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ORIGINAL ARTICLE

EDM electrode manufacturing using RP combining electroless plating with electroforming

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Abstract This study investigates an effective method for manufacturing electrical discharge machining (EDM) electrodes using the rapid prototyping (RP) system based on electroless plating (nickel plating) and electroforming (copper). This method was shown to finish the development of die-sinking electrical discharge machining (EDM) electrodes, shorten the electrode manufacturing process, decrease the manufacturing duration as well as the cost of electrodes. The electrode prototype was drawn with Pro/E 3D CAD, and the CAD model was then transformed into the stereo lithography (STL) file format. A Zcorp 402 3DP rapid prototyping machine was adopted to make a gypsum powder electrode prototype with a complex appearance. The gypsum material is sealed by resin permeation, enhancing its water-resistance and strength. Electroless plating was then performed to introduce electric conductivity onto the gypsum electrode surface, followed by copper electroforming of the thickness about 1 mm to obtain the EDM electrode. Furthermore, die-sinking electric discharge machining was performed. Test results indicate that no crack was found on the electrode and that the electrical discharge machining effects are promising.

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Keywords Rapid prototyping (RP) · Electroless plating · Electroforming · EDM · Electrode

1 Introduction

Electrical discharge machining (EDM) is a non-conventional machining processes used extensively in the machining of dies and moulds with hardened material. Typically, the cost and time consumption in the die and mould machining by EDM is the manufacturing of electrodes, which can account for over 50% of the total machining cost [1]. In general, the cost and time depend on the complexity of the geometry and the precision demanded. The EDM electrode material must provide some fundamental properties such as the electrical and thermal conductively, a high melting temperature, a low wear rate, and resistance to deformation during the machining process. The simple electrodes for EDM are normally fabricated by conventional cutting methods, but for complicated shapes, the electrodes may be produced by machining, casting, electroforming or metal spraying. Manufacturing of EDM electrodes with rapid prototyping (RP) technology can reduce the cost of fabrication electrodes with complex geometry [2]. Rapid prototyping (RP) potentially offers great benefits; it can help shorten the time to market, improve quality, and reduce traditional tooling costs [3].

Zaw et al. [2] had compounded of ZrB_2 and TiSi with Cu at various compositions to study the EDM electrodes by either solid-state sintering or liquid-phase sintering, and they directly applied the electrodes with the RP system, while furnace sintering was used to determine the proper composition of elements and to prepare the specimens for experiments. Stucker et al. [4] attempted to apply a composite of ZnB_2/Cu mixed with an adhesive to prepare

an RP model by selective laser sintering (SLS), and then to make an EDM electrode after the removal of the adhesive by heating. Arthur et al. [5] presented a method to find a direct generation route with rapid prototype parts as the electrodes for EDM. The photo-polymer electrode is coated by silver nearly 10 μm thick onto the surface, then electroformed of copper with thickness of 180 μm. They claimed that these electrodes are suitable for finishing cut in EDM die-sinking.

Allan et al. [6] describes the use of electroforming for the production of EDM electrodes, and the use of a different RP technique in the fabrication of these electroforms. In this study, the electrode life, wear of electrodes, and eroded cavity depth against wall thickness has been discussed. It is shown that to use filled thin-walled electroforms as EDM electrodes is possible. Arthur et al. [7] explored manufacturing parameters and discovered that when the copper plating layer on the electrode prototype is above 175 μm thick it can help prevent the electrode prototype from breaking during electrical discharge machining. Zhao et al. [8] can manufacture an EDM metal prototype directly using the selective laser sintering (SLS) process. The direct sintering applications powder system consists of steel, polyester, and phosphate, which are mixed mechanically. The preferable surface finish of a cavity can be acquired using roughening or semi-finish machining parameters with this kind of electrode. Yarlagadda et al. [9] used a rapid prototype pattern made by the stereolithography technique to fabricate the EDM electrodes. Based on their study, it could be concluded that the electroformed copper electrodes seem to provide an excellent potential for use. Noguchi and Nakagawa [10] developed the laser sintering method to make the precision tool by mixing tiny particles to improve surface roughness.

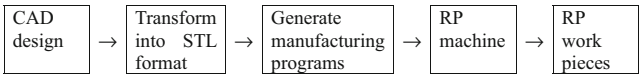

Fig. 2 Flowchart of manufacturing procedure of a rapid prototyping electrode

This investigation adopted the Zcorp 3D Printing rapid prototyping (RP) system to prepare a die-sinking electric discharge machining electrode with a complex geometry. The cost of Zcorp 3D Printing is only half that of photo-polymer rapid prototyping system. Moreover, the cost of the gypsum powder material used for Zcorp 3D Printing is much less than that of a photo-polymer.

After the surface of RP prototype electrode was treated with electroless plating (a chemical plating process), the gypsum powder electrode prototype became conductible, and the conductive layer of this electrode could be thickened by electroforming. Finally, the electrical discharge machining performance of the electrode manufactured by this process was measured.

2 Experimental method

This investigation presents an EDM electrode with a complex appearance. Figure 1 illustrates the experimental procedure. The electrode was further strengthened and waterproofed by resin permeation and then manufactured with electroless plating and electroforming. Finally, an

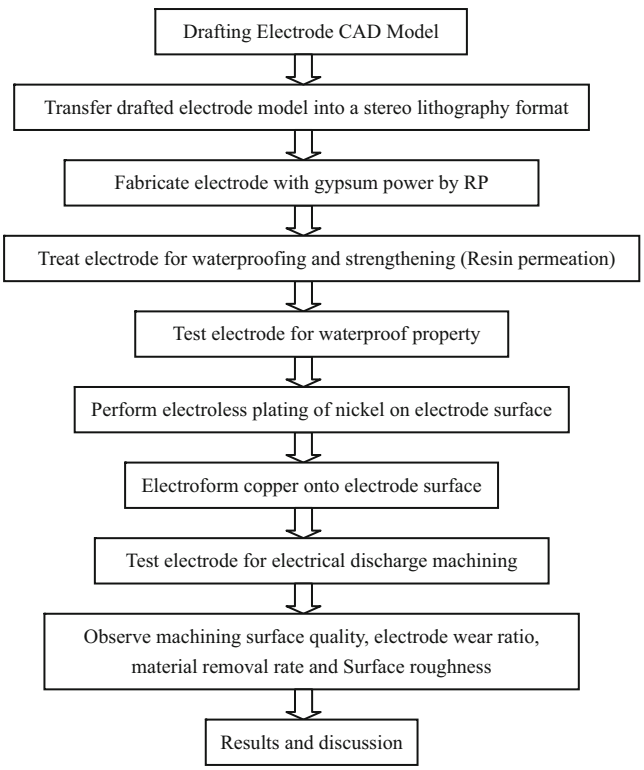

Fig. 1 Flowchart of the experimental procedure

Fig. 3 Rapid prototyping gypsum powder electrode

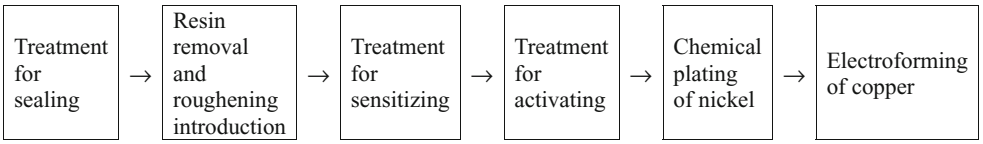

Fig. 4 Procedure of the gypsum electrode covered by copper

electrical discharge machining test was performed to assess the outcome of the proposed electrode manufacturing process.

2.1 Preparation of a rapid prototyping electrode and strengthen

Figure 2 illustrates the manufacturing procedure of a rapid prototyping electrode. The electrode prototype was drawn by the Pro/E 3D CAD software, and the CAD Model was then transformed into the stereo lithography (STL) format. A Zcorp 402 3DP rapid prototyping machine used gypsum powder (Model no. ZP100) to provide the electrode prototype illustrated in Fig. 3.

2.2 Treatments for sealing and strengthening a gypsum electrode prototype

The waterproof sealing and strengthening treatments are necessary to prevent deformation or dissolution of the porous gypsum powder electrode. We found a heat-resistant resin (Kwang Hwa Elect. Material AB-901) of moderate viscosity was suitable for permeation after many testings, where reagent A is an epoxide resin and reagent B is a curing agent. They were mixed in a 1:1 ratio. After resin permeation and polymerization curing, the electrode prototype was soaked in hot water of 80°C for 8 h. The test results revealed that the gypsum electrode did not absorb water and was not weakened or deformed, which indicates that the electroless plating electrode is durable in a manufacturing environment.

3 Manufacturing process of inducing conductivity onto an electrode prototype surface

The resin-permeated electrode was treated to a roughening, sensitizing and activating surface. Then we applied electroless plating to make the electrode conductive and to increase the thickness of conduction layer by electro-

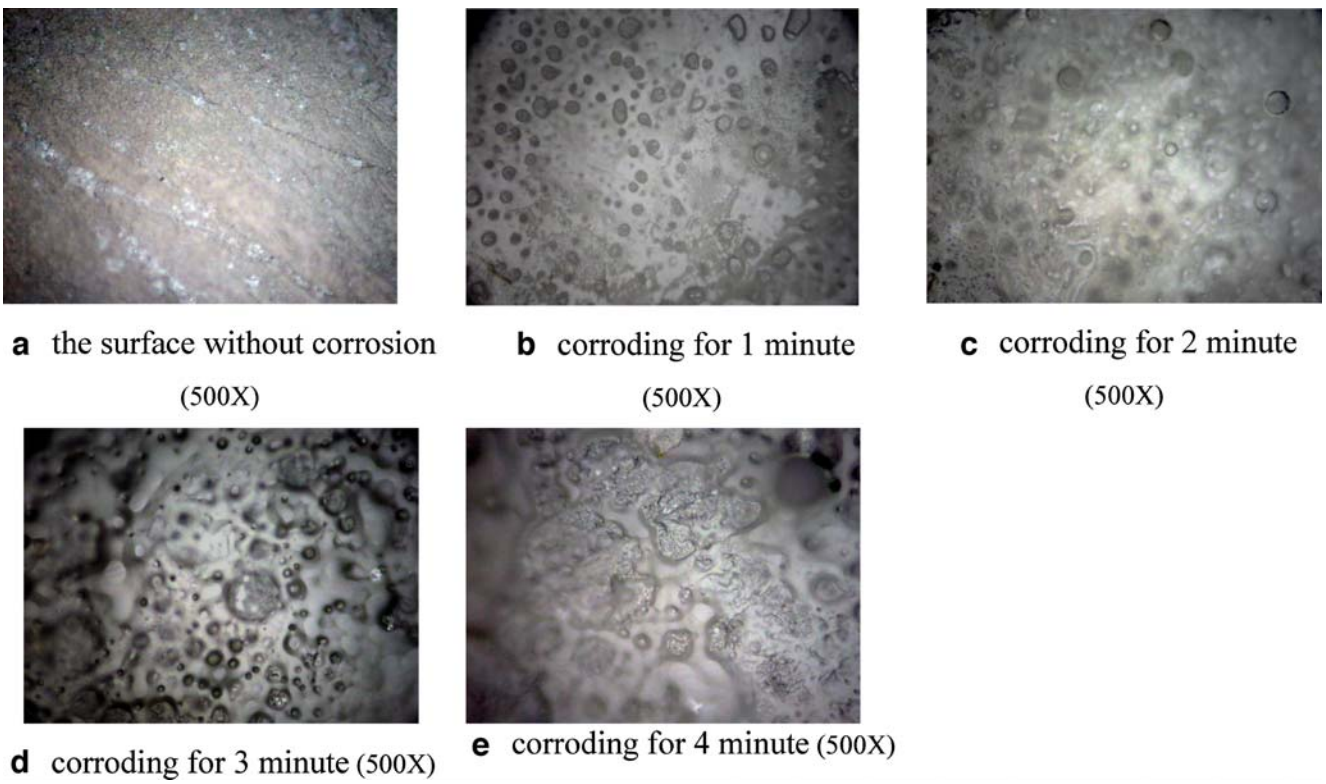

Fig. 5 Surface conditions of the RP gypsum electrode prototype at different roughening and corrosion time. **a** Plane without any aperture on the surface without corrosion; **b** small circular apertures occurred on the surface after corroding for 1 min; **c**, **d** larger apertures formed after corroding for 2 and 3 min; **e** apertures became large enough to overlap after corrosion for 4 min.

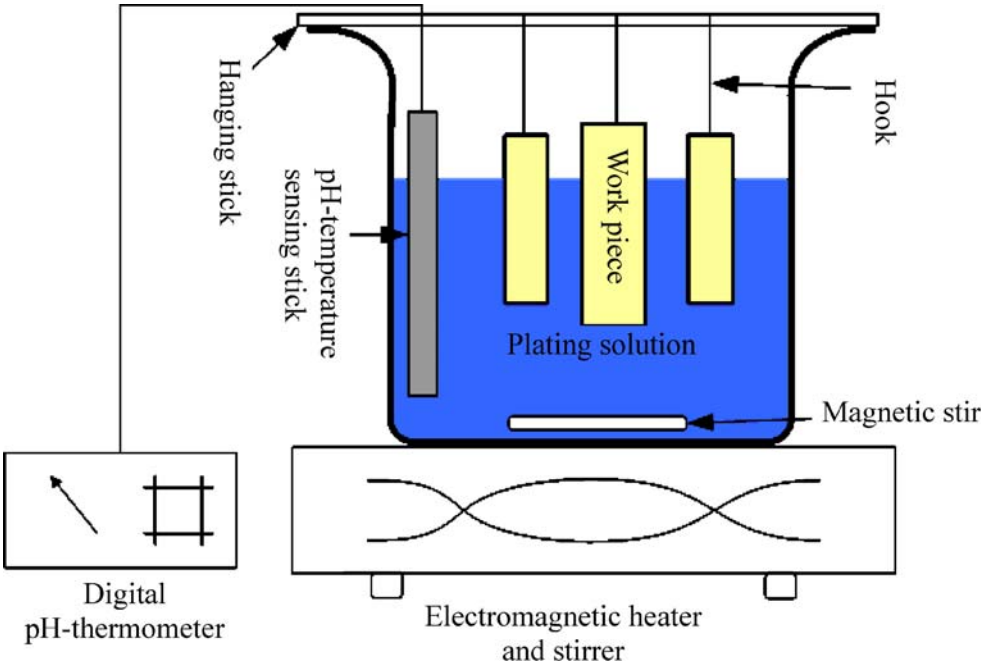

Fig. 6 Schematic experimental configuration for electroless plating deposition of nickel

forming. This provides conductivity of the electrode. Figure 4 illustrates this procedure.

3.1 Fundamental principles of electroless plating

The procedure of electroless plating for a non-conductive material is as follows:

(1) Pretreatment: this step involves sealing, degreasing, etching, washing and roughening of surfaces.
(2) Treatments for sensitizing and activating: these manufacturing processes are adopted for noncatalytic metals, where SnCl2 is a typical sensitizer and Pd Cl2 as an activator.
(3) Autocatalytic plating: this process can be performed in either an aqueous or non-aqueous solution. The plating bath includes the metal salts, the associate chemicals, reducing agent, chelating agent, buffer solution, and stabilizer.
(4) Post-treatment: this step includes neutralizing, washing, thermal treatment, and further electrical plating.

3.2 Degreasing and roughening introduction for the surface

The gypsum electrode (plating material) surface after resin permeation is hydrophobic, and must be made hydrophilic and without grease or dirt. Therefore, the plating material surface should be rough enough to enhance the adhesion between the plating metal layer and the plating material. This study applied chemical corrosive method to degreasing and roughening of surfaces, while the corrosive compound was prepared by mixing 15 g of the potassium dichromate, 150 cc of the sulfuric acid, and 150 cc of water.

Surface roughening is the most important step in pretreatment engineering for electroless plating. Insufficient roughening time means that oxidation is too low to generate an anchoring effect, but if the roughening time is too long, then over-oxidation deteriorates the surface and destroys the adhesion of the plating film. This study searched for an optimal roughening time and found the effects of roughening conditions on the plating layer. Deposition tests performed at corrosion times of 1, 2, 3, and 4 min. Figure 5 displays the resulting surface corrosion level, which was observed by a microscope of 500 power. Figure 5a shows the plane without any aperture on the surface without corrosion. Figure 5b shows small circular apertures that

Table 1 Electroless plating solutions of nickel and deposition parameters

Parameters	
Nickel sulfate ($NiSO_4$ $6H_2O$)	29 g/L
Sodium hypophosphite (NaH_2PO_2 H_2O)	18 g/L
Sodium acetate (CH_3COONa $3H_2O$)	30 g/L
Sodium succinct acid ($NaOOCCH_2CH2COONa$ $6H_2O$)	4 g/L
Citric acid ($C_3H_4(OH)(COOH)_3$ H_2O)	2 g/L
Lead acetate ($Pb(CHCOO)_2$ $3H_2O$)	1.5 ppm
pH value (Adjusted by ammonia water titration)	9.0
Deposition temperature	70°C
Deposition time	60 min
Stirring rate	200 rpm

Table 2 Procedure and parameters for electroforming copper

Program	Procedure	Major component	Aim of procedure	Control parameters
1	Grease and oil removal	Basic degreaser	Complete cleaning for surface	Degreaser 50 g/L Temperature 50°C Degreasing time 3 min
2	Neutralization and acid washing	Amino-sulfonic acid	Neutralizing basic layers and removing oxidant layers on the surface	Aminosulfonic acid 30 g/L Room temperature Acid washing time 30 s
3	Surface activation	Poly-phosphoric acid	Surface activation	Polyphosphoric acid 50 g/L Room temperature Soaking 30 s
4	Electroforming of copper	Table 3	Depositing copper of the thickness of 1 mm on substrate surface	Current density 3 A/dm^2, Time 25 h Temperature 57°C
5	Anti-oxidation on surface	SCu-500 copper anti-oxidant	Suppress surface oxidation on the surface of copper layer of electroforming	SCu-500: 5~10% Water: 90~95% Soaking: 30 s
6	Drying	Dry with hot air	Surface drying	Temperature 80°C Time 3 min

Note: Wash each substance surface with water for 1 min in each procedure

occurred on the surface after corroding for 1 min. Larger apertures were also formed after corroding for 2 and 3 min and this is shown in Fig. 5c and d. Figure 5e shows the apertures became large enough to overlap after corrosion for 4 min, which leads to surface deterioration. This experiment reveals that a corrosion time of 3 min yielded enough surface apertures to generate the appropriate anchoring effect and for sufficient electroless deposition.

3.3 Sensitization treatment

The surface layer was sensitized after corrosion treatment. This process increases its ability to absorb reducing agents, thus improving the compatibility of a catalytic film on the surface. The sensitizer was prepared by dissolving 10 g of SnCl2 in 10 cm^3 of concentrated hydrochloric acid, from which 1 cm^3 was dropped into 100 cc of distilled water for dilution. The sensitization treatment was performed by soaking the workpiece in the sensitizer at room temperature for 1 to 2 min and stirring for an even surface coating.

3.4 Treatment of activating

To afford chemical plating of gold on the surface of a non-conductor, it is necessary to paint the catalyst on the surface of a plating material, which is the so-called treatment of activating. The activator was prepared by dissolving 1 g of $PdCl_2$ into 1 cm^3 of concentrated hydrochloric acid, then adding 10 cm^3 of distilled water, from which 1 cm^3 was dropped into 50 cm^3 distilled water for dilution. When we needed to use the activator, we took 10 cc solution as described above and added 200 cc of distilled water. Then

Table 3 Parameters for electroforming of copper

Parameters	
Copper pyrophosphate	85 g/L
Potassium pyrophosphate	310 g/L
Ammonium water	3 ml/L
PCU-10X Pyrolume Brightener	0.3 ml/L
pH value	8.7
Temperature	60°C
Current density at cathode	4 A/dm^2
Anode	Copper for electrical decomposition
Current density at anode	2 A/dm^2
Stirring	Vigorous stirring with air

Table 4 Parameters for die-sinking electrical discharge machining

Electrical discharge parameter	E01	E02	E03	E04	E05
Electrical discharge depth	2.5 mm	2.5 mm	2.5 mm	2.5 mm	2.5 mm
Pulse width	26 μs	100 μs	200 μs	47 μs	47 μs
Cease	15 μs	35 μs	50 μs	110 μs	120 μs
Current (Amperes)	3 A	8 A	15 A	20 A	25 A
Voltage (Volts)	180 V	180 V	180 V	180 V	180 V
Polarity	+	+	+	+	+

Table 5 EDM results of RP electroformed electrodes

Electrode number	Current (Amperes)	Discharging time (min)	Electrode wear ratio (%)	Material removal rate (g/min)	Surface roughness Ra (um)
E01	3 A	255	3.8	0.06	4.49
E02	8 A	105	10.6	0.125	7.48
E03	15 A	32	16	0.322	10.5
E04	20 A	63.45	31.7	0.129	7.67
E05	25 A	49.1	34.4	0.177	7.85

we added one drop of the concentrated hydrochloric acid into the solution. The activation treatment was performed by soaking the workpiece in the activator agent at room temperature with stirring for 1 to 2 min to produce an even surface.

3.5 Electroless plating of nickel

This study employed electroless plating of nickel to cerate an even conductive surface. The deposition temperature was 70°C; the deposition time was 60 min, and the stirring rate was 200 rpm. We added ammonium water to the deposition solution to maintain the pH value. Figure 6 illustrates the schematic experimental configuration for electroless plating deposition of nickel. Table 1 presents the electroless plating solutions of nickel and deposition parameters.

3.6 Electroforming of copper

The surface of the electroformed electrode comprises a nickel layer with a thickness of 25 μm. The electrode breaks easily because the thin conductive film layer cannot resist the voltage, current, and heat during the electrical discharge machining process. In this study, we performed electroforming with copper layer for a 1-mm thickness. The electroforming process includes degrease, neutralization and acid washing, surface activation, electroforming of copper, anti-oxidation of the surface and drying. Table 2 presents the procedure and parameters for electroforming copper. The process described as follows. The electrolytic copper for electrical decomposition was placed at the anode, with a small current density of 2 A/dm^2 owing to the large surface. The plating electrode was placed at the cathode, using a current density of 4 A/dm^2. The plating solution maintained pH value at 8.7, and the temperature at 60°C. We adopted air to stir and yields a homogeneous plating solution. Table 3 presents parameters for electroforming copper.

4 Die-sinking electrical discharge test

The electrode made as described above was then used to test its performance. An electrical discharge machining test performed on the SKD11 mold steel with a depth 2.5 mm under five electrical discharge values, 3A, 8A, 15A, 20A and 25A, respectively. Table 4 presents the electrical discharge parameters of die-sinking.

Performing die-sinking electrical discharge under low current (3A) yielded machining time is 225 min, electrode wear ratio 3.8%, material removal rate of 0.06 g/min and a workpiece surface roughness of 4.49 μm (Ra). While under medium current (15A) yielded machining time is 32 min, electrode wear ratio 16%, material removal rate of 0.322 g/min and a workpiece surface roughness of 10.5 μm (Ra). Under high current (25A) yielded machining time is 49.1 min,

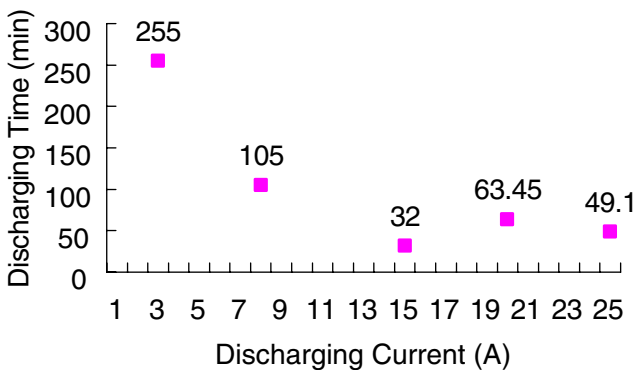

Fig. 7 Shows testing results of discharging time

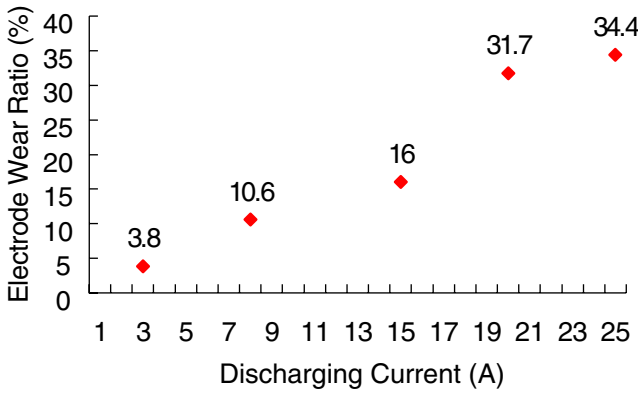

Fig. 8 Shows testing results of electrode wear rate

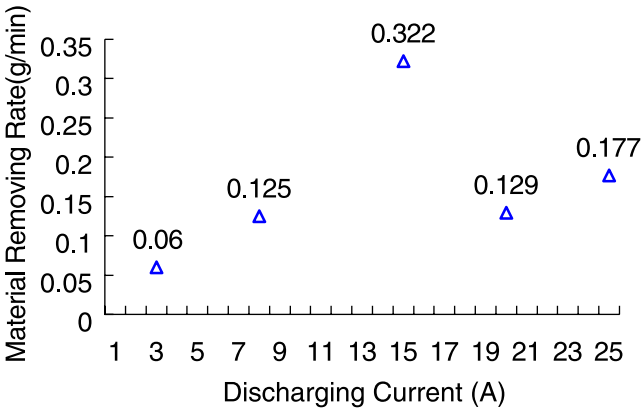

Fig. 9 Shows testing results of material removing rate

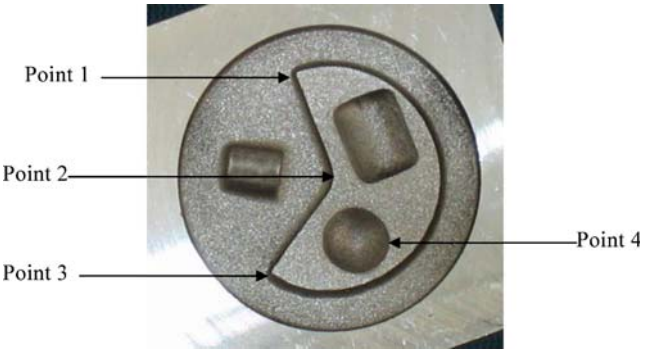

Fig. 11 Trace observation points of an RP electroformed electrode after electrical discharge machining

electrode wear ratio 34.4%, material removal rate of 0.177 g/min and a workpiece surface roughness of 7.85 μm (Ra). Table 5 presents these test results. Figures 7, 8, 9 and 10 shows these test results. Figure 11 displays the micro view of a partial weave of an RP electroformed electrode, which is magnified in Figs. 12, 13, 14 and 15. These figures reveal no obvious damage of the electrode. The diameters of the surface particles of the electrodes after electrical discharge tests, measured by a toolmaker microscope, were 0.065, 0.121, and 0.223 mm under currents of 3, 8, and 15A, respectively. The electrical discharge test results demonstrate that an RP electroformed electrode is capable of electrical discharge machining.

The machining time is lower as the current is higher and we find the minimum time is 32 min under 15 A of current. The electrode wear ratio seems to increase with current but jumps to a higher rate for higher current such as 20 and 25 A. The material removing rate increases as the current increases from 3 to 15A, but then decreases as the current exceeds 15 A. The surface roughness shows the same trend as the material removal rate. It seems that the best machining efficiency may be around 15 A of current.

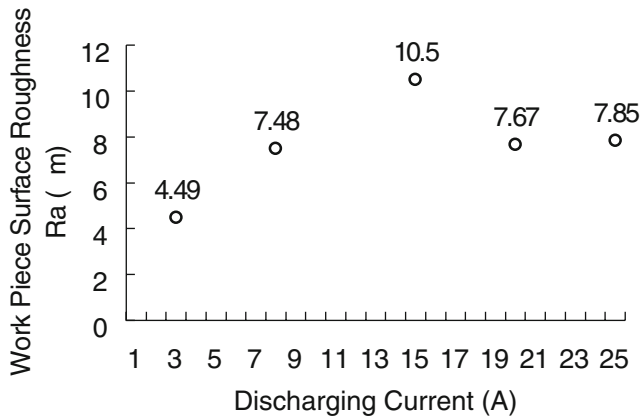

Fig. 10 Shows testing results of surface roughness Ra (μm)

5 Conclusions

This investigation explores the EDM electrode fabrication with gypsum powders (ZP100) rapid prototyping (RP) system based on electroless plating with electroforming processes, and developing new electrode materials that can be produced in RP technology. Manufacturing an EDM electrode with a complex shape was shown to accelerate the development of molds and decrease the production cost. The conclusions of this study may be presented as follows:

1. The electrode required for die-sinking electrical discharge can be feasibly prepared using electroless plating associated with electroforming, to cover the surface of a rapid prototyping gypsum powders electrode with copper.
2. The requirements of strengthening a gypsum electrode by permeating and solidifying RP powder could not be satisfied by CA-260 cyanoethyl acetate instant adhesive, AB 301 epoxide resin AB glue or E-30CL epoxide resin AB glue. A waterproof test (heating to 80°C for 8 h) was finally demonstrated to permeate and solidify a gypsum electrode by AB-901 epoxide resin glue.
3. The critical step in pretreatment engineering for electroless plating is surface roughening. Insufficient roughening time leads to insufficient oxidation to produce an anchoring effect. However, if the roughening time is too long then too much oxidation deteriorates the surface, and destroys the adhesion of the plating film. In this study, each gypsum electrode was roughened on the surface and corroded for 3 min, producing many even apertures on the surface, leading to a strong anchoring effect. Thus, corrosion for 3 min yielded the best electroless deposition effect.
4. No remarkable damages were observed in the micro view of the weave from an electrode after tests for die-sinking electrical discharge.
5. Many identical electrodes can be produced in one batch after manufacturing RP by electroless plating and

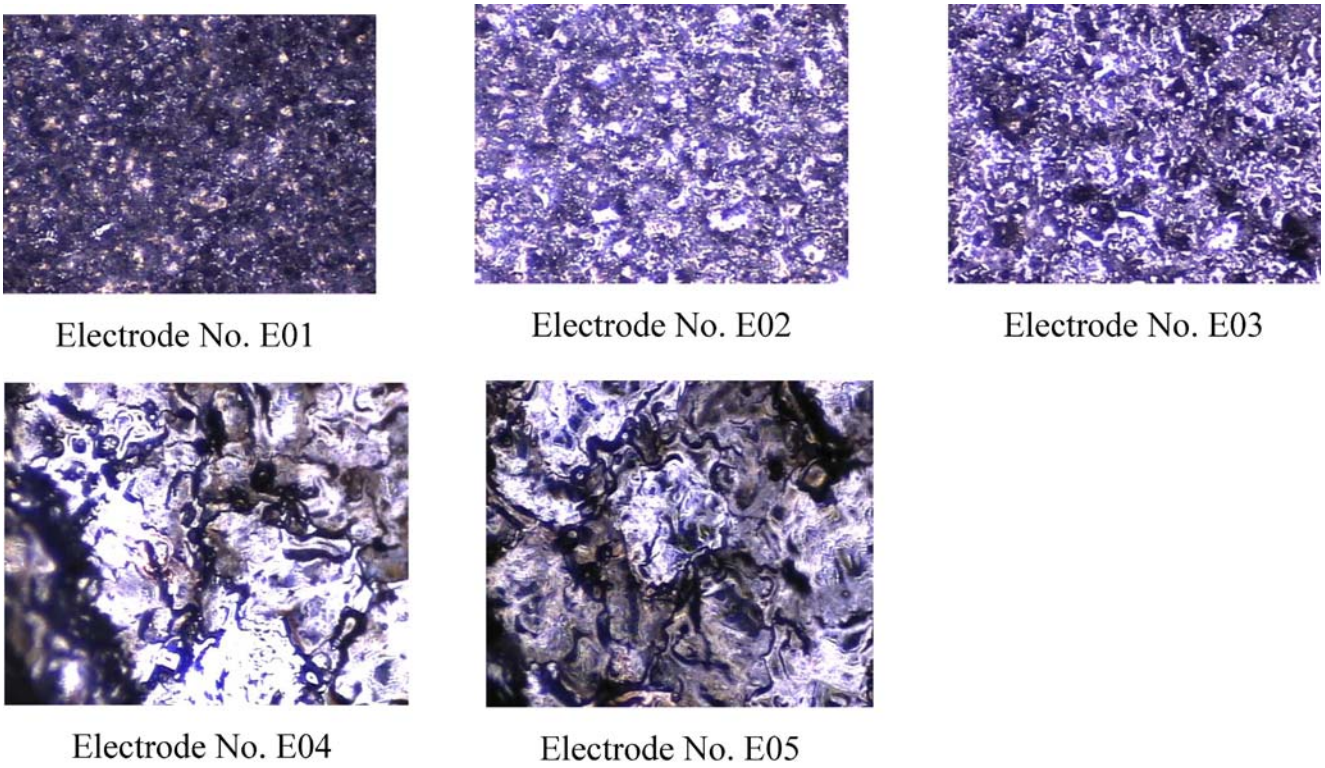

Fig. 12 Observation point 1 (in Fig. 7) of an RP electroformed electrode (167×)

electroforming. These electrodes are not like mechanically formed electrodes. Producing electrodes with complex shapes can lead to cost savings.

6. The electroforming result is affected by factors such as the current electroforming density, the direction of current, the concentration of the plating solution and the ratio of depth over width of the hole in the plating material. Therefore, the electrode inversion should be designed with a CAD system according to factors affecting the appearance and roughness of the electroformed surface. Additionally, the gypsum electrode inversion should then be removed from electroless

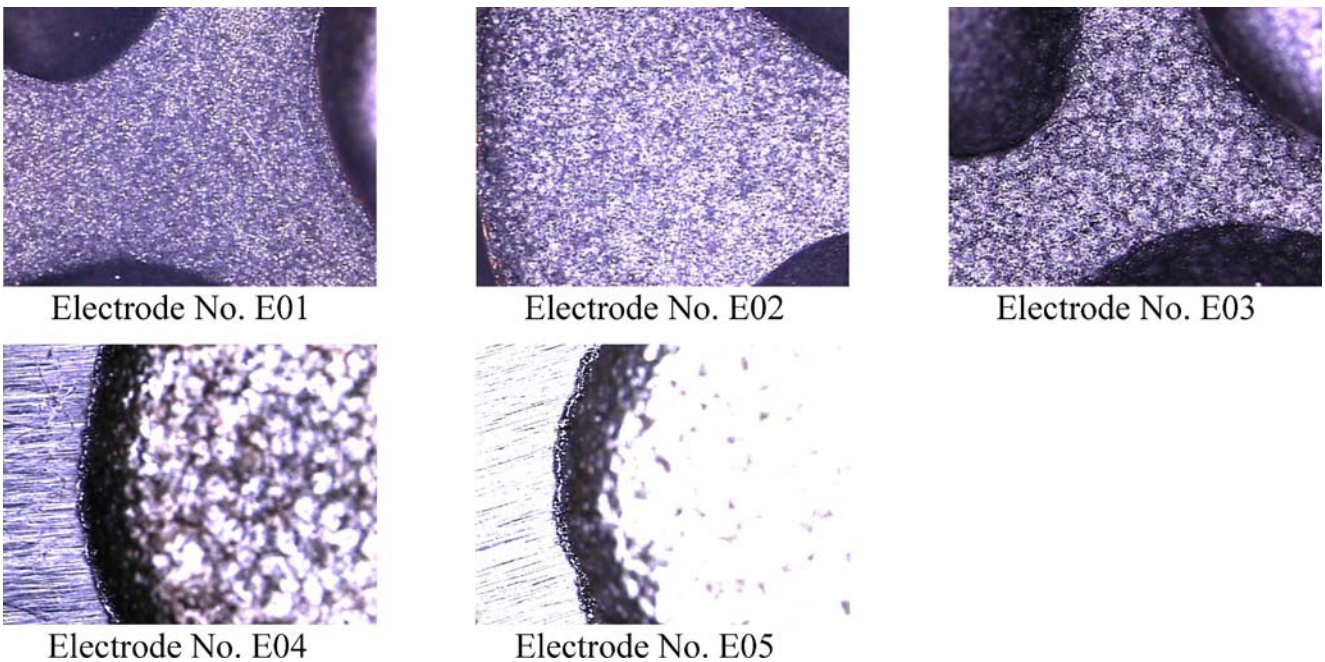

Fig. 13 Observation point 2 (in Fig. 7) of an RP electroformed electrode (30×)

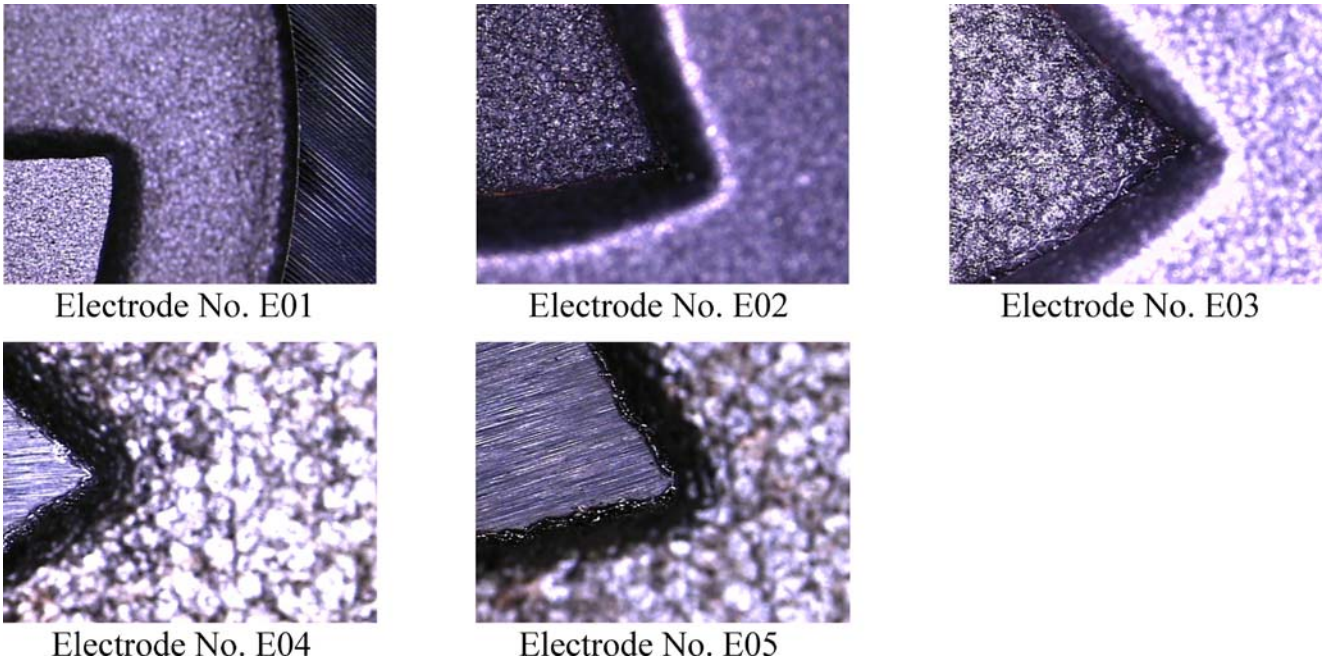

Fig. 14 Observation point 3 (in Fig. 7) of an RP electroformed electrode (30×)

plating to yield a copper-electroformed electrode is a feasible process.

7. It shows that the machining time of EDM is lower as the current is higher and we find the minimum time is 32 min under 15 A current. The electrode wear ratio seems to increase with current but jump to a higher rate for higher current such as 20 and 25 A. The material removing rate is optimal as the current is near 15 A, but the surface roughness is worst near 15 A current. It seems that the best machining efficiency may be near 15 A current.
8. The machining time of 15 pieces of electrode made by RP process mentioned above is 40 h in our laboratory, while the electrode made by conventional CNC machining is estimated about 57 h as shown in Table 6.

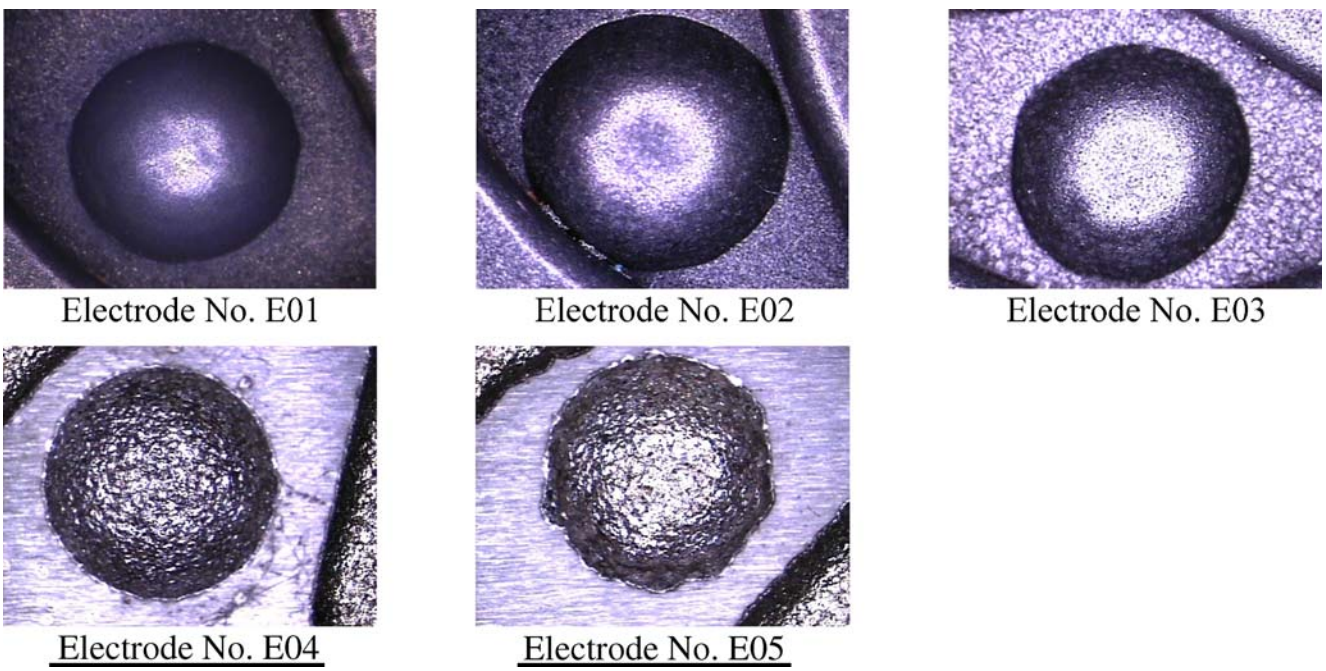

Fig. 15 Observation point 4 (in Fig. 7) of an RP electroformed electrode (14×)

Table 6 Comparison of the machining time of electrode with RP process and CNC process

Electrode manufacturing process		Working hours	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8
RP Electroforming process	CAD	4								
	RP gypsum prototype	8								
	Resin permeating	4								
	Waterproof testing	4								
	Electroless plating	8								
	Electroforming of copper	8								
	trimming	4								
	Total time	40								
CNC machining center process	CAD	4								
	CNC code	4								
	Arrangement of tools and materials	4								
	Cutting time (3 hours for one piece) (*15)	Estimated 45								
	Total time	Estimated 57								

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