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Preparing porous diamond composites via electrophoretic deposition of diamond particles on foam nickel substrate

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ABSTRACT

Porous diamond composites with excellent mechanical properties were successfully prepared using foam nickel as substrate. Diamond particles with the size of 1–2 μm were electrophoretic deposited on foam nickel, followed by electroless nickel plating on the diamond-coated foam nickel to enhance the adhesion between diamond particles and the foam nickel substrate. The optimum electric field intensity was explored and determined to be 6 V/cm. Field emission scanning electron microscope was employed to investigate the morphologies of diamond coatings with different electrophoretic time and Ni-diamond composite coatings after electroless plating. The results showed that the diamond deposits increased with the electrophoresis time extended, while uniform and fully-covered diamond coatings were formed after 20 min deposition. Besides, diamond particles were held tightly by Ni coatings which played the role of metal bond. The bending strength of the porous composites was about 100 MPa determined by three-point bending test, and the composites were turned out to be suitable for grinding.

1. Introduction

Diamond composites are widely applied for advanced precision machining of hard and fragile materials, owing to the high hardness and excellent thermal conductivity of diamond [1,2]. For instance, monocrystalline silicon, as a main raw material of electronic components and solar cell, is generally processed by diamond composites [3]. Nevertheless, lacking pores prevents the discharge of chips and frictional heat generated during operating, which directly lessen the composites tools' long-term durability and grinding efficiency [4,5]. Thus, composites with high porosity are demanded.

Electrophoretic deposition (EPD) is widely applied as an easy and versatile technique for a variety of coating applications [6–10]. Particles in a EPD suspension are forced to migrate towards an oppositely charged electrode by electric field, and deposit on the substrate forming a relatively dense and homogeneous coating [11–13]. The interior surface of porous materials can be coated by EPD in respect that particles can be deposited on whatever soaked in suspension.

In this work, foam nickel is used as substrate owing to its good mechanical properties, thermostability, especially its high porosity [14]. Diamond particles are expected to be deposited on foam nickel and form uniform coatings by EDP. Moreover, Ni acted as metal bond is electroless plated on the diamond-coated foam nickel to enhance the adhesion between diamond particles and substrate [15]. In addition, optimal EPD parameters as well as friction performance of the composites have been explored.

2. Experimental

The pristine foam nickel's porosity was 93%, its thickness was 1 mm and surface density was 625 g/m^2. Foam nickel substrates were subjected to pre-treatment and activation prior to EPD. The substrates were dipped into distilled water for 30 min ultrasonic treatment, and degreased with a 45 g/L KOH solution at 65 °C for 20 min, rinsed with distilled water, then dipped in 3 vol% H_2SO_4 solution for 30 s, rinsed with distill water and dried.

Diamond powders (average size of 1–2 μm) were dispersed in deionized water and magnetically stirred for 5 min followed by 10 min ultrasonication, and the concentration of diamond was 1 g/L. EPD was carried out under uniform electric field conditions in the range of 3–8 V/cm within the deposition time scope of the research work (5, 10, 15, 20, 25, and 30 min). For deposition on foam nickel,

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the EPD cell included the Ni foam working electrode ($40 \times 40\ mm^2$) centered between two parallel planar Ni foam counter-electrodes, and the distance between the anode and cathode was 1 cm, as shown in Fig. 1. This configuration allows the deposition of suspending particles on both faces of working electrode simultaneously [16]. Diamond particles were negatively charged in the suspension and moved towards the anode under the applied electric field. Besides, the samples before and after deposition were weighted.

Ni was deposited on diamond coated foam nickel by electroless plating, and the base composition of electroless plating solution was 30 g/L $NiCl_2$, 10 g/L NaH_2PO_2 and 50 g/L NH_4Cl. In addition, electroless nickel-plating was carried out at 70 °C for 2.5 h, and the PH was maintained at 8 with the addition of ammonium hydroxide.

The morphologies of deposited coatings were obtained using S4800 field emission scanning electron microscope (FESEM). The porosity of the composites was calculated according to the following equation:

$$P = P_0 - \frac{m_c \rho_s}{m_s \rho_c}(1 - P_0) \qquad (1)$$

where P is the porosity of the porous composites, P_0 is the porosity of the bare foam nickel, m_c and m_s are the masses of the coating and the substrate (g), ρ_c and ρ_s separately are densities of the coating and the substrate (g/cm^3). The bending strength of samples (size: $40 \times 10 \times 1\ mm^3$) was tested by three-point bending test with DKZ-5000 testing machine and calculated by the measured force according to $\sigma_b = 3PL/2bd^2$ (where σ_b is bending strength, P force, L span, b width, and d thickness). Besides, grinding texting was performed on UNIPOL-802 auto precision grinding machine. In this paper, ceramic-bond SiC (#320) grinding wheel was chosen to be grinded with a line speed of 12 m/min. The composites were pressed by 150 N and grinded for 5 min. Abrasive ratio together with removal rate was calculated to evaluate friction performance of the composites.

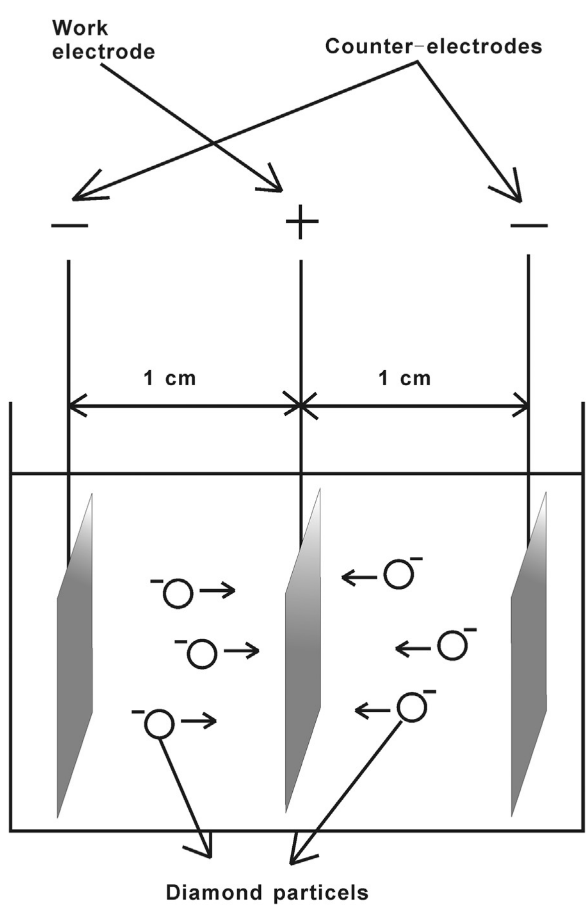

Fig. 1. Schematic of the EDP cell.

3. Result and discussion

Determination of optimum EPD parameters: Fig. 2a shows deposition mass versus electric field intensity when the deposition time was 10 min. The deposition mass grew constantly with electric field intensity varying from 3 to 6 V/cm because the higher field intensity, the stronger electric field driving force, and the higher diamond particles' migration rate which resulted in the increment of diamond deposition directly. The results approximately fit the linear Hamaker equation [17]. However, when field intensity was up to 6 V/cm, the deposition mass appeared to leave off and remained constant at about $68\ mg/cm^2$, and the linear Hamaker equation cannot be applicable. This phenomenon indicated that the diamond coating was thick enough to cause electric field shielding resulting from the poor electroconductivity of diamond. So the optimum electric field intensity was determined to be 6 V/cm.

The deposition time is another significant factor in EPD. Suspensions with different properties and concentration may possess different optimum deposition times. In this paper, 1.0 g/L diamond suspension was used. Fig. 2b shows deposition mass versus deposition time under the electric field intensity of 6 V/cm. It was obvious that deposition mass increased continually with deposition time extension mainly following the law of Hamaker, but when the time was longer than 20 min, the increase of deposition mass started to slow down and deviate from the Hamaker equation. On one hand, the saturation of deposit thickness with increasing deposition time could be easily found in EPD under constant electric field intensity, which was the result of the increasing electric resistance offered by the growing deposit [18]; on the other hand, most of diamond particles aggregated and precipitated instead of depositing with the deposition time extended.

Fig. 3 shows SEM images of pristine foam nickel and diamond coatings deposited for 5 min, 15 min, and 20 min under the field strength of 6 V/cm. It is easy to find in Fig. 3a that diameters of pores were about 10–30 μm, and the pores were well-distributed. In Fig. 3b, the foam nickel exhibited a rough surface with some defects on, which was beneficial for diamond to deposit. When deposition time was 5 min (Fig. 3c), just a few diamond particles were deposited on the foam nickel. In addition, 15 min deposition led to a thicker and more uniform coating (Fig. 3d), but still large area of the substrate was bare. By contrast, uniform and dense diamond coating covering the substrate entirely was obtained when the time increased to 20 min, and it can also be seen in Fig. 3e that some diamond particles are flocked together.

Electroless nickel-plating on diamond-coated foam nickel: Fig. 4 shows SEM image of diamond/Ni-coated foam nickel, namely the porous composite. Diamond particles were all imbedded in Ni coating without falling out. In addition, the volume ratio of diamond particles and Ni in composite coating was calculated and turned out to be approximately 1:1, which indicated the composite coating had excellent properties.

The porosity, bending strength and abrasive resistance of porous composites: The porosity of the composites was 60%, which was 65% of that of foam nickel (92.3%), and the bending strength of the composites was 100 MPa, which increased by 50 times as compared with that of substrate (1.93 MPa).