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Improved micro drill bit tool life using nano-scale SiC/Ni electroplating

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SiC/Ni composite layers were coated onto WC-Co plates to strengthen micro drill bits where the micro drill bits were machined from WC-Co plates. The composite layers were formed by direct current (DC) electrodeposition in a Watts-type bath, and two SiC concentrations were used to coat the WC-Co plates. The coating layer was optimized by evaluating the hardness and the friction coefficient. With 10 g/l of SiC, some nanoparticles agglomerated and were embedded into the coating layer; moreover, the composite coating layer was not uniform. Compared to the 10 g/l SiC coating, the nanoparticles were well dispersed and the coating was harder using 5 g/l of SiC. After electroplating the micro drill bits, a positioning accuracy test was conducted to assess processing capability. The processing capability index was measured as 1.944 for the uncoated drill bit, 2.110 for the 10 g/l SiC coating, and 2.717 for the 5 g/l SiC coating. Therefore, the micro drill bits coated with 5 g/l of SiC exhibited an optimized processing capability index. When using 100 μm-diameter drill bits, the composite coating layer, which is relatively thin, must be hard. Micro drill bits coated with 5 g/l of SiC had a 1 μm thick coating layer and an optimum processing capability.

Key words: SiC/Ni composite coating, WC-Co micro drill bit, Electrodeposition, Micro-hardness, Lifetime.

Introduction

Electrodeposited composite coatings are composed of ceramic particles, such as alumina, silicon carbide, and diamond, dispersed in a metal matrix. It is well known that composite coatings with ceramic particles improve the hardness and wear resistivity of metals. The mechanical properties of these composite coatings show increased resistance to corrosion, wear, and heat [1-6].

SiC particles are known for their thermal conductivity, corrosion resistance, stable to chemical reactions, and high mechanical hardness compared to other ceramic particles [7, 8]. SiC particles adsorbed onto Ni ions exhibit a positive charge and are embedded toward the cathode. Because these SiC/Ni composite coatings show superior wear resistance and hardness, they are used in components for high wear resistance and in various industrial fields [9, 10]. Therefore, SiC/Ni composite coatings are applied to cutting tools demanding high wear resistance. Due to recent environmental regulations, hazardous materials containing halogens have been banned in the printed circuit board (PCB) industry. To maintain the properties of PCB substrates, a non-halogenated substrate must be tangled with fine fibers so that it is able to cut through PCB substrates. Thus, despite the hardness of micro drill bits made of WC-Co, they are easily damaged during cutting. Therefore, SiC/Ni coatings are expected to increase the life of micro drill bits. In this study, SiC nanoparticles and a Watts-type bath were used along with a small quantity of saccharin and ammonium chloride to form a homogeneous and fine SiC/Ni composite coating layer [11-13]. The coated WC-Co plates were studied using two SiC concentrations (5 and 10 g/l) to form a SiC/Ni composite coating layer on a WC-Co plate via electrodeposition. This thin coating was also applied to drill bits for the first time to be used as PCB cutting tools to measure positioning accuracy.

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Experimental

To deposit a SiC/Ni composite coating on WC-Co via electrodeposition, a seed layer is required. The composition and concentration of the Watts bath are shown in Table 1. Generally, saccharine decreases the grain size of Ni and reduces internal stress, minimizing cracks in the coating [11, 14]. Moreover, when ammonium chloride is added, the deposits are compact [12]. The SiC nanopowders were obtained from Sigma-Aldrich Co., USA; its properties are shown in Table 2.

After the SiC powder was dissolved in 10% HCl solution and cleaned ultrasonically to remove impurities on the WC plates, the solution was centrifuged to remove the HCl. This process was repeated twice for reproducibility. Finally, distilled water was used to rinse the SiC powders ultrasonically and for centrifugation. Pretreatment with acetone and ethanol was conducted to remove impurities from the WC-Co plates. After pretreatment, a 15-nm-thick Ti adhesion layer was deposited on the WC-Co plates, followed by a 200 nm thick Cu seed layer, using a magnetron

Table 1. Bath composition and concentration for SiC/Ni composite coating layers.

Bath composition	Concentration
$NiSO_4 \cdot 6H_2O$	350 g/l
$NiCl_2 \cdot 6H_2O$	60 g/l
H_3BO_3	40 g/l
SiC (Particle size < 100 nm)	10 g/l, 5 g/l
Saccharin	1 g/l
Ammonium chloride	1 g/l

Table 2. Properties of SiC (Sigma-Aldrich Co., USA).

Particle size	Melting point	Density	Surface area	Purity	Bulk density
< 100 nm	2,700 °C	3.217 g/cm^2	70-90 m^2/g	99.5%	0.069 g/cm^3

Table 3. Conditions for electrodeposition of SiC/Ni composite coating layers.

Electrodeposition conditions	
pH	4.5
Magnetic stirring speed (rpm)	100
Temperature (°C)	50
Plating current density (A/cm^2)	10
Plating time (s)	60

sputter. A potentiostat (Versastate 3, Ametek Co., Ltd.) was used for the electrodeposition. The electrodeposition conditions are shown in Table 3.

For the electrodeposition, a Pt sheet (99.99% pure, 130 mm × 25 mm × 5 mm) was used as an anode, and a WC-Co plate (18 mm × 18 mm × 2 mm) coated with a Ti/Cu layer was used as a cathode. The distance between the Pt sheet and the WC-Co plate was 3.3 cm. Because SiC nanoparticles are very small and readily agglomerate, they were stirred continuously. To improve adhesion between the plate and the composite coating layer, the electrodeposited WC-Co plate was heat-treated at 250 °C for 1 h. To apply the coating to WC-Co micro drill bits (diameter ~ 100 μm), the bits were also coated with a Ti layer followed by a Cu layer. The micro drill bits were located in the middle of a cylindrical Pt sheet and electrodeposited under the conditions listed in Table 3. To optimize the conditions for coating the composite layers, the surface morphology, surface roughness, hardness, and phase were examined. The micro drill bits were coated using optimized conditions. The coated micro drill bits were tested via a positioning accuracy test.

The surface morphology and composite coating cross-sections were examined using scanning electron microscopy (SEM, VEGA II SBH, Tescan Co., Ltd.) and field-emission scanning electron microscopy (FE-SEM, S-4700, Hitachi Co., Ltd.), respectively. The surface roughness was measured with a surface profiler (P-1, Tencor Co., Ltd.). The friction properties of the

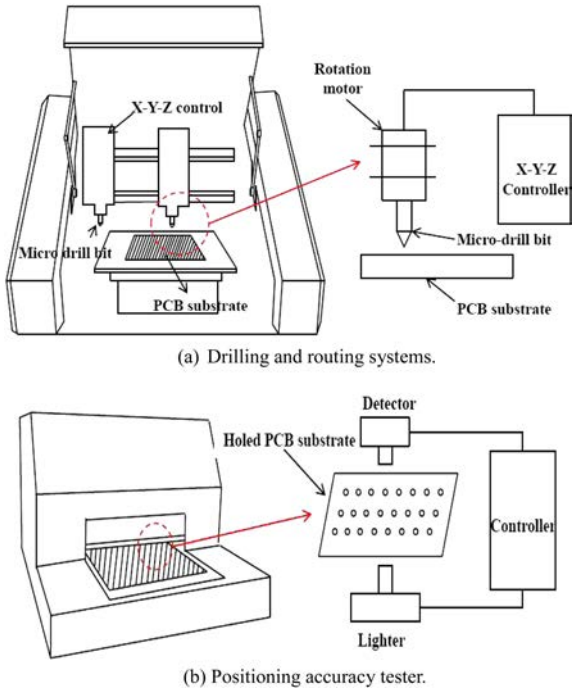

Fig. 1. Schematic diagrams of (a) drilling and routing systems and (b) the positioning accuracy tester.

composite coating layer were studied using a ball-on-disk wear tester (DTA-408, Daekyungtech Co., Ltd.). The hardness was measured with a Vickers hardness tester (MMT-7, Buehler Co., Ltd.). X-ray diffraction (XRD, D/MAX-2500/PC, Rigaku Co., Ltd.) was used to identify the phases of the composite coating layers, and the weight percent of SiC in the Ni coating layer was measured using energy dispersive X-ray spectroscopy (EDS, 7200H, Horiba Co., Ltd.). The positioning accuracy of the coated micro drill bits was analyzed at Neotis Co., Ltd., (Korea). After the holes were drilled on a PCB substrate at regular intervals by drilling and routing (MX series, Schmoll Maschinen Co., Ltd.), a positioning accuracy tester (LV265, Machvision), operated by transmitting light through the holes in the PCB substrate, was used to measure the difference between the programmed location and the actual location (Fig. 1).

Results and Discussion

Nanostructure and surface roughness

Figure 2 shows SEM images of the surface morphology of the coatings formed by the two SiC concentrations. SiC nanoparticle agglomeration was observed with the 10 g/l plating concentration. In contrast, SiC nanoparticles were well dispersed with the 5 g/l plating concentration. Therefore, the optimized SiC concentration was 5 g/l, and SiC concentrations above 5 g/l resulted in agglomeration of the SiC nanoparticles in the electrolyte due to poor wettability [13].

The surface roughness of the SiC/Ni composite coating layer was examined by a surface profiler (P-1,

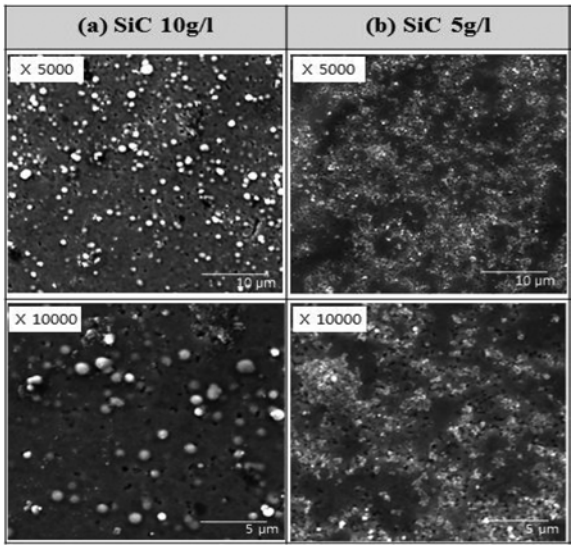

Fig. 2. SEM image of the surface of WC-Co plates coated with SiC/Ni using (a) 10 g/l and (b) 5 g/l of SiC.

Table 4. Average roughness of the SiC/Ni composite coating on a WC-Co plate.

Concentration	Average roughness, Ra (nm)
SiC 10 g/l	45.01
SiC 5 g/l	69.01

Table 5. Hardness and deposited SiC content of WC-Co plates coated with 10 and 5 g/l of SiC.

Concentration	Hardness (HV)	Deposited SiC content (Wt%)
10 g/l SiC	1283.7	4.72
5 g/l SiC	1469.9	5.91

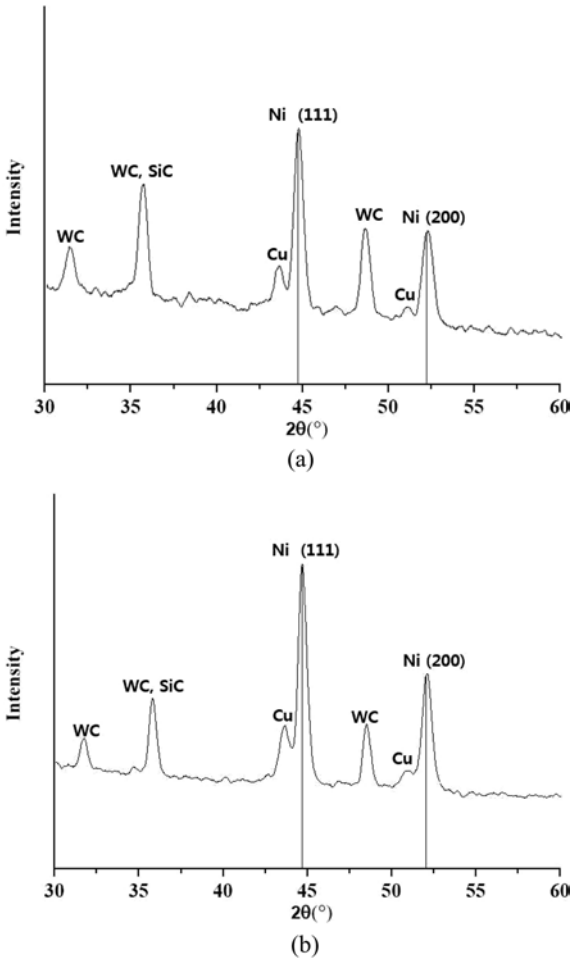

Fig. 3. XRD patterns of SiC/Ni composite coatings electrodeposited using a Watts bath with (a) 10 g/l and (b) 5 g/l SiC.

Tencor Co., Ltd.). The roughness of the surfaces coated with 5 and 10 g/l of SiC are shown in Table 4. Here, the 'Ra' value is the average deviation from the reference point, or average roughness. A high Ra value means that many SiC particles were dispersed. As shown in Table 4, the Ra values for the 5 and 10 g/l concentrations were 69.01 and 45.01 nm, respectively. These values were consistent with the SEM observations in Figure 2, in which the 5 g/l SiC/Ni composite coating was well dispersed compared to the 10 g/l SiC/Ni coating.

Micro-hardness and XRD

Table 5 shows the results of the Vickers hardness test and the composition of the SiC particles observed with EDS. The results in Table 5 indicate that the micro-hardness improved with increasing SiC content. It is known that finely dispersed SiC nanoparticles in a ductile metal matrix such as Ni increase the strength of the composite, and an increasing volume fraction of the dispersed particles improves the hardness [1]. XRD results of the SiC/Ni coating (Fig. 3) identified the phases and presence of SiC nanoparticles in the Ni matrix, and showed that only Ni, WC, and Cu + SiC were present.

After a Cu seed layer was deposited on the WC-Co plate, a SiC/Ni composite coating was electrodeposited on the Cu seed layer. Generally, growth of the electrodeposited layer is a competition between nucleation and crystal growth. The microstructure corresponding to the (100) texture exhibited by Ni electrodeposition was associated with deposits of maximum ductility and minimum hardness [13, 15]. SiC particles embedded in the Ni matrix influenced the texture of the growing nickel layer, changing the (100) texture from a Ni microstructure to a mixed structure with a preferred orientation through the (100) and (211) axes. The altered microstructure improved the hardness due to a smaller boundary size [16]. As shown in Figure 3, 5 g/l of SiC embedded a relatively high weight percent of SiC into the WC-Co plate and showed a smaller intensity (200) diffraction line compared to 10 g/l of SiC. This suggests that the intensity of the diffraction peaks due to growth of the Ni microstructure correlated with the hardness of the SiC/Ni composite coatings.

Friction coefficient

Figure 4 shows the composition with respect to the

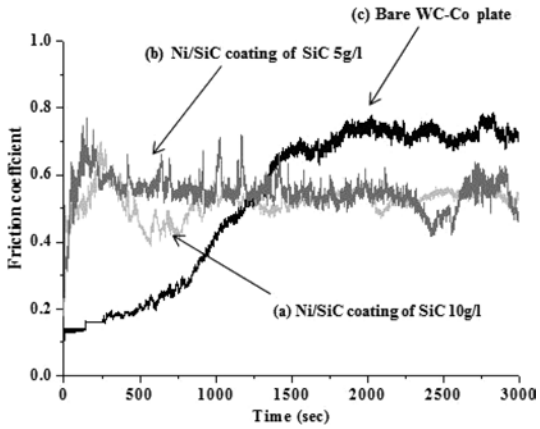

Fig. 4. Friction coefficient as a function of time: (a) SiC/Ni coated using 10 g/l of SiC, (b) SiC/Ni coated using 5 g/l of SiC, and (C) bare WC-Co plate.

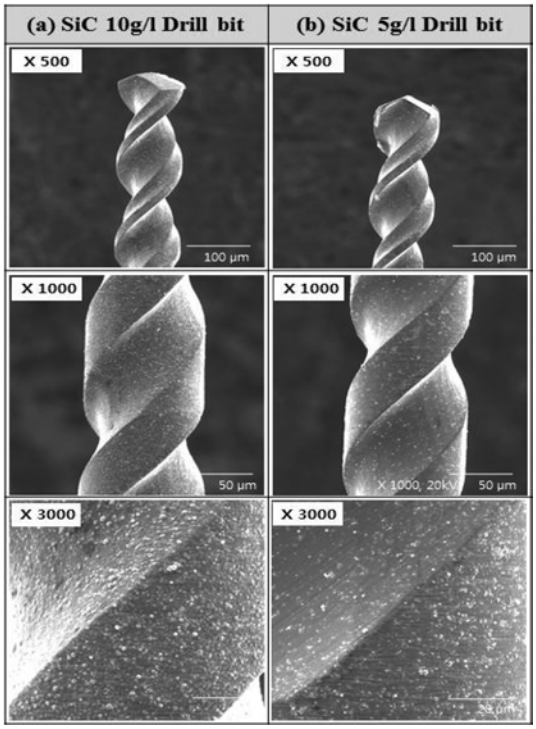

Fig. 5. SEM images of the surfaces of micro drill bits coated with SiC/Ni deposited using (a) 10 g/l and (b) 5 g/l of SiC.

friction coefficient on a bare WC-Co plate and coated WC-Co plates. The friction coefficient of the polished WC-Co plate increased with time and eventually stabilized. The initial friction coefficient of the polished WC-Co plate was low. However, due to wear between the plate and the SUS stainless steel ball from the ball-on-disk by wear tester, the friction coefficient of the polished WC-Co plate surface was the same as that of the bare plate. The friction coefficient of the electrodeposited coating layer deposited using 5 g/l of SiC was higher than that deposited using 10 g/l of SiC. As the SiC nanoparticles were embedded into the Ni matrix, the friction coefficient increased due to increasing surface roughness. Thus, the SiC content in the SiC/Ni composite increased the friction coefficient [17]. Moreover, despite the thin SiC/Ni composite layer, a coated WC-Co plate had a lower friction coefficient than the bare WC-Co plate. Thus, a coated WC-Co plate was protected by the SiC/Ni composite layer.

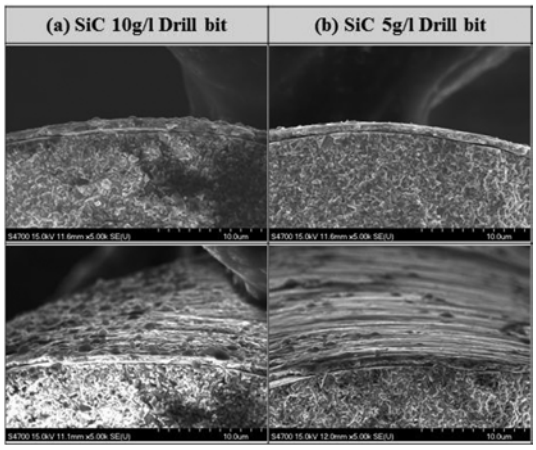

Fig. 6. SEM images of cross-sections and tilted cross-sections of micro drill bits coated with SiC/Ni using (a) 10 g/l and (b) 5 g/l of SiC.

Table 6. Results of positioning accuracy tests of micro drill bits with (a) No Coating, (b) SiC/Ni coated with 10 g/l of SiC, and (c) SiC/Ni coated with 5 g/l of SiC.

	(a) No Coating	(b) SiC/Ni coating with 10 g/l of SiC	(c) SiC/Ni coating with 5 g/l of SiC
Cp	2.611	2.737	3.367
k	0.258	0.231	0.193
Cpk	1.944	2.110	2.717

Microstructure and positioning accuracy tests of the electrodeposited micro drill bits

Figure 5 shows the surface morphology of the micro drill bits coated with SiC/Ni. The surface morphology of the micro drill bits coated using 10 g/l of SiC showed that the SiC nanoparticles were agglomerated. However, the surface morphology of the micro drill bits coated using 5 g/l of SiC showed that the SiC nanoparticles were well dispersed in the Ni matrix.

Figure 6 shows FE-SEM cross-sectional images of the micro drill bits coated using the two SiC concentrations. The SiC/Ni composite coating with 10 g/l of SiC was rough, and the thickness of the cross-section was ~ 1.3 - 1.4 μm. When the SiC concentration was reduced to 5 g/l, the nanoparticles were deposited homogeneously, the thickness of the cross-section was ~ 0.9 - 1.0 μm, and the coating was relatively smooth. The 5 g/l SiC coating layer was less agglomerated than the 10 g/l SiC coating layer.

It is important for micro drill bits to perform accurately when drilling holes in PCB substrates. However, various factors influence the positioning accuracy. Therefore, indices that show the difference between the actual and programmed data indicate the quality of the drill bit.

The results of the positioning accuracy tests for the coated micro drill bits are shown in Table 6. According to the six-sigma standard, 'Cpk' represents the process capability index, 'Cp' represents the process index without considering location, and 'k' represents the deviation from a reference point. A larger Cp and smaller k indicate good credibility. Both Cp and k were similar for the bare micro drill bit and the micro drill bit coated using 10 g/l of SiC. However, the micro drill bit coated using 5 g/l of SiC had the largest and smallest Cp and k values, respectively. Therefore, the micro drill bit coated using 5 g/l of SiC had the largest Cpk, or credibility. To coat 100 μm-diameter drill bits, the SiC/Ni composite layer should be thin, and the SiC nanoparticles should be dispersed evenly in the Ni matrix. Therefore, micro drill bits coated using 5 g/l of SiC showed highly credible positioning accuracy due to increased wear resistance.

Conclusions

Two SiC concentrations were used to optimize electrodeposition on WC-Co plates and micro drill bits. The optimized SiC/Ni composite coating was verified using a positioning accuracy test. Agglomeration of the SiC nanoparticles was observed when WC-Co plates were coated using 10 g/l of SiC, but the SiC nanoparticles were well dispersed on WC-Co plates coated using 5 g/l of SiC. The SiC/Ni composite coatings increased the surface roughness of the micro drill bits.

The hardness of the SiC/Ni composite coating layer depended on the amount of SiC nanoparticles embedded in the Ni phase. EDS results showed that 5 g/l of SiC resulted in a greater amount of embedded SiC nanoparticles than 10 g/l of SiC. XRD results showed that the (200) diffraction line of SiC deposited using 5 g/l was smaller than that using 10 g/l. The embedded SiC nanoparticles altered the (100) texture of Ni. The modified microstructure of the Ni matrix improved the hardness of the SiC/Ni composite layer. Surface projections significantly increased the friction coefficient due to SiC nanoparticles embedded in the Ni matrix.

The positioning accuracy test results indicated the quality of the coatings on the micro drill bits, which differed according to the bit diameter and hardness. The cross-sections of the SiC/Ni composite layers deposited using 10 and 5 g/l of SiC were ~ 1.3 - 1.4 and ~ 0.9 - 1.0 μm thick, respectively, and the coatings were relatively smooth. Micro drill bits with small diameters (~ 100 μm) require a very thin coating layer, less than the diameter of the micro drill bits. Therefore, relatively thin and hard SiC/Ni composite layers deposited using 5 g/l of SiC had a higher process capability index than those deposited using 10 g/l of SiC.

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