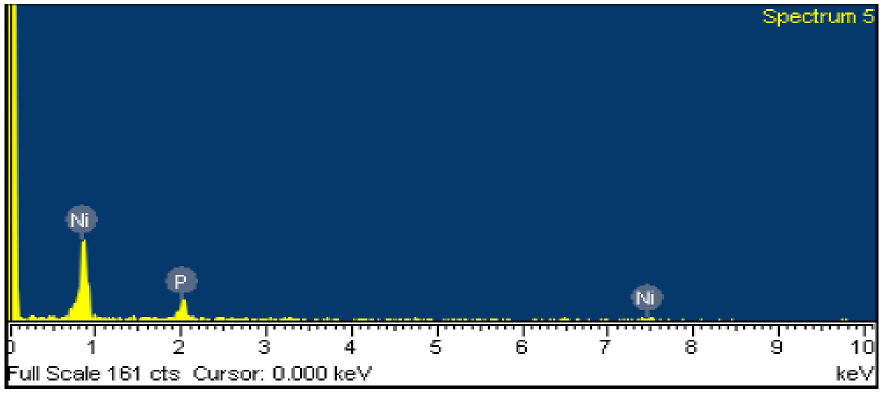


Figure 9

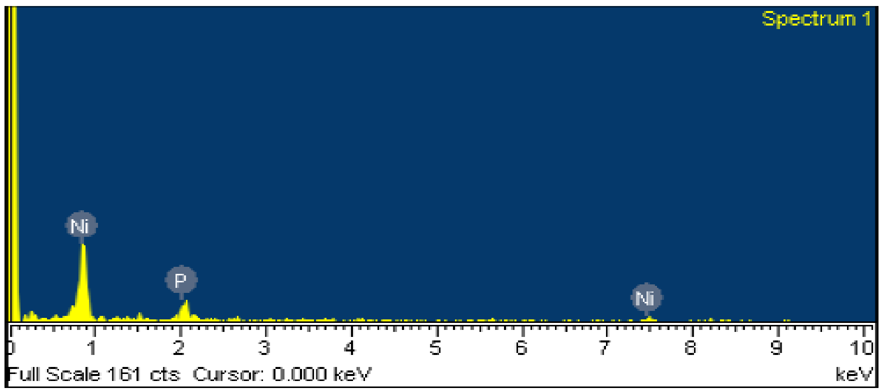
Surface morphology of electroless nickel coating (pH value of 8, bath temperature of 95oC and deposition time of 30 min) at different heat treatment temperatures.

Element	Weight%	Atomic%
P K	11.42	19.64
Ni L	88.58	80.36
Totals	100.00	



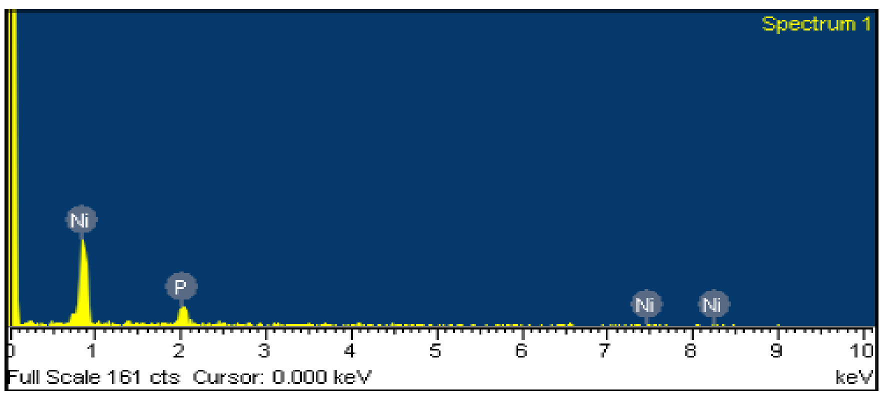
(a) Deposition time of 10 min

Element	Weight%	Atomic%
P K	12.73	21.66
Ni L	87.27	78.34
Totals	100.00	



(b) Deposition time of 20 min

Element	Weight%	Atomic%
P K	13.15	22.30
Ni L	86.85	77.70
Totals	100.00	



(c) Deposition time of 30 min

Figure 10

Elemental analysis of electroless nickel coating (pH value of 8 and bath temperature of 95oC) at different deposition times.

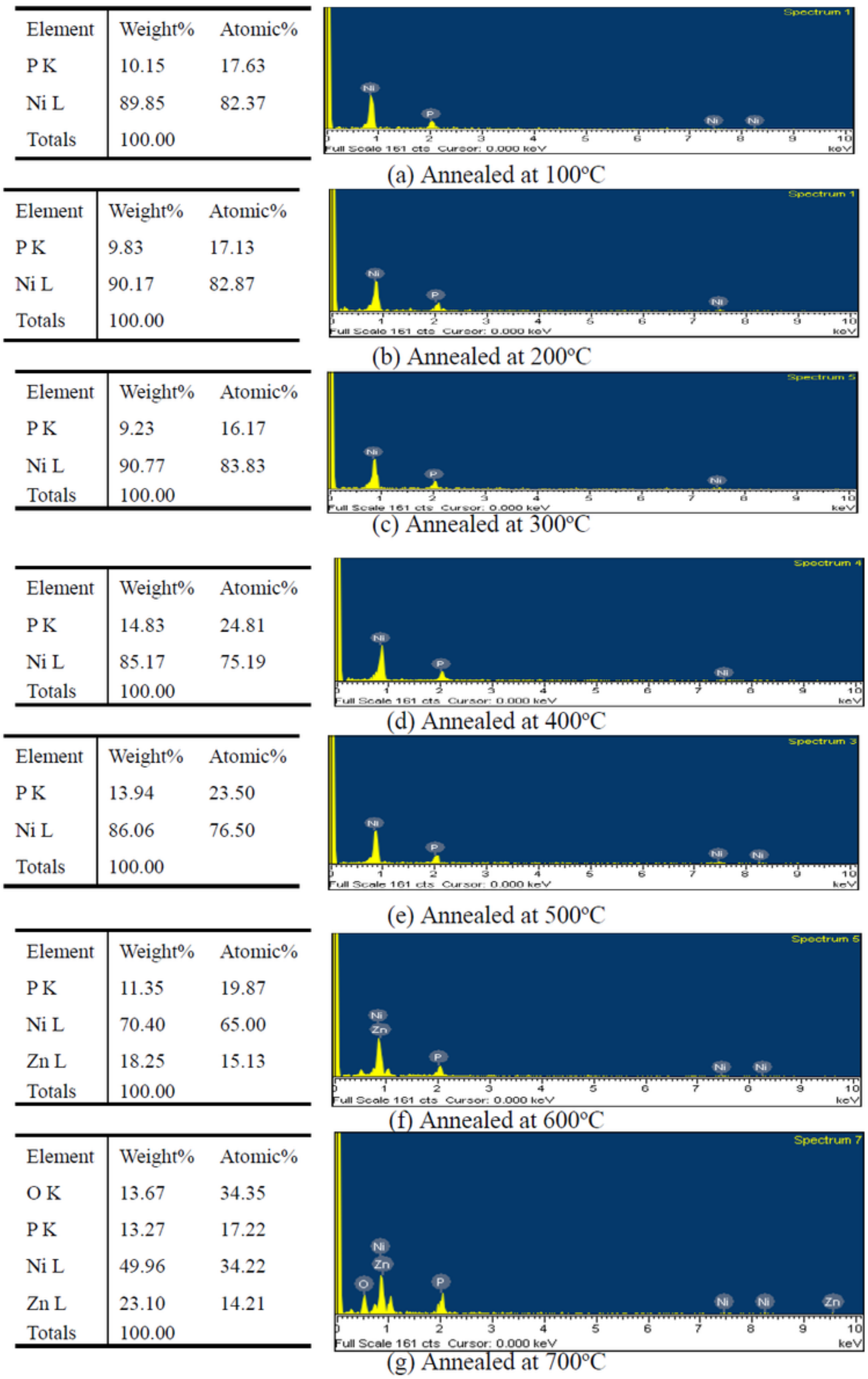


Figure 11

Elemental analysis of electroless nickel coating (pH value of 8, bath temperature of 95oC and deposition time of 30 min) at different heat treatment temperatures.

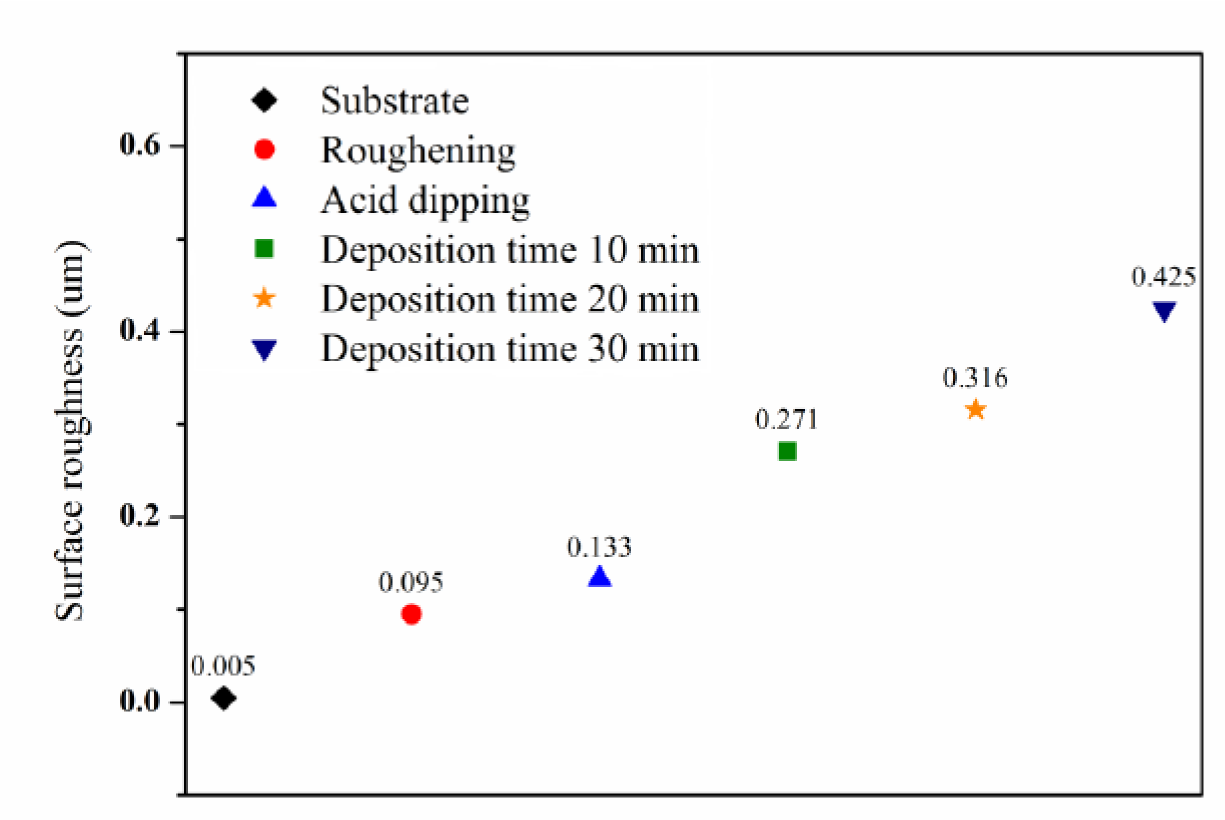


Figure 12

Surface roughness for substrate, pretreatment and electroless nickel coating (pH value of 8, bath temperature of 95oC) at different deposition times.

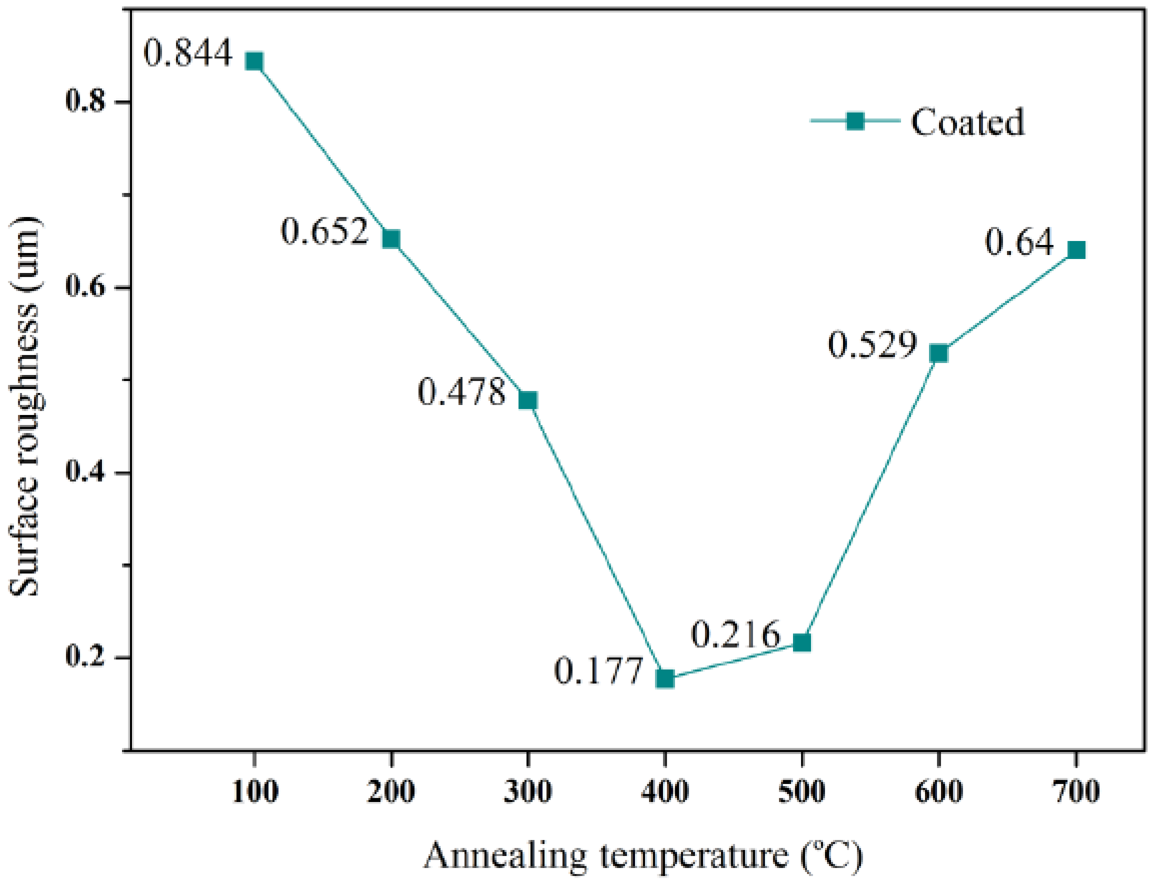


Figure 13

Correlation between surface roughness and annealing temperature for electroless nickel coating film.

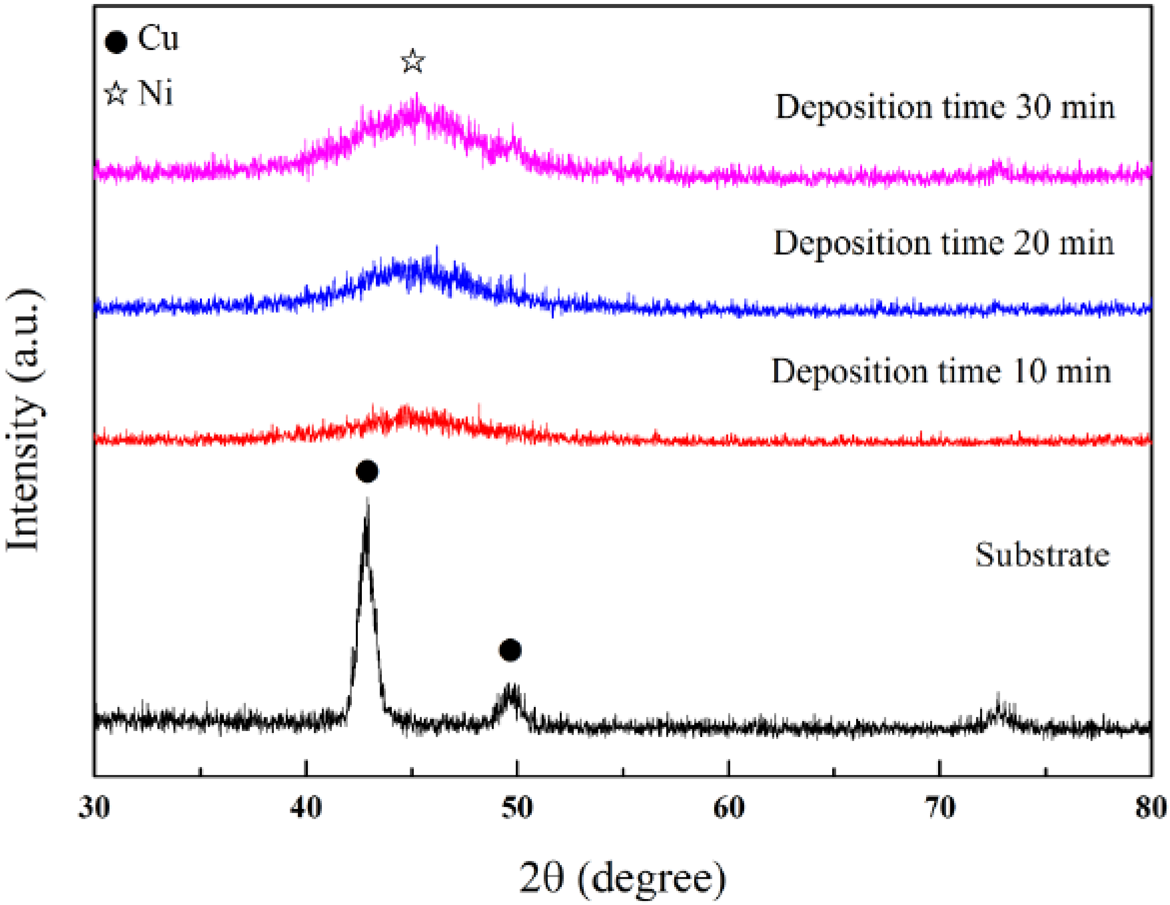


Figure 14

Comparison of diffraction XRD patterns for electroless nickel coating.

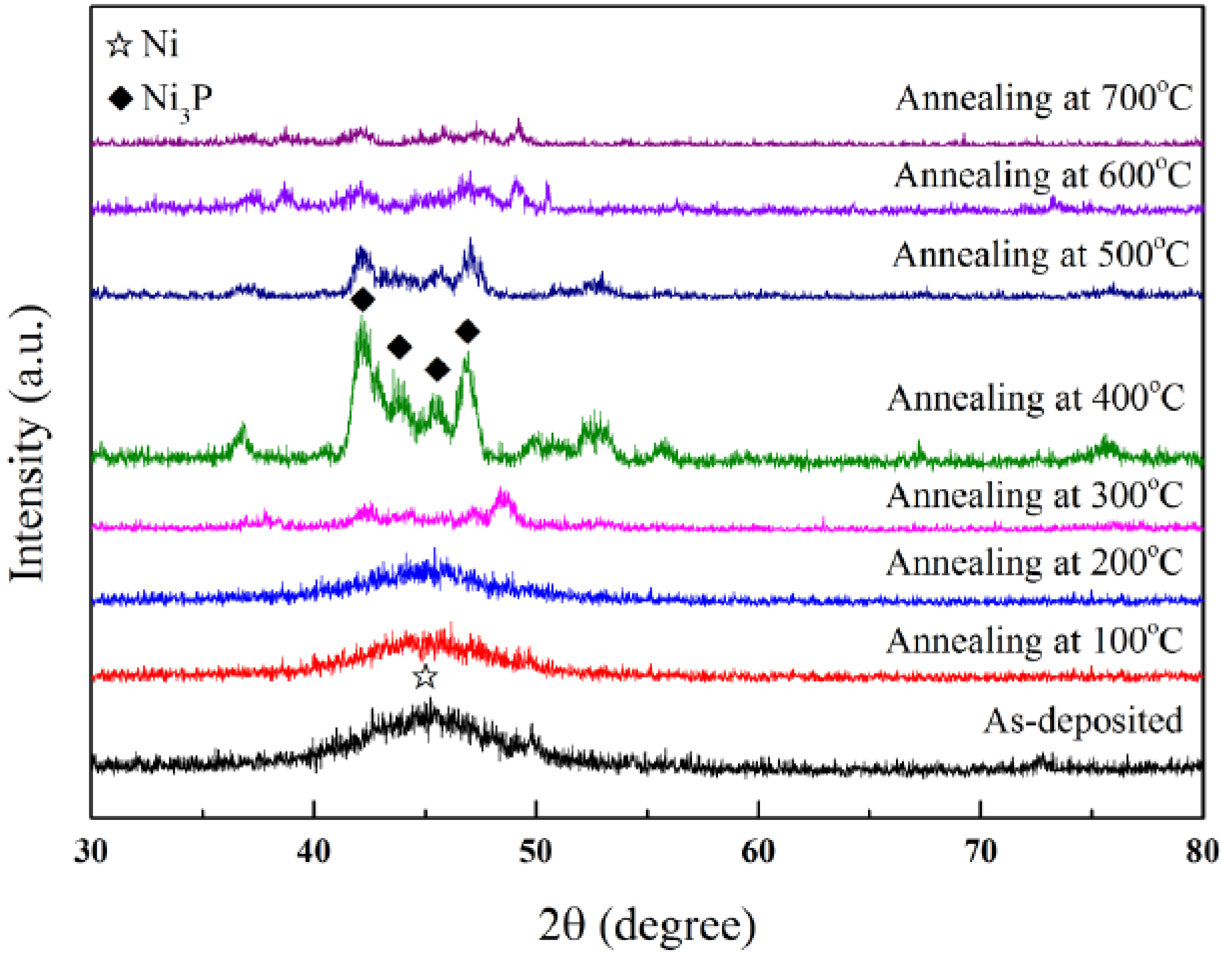


Figure 15

The diffraction XRD patterns of the Ni-P thin film after annealing (100oC~700oC).

Supplementary Files

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- SupplementaryMaterial.docx