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SCIENTIFIC PAPER

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# PERFORMANCE STUDY OF ELECTROCHEMICAL MICROMACHINING USING SQUARE COMPOSITE ELECTRODE FOR COPPER

**Article Highlights**

- In this research, an attempt is made to fabricate a micro-square hole on the copper workpiece
- Stainless steel and aluminum composite square electrode are considered for the EMM experiments
- Aluminum composite square electrodes show a significant effect on the accuracy of the micro-square hole

**Abstract**

*The use of micro components is increasing day by day in the industries such as aviation, power circuit boards, inkjet nozzle, and biomedical. Among various non-traditional micromachining methods, electrochemical micromachining (EMM) shows unique characteristics, such as no tool wear, no residual stress, and high accuracy. In this research, EMM is considered to study the effect of square-shaped stainless steel (SS) and aluminum metal matrix composite (AMC) tools on square hole generation. The significant process parameters, such as machining voltage, duty cycle, and aqueous sodium nitrate ($NaNO_3$) electrolyte of varying concentrations, are considered for the study. The performances of the EMM process are evaluated in terms of machining rate (MR) and Overcut (OC). The AMC tool shows 43.22% lesser OC than the SS tool at the parameter combinations of 8 V, 85%, and 23 g/L. Also, the same parameter combination MR for the SS tool is 71.6% higher than the AMC tool. Field emission scanning electron microscope image (FESEM) analysis shows that the micro square hole generated using composite electrode shows micro-pits on the circumference of the square hole. The energy-dispersive X-ray spectroscopy (EDAX) analysis is conducted to verify the presence and distributions of reinforcement in the AMC tool.*

*Keywords: square tool electrode, composite electrode, electrochemical micromachining, copper.*

The application of micro features, such as micro square holes, micro grooves, taper surfaces, slots, micro holes, and micro slits, was increasing enormously in microelectromechanical systems (MEMS). Also, micromachining plays a significant role in manufacturing due to the miniaturization of electronic, medical, biomedical, and automobile devices [1-4]. The documented knowledge in EMM for generation micro features is archived for micro holes. In line with that, Pradeep *et al.* [5] studied the performance of EMM using cryogenically treated graphite electrodes on SS 304. The use cryogenic treated tool shows good stray current protection and improves the accuracy of the micro-hole. Soundarrajan *et al.* [6] have utilized geometrically modified and coated electrodes on copper work material in the EMM process. They reported that electrode size (in length) contributes to the higher MR. The ceramic and hot melt glues are significantly improving the overcut and MR.

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Liu *et al.* [7] used a rotating helical electrode in EMM on SS 304 and improved the electrolyte flow in the machining zone. Kishi *et al.* [8] fabricated rectangular grooves with rotary electrodes in a hybrid electro-discharge and electrochemical machining process. The rotary motion of the electrode significantly improves the surface roughness from 3.82 µm to 0.86 µm on the machined area. Ayyappan *et al.* [9] studied the performance of EMM with abrasive and epoxy coated tools. The epoxy-coated tools were found to reduce the overcut, and also, the spark production in the inter-electrode gap was decreased significantly, resulting in a good quality micro-hole. Maniraj *et al.* [10] performed experiments with the heated electrode in EMM for machining micro holes on AMC. The heated electrode initiates the micro stirring effect at the machining zone and significantly enhances the machining performance. Arab *et al.* [11] studied the influences of tool roughness on the machining accuracy of the ECDM process. They noticed the higher surface roughness of the tool increases the overcut and reduces the accuracy of the hole. Geethapriyan *et al.* [12] conducted the experiments using copper and brass electrodes on the EMM of SS 420. They have reported that the copper electrode produces the 20.9% and 29.65% higher MR and overcut, respectively, than the brass electrode. Pang *et al.* [13] proposed the floating tool electrode in ECM to maintain a constant electrode gap between tool and work. The results obtained in modeling and experimental correlate with each other. Paczkowski *et al.* [14] investigated the EMM with a vibrated electrode on alloy tool steel. They have noticed that the kinetic movements of the electrode significantly improve the machining rate and production efficiency. Thanigaivelan *et al.* [15] fabricated the micro holes on SS 304 using flat, conical, wedge, and round-ended tools. They found uniform current distributions with the conical-shaped electrode than the other tools, enhancing machining performance. Sandip *et al.* [16] fabricated the micro slots using EMM on the titanium work material. The literature clarifies that many techniques are endeavored by the researchers in EMM with different tools from different perspectives.

Usually, square holes are fabricated in the electro-discharge machining process. However, a direct attempt at micro-square hole fabrication in EMM is attempted due to the inherent drawback of tool electrode wear. Hence, two different electrode materials, SS and AMC, of the same specifications are considered to generate the micro square hole. Generally, composite electrodes are used in wastewater treatments, electrochemical depositions, and batteries for various applications due to their effective mechanical and electrical properties [17-19]. Therefore, the accuracy and MR for both the electrodes are compared by varying process parameters such as electrolyte concentration, machining voltage, and duty cycle. Furthermore, the scanning electron microscope image and EDAX analysis were carried out to study the impact of the electrode on the micro-square hole surfaces.

## MATERIALS AND METHODS

An indigenously developed EMM setup shown in Figure 1 is used for conducting the experiments.

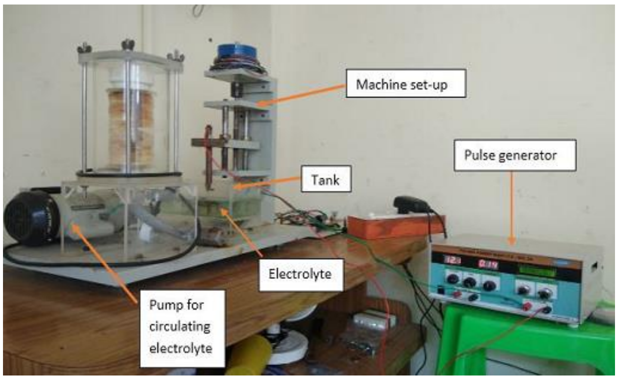


*Figure 1. Experimental setup.*

The setup included an electrolyte supply system, tool feeding system, microcontroller unit, and pulse rectifier. The stepper motor maintains the inter-electrode gap [IEG] between the tool and the electrode. The IEG is held at 40 µm with the help of a stepper motor, microcontroller, and tool feeding arrangements. The electrolyte supply system consists of a pump and filter. The used electrolyte is continuously pumped, filtered, and re-circulated to the machining chamber. Copper finds a wide range of applications in various sectors. Hence, a 2 mm thick copper plate is considered a workpiece. The workpiece is clamped in the workpiece holder made up of acrylic material. The work holder consists of two blocks that are fastened with a bolt by keeping the work material between them. Two types of square tools are prepared for the size of 1 mm x 1mm in AMC and SS 304 material. The AMC is prepared through a stir casting furnace made up of Al6063 alloy is reinforced with 12% SiCp and 5% graphite particles. The chemical composition of Al6063, SiCp, and graphite particles are presented in Tables 1, 2, and 3, respectively [20]. SODICK CNC wire cut EDM is used to prepare the square tool. The voltage in the range of 8 to 12 V, duty cycle in the range of 50% to 90%, and electrolyte concentration in the range of 21 g/L to 29 g/L are considered for the study. The experimental plan

*Table 1. Chemical composition of Al6063 Alloy*

| Elements | % of compositions |
|---|---|
| Al | 98.640 |
| Mg | 0.514 |
| Si | 0.535 |
| Cu | 0.001 |
| Mn | 0.028 |
| Fe | 0.211 |
| Zn | 0.004 |
| Cr | 0.001 |
| Ti | 0.011 |
| Ca | 0.051 |

*Table 2. Chemical composition of SiCp*

| Elements | % of compositions |
|---|---|
| SiC | 96 |
| Fe | 0.2 |
| $SiO_2$ | 0.8 |
| Si | 0.5 |
| C | 0.6 |
| Al | 0.2 |
| Ca | 0.65 |
| Mg | 1.05 |

*Table 3. Chemical composition of graphite*

| Elements | % of compositions |
|---|---|
| C | 55.2 |
| O | 24.5 |
| Ca | 8.4 |
| Si | 7.5 |
| Fe | 1.3 |
| Al | 1.7 |
| Mg | 0.8 |

follows the varying one parameter at a time design. The aqueous sodium nitrate electrolyte of different concentrations is used in the experiments. The electrolyte is prepared using distilled water and sodium nitrate salts. For example, to prepare electrolyte concentration of 20 g/L, the sodium nitrate salt of 20 g is mixed in 1 L of distilled water and stirred well. The pulse frequency is kept at a constant value of 50 Hz, while the thickness of the workpiece and the size of the square electrode are maintained constant, as mentioned throughout the experiments.

Figure 2 presents the SEM images of tool electrodes. The EDAX test is carried out on the fabricated tools to analyze the composition and distribution of reinforcement.

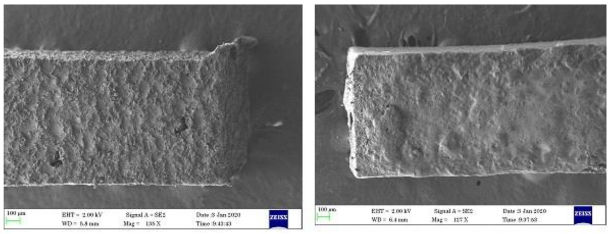

*Figure 2. SEM image of tool (a) SS (b) AMC.*

The EDAX test confirms the homogeneous distributions of reinforcements, as shown in Figure 3 for the AMC tool. The machining rate (MR) and overcut (OC) are considered to evaluate performance measures. The MR is calculated using the total machining time required for producing through the hole. The differences between the bottom area of the tool and the machined hole area are considered for the overcut. The optical microscope was used to calculate the overcut area of the square hole.

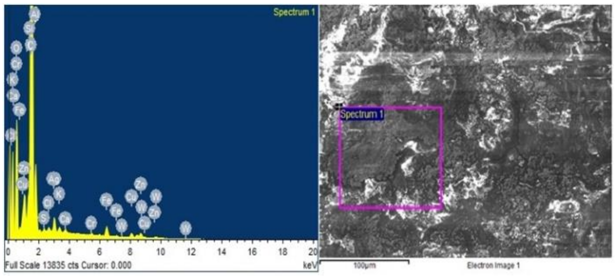


*Figure 3. EDAX image of AMC tool.*

## RESULTS AND DISCUSSION

### Influences of machining voltage on OC and MR

Figure 4 represents the influences of machining voltage on OC for the SS and AMC tools. According to the graph, SS and AMC tools create an OC of 1763 μm and 1231 μm, respectively, with a parameter combination of 8 V, 85%, and 23 g/L. Graphite reinforcement particles play a vital role in lower OC in the AMC tool. The aluminum material is a good electrical conductor, and reinforcements alter the conductivity of the AMC electrode. The presence of graphite and silica in the AMC tool reduces the conductivity of the electrode leading to lesser overcut. The AMC tool shows 43.22% lesser OC than the SS tool, and also this is the least OC value among all the experiments. Also, the parametric combinations 9 V, 85%, and 23 g/L produce 37.72% less OC than the SS tool, the second least OC among the experiments. The

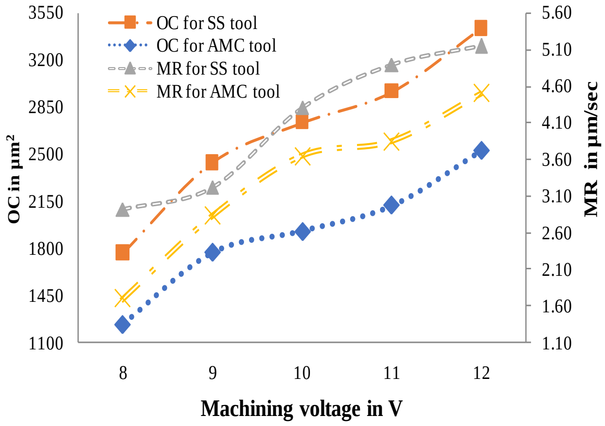


*Figure 4. Influence of Machining voltage on OC & MR.*

SEM images in Figure 5 show the square micro hole machined through AMC and SS tools, respectively, at the parameter combination 8 V, 85%, and 23 g/L. Based on the figure, the AMC tool's micro square hole shows good sharp edges with slight waviness on the circumferences. Also, the circumferences of micro-holes are seen with the micropores. It is because reinforcement particle distributions in the AMC tool alter the machining zone's current distributions. The presence of silica on the surface of the tool induces joule heating in the electrode. The Joule heat value is proportional to the square of the current that occurs in the electrode. This phenomenon creates the rapid sporadic electrolysis between the tool face and the electrode, leading to the development of micropores [10]. The tool shows the circumference with fewer pores and higher curved circumference for micro holes machined with the SS, as displayed in Figure 5. In the SS electrode, the uniform metallographic structure of metals creates a uniform flow of current, contributing to a smooth machining surface.

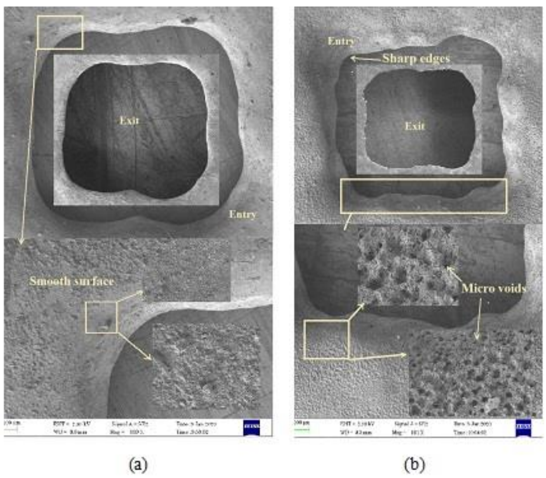


*Figure 5. SEM images of the micro holes (a) SS tool (b) AMC tool.*



Figure 4 shows the influences of machining voltage on MR for the AMC and SS tools. According to the graph, the SS tool produces higher MR than the AMC tool, and the graph trend indicates that by increasing the machining voltage, MR for both tools increases. The SS and AMC tools produce an MR of 2.908 µm/sec and 1.693 µm/sec. The disturbance of current conductivity between the tool and the electrode plays a major role in MR. The SS tool material shows good attraction between the metallic molecules attributing to a smooth current flow at the machining zone. At the same time, the AMC tool has a lesser intermolecular metallic bonding among the molecules [21]. Hence, the uniform current flow in the IEG increases the MR in the SS tool more than in the AMC tool. The SS tool produces around 71.6% higher MR than the AMC tool for the parameter combination of 8 V, 85%, and 23 g/L. Moreover, this is the highest MR of all other conducted experiments.

## Influences of duty cycle on OC and MR

The influences of SS and AMC tools on the duty cycle are represented in Figure 6.

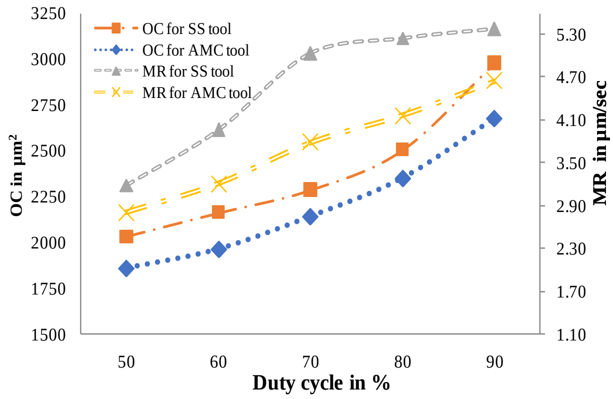


*Figure 6. Influence of Duty cycle on OC & MR.*

The graph indicates that the OC increases with an increase in duty cycle with respect to both tools. The AMC tool produces 1859 µm$^2$ OC for the parameter combination of 50%, 12 V, 29 g/L. As well as, the SS tool produces 2028 µm$^2$ OC for the same parameter combination, which is 9.1% higher than the AMC tool. The presence of aluminum in the composite provides good electrical conductivity in the electrolyte due to its low specific gravity and density nature [10]. Therefore, the AMC tool produces less OC than the SS tool. Also, the AMC and SS tools produce 2161 µm$^2$ and 1961 µm$^2$ OC, respectively, for the parametric combination of 60%, 12 V, and 29 g/L. The OC is found to be 10.21% lesser than the SS tool. Figure 7 shows an SEM image of a square micro hole machined with the AMC and SS tools, respectively, for the parameter combination of 50%, 12 V, and 29 g/L. The MR for the SS and AMC tools is 3.189 µm/sec and 2.8057µm/sec, respectively. It is evident from the graph that the SS tool produces a 13.5% higher MR than the AMC tool for the parameter combination of 50%, 12 V, 29 g/L. A higher duty cycle allows more current between the electrodes for a longer duration of time. SS tool continuously produces higher MR such as 15.1% and 23.5% for the 60% and 70% duty cycle, respectively.

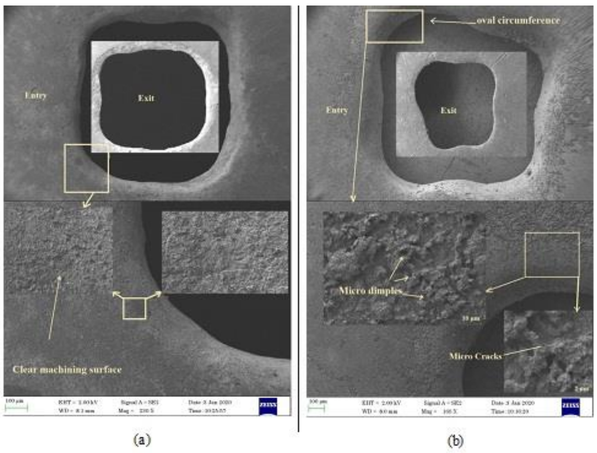


*Figure 7. SEM images of the micro holes (a) SS tool (b) AMC tool.*

### Influences of electrolyte concentration on OC and MR

Figure 8 presents the influences of electrolyte concentration on OC for the AMC and SS tools. According to the graph, the electrolyte concentration increases the OC for both tools. It is expected that ions in electrolytes increase with the concentration. Between both tools, the AMC tool produces the lower OC of 1808 µm$^2$ at the parameter combination of 21 g/L, 90%, and 12 V. The OC increased gradually from 23 g/L to 30 g/L because the square shape of the tool induces a heating effect in the inter-electrode gap (IEG) due to the electrical potential difference. Continued heat generation in the IEG causes electron energization, resulting in higher sludge formations. This higher sludge formation in the machining zone reduces the IEG, leading to the short circuit and stopping further machining. Therefore, the AMC tool produces a lower OC than the SS tool [10]. Also, the AMC tool produces 14.8% and 20.4% reduced OC for the electrolyte concentrations of 23 g/L and 25 g/L, respectively. Figure 9 shows the micro hole's SEM image machined with the square AMC and SS tools. The outer perimeter of the square hole surface, machined with the AMC tool, exhibits microvoids due to the reactions of byproducts.

The graph indicates that the SS tool produces 32.86% higher MR than the AMC tool for the parameter combination of 21 g/L, 90%, and 12 V. The machining zone's bubble generation contributes to higher MR in the SS tool. The breaking of bubbles generates the micro stirring effect in the electrolyte ensures the renewal of electrolyte at the machining zone periodically [10]. Therefore, the SS tool produces a higher MR than the AMC tool. Also, the electrolyte concentration of 23 g/L and 25 g/L produces 22.4% and 26.2% higher MR with the SS tool than with the AMC tool.

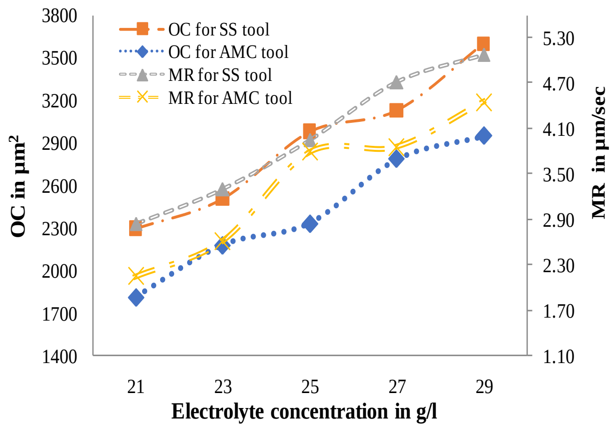


*Figure 8. Influence of Electrolyte concentration on OC & MR.*

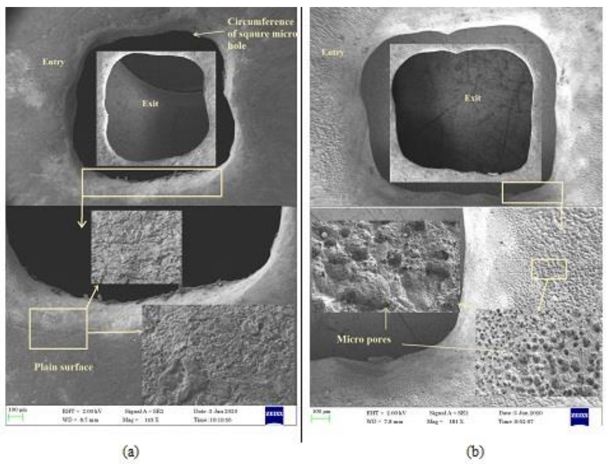


*Figure 9. SEM images of the micro holes (a) SS tool (b) AMC tool.*

## CONCLUSION

In EMM, there is no direct attempt at square hole fabrication, whereas the application of square holes is numerous in various fields. Hence, to reveal the process parameters of EMM, the square holes are fabricated. Two different tools were manufactured successfully to the required size on AMC and SS materials. The SS tool at the parameter combinations of 8 V, 85%, and 23 g/L shows 71.6% higher MR than the AMC tool. Also, the AMC tool produces 43.22% less OC than the SS tool for the same parameter combination. Square micro hole machined with AMC tool shows sharp edges when compared to SS tool. The outer perimeter surface of the square micro hole machined with the AMC tool creates more micro pits. Hence, the AMC tool electrode can be considered for making sharp edges with lesser overcuts in EMM. Further, the surface modification of biomaterials through the generation of micro-dimples and micro-pits can be performed using the AMC electrodes. More experiments can be planned with different reinforcements to generate micro features like triangles and round and hexagonal-shaped holes.


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NAUČNI RAD

# PROUČAVANJE PERFORMANSE ELEKTROHEMIJSKE MIKROMAŠINSKE OBRADE KVADRATNOM KOMPOZITNOM ELEKTRODOM ZA BAKAR

*Upotreba mikro komponenti raste iz dana u dan u industrijama, kao što su vazduhoplovstvo, strujna kola, inkjetorske mlaznice i biomedicina. Među različitim netradicionalnim metodama mikromašinske obrade, elektrohemijska mikromašinska obrada (EMO) pokazuje jedinstvene karakteristike, na primer, bez habanja alata, bez zaostalog naprezanja i visoka tačnost. U ovom istraživanju, smatra se da EMO proučava efekat alata od nerđajućeg čelika (SS) kvadratnog oblika i aluminijumske metalne matrice (AMM) na bušenje kvadratnih rupa. Za proučavanje su uzeti u obzir značajni parametri procesa, kao što su napon obrade, radni ciklus i vodeni elektrolit natrijum-nitrata ($NaNO_3$) različitih koncentracija. Performanse EMO procesa se procenjuju u pogledu brzine obrade i prekomerno bušenje. AMM alat pokazuje 43,22% manje prekomerno bušenje od SS alata pri kombinacijama parametara od 8 V, 85% i 23 g/l. Takođe, ista kombinacija parametara brzine obrade za SS alat je za 71,6% veća nega za AMM alat. Analiza slike sa skenirajućim elektronskim mikroskopom pokazuje da mikro kvadratna rupa generisana korišćenjem kompozitne elektrode pokazuje mikro udubljenja na obodu kvadratne rupe. Analiza energetski disperzivne rendgenske spektroskopije se sprovodi da bi se proverilo prisustvo i raspodela armature u AMM alatu..*

*Ključne reči: kvadratna elektroda, kompozitna elektroda, elektrohemijska mikromašinska obrada, bakar.*