Fabrication of EDM Electrodes by Localized Electrochemical Deposition

Mohammad Ahsan Habib[1,#], **Sze Wei Gan**[1], **Han Seok Lim**[2] and **Mustafizur Rahman**[1]
1 Department of Mechanical Engineering, National University of Singapore, 9 Engineering Drive 1, Singapore 117576
2 Mikrotools Pte Ltd, Ayer Rajah Crescent, Singapore 139948
Corresponding Author / E-mail: mahabib@nus.edu.sg, TEL: +65-97758155, FAX: +65-67791459

KEYWORDS : Localized electrochemical deposition, EDM electrode, Micro-EDM

The fabrication of complex three-dimensional electrodes for micro electrical discharge machining (micro-EDM) is an important issue in the field of micromachining. Localized electrochemical deposition (LECD) is a simple and inexpensive technique for fabricating micro-EDM electrodes. This study presents a new process for manufacturing electrodes with complex cross-sections using masks of different shapes. In this process, a non-conductive mask is placed between an anode and cathode that are immersed in a plating solution of acidified copper sulfate. The LECD is achieved by applying a pulsed voltage between the anode and cathode, which are separated by a small distance. In this setup, the cathode is placed above the anode and the mask, so that the deposited electrode can be used directly for EDM without changing the tool orientation. We found that the microstructure of the deposited electrode is influenced by the concentration of the plating solution and organic additives. Moreover, the values of the voltage, frequency, and duty cycle of the pulsed input have significant effects on the microstructure of the fabricated electrode. Finally, the optimum values of the voltage, frequency, and duty cycle were determined for the most effective fabrication of complex-shaped electrodes.

Manuscript received: October 5, 2007 / Accepted: January 7, 2008

NOMENCLATURE

A = deposition area (cm^3)
C_{DL} = specific double layer capacity
D = density of deposited metal (g/cm^3)
d = distance between the electrodes
F = Faraday constant
H = height of deposited metal (cm)
I = current (A)
M = metal
M_w = atomic weight of deposited metal
n = valency
t = deposition time (s)
w = deposition weight (g)
τ = time constant
ρ = specific electrolyte resistivity

1. Introduction

Micro electrical discharge machining (micro-EDM) has become one of the most popular advanced manufacturing technologies at the micro level. EDM is an electrothermal machining process that relies on the ablative effect of electrical discharges. It removes the metal by producing a rapid series of repetitive electrical discharges unrelated to the hardness or brittleness of the material. Micro-EDM is a flexible machining process that is capable of fabricating high-accuracy micro-components of arbitrary structures.

Many variations of micro-EDM technologies are used for manufacturing micro-features, depending on the type of electrode and electrode/workpiece movement. These include micro-wire EDM, micro-EDM die-sinking, micro-EDM drilling, and micro-EDM milling.[1,2] In micro-EDM die-sinking, micro-EDM drilling and milling, different methods and devices can be used to create the small details on electrodes or components.[3,4,5] Micro-EDM die-sinking is a more effective technique than trajectory micro-EDM. In micro-EDM die-sinking, more than one electrode is required when fabricating high-accuracy micro-components. Generally, those electrodes can be produced in advance by micro-milling, micro-turning, or micro-grinding[1]. However, there are some limitations in the above techniques, such as the electrode clamping error that may result in degraded accuracy, long production times, and high production costs. To compensate for these limitations, on-machine electrode fabrication is required. Takahata *et al.* used the *lithographie, galvanoformung, und abformung* (LIGA) process to fabricate micro-EDM electrodes.[6] Localized electrochemical deposition (LECD) is another popular and cost-effective method for direct fabrication of small-shaped electrodes.

About a decade ago, the LECD process appeared to be an excellent approach to freeform micro-fabrication that addressed a number of outstanding challenges at the time[7]. Madden and Hunter were the first to apply LECD to the microfabrication of three-dimensional metal structures.[8] Jansson *et al.* tested the LECD process

Table 1 Experimental parameters for different types of tests

	Voltage test	Frequency test	Duty cycle test
Voltage (V)	0.5, 1.0, 1.5, 2.0, 3.0	1.0	1.0
Frequency (Hz)	100k	1k, 10k, 100k, 1M, 10M	100k
Duty cycle (on-time / total pulse duration)	0.5	0.5	0.25, 0.33, 0.5, 0.67, 0.75

with different kinds of nickel plating solutions to deposit nickel structures.[9] El-Giar *et al.* used the same method to deposit the long thin micrometer-size copper columns, copper electrical inter-connects, and tips required for scanning probe microscopy applications.[10,11] Park *et al.* used ultra-short pulses in LECD process and compared the efficiency of such pulses to DC voltage.[12] Yeo *et al.* investigated the deposition phenomena of LECD for nickel micro-column structures using open-loop (without analog feedback) and closed-loop (with analog feedback) systems.[13] Other investigations have been conducted on the effect of rotational electrodes on the growth of nickel micro-column structures[13] and the effect of ultrasonic vibrations on the rate of deposition, concentration, and porosity of the nickel micro-columns.[14] Most studies have used copper as a substrate and platinum as a counter electrode to fabricate a column structure using LECD. In this study, we use LECD to fabricate electrodes with complex cross-sectional shapes using copper for both the substrate and the counter electrode. Masks made from non-conductive materials and with different designs are used to provide pre-shaping for the deposition. The substrate is located on the machine *z*-axis, which is above the counter electrode because this eases the transition to the EDM process directly after the deposition. Using this method, the electrode clamping error can be minimized and the production rate can be increased.

A simple experimental LECD setup developed for this study was mounted on a multi-process machine. We experimentally investigated the effects on the LECD process of variables such as concentration of plating solution, organic additives, voltage amplitude, frequency, and duty cycle in the creation of an electrode with a good structure and high aspect ratio. Our results show that the deposited electrodes are capable machining workpieces for a micro-EMD die-sinking process.

2. Localized Electrochemical Deposition

2.1 Concept

LECD involves electrochemical deposition in a predetermined and controlled area. Electrochemical deposition or electroplating is a process where the metallic ions become solid metal and are deposited on the cathode surface when a sufficient amount of electric current passes through an electrolyte or plating solution that contains charged ions. These charged ions, especially positively charged ions, can be produced by dissolving metallic salt in water. For a metal "M" of valency "*n*", *n* electrons are required to reduce the cation to its metallic form. A more realistic equation is $\mathrm{M}^{+n} + ne^{-} \Rightarrow \mathrm{M}$, where M metal will be deposited on the cathode by receiving *n* number of electrons.

Figure 1 shows a schematic diagram of the LECD process that we implemented in this study. The anode is immersed in an electrolyte of copper sulfate ($CuSO_4$) solution, and the cathode is located above the anode. A non-conductive mask is located directly on the cathode, and a small gap is maintained between the anode and the mask during the deposition. When an electrical charge is placed across the electrodes, current will pass through the plating solution. The positively charged metal ions (Cu^{2+}) are deposited as solid metal on the cathode after receiving electrons from the anode. The shape of the deposit will conform to the shape of the mask on the exposed surface of the cathode.

When a voltage is applied between two electrodes in the electrolyte, a so-called double layer (DL) is formed. The DL constitutes a capacitance on both the anode and cathode electrodes that is charged when the voltage is applied. The electrolyte acts as a resistance for the charging current that is proportional to the length of the current path and the distance *d* between the electrodes.[15] This leads to locally varying time constants as shown in the following equation:

$$\tau = \rho d C_{DL} \tag{1}$$

Therefore, a pulse voltage is applied to the LECD process to control the charging of the DL, which is related to the pulse duration.

The height of the deposition can be calculated from the following equation:

$$H = \frac{w}{AD} = \frac{M_w}{nFAD}\int I dt \tag{2}$$

Since the height of deposition depends on the current passing through the electrolyte during a certain time interval, it is possible to measure the height of deposition simply by measuring the current.

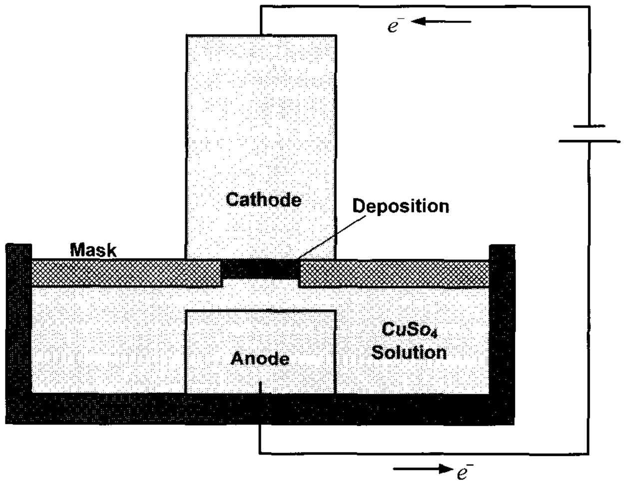

Fig. 1 Schematic diagram of the LECD process

2.2 Experimental Procedure

Figure 2 shows the complete experimental setup for the LECD process. The apparatus was mounted on a four-axis multi-process machine. The setup consisted of two main parts: an electrode holder (cathode), and a deposition tank (anode). The electrode holder was a flexure structure with a capacitance gap sensor to detect the contact point between the electrode and the mask. It was fixed on the *z*-axis of the machine. The deposition tank consisted of the working electrode (anode) and the mask. The mask was made of polymethyl methacrylate (PMMA). It has some advantages over other materials,

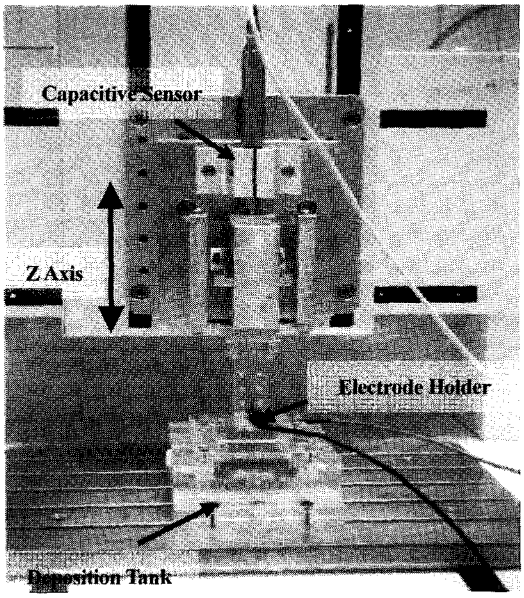

Fig. 2 (a) Photograph of the complete LECD experimental setup

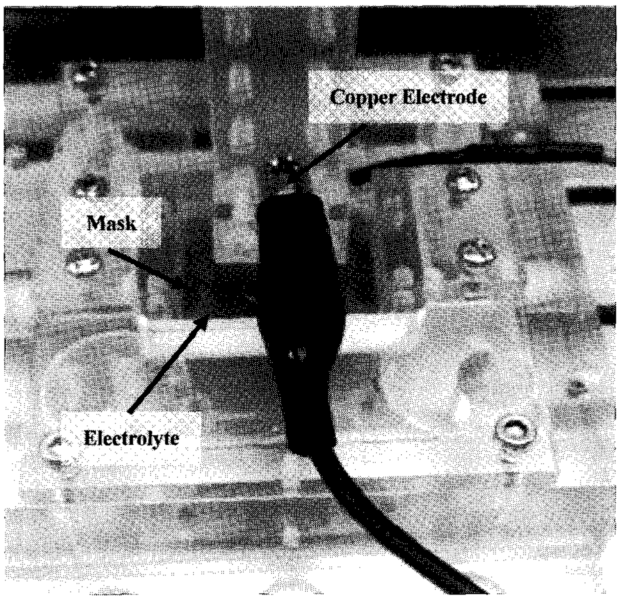

Fig. 2 (b) Photograph of the LECD deposition tank

such as transparency, ease of fabrication, excellent alkalinity, and good acidic resistance. The masks were machined in different cross-sectional shapes, such as X-, Y-, and cloverleaf shapes using micro-milling.

This study focused mainly on four observations related to the effects of complex shapes on LECD electrode fabrication. First, we investigated the effect of the plating solution concentration and organic additives on the microstructure of the deposited electrode. Second, we examined the effect of different pulsed voltage amplitudes on the deposited electrode. Third, we studied the effect of the pulse frequency. Fourth, we experimentally investigated the effect of the pulse duty cycle, where the duty cycle is the pulse-on time divided by the total pulse duration. Table 1 shows the different experimental parameters for our tests. We used copper rod for the substrate and counter electrodes, and the electrolyte was $CuSO_4.5H_2O$ (200 g/l) and H_2SO_4 (75 g/l) with thiourea $(NH_2)_2CS$ (0.04 g/l).[11] All the experiments were for a deposition time of 15 min. To ensure good deposition conditions, we polished the electrode surfaces with successive grades of 600, 1200, 1500, and 2000 silicon carbide papers. A final fine polishing was done with 1.0-μm diamond polish on a nylon cloth to obtain a smooth mirror surface.

We collected only two parameters from each test: the height and density of the deposit. The height was measured with a digital microscope (VHX 100, Keyence). The density of the deposit was calculated from the net weight of the deposit divided by its volume.

3. Results and Discussion

3.1 Effect of Plating Solution Concentration and Organic Additives

We varied the Cu^{2+} concentration in the plating solution over the range 0.05–1.5 M to observe the effect on the deposition rate. We observed that the concentration had no significant effect on the deposition rate but the deposited structures were irregular and highly porous when the concentration was less than 0.1 M. This is because the number of ions available for discharging is low when the concentration is low, creating a depletion layer just beneath the electrode. However, when the concentration is high, many ions are available for deposition, resulting in firm and consistent deposits. Similar observations were made by El-Giar *et al.* with a different experimental setup and electrode materials.[11]

We found that fine-grained and microcrystalline deposits can be achieved by adding organic substances such as thiourea to the acidic copper sulfate solution. Figure 3 shows a comparison between deposition with and without 0.04 g/l thiourea added to the $CuSO_4$ solution. It is clear that the presence of thiourea improved the surface structure of the copper deposit.

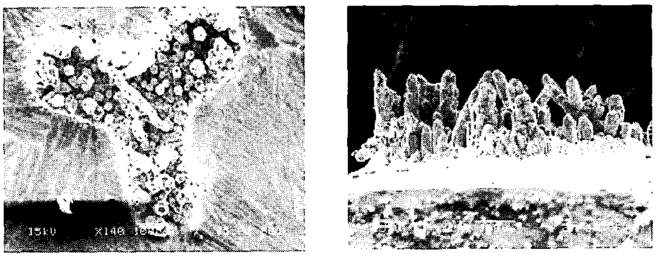

Fig. 3 (a) SEM images of the deposit without thiourea

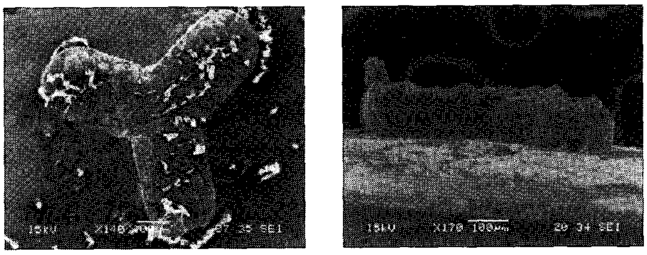

Fig. 3 (b) SEM images of the deposit with 0.04 g/l thiourea

3.2 Effect of Voltage Amplitude

To investigate the effect of the voltage amplitude on the LECD process, we varied the pulsed voltage amplitude over the range of 0.5 to 3.0 V while maintaining a frequency of 100 kHz and duty cycle of 0.5. Figure 4 shows that the optimum voltage of 1 V produced a higher deposition height and density. As indicated by Eq. (2), a high voltage means a high current, and consequently a greater deposit height. However, at a certain point, the higher voltage will result in a current that exceeds the limit value of the electrolyte, which causes the deposit to become powdery. This is because the area surrounding the anode becomes depleted of ions for discharging the anode. At the same time, a high volume of hydrogen gas is produced around the anode. An agitation system in the deposition tank can solve this problem. By applying force convection inside the electrolyte, it is possible to minimize the formation of hydrogen bubbles beneath the mask during deposition.

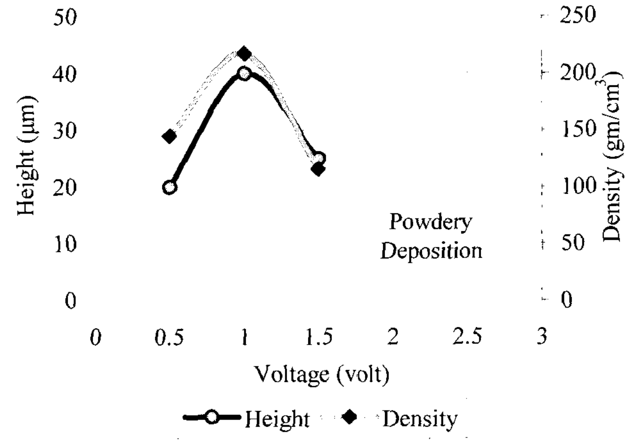

Fig. 4 Deposit height and density as functions of voltage amplitude

3.3 Effect of Frequency

Since a pulsed voltage is used in the LECD process, the frequency can affect the deposit. We tested different frequencies in the range of 0.001 to 10 MHz with an amplitude of 1 V and a duty cycle of 0.5. Figure 5 shows that the frequency had no significant effect on the deposit height because the total supplied energy was the same for all frequencies. However, a frequency of 100 kHz produced a high-density copper deposit. This is likely due to achieving the proper charging of the electrode, which depends on the DL time constant shown in Eq. (1).

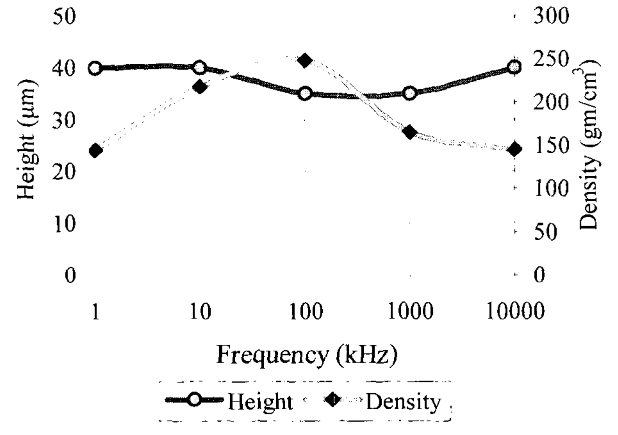

Fig. 5 Deposit height and density as functions of frequency

3.4 Effect of Duty Cycle

The duty cycle is the ratio of the pulse-on time to the total pulse duration. We varied the duty cycle over the range of 0.25 to 0.75 with a constant amplitude of 1 V and a frequency of 100 kHz. Figure 6 shows that the deposit height increased with the increase in duty cycle. This can be explained by the fact that an increased duty cycle increases the total energy for each pulse, and thus also increases the deposition rate. However, the deposit density decreased for a duty cycle above 0.5. For a constant frequency, if the pulse-on time higher than the pulse-off time, then the electrode charging time will be greater than the discharge time. This may cause a low density structure.

3.5 Outputs from Different Mask Shapes

We conducted tests using an amplitude of 1.0 V, a frequency of 100 kHz, and a duty cycle of 0.5 for different cross-sectional mask shapes. This produced smooth and fine-grained copper deposits for X- and Y-shaped masks, as shown in Fig. 7. Figure 8 compares the different types of mask cross-sectional shapes, the deposited electrodes, and the EDM-machined parts. This illustrates possibility of using micro-electrodes formed by LECD to machine workpieces using micro-EDM.

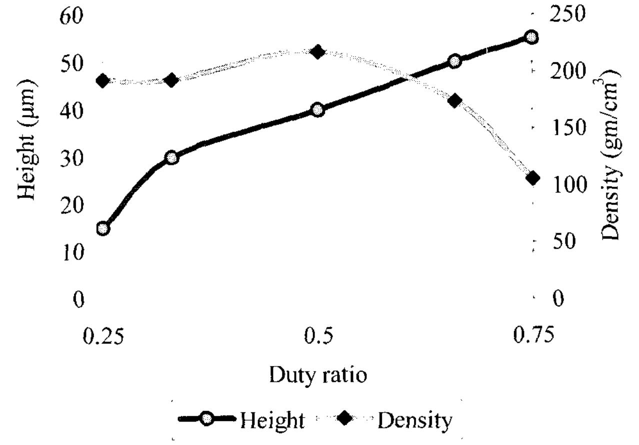

Fig. 6 Deposit height and density as functions of duty cycle

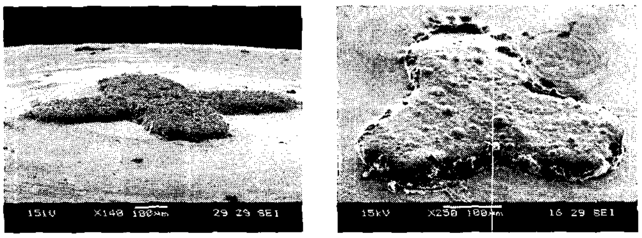

Fig. 7 (a) SEM image of copper deposition for X- and Y-shaped masks under optimized conditions for a deposition time of 15 min

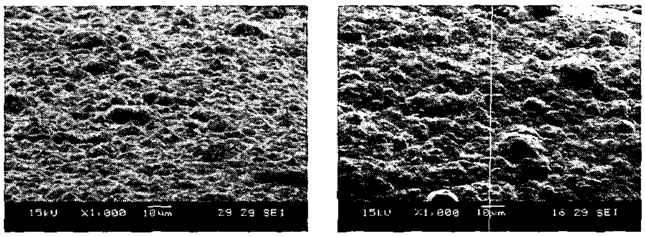

Fig. 7 (b) SEM image of copper deposition microstructures deposited through X- and Y-shaped masks

4. Conclusions

We have shown using a simple experiment that it is possible to fabricate copper electrodes with complex cross-sectional shapes for micro-EDM using the LECD process. This on-machine electrode fabrication process is also capable of minimizing the clamping error. From this study, we can draw the following conclusions.

- A plating solution of acidic $CuSO_4.5H_2O$ with a Cu^{2+} ion concentration of 1.0 to 1.25 M and some organic additives such as thiourea significantly improves the microstructure of the copper deposit.
- The voltage amplitude, frequency, and duty cycle have noticeable effects on the deposited microstructure. An amplitude of 1 V, a frequency of 100 kHz, and a duty cycle of 0.5 produce the best structure of copper deposit.
- The optimum conditions produce a smooth, fine-grained, and low porosity copper electrode suitable for use in EDM.
- This new technology of on-machine fabrication of micro-electrodes will have a great impact on micro-machining industries fabricating micro-features.

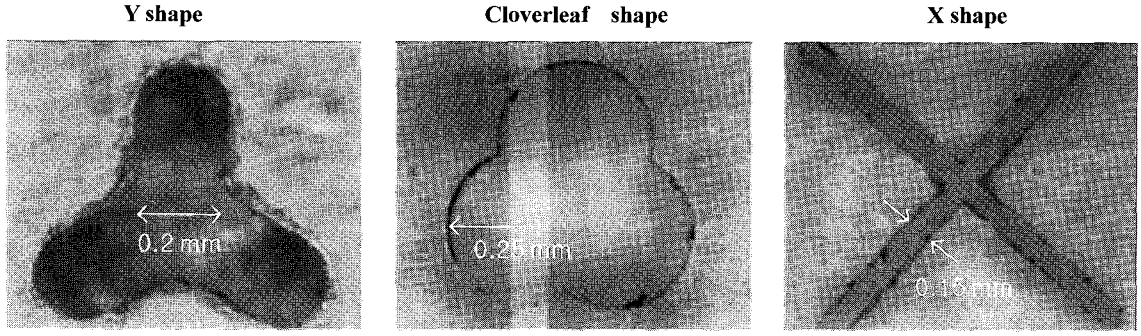
Y shape **Cloverleaf shape** **X shape**

Fig. 8 (a) Different mask shapes, such as Y, cloverleaf, and X

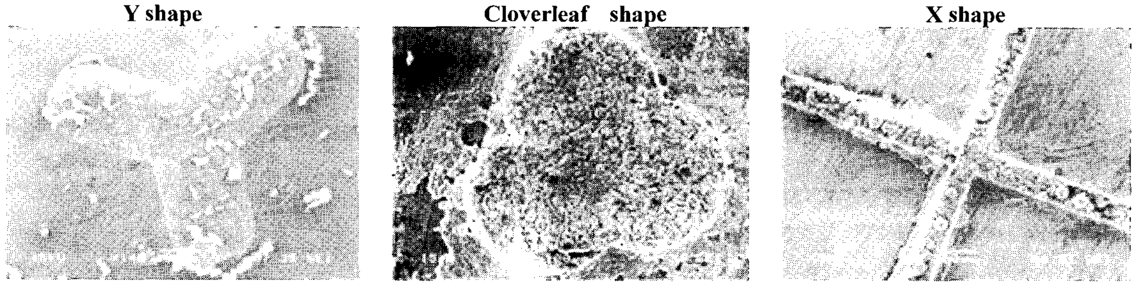
Y shape **Cloverleaf shape** **X shape**

Fig. 8 (b) Scanning electron microscopy image of electrodes deposited by the LECD process

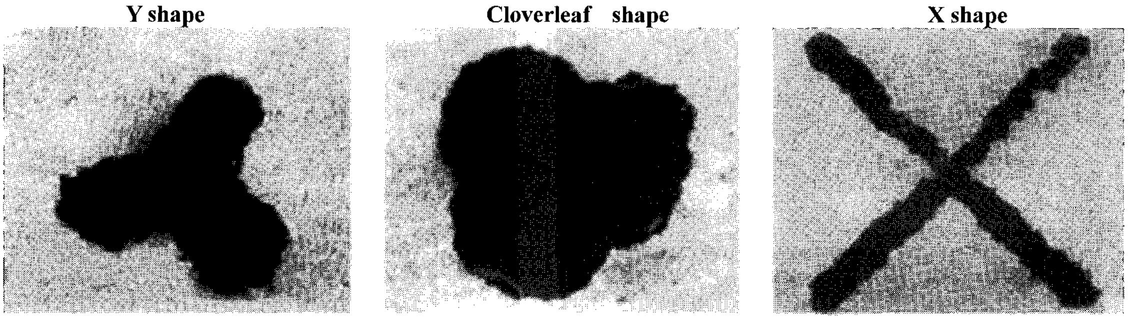
Y shape **Cloverleaf shape** **X shape**

Fig. 8 (c) Machined workpieces using the deposited electrodes from EDM

REFERENCES

1. Masuzawa, T., "State of the Art of Micromachining," Annals of the CIRP, Vol. 49, No. 2, pp. 473-488, 2000.
2. Pham, D. T., Dimov, S. S., Bigot, S., Ivanov, A. and Popov, K., "Micro-EDM — Recent Developments and Research Issues," Journal of Materials Processing Technology, Vol. 149, Issues 1-3, pp. 50-57, 2004.
3. Kim, Y. T., Park, S. J. and Lee, S. J., "Micro/Meso-Scale Shapes Machining by Micro EDM Process," International Journal of Precision Engineering and Manufacturing, Vol. 6, No. 2, pp. 5-11, 2005.
4. Lim, J. H., Je, S. J., Ryu, S. H. and Chu, C. N., "Distortion of the Bottom Surface in Micro Cavity Machining Using MEDM," International Journal of Precision Engineering and Manufacturing, Vol. 6, No. 4, pp. 44-48, 2005.
5. Lim, H. S., Wong, Y. S., Rahman, M. and Lee, M. K. E., "A study on the machining of high-aspect ratio micro-structures using micro-EDM," Journal of Materials Processing Technology, Vol. 140, Issues 1-3, pp. 318-325, 2003.
6. Takahata, K., Shibaike, N. and Guckel, H., "High-Aspect-Ratio WC-Co Microstructure Produced by the Combination of LIGA and Micro-EDM," Microsystem Technologies, Vol. 6, No. 5, pp. 1432-1858, 2000.
7. Hunter, I. W., Lafontaine, S. R. and Madden, J. D., "Three-Dimensional Microfabrication by Localized Electrochemical Deposition and Etching," US Patent, No. 5641391, 1997.
8. Madden, J. D. and Hunter, I. W., "Three-Dimensional Micro-Fabrication by Localized Electrochemical Deposition," Journal of Microelectromechanical Systems, Vol. 5, Issue 1, pp. 24-32, 1996.
9. Jansson, A., Thornell, G. and Johansson, S., "High Resolution 3D Microstructures Made by Localized Electrodeposition of Nickel," Journal of the Electrochemical Society, Vol. 147, Issue 5, pp. 1810-1827, 2000.
10. El-Giar, E. M. and Thomson, D. J., "Localized Electrochemical Plating of Interconnectors for Microelectronics," Proceedings of IEEE Conference on Communications, Power and Computing, WESCANEX, pp. 327-332, 1997.
11. El-Giar, E. M., Said, R. A., Bridges, G. E. and Thomson, D. J., "Localized Electrochemical Deposition of Copper Microstructures," Journal of the Electrochemical Society, Vol. 147, Issue 2, pp. 586-591, 2000.
12. Park, J. W., Ryu, S. H. and Chu, C. N., "Pulsed Electrochemical Deposition for 3D Micro Structuring," International Journal of Precision Engineering and Manufacturing, Vol. 6, No. 4, pp. 49-54, 2005.
13. Yeo, S. H. and Choo, J. H., "Effects of Rotor Electrode in the Fabrication of High Aspect Ratio Microstructures by Localized Electrochemical Deposition," Journal of Micromechanics and Microengineering, Vol. 11, No. 5, pp. 435-442, 2001.

14. Yeo, S. H., Choo, J. H. and Sim, K. H. A., "On the Effects of Ultrasonic Vibrations on Localized Electrochemical Deposition," Journal of Micromechanics and Microengineering, Vol. 12, No. 3, pp. 271-279, 2002.

15. Schuster, R., Kirchner, V., Allongue, P. and Ertl, G., "Electrochemical Micromachining," Science, Vol. 289, No. 5476, pp. 98-101, 2000.