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Experimental study on developed electrochemical micro machining of hybrid MMC

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An electrochemical micro machining (ECMM) set-up has been developed and utilized for experiments. The effects of ECMM parameters on material removal rate and electrode wear rate have been analyzed during micro drilling of hybrid Al/(Al_2O_{3p}+SiC_p+C_p)-MMC with tungsten electrode of diameter 298 µm. The machined surface texture, and decomposition of metallic compounds deposited on the workpiece as well as on micro tool have been analysed through SEM, EDX and XRD images. It may occur due to the reaction of the anode with electrolyte (NaCl). The formation of a new compound sodalite has been identified. This is due to the reaction between sodium chloride and reinforced particles *i.e.* Al_2O_3, SiC, C elements presence in hybrid MMC. It has also been identified that the formation of ferropargasite chlorous compound might be due to a chemical dissolution of ferrous material and reaction with sodium chloride. Formation of voids, micro-cracks, craters, debris, pulled out materials and pockmarks have been analyzed during micro machining at high current and pulse-on time parametric setting. From EDX analysis, it has been noticed that the reinforced particles present in hybrid metal matrix composite have been deposited on a micro tool. This is due to the melting and re-solidification of hybrid Al/MMC during machining by micro sparking at high supply voltage and pulse on time.

Keywords: Electrochemical micro machining, Hybrid MMC, Material removal rate, Electrode wear rate

1 Introduction

Hybrid metal matrix composite (MMC) is a heterogeneous solid consisting of more than two different materials that are mechanically or metallurgically bonded together. Hybrid Al-MMCs have used in aerospace, defence and automobile sector. Some of the specific use in automobile engines as cylinder liners, piston, drive shafts, etc. It possesses surprising physical and mechanical properties like high stiffness to weight ratio, high strength to weight ratio, good resistance to corrosion and wear, high fatigue resistance, high temperature durability etc.[1-3]. However, the presences of abrasive reinforcements (i.e. Al_2O_3 and SiC) make it hard to machine by using any well-known traditional machining processes[4]. Electrochemical machining method (ECM) has a potential for machining of difficult to machine materials. It is a stress-free, non-contact, no heat affected zone, and however, this process is only used for machining of electrically conductive materials[5]. In electrochemical micro machining, the machining precision might increase by reducing the electrolyte concentration and pulse on time[6]. The use of an insulated electrode with applied pulse voltage could control the micron level gap during machining[7]. The service life of electrode has improved by coating the double TiO_2 ceramic insulating layers[8]. The ultrasonic assistance in ECMM increased material removal rate and reduced hole taper[9]. Micro ECM can machine the 0.38 mm diameter of micro hole on composite specimen[10]. During the investigation of the effect of ECMM parameters for machining of 304 stainless steel, it was found that electrolyte concentration and tool tip shape were most significant process parameters[11].

Kurita *et al.*[12] explained the difficulties in driving out the sludge particles from the micro machining gap during micro machining of deep hole on ECMM. To clean the sludge particles and improve the machining precision, Fan and Hourng[13] used rotational tool and supplied high frequency pulsed voltage. Chiou *et al.*[14] fabricated the micro-tools made of tungsten having high aspect ratio and used these tools to give the reciprocating motion along the vertical direction for micro machining. Ghoshal and Bhattacharyya[15] claimed that the electrochemical machining is one of

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the most suitable and quickest methods for fabrication of micro tools used in electrochemical machining. Choi *et al.*[16] utilized ultrashort pulse voltage machined tungsten carbide-cobalt alloy 3D structures on micro electrochemical machine (ECM). They used a mixture of sodium nitrate ($NaNO_3$) and sulphuric acid (H_2SO_4) for machining of tungsten carbide cobalt alloy.

Kumar *et al.*[17] applied response surface methodology (RSM) and analyzed the effect of electrochemical machining process parameters on the material removal rate (MRR) during machining of Al/SiC MMC. They claimed that the MRR increases with increase in supply voltage, feed rate and current. Sankar *et al.*[18] optimized the process parameters of abrasive assisted electrochemical machining process for machining of Al/boron carbide and graphite composite. They claimed that the abrasive assisted ECM has relatively higher capability with respect to the MRR over ECM.

The main aim of the research is to developed an ECMM set-up and machined the fabricated liquid stir cast hybrid Al/(Al_2O_3p + SiCp + Cp)-MMC workpiece. The mesh size of aluminium oxide reinforced particles (Al_2O_3p) was 400 (38µm), silicon carbide reinforced particles (SiC) was 400 (38µm), and carbon reinforced particles (C) was 1000 (15.2µm). Table 1 represents the composition of the fabricated hybrid Al/(Al_2O_3p+SiCp+Cp)-MMC. It also aims to analyze the effect of machining parameters on developed ECMM performance characteristics. Table 2 represents the chemical composition of aluminium alloy.

2 Experimental Work

The permanent metal molds were fabricated from IS 2002-1962/ high-temperature service pipe, medium grade of 40 mm nominal diameter x 3.15 mm thickness. One mold was also fabricated from IS 226/10 mm thick plate. The mold size was 70 mm x 30 mm x 350 mm long. The rectangular and circular shape cast samples of Al-MMCs were fabricated by liquid stir casting technique. These fabricated cast Al-MMCs samples were utilized for testing of mechanical properties. Figure 1 shows the clay coated actual mold used for fabrication of MMCs and hybrid MMCs. Table 3 represents the mechanical properties acquired during testing.

Electrochemical micro machining (ECMM) is a non-contact metal removal process for machining of electrically conductive materials, without applying any cutting forces on cutting zone. A low pulse DC voltage is applying between the micro tool (cathode) and the work piece (anode), which are separated by a thin film of electrolyte. Figure 2 and Fig. 3 shows a schematic block diagram and real picture of the designed and fabricated ECMM setup respectively. The developed set-up has the following subsystems such as mechanical machine unit, electrical power supply and control unit, electrolyte flow and control unit, servo control and electrode feed unit.

The mechanical machine unit consists of the main body frame, machining chamber, work holding arrangement; and tool feeding device. There is a stepper motor and a bevel gear arrangement to provide the feed movement to the microelectrode. Electrical power supply and control unit consists of a step-down transformer, rectifier, voltage variable, and pulse generator. A step-down transformer and silicon controlled rectifier unit used to convert 220V AC supply to DC output with variation from 0 - 20V.

Table 1— Composition of hybrid Al/(Al_2O_3p+SiCp+Cp)-MMC.

Hybrid MMC	Al_2O_3	SiC	C	Cu	Mg	Si	Fe	Mn	Ti	Al
%	10	20	7.5	0.02	0.62	0.49	0.32	0.12	0.01	60.92

Fig. 1 — Clay coated actual mold used with cast MMCs.

Table 2 — Composition of A-6061 aluminum in got material.

Grade	Si (%)	Fe (%)	Cu (%)	Mn (%)	Mg (%)	Cr (%)	Zn (%)	Ti (%)	Un-Specified elements (%)	Aluminium (%)
6061	0.40-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.04-0.35	0.25	0.15	0.15	95-98

Table 3 — Mechanical properties results acquired during testing.

Material	Impact Strength	Hardness	Tensile Strength
Al/10 wt%SiC + 10% wt Al_2O_3 + 5 wt%C- hybrid MMC	10.13 (N)	130(HRB)	255 (N/mm^2)

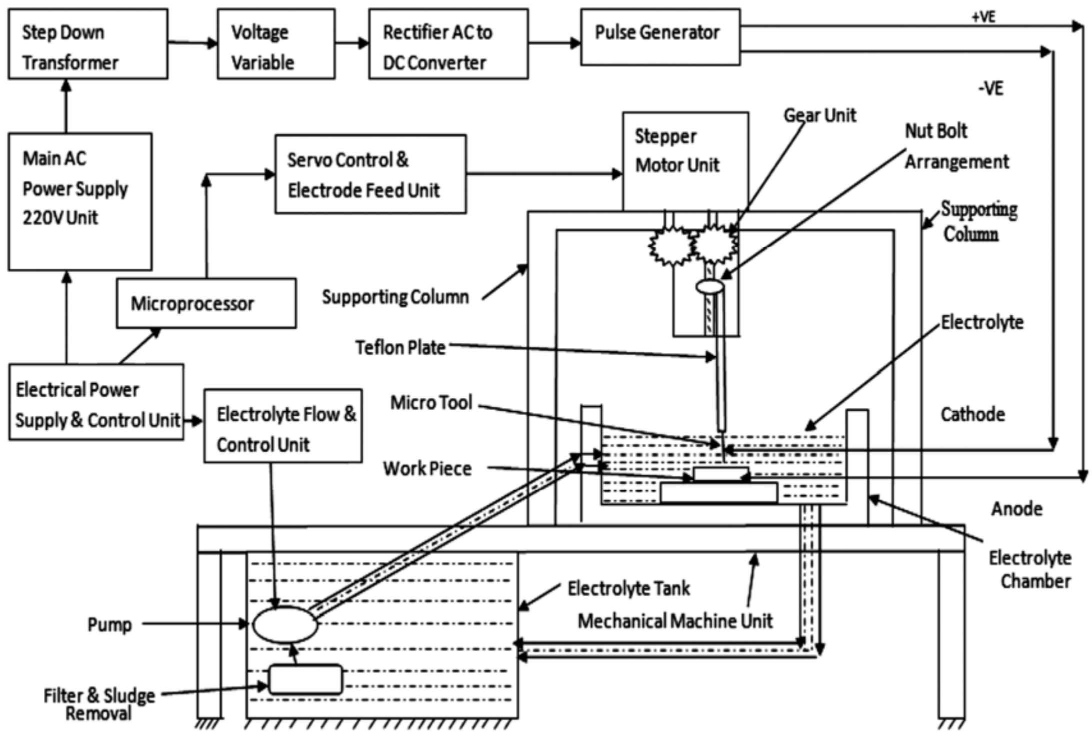


Fig. 2 — Schematic diagram of the developed ECMM set-up.

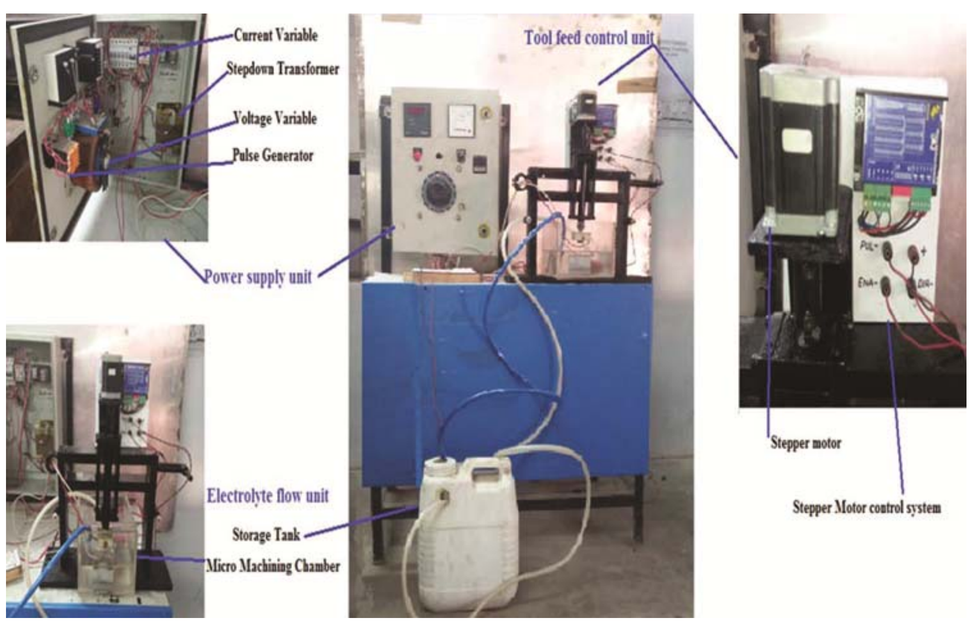


Fig. 3 — Developed ECMM set-up.

Electrolyte flow unit consists of a pump, hosepipes, nozzle, filter, and storage tank for continuous flow of electrolyte over the machining zone. The flow rate of electrolyte varies from 0.2 – 1.0 l/min with a flow control valve. Servo control and electrode feed unit is a microprocessor unit used to maintain the inter electrode gap (IEG).

The micro tools are fabricated from 2 mm diameter tungsten wire by grinding, polishing and cleaning operations. Figure 4 shows a used fabricated micro tool. Table 4 represents the ECMM parameters and their ranges considered for experiments. The work-pieces samples of size 10x10x2 mm^3 were prepared from the fabricated hybrid MMC for micro drilling experiments.

3 Results and Discussion

Figure 5 shows the various interactions graphs for material removal rate (MRR). From interaction graphs Fig. 5, it is clear that the MRR increases with increase in supply current and supply voltage. The machining current increases in the inter electrode gap (IEG) with increase in supply voltage, as a result, increases MRR. Again, with increase of supply voltage increases the potential difference between cathode and anode, thereby intensively increases electrolyte ionization and current density, which in turn increases MRR. Therefore, the material removal rate increases with increase in dissolution efficiency[19]. It has also noticed that the MRR increases with increase in pulse on time. When the pulse on time is too short, material dissolution is negligible. With high pulse-on time, both faradic current and time period of supply current increase, thereby increases faradic effects rapidly. Also by increasing of concentration of electrolyte, the MRR increases, it is due to increase of conductance of the electrolyte[20]. The more ions associated in the IEG at higher concentration of electrolyte means increase the machining current and conductivity; thus increases material removal.

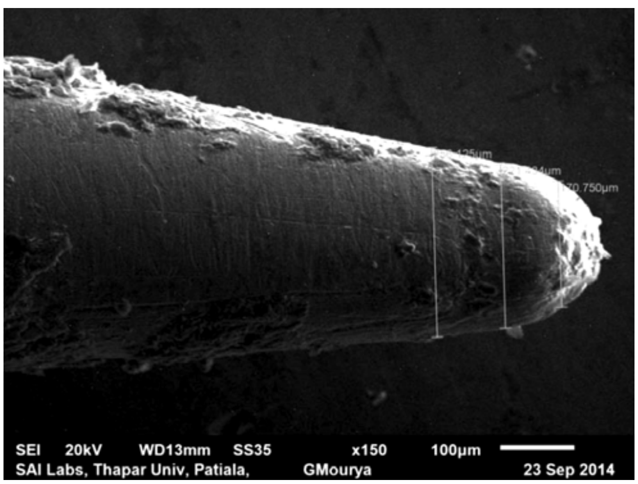


Fig. 4 — Fabricated micro tool after experiment.

Table 4 — Control factors and their levels.

Symbols	Parameters	Unit	Ranges considered for experiments
I_p	Supply Current	Amp	0.5 to 3
V	Supply Voltage	Volts	2 to 25
T_{on}	Pulse ON Time	μ_s	0.5 to10
T_{off}	Pulse Off Time	μ_s	0.5 to 10
E_c	Electrolyte Concentration	g/l	5 to 25
F_r	Electrolyte Flow rate	l/min	0.2 to 1

Table 5 show the ANOVA for MRR with percentage of contribution i.e. the effectiveness of ECMM process parameters on MRR. This table also show the significant and non-significant ECMM process parameters during micro machining of hybrid MMC for MRR. The associated P value for the ECMM process parameter is lower than 0.05 (i.e., p=0.05, or 95% confidence) indicates that the ECMM process parameters is considered to be statistically significant. The P value of supply voltage, supply current, pulse on time and electrolyte concentration is lower than 0.05, means these parameters are significant.

Saravanan *et al.*[21] carried out study to identify the optimal machining parameters for machining of super duplex stainless steel using ECMM. They found that duty cycle and electrolyte are significant factors and as the duty cycle increases, the pulse on time also increases which contributes to more MRR.

Figure 6 shows the effects of ECMM process parameters mean of SN ratios of MRR. The graph is plotted by utilizing the MRR results, which were obtained by varying of supply current from 0.5 to 3 Amp, supply voltage from 2 to 25 V, pulse on-time from 0.5 to 10 µs, pulse off-time from 0.5 to 10 µs, electrolyte concentration from 5 to 25 g/l, and electrolyte flow rate from 0.2 to 1 l/min. It is clear from the graph that mean of SN ratios of MRR increase thereby increase in supply current, supply voltage, pulse on time, and electrolyte concentrations. The optimum combination parameters for machining of hybrid MMC using ECMM for higher material

Table 5 — Analysis of variance for MRR.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution (%)
Supply Current (Amp)	2	16.472	17.429	8.715	8.74	0.001	8.92
Supply Voltage (V)	2	28.715	27.104	13.552	13.60	0.000	15.55
Pulse on Time (µs)	2	15.077	14.543	7.271	7.30	0.002	8.16
Pulse off Time (µs)	2	3.263	3.456	1.728	1.73	0.189	1.76
Electrolyte Concentration (g/l)	2	79.129	79.492	39.746	39.88	0.000	42.85
Electrolyte Flow rate (l/min)	2	1.143	1.143	0.572	0.57	0.568	0.61
Error	41	40.859	40.859	0.997			22.12
Total	53	184.657					100

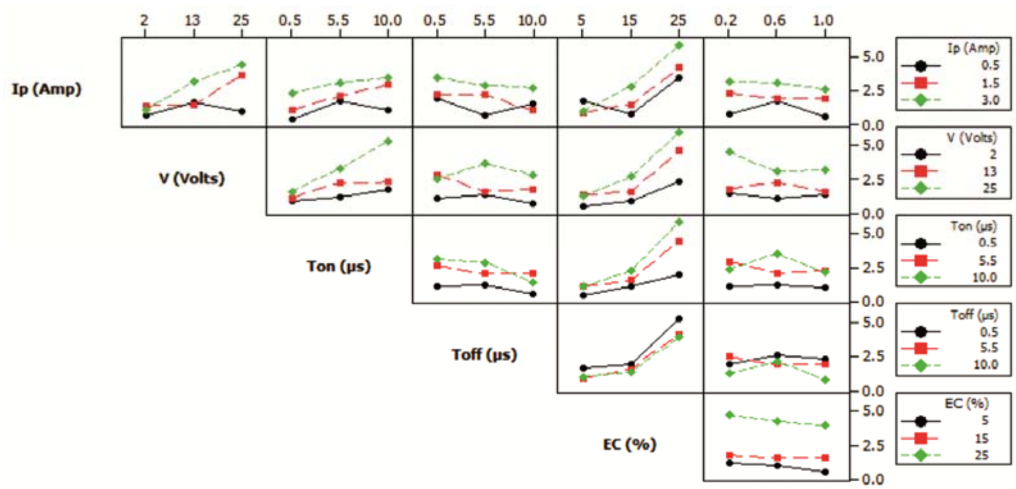


Fig. 5 — Interaction plot for MRR.

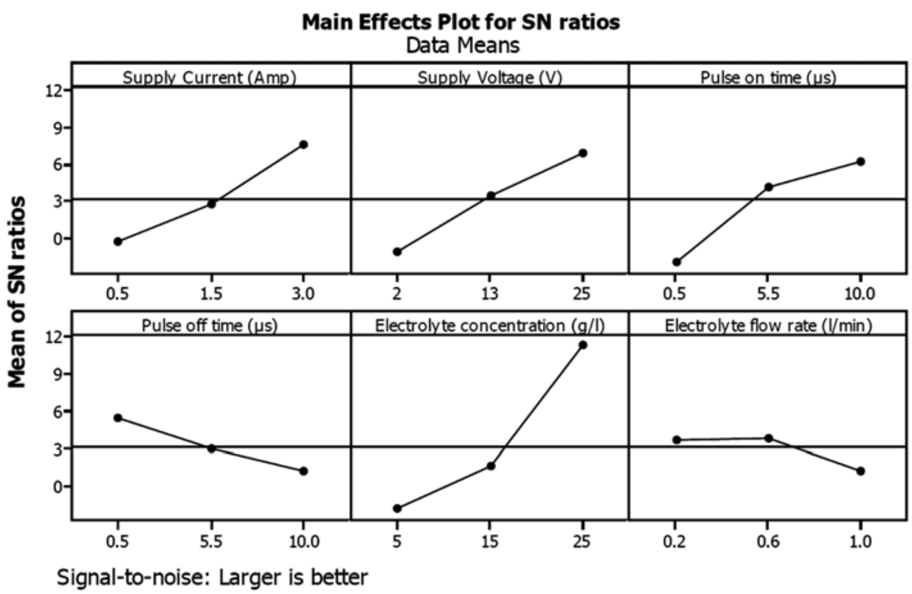


Fig. 6 — Effects of ECMM process parameters on SN ratios for MRR.

removal rate are 3amp supply current, 25V supply voltage, 10µs of pulse on time, 0.5µs of pulse off time, 25g/l concentration of electrolyte, and 0.6l/min electrolyte flow rate. Figure 7 shows the interaction plots of electrode wear rate (EWR). From Fig.7, it is clear that the EWR increases with an increase in supply voltage, electrolyte concentration and supply current. With an increase of supply voltage, there is an increase of potential difference between cathode and anode, which intensively increases electrolyte ionization, enhance electrode wear. This is because of the increased number of the hydrogen gas bubbles at the higher supply voltage, which is entrapping between electrode and workpiece surface at IEG. An increase of pulse on time, pulse off time becomes shorter which is insufficient to remove all machined particles separated by scattered and dissolution of anode completely with the flow of electrolyte from IEG. The presence of machined particles in the micro machining inter electrode gap may cause sparking, which may lead to electrode wear and decreases machining accuracy. With increase in the electrolyte concentration, the reaction rate also increased. The electrolyte conductivity and current density increases due to poor agitation rate. This leads to a non-uniform reaction on electrode surface, thereby generated a large number of hydrogen gas bubbles at the front end of the electrode. Ultimately, increase tool wear rate and micro tool length reduces with increase in electrolyte concentration.

Table 6 shows the ANOVA for EWR with percentage of contribution i.e. the effectiveness of ECMM process parameters on EWR. This table also shows the significant and non-significant ECMM process parameters during micro machining of hybrid MMC for EWR. The p-value of supply voltage, supply current, pulse on time, electrolyte concentration and electrolyte flow rate is lower than 0.05, which means these parameters are significant. Figure 8 shows the effects of ECMM process

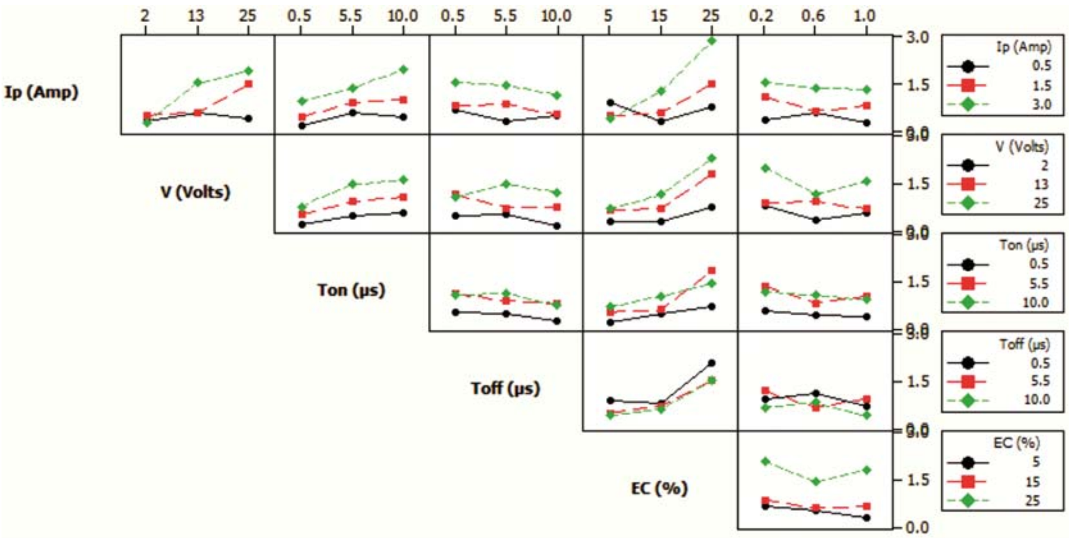


Fig. 7 — Interaction plot for EWR.

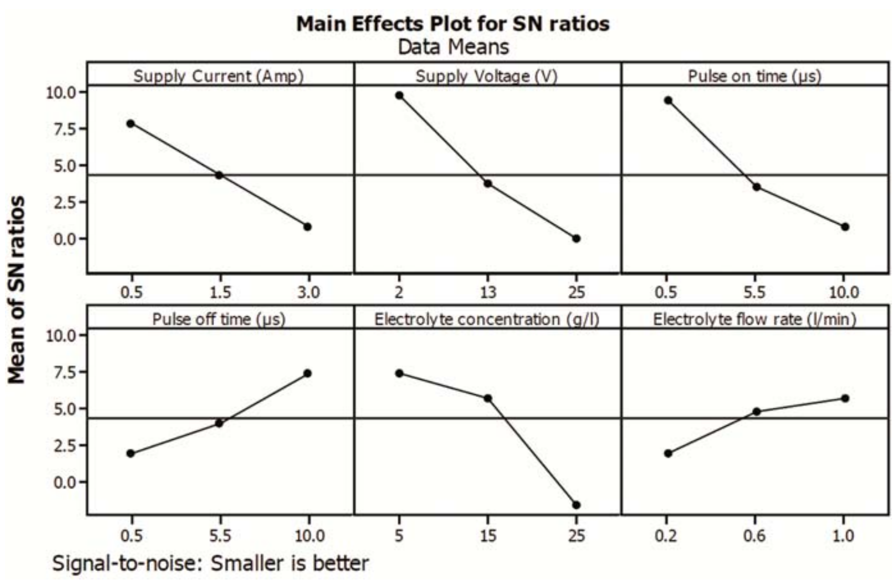


Fig. 8 — Effects of ECMM process parameters on SN ratios for EWR.

Table 6 —Analysis of variance for EWR.

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Contribution (%)
Supply Current (Amp)	2	4.9656	5.3278	2.6639	13.27	0.000	15.69
Supply Voltage (V)	2	5.2961	5.1918	2.5959	12.93	0.000	16.73
Pulse on Time (µs)	2	2.2386	2.2613	1.1306	5.63	0.007	7.07
Pulse off Time (µs)	2	0.6155	0.5728	0.2864	1.43	0.252	1.94
Electrolyte Concentration (g/l)	2	8.9680	9.3335	4.6668	23.25	0.000	28.34
Electrolyte Flow rate (l/min)	2	1.3257	1.3257	0.6628	3.30	0.047	4.19
Error	41	8.2295	8.2295	0.2007			26.01
Total	53	31.6389					100

parameters' mean of SN ratios of EWR. The graph plotted by utilizing the EWR results obtained by varying of supply current from 0.5 to 3 Amp, supply voltage from 2 to 25 V, pulse on-time from 0.5 to 10 µs, pulse off-time from 0.5 to 10 µs, electrolyte concentration from 5 to 25 g/l, and electrolyte flow rate from 0.2 to 1 l/min. It is clear from the graph that mean of SN ratios of EWR increased thereby decrease of supply current, supply voltage, pulse on time, and electrolyte concentrations. The optimum combination parameters for machining of hybrid MMC using ECMM for lower electrode wear rate are 0.5amp supply current, 2V supply voltage, 0.5µs of pulse on time, 10µs of pulse off time, 5g/l concentration of electrolyte, and 1l/min electrolyte flow rate.

Figure 9a shows SEM photograph of machined hole when machining was carried out at 1.5A supply current, 13 V supply voltage, 5.5µs pulse on time, 5.5µs pulse off time, 15 g/l electrolyte concentration and 0.6 l/min electrolyte flow rate. Figure 9b shows another SEM photograph of the machined micro hole generated at 1.5A supply current, 13V supply voltage, 10µs pulse on time, 10 µs pulse off time, 15 g/l electrolyte concentration, and 0.2 l/min electrolyte flow rate. From Fig. 9 (a &b), it is clear that the hole is circular. From Fig. 9b, it is also clear that the parametric setting gives better performance with respect to MRR as well as low taper cut, over cut and micro spark affected zone. However, generated machined surface texture has some debris. Figure 9c shows SEM photograph of a machined hole generated utilized developed ECMM set-up at 3A supply current, 25 V supply voltage, 5.5 µs pulse on time, 0.5µs pulse off time, 15 g/l electrolyte concentration and 0.6 l/min electrolyte flow rate. When machining operation was carried out at high supply voltage, high heat generated in between the IEG, as a result varying the electrolyte conductivity thereby, a non-uniform current distribution in the gap has been formed. As the pulse off time become shorter, it may not be enough to clean the machined surface i.e. sludge has not completely remove from the IEG, thereby generates micro sparking. Figure 9d shows SEM photograph of a machined micro hole generated at 1.5A supply current, 25 V supply voltage, 5.5µs pulse on time, 5.5µs pulse off time, 25 g/l electrolyte concentration, and 0.2 l/min electrolyte flow rate. Some irregularities in the shape of small groove and pitting are also identified (Fig. 9d), it may be due to developing of micro sparks in presence of sludge, which has not properly cleaned from the IEG with the flow of electrolyte during machining. These micro sparks caused uncontrolled material removal, resulting in improper generation of shape of micro hole.

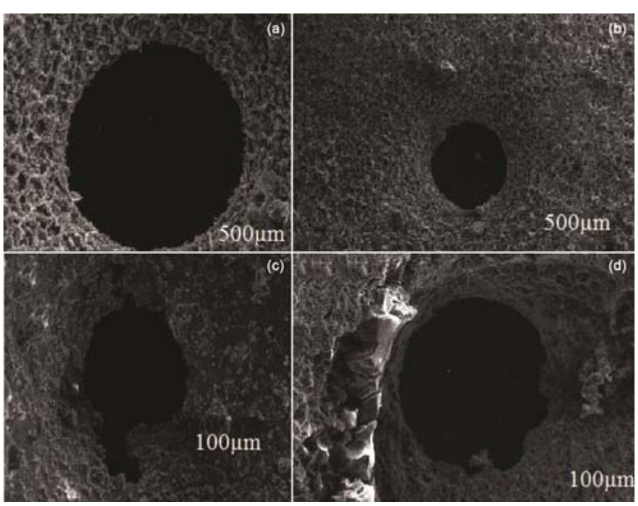


Fig. 9 — SEM photographs of machined holes on hybrid MMC.

Figure 10 shows the different SEM photographs of the machined holes generated at higher level of

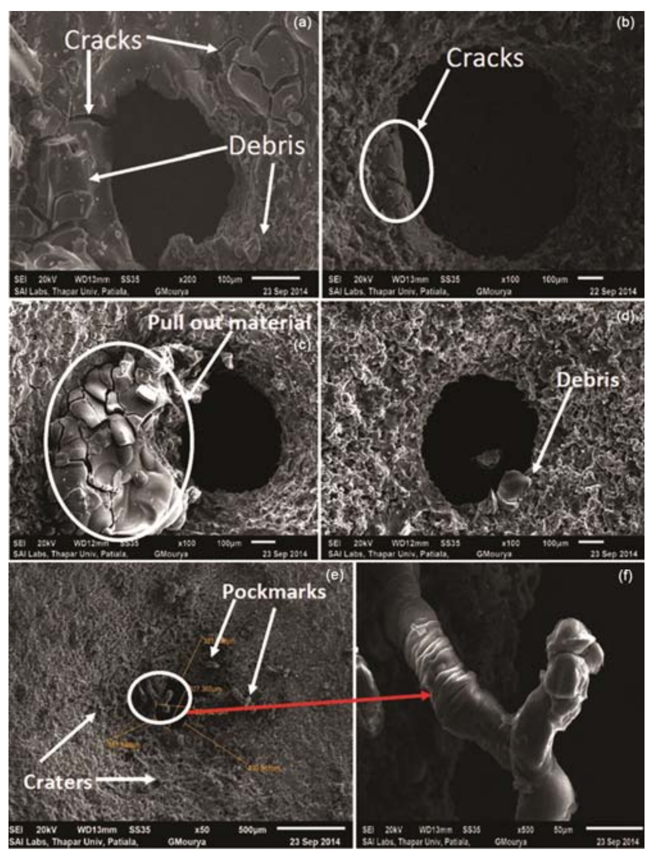


Fig. 10 — SEM of micro machined hole at higher level of ECMM machining parameter.

parametric setting *i.e.* at 3A supply current, 25 V supply voltage, 10µs pulse on time, 10µs pulse off time, 20 g/l electrolyte concentration and 1.0 l/min electrolyte flow rate. From Fig. 10, it is clear that the some of the material has deposited on micro machined surface. Some of the micro machined material have not been removed from the inter electrode gap and some parts of the micro machined material has solidified on the machined surface in the form of rubble.

The overlapping craters, cracks and pockmarks have appearance on the machined micro surface due to supply of higher current at high pulse on time. The deep crater and wider was formed when machining operation was carried out at high supply current (3 A) and pulse on time (10 µs). The dissolution rate increases by supply of high current, thereby increases deterioration in surface roughness. Figure 10 (a-f) shows the crack, debris, pulled out materials, pockmark, crater *etc.*, respectively on the generated machined holes.

Figure 11a shows SEM photograph of machined holes generated at 0.5A supply current, 13 V supply voltage, 0.5µs pulse on time, 5.5µs pulse off time, 15 g/l electrolyte concentration, and 1 l/min electrolyte flow rate. Figure 11b shows another SEM photograph of the micro machined hole generated at 0.5A supply current, 2V supply voltage, 5.5µs pulse on time, 10 µs pulse off time, 15 g/l electrolyte concentration, and 0.6 l/min electrolyte flow rate. From these SEM photographs, it clear that the hole is circular. The machining condition in these parametric setting gives better performance *i.e.* low taper cut, low over cut, low micro spark affected zone. Figure 12 (a &b) shows EDX of micro machined holes with reference to the SEM photographs Fig. 9 (c &d), respectively. From EDX, it is clear that the small particles of sodium and chloride on the periphery of machined hole may be due to the reaction product of anode with electrolyte NaCl. In EDX, the percentage of residuals such as sodium (Na), carbon (C), silicon (Si), aluminium (Al), and oxygen (O) was detected on surface of micro holes. The micro machined surface was distorted due to sodium chloride impedes during electrochemical dissolution. The oxygen is present in the workpiece due to the fact that the electrolyte normally contains water.

Figure 13 shows EDX of micro machined hole with reference SEM photo Fig 10e. From Fig. 13, it is clear that there is some irregularity and deposition of some reaction products surrounding the micro machined surface. It may be due to supply of high voltage and large amount of heat generated in the IEG, thereby variation of electrolyte conductivity,

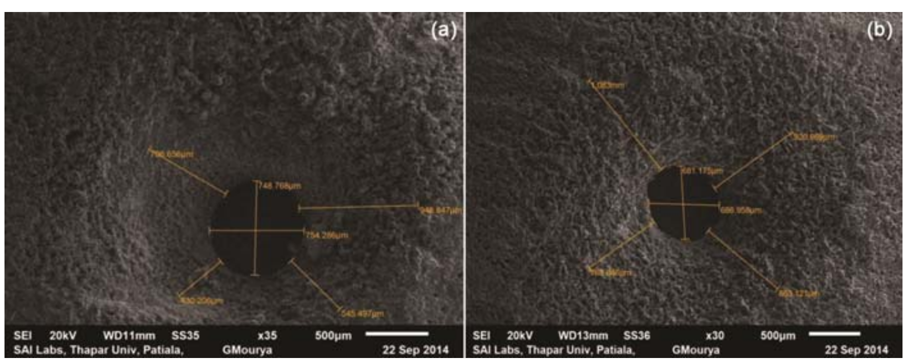
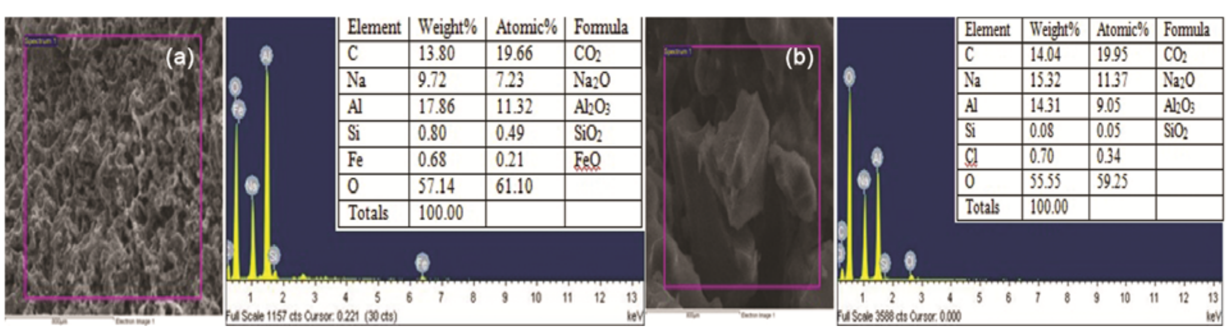


Fig. 11— SEM of micro machined hole at lower level of ECMM machining parameter.



Element	Weight%	Atomic%	Formula
C	13.80	19.66	CO_2
Na	9.72	7.23	Na_2O
Al	17.86	11.32	Al_2O_3
Si	0.80	0.49	SiO_2
Fe	0.68	0.21	FeO
O	57.14	61.10	
Totals	100.00		

Element	Weight%	Atomic%	Formula
C	14.04	19.95	CO_2
Na	15.32	11.37	Na_2O
Al	14.31	9.05	Al_2O_3
Si	0.08	0.05	SiO_2
Cl	0.70	0.34	
O	55.55	59.25	
Totals	100.00		

Fig. 12 — EDX shows the presence of different elements.

hence and non-uniform distribution of current in the gap. Figure 14 shows the element pattern of a specimen taken from micro machined hole generated at 0.5A supply current, 13V supply voltage, 10µs pulse on time, 5.5µs pulse off time, 15 *g/l* electrolyte concentration and 1 l/min electrolyte flow rate. The presence of Al_2O_3, C, SiC particles, sodium chloride and formation of new compound sodalite and ferropargasite chlorous was identified from XRD plot. The formation of new compound sodalite may be due to reaction between sodium chloride, Al_2O_3, SiC reinforced particles and aluminium itself due to high temperature in machining zone. The formation of compound ferropargasite chlorous may be due to chemical dissolution of ferrous and reaction with sodium chloride.

Figure 15 shows the SEM photographs of microelectrode tool before and after electrochemical

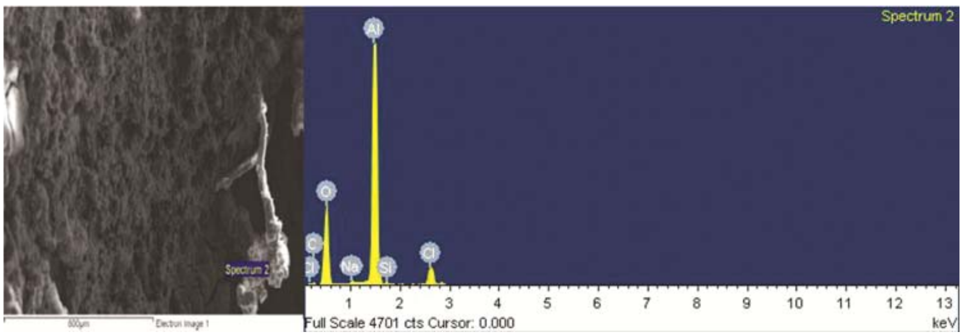


Fig. 13 — EDX shows the presence of different elements.

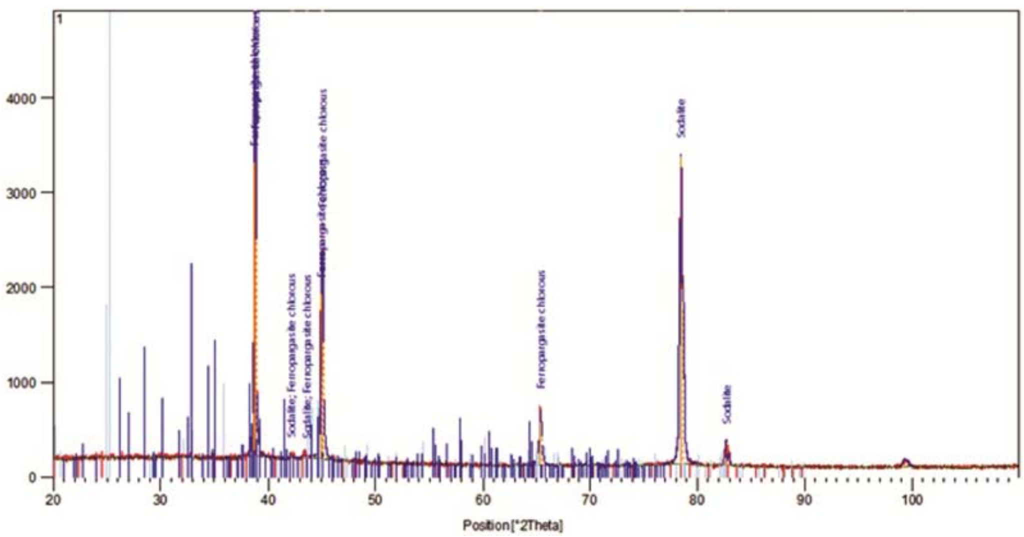


Fig. 14 — XRD pattern of machined hole.

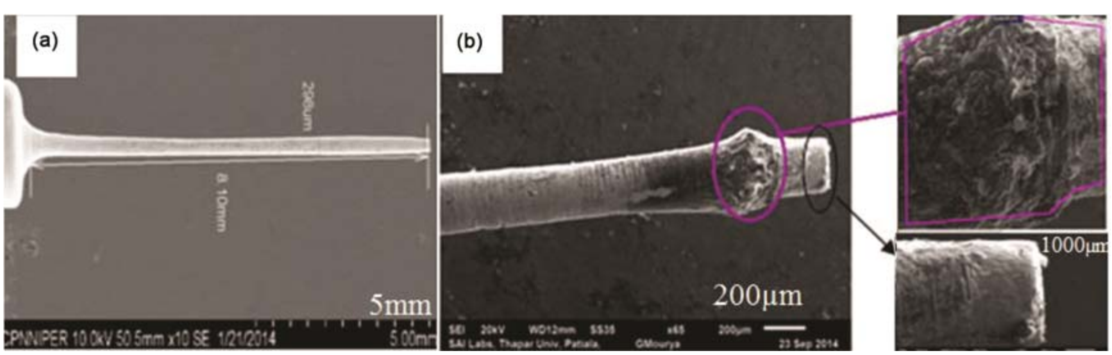


Fig. 15 — SEM of fabricated micro tool (a) Before machining and (b) After machining.

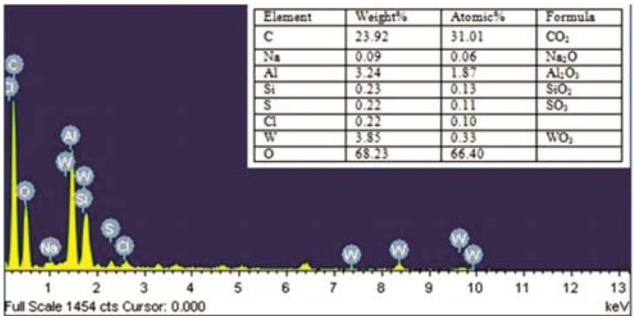


Fig 16 — EDX of micro tool.

micro machining. The micro tool was worn out when machining operation was performed with increasing pulse-on time from 5.5 to 10 μs and at constant 25 V power supply. This phenomenon may attribute to the relative increase in electrolyte conductivity and current density, it is the cause of generating micro sparks, hence increases in tool wear. As the electric field at the site of electrode was stronger, causing the supply current higher than other site, the bottom surface of electrode has corroded from a flat surface to a circular surface. While experimenting in electrolyte, there was an obvious material deposition. Fig. 16 shows EDX of micro tool after machining. From Fig. 16, it is clear that the some particles are deposited on the micro tool edge during micro sparking. It is due to increase of pulse-on time. In EDX, the different elements and their percentage as residuals such as sodium (Na), carbon(C), silicon (Si), aluminium (Al), sulphur(S), chlorine (Cl), tungsten (W) and oxygen (O) was identified as deposited particles on micro tool. It was due to melting, re-solidification and deposition of the hybrid $Al/(Al_2O_{3p}+SiC_p+C_p)$-MMC during micro machining.

4 Conclusions

The different sets of experiments have been conducting during micro machining of hybrid MMC on ingeniously developed ECMM set-up. The machined surfaces have been analysed using SEM, EDX and XRD. Formation of dissolution micro machined surface, voids and micro-cracks, craters, debris, pulled out materials and pockmarks have been identified on the machined surface. It is due to high supply current and pulse-on time. The small particle of sodium and chloride was identified on the periphery of machined hole. It may be occured due to the reaction of anode with electrolyte (NaCl). The formation of new compound sodalite was also identified. This may be due to the reaction between sodium chloride and reinforced particles *i.e.* Al_2O_3, SiC, C elements presence in hybrid MMC. It was also identified that the formation of ferropargasite chlorous compound and it may be due to chemical dissolution of ferrous material and reaction with sodium chloride. The micro tool is likely to be highly worn out with increase in pulse-on time. From the EDX analysis of micro tool, it is clear that the reinforced particles were present in hybrid MMC also deposited on micro tool. This was due to the melting and re-solidification of hybrid MMC during machining by means of micro sparking at high supply current and pulse on time. The optimum combination parameters for machining of hybrid MMC using ECMM for higher material removal rate are 3amp supply current, 25V supply voltage, 10μs of Pulse on time, 0.5μs of Pulse off time, 25g/l concentration of electrolyte, and 0.6l/min electrolyte flow rate. The optimum combination parameters for machining of hybrid MMC using ECMM for lower electrode wear rate was 0.5amp supply current, 2V supply voltage, 0.5μs of Pulse on time, 10μs of Pulse off time, 5g/l concentration of electrolyte, and 1l/min electrolyte flow rate.

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