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SCIENTIFIC PAPER

UDC

EFFECT OF ELECTRODE HYBRIDIZATION IN ELECTROCHEMICAL MICROMACHINING OF ALUMINUM ALLOY COMPOSITE

Highlights

- Compared CRCT, RUIT, RFHT and NRMT in ECMM of aluminum scrapped alloy composite
- RUIT achieved 2.09 times higher MRR than NRMT
- CRCT delivered 1.7 times higher MRR at 23 g/L, 13 V, 80% duty
- RFHT produced the least overcut of 58.56 µm
- SEM analysis exposed tool effects on surface morphology

Abstract

The need for micro-level components in aerospace, automotive, and medical fields has continuously risen in recent years. In electrochemical micromachining (ECMM), due to the presence of hard particles like aluminum scrap alloy, it is difficult to make micro holes in such materials, as most micro holes appear with high overcut (OC). Also considering the need for higher material removal rate (MRR) and improved accuracy in micro-component fabrication, work is planned on the type of tool electrode and its insulation. Hence, different tool electrodes, including ceramic composite tool (CRCT), rubber insulated tool (RUIT), rubber filled hollow tool (RFHT), and normal tool (NRMT), are used to address these challenges. The effects of key input parameters, including machining voltage, duty cycle, and electrolyte concentration, were systematically investigated. An experimental result indicates that RUIT achieves MRR 2.09 times higher than NRMT. Also, CRCT demonstrates higher MRR, which is 1.7 times better than NRMT under the selected parameter set of 23 g/L, 13 V, and 80% duty cycle. Among the different tools, RFHT produces the lowest OC of 58.56 µm. Additionally, to reveal the effect of tool electrode impact on machining outcome and metal surface nature, scanning electron microscope (SEM) image analysis is carried out.

Keywords: electrochemical micromachining (ECMM), aluminum scrapped alloy, insulation, field emission scanning electron microscope (FESEM).

INTRODUCTION

Micro-manufacturing has emerged as a focused area of research due to the growing demand for miniaturized products capable of performing multiple functions. These products offer advantages including reduced material usage, lower weight, compact size, enhanced functional performance, and decreased energy consumption. Consequently, the fabrication of micro-scale components from advanced engineering materials has gained increasing importance as micro- and nanotechnology continue to play a vital role in meeting modern societal and industrial needs. Metal matrix composites (MMC) are widely fabricated because of their adequate properties, such as high thermal conductivity, high impact strength, high wear resistance, High surface durability, high strength-to-weight ratio, modulus of resilience, and low ductility. Especially aluminum scrap alloy is one of the most promising lightweight materials in the applications of industries like automobile, aerospace, biomedical, biotechnology, electronics, and home appliances, etc. [1-4]. Due to an enormous demand for micron-level machined components, researchers concentrated on micromachining composite materials. One of the most promising non-traditional machining methods is

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ECMM because it gives better precision, high machining rate, no tool wear, no thermal damage control and the capability to machine the toughest materials. The micro hole accuracy prominently depends on input parameters, namely type of electrolyte, electrode size, insulation of tool electrode, and electrical parameters [5]. The researchers take various efforts to get optimal results through chemical vapour deposition coating, chemical coating, and polymer coating. Still, it has the markable problemsin insulation, tool electrode size, and shape, which induce higher OC [6,7]. Hence, researchers have optimized the necessary changes like tool geometry and insulation electrode to reduce the OC and get higher MR. Kumar *et al.* [8] investigated machining using two different tool tips, that is, a flat and ball-end tungsten tool on SS material. The results reveal that the end tool overcut was 120 µm compared with the flat end. Pradeep *et al.* [9] explore the machining performance of a cryogenically treated polymer graphite electrode. It decreases the effect of the micro spark and stray current. Maniraj *et al.* [10] proposed a heated electrode while machining aluminum metal matrix composite; it diminishes ROC, conicity factor (CF), and achieves a remarkable material removal rate (MRR). Chen *et al.* [11] used a disc electrode with ultrasonic assistance. They noticed that ultrasonic assistance is helpful to reduce taper and to improve MRR. Liu *et al.* [12] tried the tool of a heavily doped monocrystalline electrode, sidewall insulated with the help of deposition of silicon dioxide and silicon nitride; they obtained an inlet diameter of 146 µm and a 0.58° tapered micro hole. Liu *et al.* [13] have utilized the micro tool with a retracted tip on aluminum and 304 SS sheets and found notable improvement in machining. Liu *et al.* [14] investigated a nickel-based superalloy by using a high-speed spiral electrode. They found good machining efficiency and stability. Palaniswamy *et al.* [15] investigated the machining of copper with the help of four tools, namely the electromagnetic graphite tool, permanent magnet graphite tool, graphite tool, and stainless steel. They claimed that the graphite and EMGT electrodes are better compared with the remaining. Hung *et al.* [16] compared the tool behaviour of electro-deposited nickel-nickel-coated electrodes and without. They found that nickel coating is stable to produce electrodes with different machining. Maniraj *et al.* [17] fabricated micro holes in stainless steel 316L (SS 316L). They tried copper metal powder suspended in a citric acid electrolyte with stirring effect; it gives the least MRR and reduced OC. Soundarrajan *et al.* [18] studied the effect of electrolyte concentration in g/L, machining voltage in V, and duty cycle in % on the OC and MR with different electrode likely ceramic, hot melt adhesive (HMA), hollow wedge, and short solid tools. They suggested a geometrically modified ceramic tool and short solid tool for machining copper material. Vinod Kumaar *et al.* [19] investigated the performance of citric acid mixed with sodium chloride of various concentrations to produce a micro-hole on SS 316L. They found it to be good in a magnetic field-assisted citric acid electrolyte over a mixed electrolyte. Sivashankar *et al.* [20] fabricated microholes in magnesium AZ31 alloy. They revealed the performance and characteristics of minimum-quantity sodium nitrate ($NaNO_3$) and a citric acid (C_6H_8OS) electrolyte. Palaniswamy *et al.* [21] investigated ECMM of aluminum scrap metal matrix composite reinforced with alumina. In optimization and prediction, they used SAW, CRITIC, and ANN. They found the best performance obtained at 28 g/L $NaNO_3$ + 0.05 M HNO_3, 10 V, and 80% duty cycle. Gokulanathan *et al.* [22] studied the performance of ECMM of Monel 400 alloy using different particle-mixed electrolytes and optimized the process parameters through MOORA and VIKOR techniques. They found carbon pellet mixed electrolyte with a 50% duty cycle, 11 V machining voltage, and 28 g/l electrolyte concentra-tion generates the optimal parameter solution for machining. The above literature shows that the micro-machining of hardened materials is more important in tool insulation, shape of the tool, externally assisted tool, and selection of tool materials. In this research, four different kinds of tools, CRCT, RUIT, NRMT, and RFHT, were employed for their exclusive characteristics. The modified tools, such as CRCT, RUIT, and RFHT, narrow the flow of current between the interelectrode gap (IEG). In this study, these tools reveal the machining characteristics like OC and MR against the process parameters, such as electrolyte concentration in g/L, machining voltage in V, duty cycle in %, and frequency in %. In addition, SEM image analyses are used to identify the tool's effect on machining performance.

MATERIALS AND METHODS

Selection of materials

Aluminum metal matrix composites (AMMCs) were fabricated by employing scrap aluminum alloy as the matrix material and 80 nm sized nano aluminum oxide (Al_2O_3) particles as reinforcement, with the matrix and reinforce-ment incorporated at a weight ratio of 94 wt.% and 6 wt.%, respectively. AMMC is produced using a bottom-poured stir casting machine, the setup equipped with a stirrer that operates at speeds ranging from 300 to 1400 rpm and a hydraulically powered 5 HP motor capable of applying a squeeze load of up to 100 MPa [23]. The matrix material, scrap aluminum alloy, is first cleaned using methyl ethyl ketone before being placed in the preheated furnace of the stir casting machine (Fig. S1), where it is melted and maintained at 750 °C. Any slag present in the retort is removed using the supplied scoops from the top of the furnace. The Al_2O_3 reinforcement is preheated to 350 °C in the reinforcement preheating chamber. Once ready, the preheating valve is released, and the heated reinforcement is gradually added to the liquefied matrix. While preparing the AMMC, nanoparticles were initially not mixed well, and its get spared around the dye. Hence, the composites are kept in the furnace itself for 45 minutes at 500 rpm for stirring. Afterward, the stirring speed is increased to 575 rpm for five minutes [24,25].

The molten metal is then poured into a preheated squeeze casting mold. A height of 240 mm is achieved by applying a squeeze pressure of 125 MPa to casting ingots with a diameter of 50 mm. The ingots are cut into 2 mm thick slices using a laser cutting machine for machining purposes [26].

Machining experiments are performed using a domestically developed ECMM structure. The ECMM setup consists of several subsystems, including an electrolyte supply system, microcontroller, pulse rectifier, stepper motor for the tool feeding system, and work-holding system (Fig. S2).

Preparation of Tool Electrode

The tools, such as RUIT, RFHT, CRCT, and NRMT, are prepared using different methods. The RUIT, a comercially available conical swaying solid stainless steel needle with a diameter of 500 µm, is insulated by rubber material. Self-drying silicone gel is considered as rubber for both RUIT and RFHT, which prevents the stray current at the machining zone. The rubber material is applied over the SS conical tool surface and kept for 24 hours for curing [27,28]. In the case of RFHT, rubber material is inserted into the hollow tool and covered by the rubber, which controls the unwanted conduction and power distribution at the machining zone. The rubber insulation thickness is 2 mm. The primary function of the insulation is to electrically isolate the sidewalls of the tool, thereby restricting the current flow to the exposed tool tip. This confinement of current minimizes stray current distribution, reduces surplus material dissolution, and improves machining accuracy.

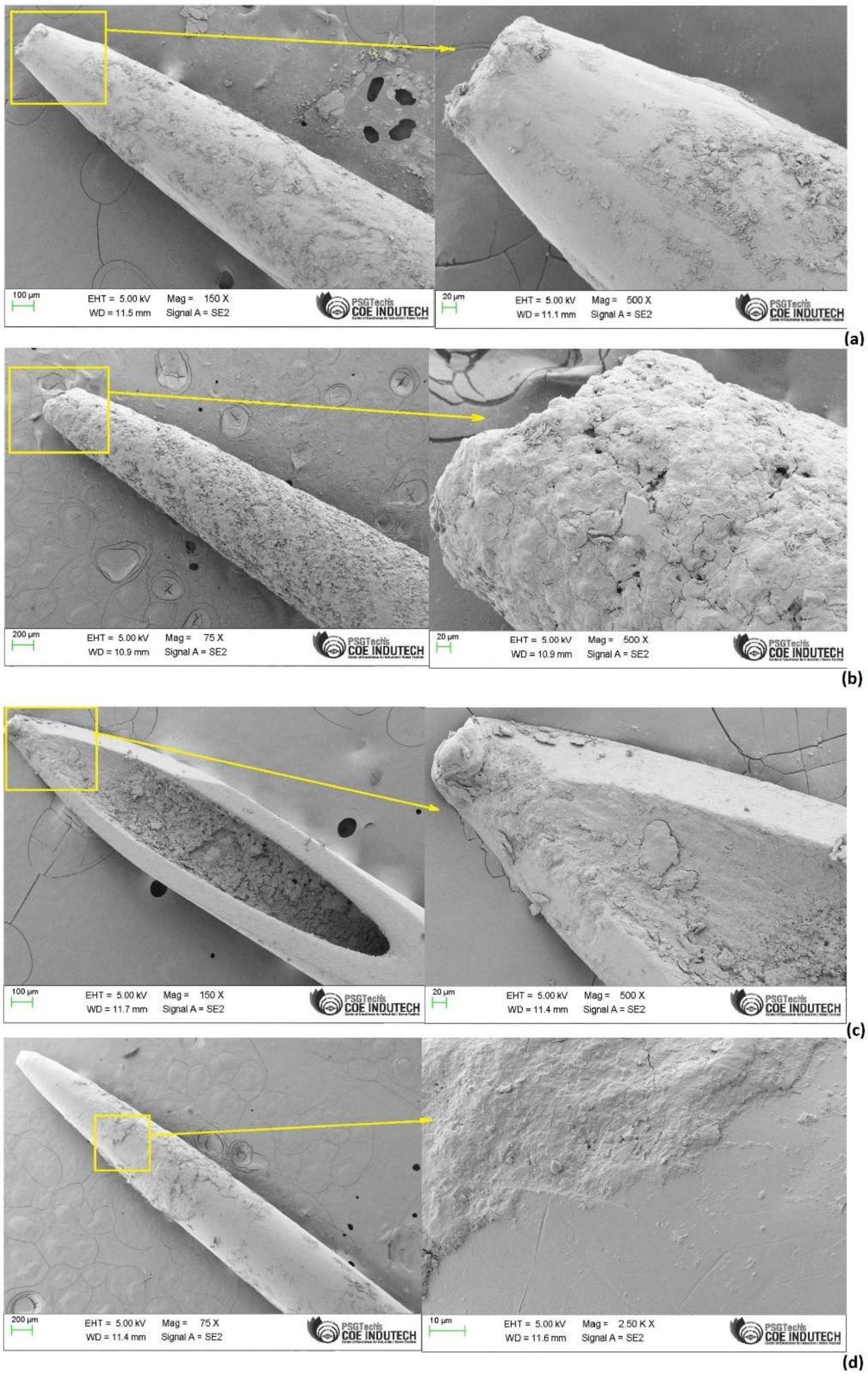

Figure 1. SEM pictures of tool electrode a) RUIT, b) CRCT, c) RFHT, and d) NRMT.

CRCT was fabricated by mixing epoxy resin and epoxy putty. The epoxy resin and hardener are obtained comercially, and along with that, 10 µm copper particles (10 g) are included while mixing resin and hardener together. The mixture was thoroughly blended and then pressed into a 1 mm hollow tube and left to cure in an oven at 150 °C. The SEM pictures of the tool electrodes are shown in Fig. 1.

Table 1. Machining parameters.

Process parameter	Levels
Electrolyte concentration (g/L)	23, 25,27,29,31
Machining voltage (V)	7,9,11,13,15
Duty cycle (%)	45, 50, 55, 60, 65

Table 2. Experimental details.

Ex. NO.	Electrolyte concentration (g/L)	Machining voltage (V)	Duty cycle (%)
1	23	15	65
2	25	15	65
3	27	15	65
4	29	15	65
5	31	15	65
6	31	7	65
7	31	9	65
8	31	11	65
9	31	13	65
10	31	15	65
11	31	15	45
12	31	15	50
13	31	15	55
14	31	15	60
15	31	15	65

RESULTS AND DISCUSSION

Effect of Electrolyte Concentration on Machining Outcomes

The impact of several ECMM tool electrodes, including CRCT, RUIT, RFHT, and NRMT, on OC and MRR at different electrolyte concentrations is depicted in Fig. 2. It is evident from the graph that the OC increases as the electrolyte concentration rises. All tools exhibit higher OC with increasing electrolyte concentration; the higher ionic concentrations in the electrolyte accelerate the ion movement, which causes the higher OC. For input parameters of 23 g/L, 15 V, and 65%, RUIT shows the lowest OC of 34 µm among the tool electrodes, which is 72% lower OC than NRMT. Similarly, the OC increases almost linearly as electrolyte concentration rises from 25 to 31 g/L. At lower electrolyte concentrations, fewer ions exist for machining due to reduced ionization, which tends to decrease OC [29,30]. In addition to this, a strong, thick electrode coating of rubber hinders the stray current and reduces the OC with the RUIT. The rubber insulation has a thickness of 1 mm. When current flows through RUIT, the resistance of the rubber generates heat (joule heating), which is transferred to the tool tip, causing hydrogen bubbles to form inside and around the electrode tip. The generation of these bubbles produces a micro-stirring effect near the machining zone, which prevents micro-sparks in the IEG and removes debris generated during machining. This mechanism also promotes electrolyte circulation and further reduces OC. Microhole breakthrough identified by the appearance of gas bubbles emerging from the underside of the workpiece, which served as a clear indication that the tool successfully penetrated the workpiece

Additionally, the insulation limits stray current in and around the electrode, which controls the current flow in IEG. Fig. 3 shows the SEM pictures of micro holes machined through a) RUIT, b) RFHT, c) CRCT, and d) NRMT. SEM image of the microhole fabricated through NRMT clearly illustrates the effect of stray currents, which disrupt the circular profile and form micro pits due to debris attachment along the hole perimeter. In contrast, SEM images of microholes machined with RUIT in Fig. 3a reveal round holes for the parameter combination of 23 g/L, 15 V, and 65%, without peripheral etching. Based on the graph, OC in RFHT is 61% lower than in NRMT, which is second least OC among other tool electrodes. However, RFHT produces partially detachable sections around the microhole perimeter. It is generally observed that growing electrolyte concentration increases conductivity, which in turn raises OC.

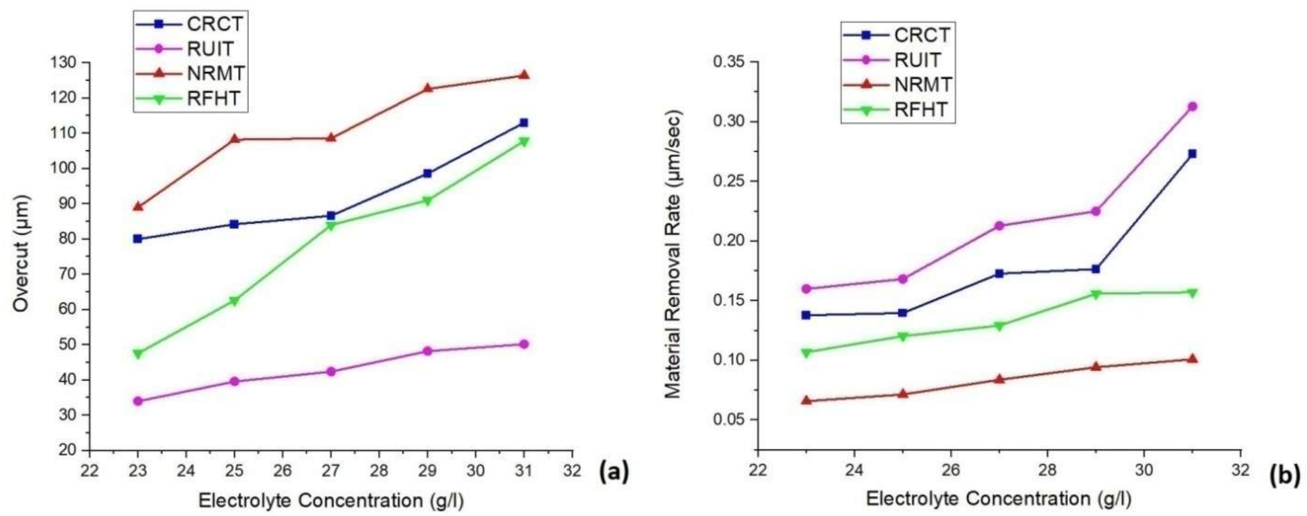

Figure 2. Effect of electrolyte concentration on a) OC and b) MRR.

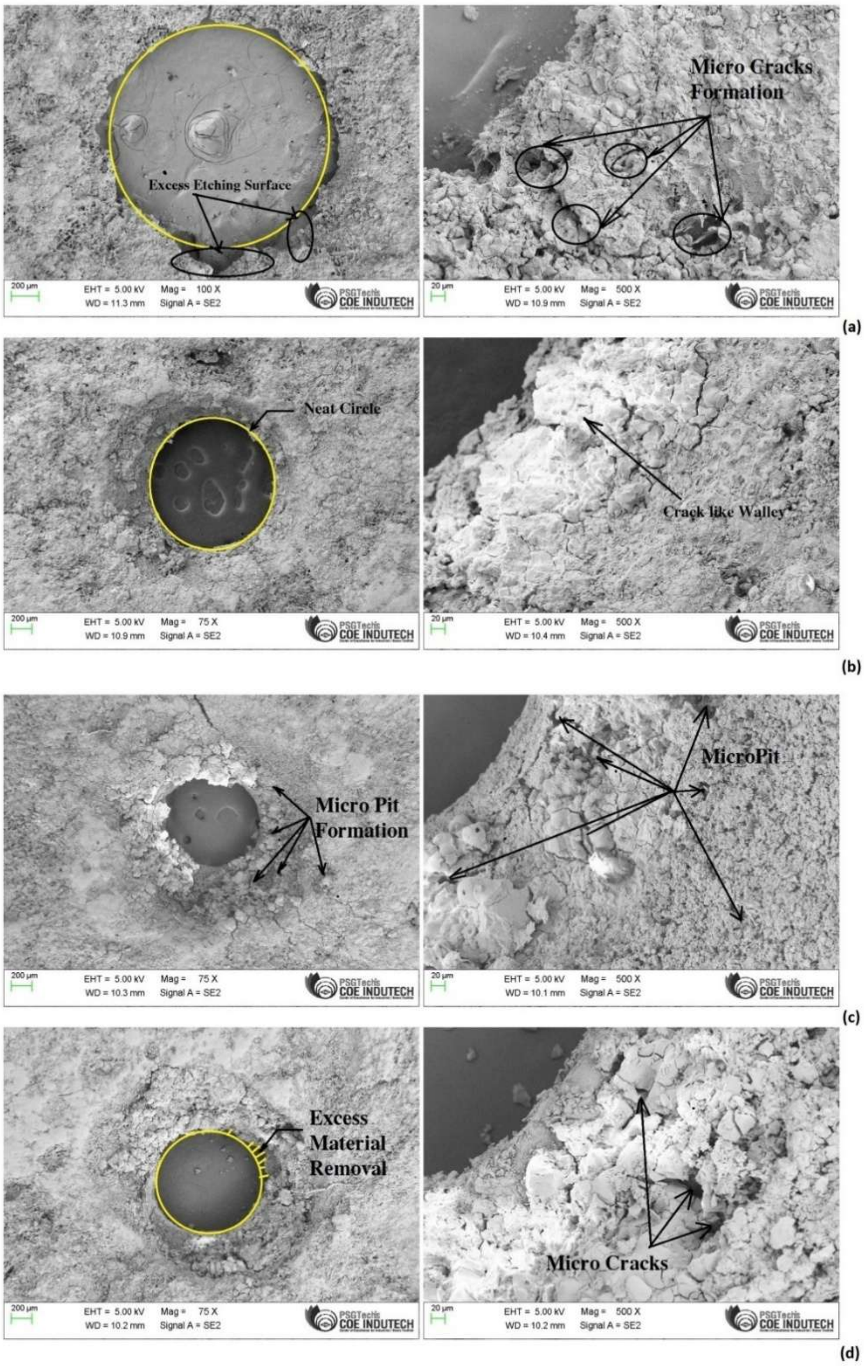

Figure 3. SEM pictures of micro holes created through a) RUIT, b) RFHT, c) CRCT, and d) NRMT.

CRCT offers an OC of 78 µm, which is 52% lower than NRMT for the parameter mixer of 23 g/L, 15 V, and 65%. The copper particles mixed with CRCT provide a uniform current flow in the machining zone and also cause cupric oxide formation. The cupric oxide is nonconductive debris that controls the diverse current in IEG. This phenomenon leads to less OC with CRCT.

The use of RUIT enhances the electrochemical reaction by providing uninterrupted current, and an increase in electrolyte concentration raises the ionic availability, which is necessary for the machining process. This effect accelerates the disintegration of the workpiece material, resulting in higher MRR with RUIT.

Therefore, RUIT produces 2.93 times higher MRR than NRMT at a parameter mixer of 23 g/L, 15 V, and 65%. Similarly, under the same conditions, CRCT exhibits the second-highest MRR compared to NRMT. The copper particles dispersed in the tool electrode create the clustered power supply at the edge of the tool. The clustered power supply at the machining zone hits and removes the debris faster, which leads to 2.53 times higher MRR than NRMT with the CRCT (Fig. S3). The RFHT produces 2.19 times higher MRR than NRMT. Since the hollow tool electrode passes the electric current narrowly to the machining zone [31]. In addition, inside tohollow tool is filled with nonconductive rubber, which isolates the internal surface power (Fig. S4). The controlled and narrow power supply with the RFHT contributes to better MRR at the parameter mixer of 23 g/L, 15 V, and 65%. In RUIT, it is covered with a rubber insulation layer to prevent unwanted sidewall machining. Rubber insulation helps maintain precise tool geometry, minimizes stray current, improves dimensional accuracy, and protects the tool from effects such as moisture, electrolyte splashing, temperature variation, and corrosion (Fig. S5).

Effect of Machining Voltage on Machining Outcomes

The effects of machining voltage on OC and MRR for various tools are shown in Fig. 4. According to the graph, RUIT exhibits the least OC of 38.4 µm at the parameter mixer of 7 V, 15 g/L, and 65%. The data indicate that raising the machining voltage leads to higher OC regardless of all electrodes. According to the graph, RUIT produces 58.23% less OC when compared to the NRMT. Fig. 5a indicates an SEM image of the micro-hole circumference using RUIT. This is due to the fact that composed of rubber and stainless steel and, when submerged in electrolyte, produces remarkable electrical conductivity. Also, it creates the electrostatic pull-out forces on the electrode surface due to the rubber insulation, which results in a reduction in OC with the RUIT compared to NRMT. Under the same input parameters, RFHT produces the next-lowest OC of 48 µm, which is 34.7% lower than NRMT. Fig. 5b shows the SEM image of the micro-hole circumference using RFHT. Also, CRCT produces an OC of 66 µm, which is 17.55% lower than NRMT at 7 V, 31 g/L, and 65%. Fig. 5c demonstrates the SEM image of the micro holes' circumference using CRCT.

Fig. 5d illustrates the SEM image of the edges of micro holes created with NRMT. The effect of machining voltage on MRR for different tool electrodes is presented in Fig. 4b. It is evident that higher input parameters lead to increased MRR. As machining voltage rises, the current density in the electrolyte increases, which causes the electrolyte in the IEG to heat up due to the faster movement of electrons [32]. The RUIT produces 2.65 times higher MRR than NRMT with the parametric mixer of 7 V, 31 g/L, and 65%. This is due to the higher production of gas bubbles in IEG. The hydrogen bubbles are generated in the machining zone due to ion dispersion, and it breaks down on the surface of the electrolyte surrounding the tool electrode which creating a micro-stirring effect [33]. This effect promotes electrolyte circulation and accelerates electron movement, thereby increasing MRR (Fig. S6). Under the same parametric combination conditions with 9 V, 31 g/L, and 65%, the CRCT achieved the next-best performance, with an MRR 1.97 times higher than NRMT. In CCT, positively charged ions separate from the copper work material, further increasing MRR. Additionally, elevated temperatures enhance ion activation and electrolyte flow, accelerating the ECM process. For the case of RFHT, the corroded rubber insulation surface exhibits surface piezoelectricity, which facilitates detection of H^+ and OH^- ions from the electrolyte. As a consequence, MRR rises with rising ion concentration in the IEG at the parameter mixer of 7 V, 31 g/L, and 65%; the MRR achieved by RFHT is 55% higher than that of NRMT.

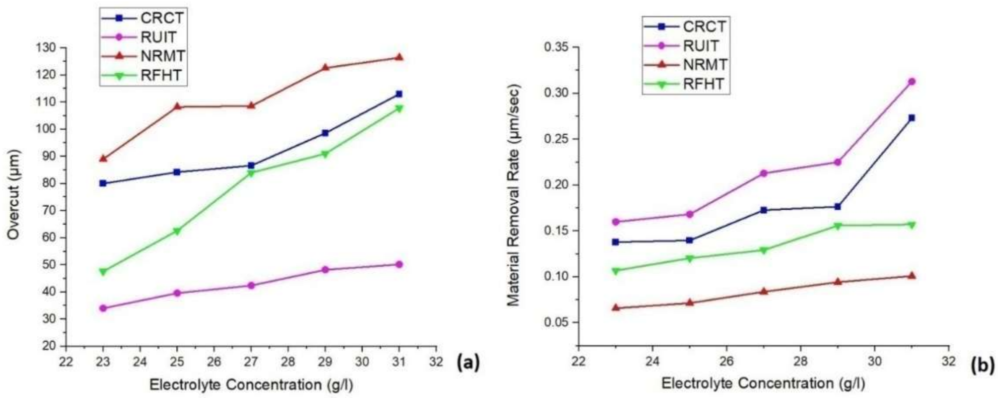

Figure 4. Effect of machining voltage on a) OC and b) MRR.

Effect of Duty Cycle on Machining Outcomes

Fig. 6a illustrates the effect of duty cycle over various tool electrodes such as RUIT, RFHT, CRCT, and NRMT. The RUIT creates 36.8 µm OC at the parameter mixture of 45%, 15 V, and 31 g/L. This OC is 51.23% lower when compared to NRMT. Also, the graphs linearly rise with the rise in duty cycle. Furthermore, for the next level of duty cycle, i.e., 60% is produces 31% less OC than NRMT. In the case of RFHT produces the next least OC, which is 58.56 µm. Since the epoxy coating and tool filled with rubber restrict the process and excess flow of current. Similarly, the CRCT, copper oxidizes and forms a coating of hydrated copper carbonate on its surface [33]. After reacting with the electrolyte, this layer quickly delaminates from the work material. This occurrence results in a decrease in conductivity and an electric barrier between the tool and work, which lowers the OC. As a result, 27.3% less OC was obtained with the CRCT than NRMT. Furthermore, in comparison to the NRMT, RUIT and RFHT produce lower OC of 40.6 µm (i.e., 52%) and 58.6 µm (i.e., 16.5%) for the parametric mixer of 60%, 15 V and 31 g/L.

The impact of duty cycle on MRR for each tool electrode is depicted in Fig. 6b. The MRR for RUIT rises as the duty cycle range increases. This is due to the fact that the faradic effect enriches the process and causes material to dissolve quickly during machining. Additionally, there is a gap between the rubber and SS tool, which stimulates the synergetic effect in the machining zone [34,35].

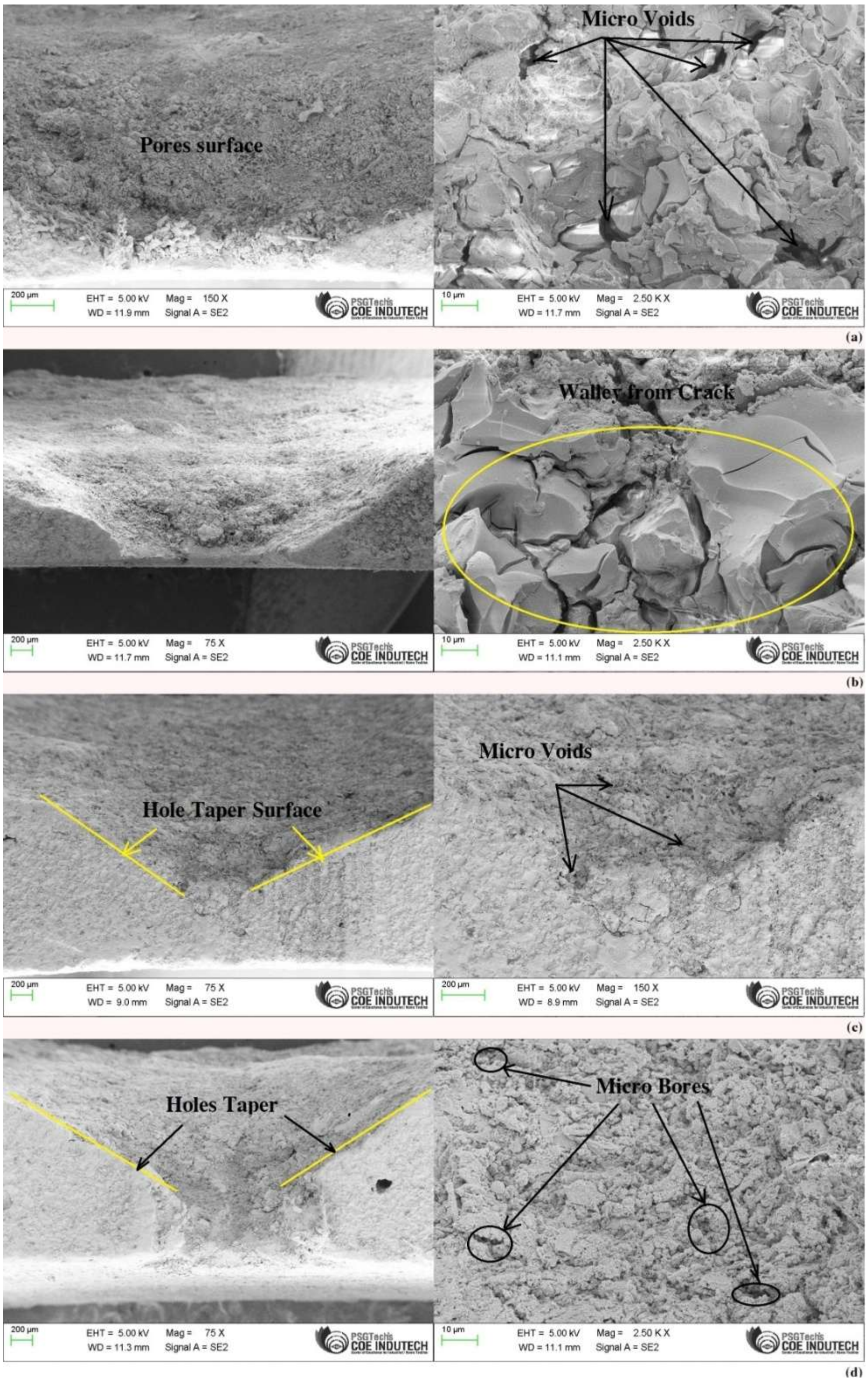

Figure 5. SEM image of micro holes circumference using a) RUIT, b) RFHT, c) CRCT and d) NRMT.

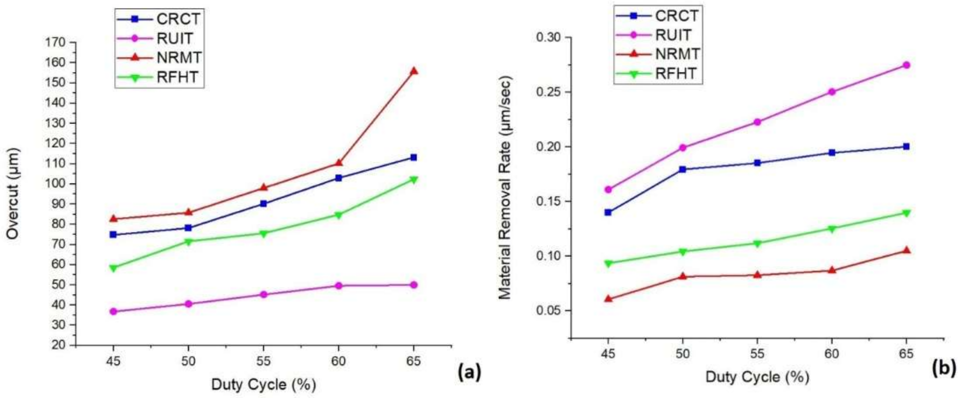

Figure 6. Effect of duty cycle on a) OC and b) MRR.

Therefore, RUIT generates 1.88 times more MRR at parametric combinations of 45%, 15 V, and 31 g/L than NRMT [36]. The CRCT generates 1.31 times more MRR than NRMT, which is the next highest MRR at the parameter combination of 45%, 15 V, and 31 g/L [36]. The RFHT produces 1.53 times higher MRR than NRMT for the same parametric combination as NRMT.

CONCLUSION

The overall performance of the ECMM process is strongly influenced by factors such as electrode selection, electrical parameters, insulation of the tool electrode, and the nature of the electrolyte, as these variables govern MRR, surface characteristics, and dimensional accuracy. In this present work, CRCT, RUIT, RFHT, and NRMT electrodes were applied in machining AMMC to assess their effects and to identify the most appropriate electrode for enhanced machining performance.

- For the input parameters of 23 g/L, 15 V, and 65%, RUIT shows the lowest OC of 34 µm among all tool electrodes, which is 72% lower OC than NRMT.
- The strong and thick electrode coating of rubber hinders the stray current and reduces the OC with the RUIT.
- The RUIT produces 2.93 times higher MRR than NRMT at the parameter combination of 23 g/L, 15 V, and 65%. Similarly, under the same conditions, CRCT exhibits the second-highest MRR compared to NRMT.
- The copper particles dispersed in the tool electrode of CRCT create a clustered power supply at the edge of the tool. This clustered power supply at the machining zone causes faster removal of debris, which leads to the 2.53 times higher MRR than NRMT with the CRCT.
- Further experimental studies may be performed using heated polymer electrolytes to reduce surface over-etching in the machining zone.

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NAUČNI RAD

UTICAJ HIBRIDIZACIJE ELEKTRODA PRI ELEKTROHEMIJSKOJ MIKROOBRADI KOMPOZITA NA BAZI LEGURE ALUMINIJUMA

Potreba za komponentama mikrodimenzija u vazduhoplovnoj, automobilskoj i medicinskoj industriji kontinuirano raste poslednjih godina. Kod elektrohemijske mikroobrade (ECMM), zbog prisustva tvrdih čestica u kompozitima na bazi legura aluminijuma dobijenih iz otpadnog materijala, izrada mikrootvora je otežana, pri čemu se kod većine mikrootvora javlja veliko prekoračenje dimenzija. Imajući u vidu potrebu za većom brzinom uklanjanja materijala (MRR), kao i za povećanjem tačnosti pri izradi mikrokomponenti, istraživanje je usmereno na izbor tipa alatne elektrode i načina njene izolacije. U cilju prevazilaženja navedenih problema korišćene su različite alatne elektrode: keramičko-kompozitna alatna elektroda (CRCT), alatna elektroda izolovana gumom (RUIT), šuplja alatna elektroda ispunjena gumom (RFHT) i standardna alatna elektroda (NRMT). Sistematski je ispitan uticaj ključnih procesnih parametara, uključujući napon obrade, faktor ispune impulsa i koncentraciju elektrolita. Eksperimentalni rezultati pokazuju da se primenom RUIT elektrode postiže 2,09 puta veća MRR u poređenju sa NRMT elektrodom. Takođe, CRCT elektroda ostvaruje 1,7 puta veću vrednost MRR u odnosu na NRMT pri odabranim parametrima procesa: koncentraciji elektrolita od 23 g/L, naponu od 13 V i faktoru ispune impulsa od 80%. Među ispitivanim alatnim elektrodama, RFHT je omogućila najmanje prekoračenje dimenzija (OC), u vrednosti od 58,56 µm. Pored toga, radi utvrđivanja uticaja tipa alatne elektrode na rezultate obrade i karakteristike obrađene metalne površine, izvršena je analiza snimaka dobijenih skenirajućom elektronskom mikroskopijom (SEM).

Ključne reči: elektrohemijska mikroobrada, kompozit na bazi legure aluminijuma iz otpadnog materijala, izolacija, FESEM.