Improvement in the working life of a micro journal bearings with an electroless Ni–P coating

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Abstract
The improvement of working life is the main purpose of this paper to evaluate the mechanical properties of the electroless Ni–P coatings of radial micro journal bearings. The study was carried out using different plating parameter combinations, namely, pH values of the plating solution (6, 7, and 8), deposition time (10, 20, and 30 min), and bath temperature (60, 80, and 95 °C). The structure, surface morphology, hardness, and wear resistance of the electroless Ni–P coatings were measured and analyzed. The optimum combination of plating parameters for minimum wear is a pH value of 8, deposition time of 30 min, and bath temperature of 95 °C. When the Ni–P film is annealed at 400 °C, the hardness, wear and surface roughness can get the best values of 960 HV, 0.1 mg, and 0.177 μm, respectively, and this is because the Ni–P coating has changed from an amorphous phase to a crystalline composite phase (Ni + Ni₃P) structure. However, as the annealing temperature continues to increase; the hardness, wear, and surface roughness begin to deteriorate. The coherent relationship of the crystalline composite phase is broken, the grains of the Ni–P coating will grow, and the tensile stress of the Ni–P coating will increase.

Keywords Electroless Ni–P · Micro journal bearing · Annealing · Wear resistance · Hardness

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, and 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 that 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 that 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 that the microhardness increases with increased P content in Ni–P coating after annealing treatment. Many studies mention that 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 Ni3P. In Allen and Vander Sande research [12], the amorphous nickel phosphorus matrix was replaced by nickel FCC crystals at 247 °C, and Ni3P was precipitated and grown above 367 °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. However, there are few literatures on the use of electroless coating to prepare smaller, high hard-ness, and wear-resistant radial micro journal bearings. 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 journal 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 chemical coating parameters with the smallest radial micro journal bearing wear. Nickel-coated micro-bearing are annealed under various temperatures (100, 200, 300, 400, 500, 600, and 700 °C) at the same time to analyze the effects of the film surface microstructure, crystal properties, microhardness, surface roughness, and abrasion tests.

| Table 1 Pretreatment solution for roughening and activation |
|------------------------------------------------------------|
| Pretreatment liquid | Composition | Content (g/L) |
| Roughening liquid | H2CrO4 | 120 |
| | H2SO4 | 10 |
| Activation liquid | HCl | 100 |

| Table 2 Composition of the electroless coating solution |
|-------------------------------------------------------|
| Process liquid | Composition | Content (g/L) |
| Chemical plating solution | NiSO4 | 25 |
| | NaH2PO2 + H2O | 25 |
| | Na2C6H5O7 | 40 |
| | NH4Cl | 30 |

| Table 3 Experimental parameters of pretreatment |
|-------------------------------------------------|
| Temperature | 0 °C |
| Magnet stirring rate (fixed) | 300 rpm |
| Roughening (min) | 1, 3, and 5 |
| Activation (min) | 1, 3, and 5 |
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.

| 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 °C |
| Deposition time | 10, 20, and 30 min |

| Table 5  | Experimental parameters of heat treatment |
|----------|------------------------------------------|
| Vacuum pressure | $1 \times 10^{-1}$ torr |
| Heating rate | 20 °C/min |
| Cooling method | Furnace cold |
| Holding time | 1 h |
| Heat treatment temperature ($1 \times 10^{-1}$ torr) | 100 ~ 700 °C |

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) mm³. 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 mm³ 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.

![Stainless steel shaft](image1)
![Micro journal bearing](image2)

(a) Micro journal bearing

(b) Micro journal working life tester
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 min. The roughening treatment can obtain appropriate substrate surface roughness. The roughening formula is a mixed solution of chromic acid and sulfuric acid \( (\text{H}_2\text{CrO}_4 + \text{H}_2\text{SO}_4) \). The activation treatment uses diluted hydrochloric acid \( (\text{HCl}) \) 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.

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. Figure 1 is a schematic diagram of the electroless coating experiment.

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 min. Therefore, three changes of 1, 3, and 5 min 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 \((100, 200, 300, 400, 500, 600, \text{ and } 700 \degree \text{C}) \) on the characteristics of electroless coating. The vacuum pressure is \(1 \times 10^{-1} \text{ torr}\), the heating rate is \(20 \degree \text{C/min}\), and the holding temperature is \(1 \text{ h}\). The furnace cooling method is used to cool to room temperature. The experimental parameters of the heat treatment are shown in Table 5.

### 2.2 Experiment equipment

To obtain the data of micro journal bearing (copper alloy, Fig. 2a working life, a self-developed testing machine is used to perform the abrasion test, as shown in Fig. 2b. The working 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 working 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 2.97 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:

\[ HV = 0.204F \sin(\alpha/2)/d^2 \approx 0.1891F/d^2 \]  

where \( F \) is the load of Vickers hardness (N), \( d \) is the indentation diagonal length (mm), and \( \alpha \) is the angle between the opposite side of the indenter (136°).

### 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. Figure 3 shows the surface morphologies of without and with roughened substrates. Figure 3b shows less corrosion, while Fig. 3c, d clearly displays 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 min was selected as the benchmark before activation. Figure 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 min is selected to make the benchmark before electroless nickel coating.

3.2 Abrasion test

Figure 5 shows the experimental results of micro journal bearing wear at different deposition parameters (6–8 pH values, 60–95 °C bath temperatures, and 10–30 min deposition times). The bearing wear of 60 °C bath temperature is greater than that of the copper bearing substrate, as shown in Fig. 5a. As the bath temperature increases, the nascent atomic hydrogen of hypophosphite in the aqueous solution increases, and the nascent atomic hydrogen will adsorb and activate the catalytic metal surface, reducing the nickel cations in the plating bath, and catalyze metallic nickel is deposited on the metal surface. As the decomposition of hypophosphite increases, so does the reduction to phosphorus. At this time, nickel atoms and phosphorus atoms co-deposit to form Ni–P solid solution also increase. At a bath temperature of 80 °C and 95 °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

![Graphs showing wear results at different pH values](image)

Fig. 5 Wear diagram of micro journal bearing at different pH values and deposition times. (a) pH value of 6. (b) pH value of 7. (c) pH value of 8

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better wear resistance, as shown in Fig. 5b, c. At 95 °C, the abrasion is lower than 80 °C (pH value of 8). It is possible that 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 °C, and deposition time of 30 min, which has the minimum wear (0.5 mg) of electroless nickel plating on micro journal bearing, are the selected deposition parameters in this study, as shown in Fig. 5c. Figure 6 is a comparison diagram of wear with and without electroless nickel coated as a function of annealing temperature. The with heat treatment nickel-coated bearings have less wear than substrates (copper bearings) and without heat treatment nickel-coated bearings. As the annealing temperature increases from 100 to 400 °C, the wear of the coating decreases, reaching a minimum of 0.1 mg at 400 °C. After the annealing temperature exceeds 400 °C, the grain size gradually increases, and P is dissolved out from the Ni lattice in the form of hard Ni₃P phase, so that the wear of the coating gradually increases. Figure 7 shows the surface morphology of wear for the copper bearings, chemical nickel-coated bearings (pH value of 8, bath temperature of 95 °C, deposition time of 30 min), and heat treatment nickel-coated bearings (100 ~ 700 °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 °C is slight, the abrasion crack is large at 600 °C, and the surface products still exist after the heat treatment at 700 °C.

3.3 Surface morphology and composition analysis

Figure 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 °C). It can be seen that 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 min were 1.43, 2.42, and 3.58 μm, respectively. Figure 9 shows the surface morphology of electroless nickel coating (pH value of 8, bath temperature of 95 °C and deposition time of 30 min) at different heat treatment temperatures. There are cracks at 600 °C, and the obviousness of grains at 700 °C is worse than others. Figure 10 shows the elemental analysis of electroless nickel coating film (pH value of 8 and bath temperature of 95 °C) at different deposition times. It is confirmed for the composition of nickel and phosphorus elements that the longer the deposition time, the more the phosphorus element will increase. Figure 11 shows the elemental analysis of heat treatment temperature (100 ~ 700 °C). Zinc is precipitated at 600 °C; oxides are generated at 700 °C. It
is estimated the reason for the sudden increase in wear at 600 °C and 700 °C is related to the surface products.

3.4 Roughness measurement

Figure 12 shows the surface roughness for the substrate, pretreatment, and electroless nickel coating (pH value of 8, bath temperature of 95 °C) 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 °C for 10, 20, and 30 min) show that the longer the deposition time, the greater the surface roughness. It was found that the surface roughness was directly proportional to the deposition time of the electroless nickel coating. Figure 13 shows the correlation between surface roughness and annealing temperature for electroless nickel coating film after a heat treatment time of 30 min. Comparing the results of Figs. 6 and 13 after annealing heat treatment, it can be seen that the surface roughness trend is similar to wear. The higher the surface roughness, the greater the amount of wear. The minimum surface roughness (0.177 μm) occurs at 400 °C. As the heat treatment temperature increases again, the hardness of the Ni₃P phase gradually decreases, and the crystal grains become very coarse.

Fig. 7 The surface morphology of wear for the micro journal bearings, chemical nickel-coated bearings (pH value of 8, bath temperature 95 °C and deposition time 30 min) and heat treatment nickel-coated bearings (100–700 °C). (a) Substrate. (b) As-deposited. (c) Annealed at 100 °C. (d) Annealed at 200 °C. (e) Annealed at 300 °C. (f) Annealed at 400 °C. (g) Annealed at 500 °C. (h) Annealed at 600 °C. (i) Annealed at 700 °C
3.5 Structural analysis of deposition film

Figure 14 shows the diffraction XRD patterns for substrate and electroless coating times of 10, 20, and 30 min (pH value of 8, bath temperature of 95 °C). It can be seen that the electroless Ni–P thin film is an amorphous structure. However, there is a strong camel peak (2θ = 45°) at an electroless coating time of 30 min. Figure 15 shows

![Electroless nickel coating (pH value of 8 and bath temperature of 95 °C) at different deposition times. (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.](image-url)
(a) Annealed at 100°C

(b) Annealed at 200°C

(c) Annealed at 300°C

(d) Annealed at 400°C

(e) Annealed at 500°C

(f) Annealed at 600°C

(g) Annealed at 700°C
The diffraction XRD patterns of the Ni–P thin film after annealing (100–700 °C). It can be seen that the Ni–P thin film is still amorphous at a lower annealing temperature (200 °C). When the annealing temperature is 300 °C, Ni–P films have Ni₃P diffraction peaks at 2θ = 48°. When the annealing temperature reaches 400 °C, the Ni–P films have crystalline Ni and Ni₃P structures [13]. Due to the precipitation hardening effect of Ni₃P, the hardness of the coating is increased. Allen and Vander Sande [12] found a heat treatment temperature for Ni–P films of above 367 °C that will create Ni₃P precipitates. Ni is dissolved in Ni₃P.

**Fig. 9** Surface morphology of electroless nickel coating (pH value of 8, bath temperature of 95 °C and deposition time of 30 min) at different heat treatment temperatures. (a) Annealed at 100 °C. (b) Annealed at 200 °C. (c) Annealed at 300 °C. (d) Annealed at 400 °C. (e) Annealed at 500 °C. (f) Annealed at 600 °C. (g) Annealed at 700 °C.

**Fig. 10** Elemental analysis of electroless nickel coating (pH value of 8 and bath temperature of 95 °C) at different deposition times. (a) Deposition time of 10 min. (b) Deposition time of 20 min. (c) Deposition time of 30 min.
| Element | Weight% | Atomic% |
|---------|---------|---------|
| P K     | 10.15   | 17.63   |
| Ni L    | 89.85   | 82.37   |
| Totals  | 100.00  |         |

(a) Annealed at 100°C

| Element | Weight% | Atomic% |
|---------|---------|---------|
| P K     | 9.83    | 17.13   |
| Ni L    | 90.17   | 82.87   |
| Totals  | 100.00  |         |

(b) Annealed at 200°C

| Element | Weight% | Atomic% |
|---------|---------|---------|
| P K     | 9.23    | 16.17   |
| Ni L    | 90.77   | 83.83   |
| Totals  | 100.00  |         |

(c) Annealed at 300°C

| Element | Weight% | Atomic% |
|---------|---------|---------|
| P K     | 14.83   | 24.81   |
| Ni L    | 85.17   | 75.19   |
| Totals  | 100.00  |         |

(d) Annealed at 400°C

| Element | Weight% | Atomic% |
|---------|---------|---------|
| P K     | 13.94   | 23.50   |
| Ni L    | 86.06   | 76.50   |
| Totals  | 100.00  |         |

(e) Annealed at 500°C

| Element | Weight% | Atomic% |
|---------|---------|---------|
| P K     | 11.35   | 19.87   |
| Ni L    | 70.40   | 65.00   |
| Zn L    | 18.25   | 15.13   |
| Totals  | 100.00  |         |

(f) Annealed at 600°C

| Element | Weight% | Atomic% |
|---------|---------|---------|
| O K     | 13.67   | 34.35   |
| P K     | 13.27   | 17.22   |
| Ni L    | 49.96   | 34.22   |
| Zn L    | 23.10   | 14.21   |
| Totals  | 100.00  |         |

(g) Annealed at 700°C
During high phosphorus content coatings, and Ni$_3$P is dissolved in Ni during low phosphorus content coatings. When the annealing temperature is higher than 400 °C, 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. The hardness of the substrate and chemical nickel plating films was measured at...
room temperature using a nano-indenter (Mitutoyo HM-100 Series). 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 that 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 to 300 °C, but did not reach the indentation hardness of 400 °C. It is presumed no Ni₃P crystal phase was generated. Besides, there is no precipitation hardening effect to make the hardness drop greatly change. Comparing the 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 that 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 that the higher the heat treatment temperature, the lower the hardness is. The main reason is that the surface has no coating layer. There are differences in hardness obtained by heat treatment of different components.

### Table 6

| 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

| 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

| 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. The experimental results are summarized as follows:

1. The roughening and activation treatment of the metal surface can significantly increase the real surface area of the metal surface and promote subsequent chemical reactions on the metal surface. In this study, roughening and activation times of 1 min and 5 min were selected as the pretreatment procedures for electroless nickel plating.

2. The minimum wear of electroless nickel plating on micro journal bearing with optimal parameters (pH value of 8, bath temperature of 95 °C, and deposition time of 30 min) was 0.5 mg. The wear of the coated journal bearings is less than the uncoated wear, and the annealing heat treatment at 400 °C has the best resistance of 0.1 mg.

3. The electroless Ni-P film has a strong hump peak (2θ=45°) within 30 min of deposition time. When the annealing temperature reaches 400 °C, the Ni-P film has
the crystal structure of Ni and Ni₃P. Due to the precipitation hardening effect of Ni₃P, the hardness of the coating increases. When the annealing temperature is higher than 400 °C, the Ni-P film has no obvious diffraction peaks. However, zinc is precipitated at 600 °C; oxides are generated at 700 °C.

4. The surface roughness of micro journal bearings is proportional to the deposition time of the electroless nickel coating. The higher the surface roughness, the greater the wear of the micro journal bearing. In this study, the minimum surface roughness at a heat treatment of 400 °C is 0.177 μm.

5. When the annealing heat treatment temperature is 400 °C, the maximum hardness is 960 HV. The reason is that the precipitation hardening effect of Ni₃P increases the hardness of the coating. As the annealing temperature increases, the indentation hardness shows a softening trend, which is related to surface zinc precipitation and oxides.

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

Code availability Not applicable.

Declarations

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