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Preparation of Ni-P-diamond coatings with dry friction characteristics and abrasive wear resistance

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ABSTRACT

The Ni-P-diamond composite coatings that contained diamond particles with various sizes in microns have been prepared by electroless plating. The effects of diamond particle size and heat-treatment on the microstructure, mechanical properties, dry friction behavior and abrasive wear performance of the Ni-P diamond composite coatings were investigated. It was discovered that a Ni-P diamond composite coating with the thickness of 30 μm could be obtained. The diamond particles (2–9 μm) could be homogeneously dispersed in the coatings with the volume fractions of 21%–25%. Subsequently to 400 °C for 2 h of heat treatment, the hardness of the Ni-P diamond coatings increased to approximately 1200 HV. The friction coefficients of the Ni-P diamond composite coatings were stable in the range of 0.4–0.52, whereas the Ni-P coating coefficient increased with time and finally reached to beyond 0.50. The addition of diamond particles could improve the wear resistance significantly, whereas as the diamond particle sizes increased, the friction wear resistance and the abrasive wear resistance increased.

1. Introduction

Due to higher hardness, excellent wear and corrosive resistance, the Ni-P electroless-plating can be utilized in the remanufacturing of steel parts in the automotive, the oil and petroleum and the aerospace fields [1–4]. The SiC, the Al_2O_3, the diamond or Polytetrafluoroetylene (PTFE) and the MoS_2 can be introduced into Ni-P coatings to improve the wear resistance or decrease the friction coefficient. The micro/nano size of diamond particles is an ideal reinforcement phase to enhance the coating hardness and wear resistance [5–8].

As electroless plating contained with diamond particles shows great potential for industrial applications, especially for the wear-resistant parts, several studies are performed to investigate the characteristics of Ni-P diamond coatings. As an example, Shenderova [9] and Petrova [10] respectively, observed that the incorporated diamond particles could significantly affect the wear resistance of deposits or lower the friction co-efficient and improve the lubrication. Mazaheri [11] and Habib [12] observed that the corrosion resistance of the Ni-P-ND (Nano-diamond) is superior to the Ni-P coating corrosion resistance. A study by Petrova et al. [13] demonstrated that the parts where the corresponding coating contained diamond particles displayed an abrasion resistance many times higher than the normal coatings.

The performance of Ni-P diamond coatings could be highly affected by the diamond particle size. Xu [14] and Wang [15] observed that the wear resistance of Ni-P-ND coatings was improved compared to the Ni-P coating. Reddy et al. [16] observed that the wear resistance of electroless Ni-P coating containing the diamond particle sizes of 3–6 μm compared to the electroless Ni-P coating wear resistance with the coarser diamond particles. Nabeen [17] studied the effects of particle size (0.21–2.91 μm) and volume friction of the diamond particle on the hardness and wear resistance of the Ni-P diamond coatings. It was discovered that the hardness and wear resistance were hardly affected by the particle size, whereas significantly affected by the volume percentage of the reinforcement.

In previous studies, quite few have been reported to investigate the effect of the diamond particle's size in microns on the mechanical properties, friction behavior and abrasive wear resistance of the Ni-P diamond coatings. In the present study, Ni-P coatings contained diamond particles in various micron sizes were prepared, whereas the effect of diamond particle sizes on the surface morphology, the microstructure, the hardness, the friction behavior and the abrasive wear performance were investigated.

2. Experimental procedure

The electroless Ni-P and Ni-P-D composite coatings were deposited

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Table 1
Composition of plating solution and plating parameters.

Bath constituent	Quality	Plating parameters
$NiSO_4{\cdot}6H_2O$	30 g/L	Temperature: 80–85 °C
$NaH_2PO_4{\cdot}H_2O$	34 g/L	PH: 4.5–5.0
C_3H6O_3	20 ml/L	Agitation: 200 rpm
$C_2H_3NaO_2$	10 ml/L	Total time: 120 min
CH_3CH_2COOH	10 ml/L	
$C_{12}H_{25}SO_4Na$	5 mg/L	
CN_2H_4S	3 mg/L	

on mild steel (0.2%C; 0.05%P; 0.055%S; 190 HV) specimens with the dimension of 50 mm × 20 mm × 2 mm (for friction testing) and 40 mm × 10 mm × 10 mm (for abrasive wear testing). The samples were pre-treated in the following process. The steel substrate was firstly etched in an alkaline solution (10% NaOH and 20%Na_2CO_3) at 70 °C for 15 min, consequently pickled in a 15% HCl water solution at 25 °C for 3 min and activated in a 5% HCl water solution at 25 °C for 30 s. The diamond powder (Zhengzhou Sino-Crystal Diamond Co, Ltd) with the mean particle sizes of 2, 4 and 9 μm was utilized. A plating solution with the composition presented in Table 1 was prepared. Following, 2 g of diamond particles, 0.5 mL of dispersant (polyethylene glycol 400, PEG-400), 0.5 mL of surfactant (Alkylphenols polyoxyethylene OP-10) and 50 mL deionized water were added to obtain a Ni-P-D plating solution with the diamond concentration of 4 g/L. In order to conduct a comparison study, the Ni-P and Ni-P-D coatings were prepared respectively. The Ni-P was deposited for 2 h and the Ni-P-D plating was deposited for 90 min.

All samples were heat-treated for 2 h at 400 °C in a vacuum furnace. The surface morphology and cross section of the plated samples were examined through scanning electron microscopy (SEM, JSM-5610LV) and X-ray diffraction (XRD, D8 Advance). To examine the content of diamond particles on the Ni-P-D coatings, the volume fraction of the diamond powder in the Ni-P coatings was calculated by the Image-Pro software through Eq.(1) [18].

$$c = {}^{a_d}/_{a} \tag{1}$$

Where:

c(%) is the content of diamond in the composite coatings,
a_d is the area of diamond in the SEM picture,
a is the total area of the SEM picture.

The hardness of the coatings was determined with a micro-hardness tester (HX-1000TM) at a load of 1.96 N and dwelling duration of 15 s. Five indentations were utilized to calculate the mean value of hardness. The dry friction characteristics of the coatings were obtained from a ball on disc friction tester (WTM-2E). The upper ball specimen was a cemented tungsten carbide ball (YG-6, Hardness: 89.5 HRA) with a diameter of 6 mm. The dry friction test was executed at 300 rpm with a load of 4.9 N and the total test duration was 15 min. The friction coefficient was continuously recorded by a computer connected to the friction tester. When the Ni-P-D coatings were tested, the cemented tungsten carbide ball became worn significantly fast. The wear rate (volume loss in per unit scratch length) of the tungsten carbide ball was calculated through Eq.(2):

$$\rho = \frac{1}{6an}[2R^3 - (2R^2 + r^2)\sqrt{R^2 - r^2}] \tag{2}$$

where:

ρ is the wear rate of the WC ball,
a is the radius of the grinding ring,
r is the radius of the wear zone on the tungsten carbide ball,
R is the radius of the tungsten carbide ball,
n is the total numbers of wear tests.

The abrasive wear resistance coatings were tested on an abrasive wear test machine (MLD-10B). The quartz sand (80 mesh, grit size of approximately 200 μm) was utilized as the abrasive with the flow rate of 200 g/min. The roller was hardened mild steel (62 HRC) with the speed of 300 rpm and the wear duration of 30 min during testing. Subsequently to the abrasion wear test, the weight loss of the coatings was measured to determine the abrasive wear resistance.

3. Results and discussion

3.1. Microstructure of Ni-P-D coatings

The cross section and surface morphology of the Ni-P-D coating contained diamond particles with the sizes from 2 μm to 9 μm, as clearly illustrated in Figs. 1 and 2. It could be observed that following the 2 h plating, the thickness of the Ni-P and Ni-P-D coatings reached up to 30 μm, as presented in Fig. 3. It could also be observed that the diamond particles were homogeneously distributed in the Ni-P matrix without agglomeration.

In Fig. 3, the back scatter electron images (BSEM) were analyzed by the Image-Pro software and the diamond particles on the surface of coating were colored in red. Through calculations, it was observed that the content of diamond particles on the coatings of Ni-P-D(2 μm), Ni-P-D(4 μm) and Ni-P-D(9 μm) were 21%, 24% and 24% respectively.

The XRD patterns of the as-plated and heat-treated (HT) Ni-P and Ni-P-D coatings are presented in Fig. 4. The diffraction peaks of the diamond particles and the amorphous Ni-P matrix could be identified. Compared to the as-plated coatings with the heat treated coatings, it was demonstrated that the Ni-P amorphous phase transformed into the Ni_3P phase subsequently to heat treatment. This was interpreted that the presence of diamond particles in the coatings did not affect the Ni-P amorphous phase crystallization, whereas no reaction between the

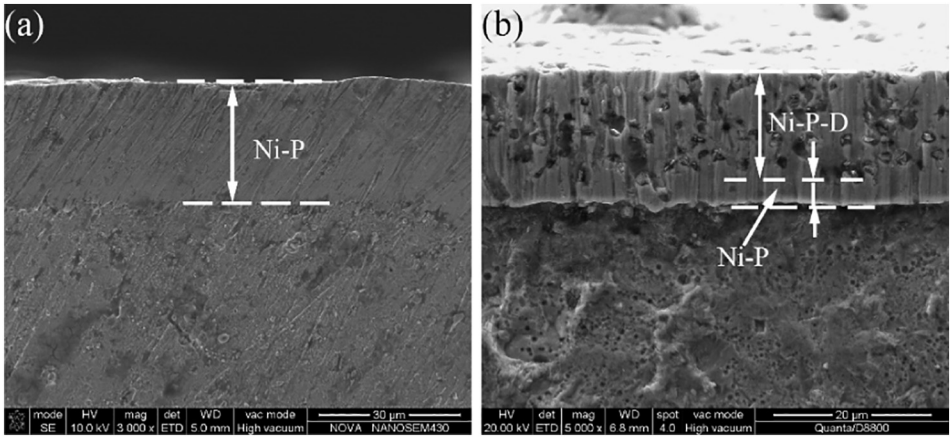

Fig. 1. Cross section SEM of Ni-P and Ni-P-D coatings: a) Ni-P, b) Ni-P-D (2 μm).

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