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ORIGINAL ARTICLE

An experimental investigation on developed WECSM during micro slicing of e-glass fibre epoxy composite

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Abstract The e-glass fibre epoxy composite is a nonconductive ceramic material, and it is difficult to machine by any well-known non-conventional machining methods like electrical discharge machining, wire electrical discharge machining, etc. This material can be machined with conventional machining but compromise with accuracy, surface texture, etc. However, conventional machining methods cannot be applied to the micro machining range for manufacturing of ultra-precision parts. Keeping in view, travel wire electrochemical spark machining (WECSM), a hybrid machining technique which is a combination of electrochemical machining (ECM) and wire electric discharge machining (WEDM) is used to machine e-glass fibre epoxy composite. This paper presents the results during machining of e-glass fibre epoxy composite on designed and fabricated WECSM. The numbers of experiments have been carried out to investigate the effect of different parameters of developed WECSM on machining performance characteristics such as material removal and spark gap width. Test results revel that the width of micro slice varied from 220 to 223 μm when slicing operation was performed with 200 μm diameter brass wire. The practical research analysis and test results present in this paper will provide new guidelines to the manufacturing engineers and upcoming researchers.

Keywords Hybrid machining · WECSM · e-glass fibre epoxy composite · Micro slicing

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1 Introduction

Advanced glass fibre composites and ceramics have good strength, light weight, good corrosion as well as creep resistance and high thermal shock resistance over monolithic metals. Advanced fibre glass-reinforced composites can be used in place of steel, aluminium alloy and other monolithic materials. These composites and ceramics have wide range of applications because of their high performance properties particularly in the area of corrosive such as chemical storage and processing, water and wastewater storage and processing, aeronautical and defense, building construction, electrical and electrical utility, marine industry, etc. However, advanced e-glass fibre epoxy composite is an electrically nonconductive material, which is very difficult to machine by any well-known nonconventional machining processes. Hence, it is essential to develop an efficient and accurate machining method for processing of e-glass fibre epoxy composite materials. For effective machining of non-conductive e-glass fibre epoxy composite materials, a wire electrochemical spark machining (WECSM) setup has been developed. The developed WECSM setup has been utilized to machine e-glass fibre epoxy composite. The acquired data has been analyzed to study the effect of various parameters of the developed WECSM setup on the machining performance characteristics.

In the WECSM process, the material removal takes place due to the combined effects of electrochemical (EC) reaction and electrical spark discharge (ESD) action. The material to be machined is dipped in the electrolyte and placed very near to the cathode. In this study, a brass wire electrode is used for experimental investigation. A constant DC voltage is applied between the travel wire (i.e. cathode) and the counter electrode known as auxiliary electrode. A flat plate 100 mm × 80 mm × 2 mm thick made of copper used as a counter electrode. The hydrogen and oxygen gas bubbles are formed at wire cathode and auxiliary electrode, respectively, when the experiments are performed with applied voltage beyond certain range. The current density rapidly increases with increase in supply voltage. The density and the mean radius of the bubbles increase and bubbles finally coalesce into a gas film around the tool electrode. A brass wire is continuously traveling and functioning as an electrode during machining operation.

From the review of literature, it is found that a number of research publications on electrochemical spark discharge and traveling wire electrochemical spark machining are available; however, still a lot of applied research in the above field is required to explore the successful utilization of the process for effective machining of nonconductive ceramics and composites materials. Some of the available published research are reviewed and explained in brief here. Electrochemical spark drilling (ECSD) with rotational tool and controlled feed can improve the process performance [1]. Basak and Ghosh [2] concluded that a substantial increment in the material removal rate can be achieved by introducing an additional inductance. The performance related to machining of electrically nonconducting materials, alumina and borosilicate glass, can be improved by electrochemical spark machining with abrasive cutting tools [3]. Kulkarni et al. [4] conducted an experimental study on discharge mechanism in electrochemical discharge machining. In the particular study, authors have attempted to identify the mechanism through experimental observations of time-varying current in the circuit. Based on the experimental study, authors also proposed the basic mechanism of temperature rise and material removal. Mediliyegedara et al. [5] studied and analyzed the electrochemical discharge machining (ECDM) process and concluded that ECDM process has advantageous over ECM or EDM because of higher machining rate. Manna and Bhattacharyya [6] studied a dual response approach for parametric optimization of CNC wire cut EDM during machining of particulate reinforced silicon carbide aluminium metal matrix composite (PRAl/SiC-MMC). They used Taguchi method for experimental design, and the significant factors were identified for machining performance characteristics during WEDM of PRAl/SiC-MMC. Mohen and Shan [7] reviewed the electrochemical macro to micro hole drilling processes and concluded that advanced hole-drilling process like jet-electrochemical drilling can be accepted in producing large number of quality holes in difficult to machined materials.

In electrochemical spark machining (ECSM) process, the electrolyte concentration has the most significant effect on material removal rate and overcut on hole radius [8]. The electrochemical discharge machining (ECDM) with suitable supply voltage and its polarity can be applied for both micromachining and micro deposition [9]. The machining speed and surface roughness cannot be resolved simultaneously by using either powder added dielectric method or ultrasonic vibrated electrode methods [10]. In ECSM process, the machining voltage range from 85 to 90 V and electrolyte concentration range from 100 to 110 g/l gives higher material removal rate [11]. The machining of partially electrically conductive materials on ECSM results in physical contact between cathode, i.e. travelling wire and workpiece or cathode and debris [12]. Material removal rate depends on a large number of parameters like material to be machined, used electrolyte and applied voltage [13]. The electrochemical discharge machining (ECDM) process has a potential in the machining of silicon nitride ceramics [14]. The material removal in ECDM process mainly takes place due to spark discharge action across the gas bubble layers formed on the workpiece surface [15]. In ECDM, the ion translation rate, the electrolyte immersing depth and the concentration of the alkali are the dominant factors of bubble reaction [16]. In micro electro-discharge machining (MEDM) process, supply of optimized discharge current is essential because the temperature during discharge is extremely sensitive to the discharge current due to the small area of the micro slit [17]. The major limitation of the ECDM process is a very low penetration depth that can be overcome by supplying high voltage across the electrodes as well as a higher temperature of the electrolyte [18]. Tungsten wire electrode of 5 μm diameter was used for production of micro parts in the slit of width less than 20 μm by Zhu et al. [19]; authors claimed that there was no electrode wear. Hybrid methodology approach is better than single methodology for modeling and optimization of TW-ECSM [20]. Bhuyan and Yadava [21] studied on TW-ECSM of borosilicate glass and found that the kerf width and MRR increased with increased in supply voltage and pulse-on time both, but these responses increased up to a certain value then decreased. Jain et al. [22] studied on TW-ECSM of composite and concluded that the

Table 1 Details of experimental conditions

Machine used	Designed and fabricated WECSM setup
Electrolyte used	Sodium hydroxide (NaOH)
Concentration of NaOH with natural water	(i) 50 g/l, (ii) 100 g/l, (iii) 150 g/l, (iv) 200 g/l
Workpiece material	Electrically non-conductive e-glass fibre epoxy composite
Workpiece thickness	2 mm
Tool used	Brass wire of diameter 200 μm

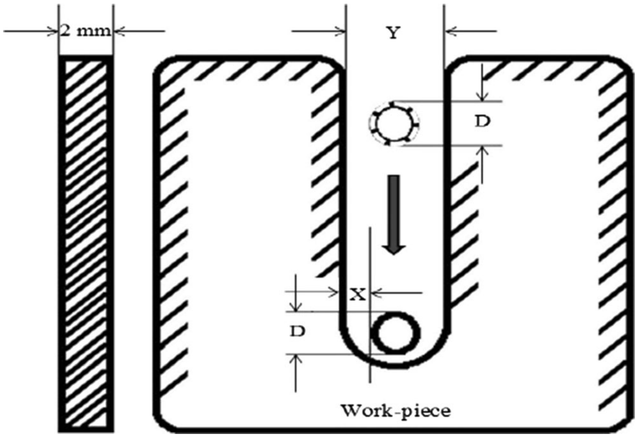

Fig. 1 Gap variation in WECSM process

higher machining accuracy can be obtained at lower values of voltage and electrolyte concentration. They also concluded that for higher machining efficiency, the distance between the anode and the cathode and the distance between the tool and the work need to be optimized.

2 Experimentation planning

A wire electrochemical spark discharge machining (WECSM) setup has been developed and utilized for experimental investigation. The different micro slicing tests were performed on electrically nonconductive high corrosive resistant and light weight e-glass fibre epoxy composite material. Table 1 represents the details of fabricated WECSM setup, tool (wire electrode), workpiece and electrolyte used for experimentation. Material removal (MR) is obtained from the difference of weight between workpiece weight before and after slicing of each operation. Contech (Instrument) Electronic Balance of resolution 0.1 mg is used to weight the workpieces before and after each run. Micro slicing width (μm) is measured by using CCD Camera of DT-110 Hybrid μEDM machine. The resolution of CCD camera is 0.1 μm. The width of micro slice is directly read from the screen of the above machine. The SEM photographs are taken to analyze the surface texture of the machined surface. The micro slicing time is recorded by using a digital stop watch of accuracy

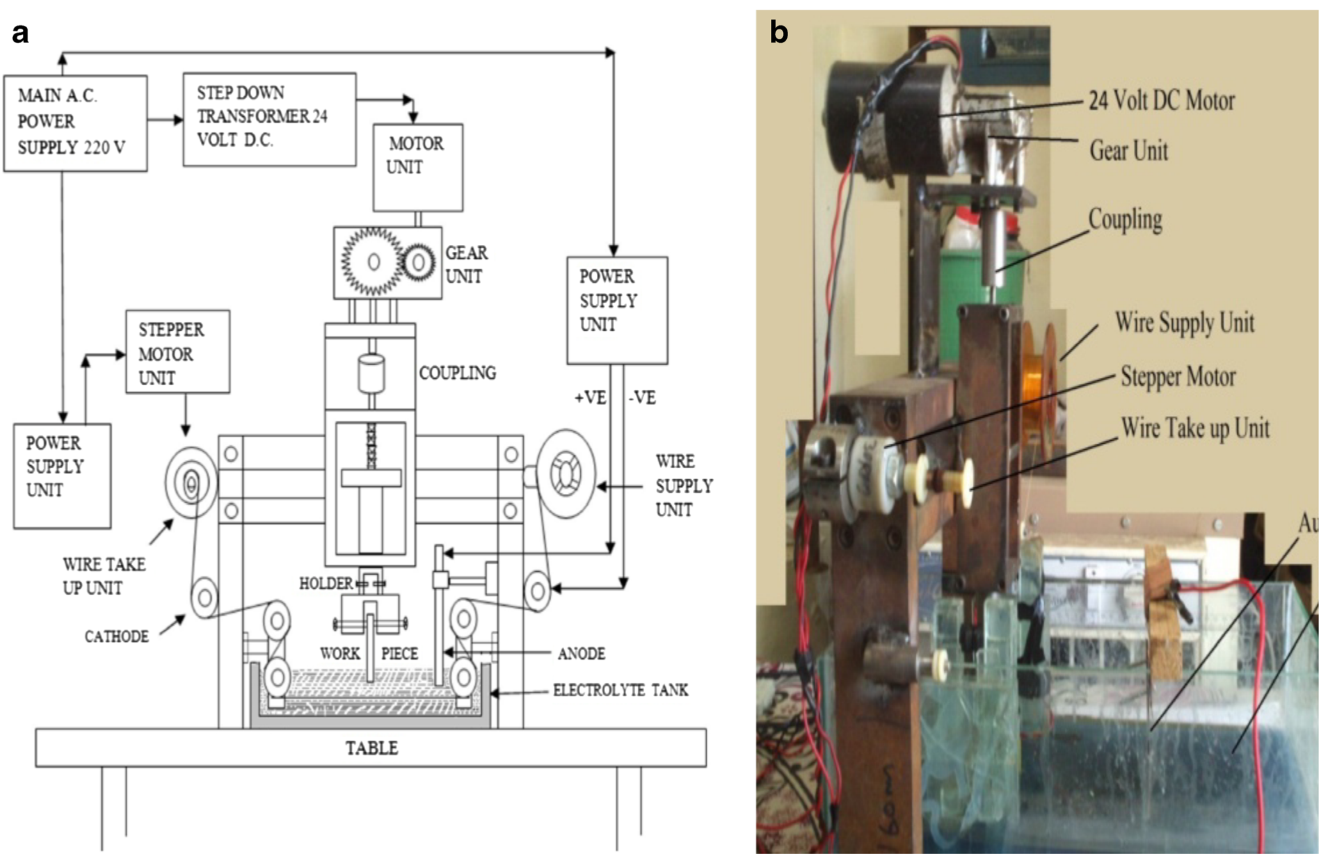

Fig. 2 **a** Schematic diagram and **b** fabricated WECSM setup

0.1 s. Figure 1 illustrates gap variation in WECSM process. The spark gap width is calculated utilizing the relation

$$X = (Y–D)/2,$$

Where D is the electrode wire (μm), X is the spark gap width (μm) and Y is the width of cut (μm).

3 Designed and fabrication of WECSM setup

Figure 2a, b shows the schematic diagram and fabricated WECSM setup, respectively. A semiconductor base rectifier converter cum regulator is used to convert 220 V AC into DC supply in the range of 10 to 110 V. Positive (+ ve) terminal of the converter cum regulator is connected to an auxiliary copper plate which, in due course, is functioning as an auxiliary anode; otherwise, it is known as auxiliary electrode. Negative (− ve) terminal of the converter cum regulator is connected to the tool, i.e. wire electrode which in turn is functioning as a cathode. An electrolytic tank is used to hold the electrolyte during machining. A scale is fixed with the electrolyte tank wall. This scale is used to check the gap between auxiliary Cu plate and traveling wire electrode. An auxiliary copper plate is hanged on a wooden bar in such a way so that the certain portion of the auxiliary Cu plate must be immersed in the electrolyte. There is a provision to move the nonconductive wooden bar along the sides of the electrolytic tank to vary the gap between auxiliary anode and traveling wire cathode. Again, another step down transformer with a regulator is also used to step down the supply voltage and regulates the same with variation of 6 to 12 V. This step down supply voltage is applied to operate a stepper motor, which gives the rotary motion to the wire take up unit. A DC supply power of 12 V is utilized for operating another stepper motor, which rolls the wire around a pulley fixed on the main frame (Fig. 2).

A special gearing with screw arrangement is used which gives upward and downward movement of the workpiece holder during cutting. It is operated by a 24-V D.C. motor. The upward and downward motion is achieved by changing the input terminals of the motor.

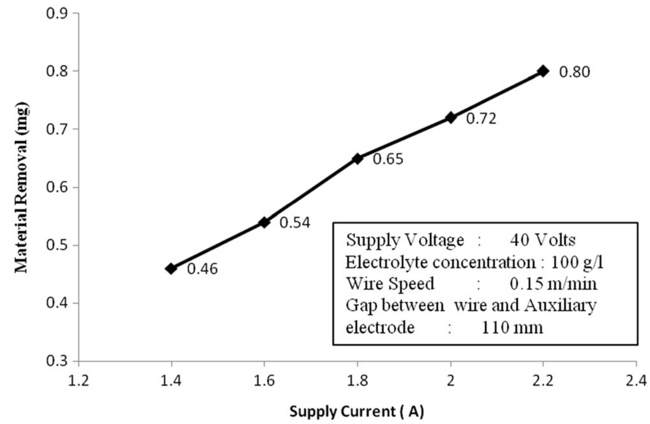

Fig. 4 Variation of material removal with supply current

4 Results and discussions

A series of experiments has been carried out with variation of different parametric setting value, and the results are utilized for further analysis. Different graphs have been plotted to analyze the effect of various parameters of developed WECSM setup on the machining characteristics such as material removal and spark gap width. Different scanning

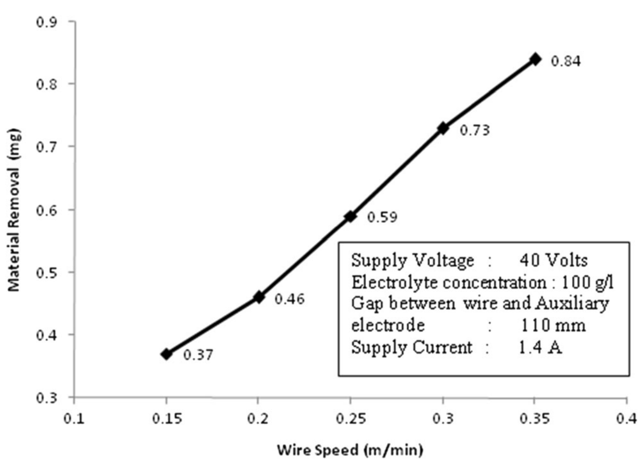

Fig. 3 Variation of material removal (MR, mg) with wire speed

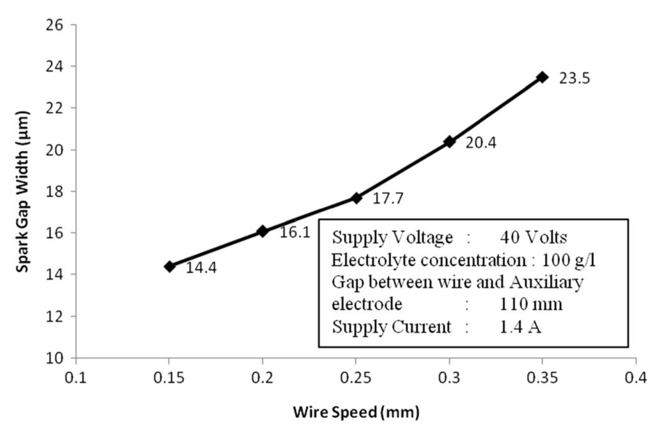

Fig. 5 Variation of spark gap width with wire speed

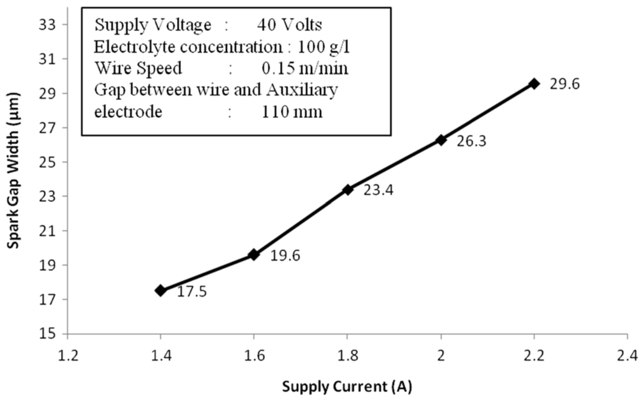

Fig. 6 Variation of spark gap width with supply current

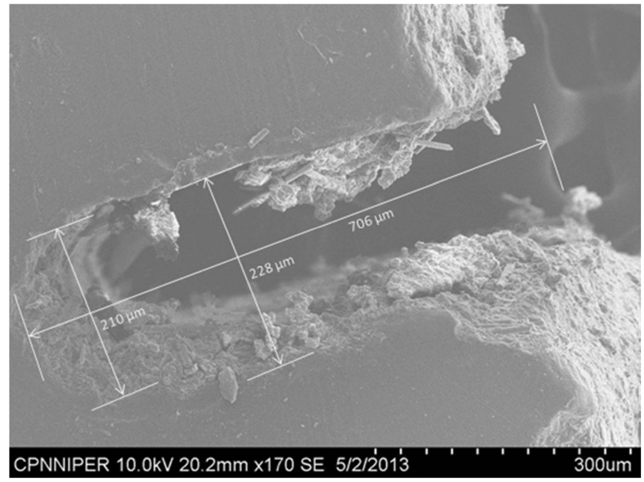

Fig. 8 SEM of a micro sliced section with 200 μm diameter brass wire

electron micrographs (SEM) show the characteristics of the generated spark gap width during WECSM operation.

4.1 Effect of parameters on material removal (mg)

Figure 3 shows the variation of material removal (MR, mg) with wire electrode speed. From Fig. 3, it is clear that the material removal increases with increase in wire speed. Wire speed has an important effect on material removal. It may be due to traveling of fresh wire quickly across the cutting zone and generates higher number of spark discharge. Higher number of spark discharge generates more numbers of craters per unit time, thereby enhancing material removal rate. Higher material removal is observed at 0.35 m/min wire speed. This graph is plotted based on the acquired results during slicing of e-glass fibre epoxy composite for continuous 90 min machining at constant 40 V supply voltage, 100 g/l electrolyte concentration, 110 mm gap between tool and auxiliary anode and 1.4 A supply current with variation of wire speed from 0.15 to 0.35 m/min.

Figure 4 shows the variation of material removal (MR, mg) with supply current. From Fig. 4, it is clear that material removal increases with increase in supply current. Higher material removal is observed at 2.2 A supply current. It is due to the increase of charge density with increase in supply current, thereby increasing formation of caters around the tool and workpiece material. This graph is plotted based on the results obtained during slicing of e-glass fibre epoxy composite with continuous 90 min machining at constant 40 V supply voltage, 100 g/l electrolyte concentration, 0.15 m/min wire speed, 110 mm gap

Fig. 7 SEM of a sliced work-piece with 200 μm diameter brass wire

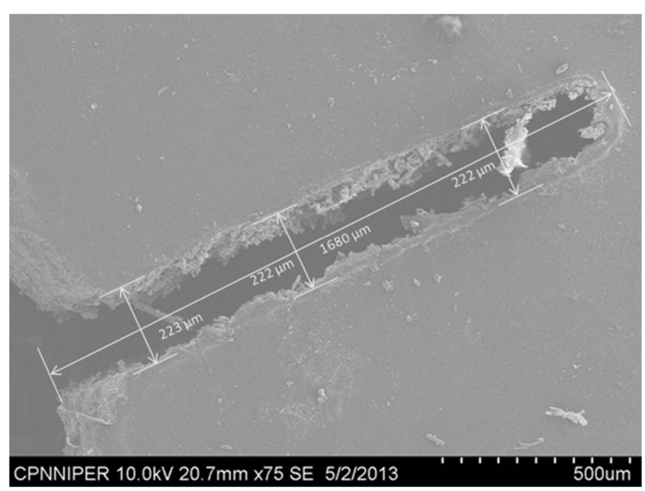

Fig. 9 SEM of a micro sliced section with 200 μm diameter brass wire

Table 2 WECSM setup parameters and their levels

Parameters, their symbols and units	Parametric levels			
	1	2	3	4
A: DC supply voltage (Volt)	40	50	60	70
B: Electrolyte concentration (g/l)	50	100	150	200
C: Wire speed (m/min)	0.15	0.2	0.25	0.3
D: Gap between wire and auxiliary electrode (mm)	50	80	110	140
E: Supply current (A)	1.4	1.6	1.8	2.0

between tool and auxiliary anode with variation of supply current from 1.4 to 2.2 A.

4.2 Effect of parameters on spark gap width (μm)

Figure 5 shows the variation of spark gap width (Wg, μm) with wire electrode speed. From Fig. 5, it is clear that the spark gap width increases with increase in wire speed. Parameter, wire speed has smaller effect on spark gap width while machining at low cutting speed. It may be due to fresh wire coming quickly across the slicing of e-glass fibre epoxy composite, and it discharges stronger spark which helps to break the gas bubbles and formation of more number of crater per unit time that is why the material removal increases with increase in wire speed. Higher spark gap width is observed at 0.35 m/min wire speed.

Figure 6 shows the variation of spark gap width (Wg, μm) with supply current. From Fig. 6, it is clear that the spark gap width increases with increase in supply current. Higher spark gap width is observed at 2.2 A supply current. It may be due to the increase of supply current which increases density of charge and thereby increases formation of caters around the wire electrode.

Figure 7 shows a SEM photograph of a micro slice section of e-glass fibre epoxy composite workpiece sliced by developed WECSM setup. Figure 7 exposes the actual condition of the micro cutting surface. This SEM photograph is an experimental result with parameters setting at 70 V DC supply voltage, 200 g/l electrolyte concentration, 0.15 m/min wire speed, 1.6 A supply current, 110 mm gap between auxiliary electrode and wire electrode.

The micro slicing shown in Fig. 7 is the result of continuous 30 min machining with 200 μm diameter brass wire. Figure 7 reveals poor machined surface; it may be due to high DC supply voltage and electrolyte concentration. It occurs due to improper removals of cutting residue are remained with undissolved fibres in the zone of micro slice part.

Figure 8 shows SEM of a micro sliced section generated at 60 V DC supply, 50 g/l electrolyte concentration, 0.20 m/min wire speed, 80 mm gap between wire and auxiliary electrode and 1.8 A supply current. Figure 8 is the result of continuous 30 min machining with 200 μm diameter brass wire electrode. From Fig. 8, it is clear that the micro slicing proceeds slightly in the conical manner, width of slicing is 228 μm and after 30 min of continuous cutting micro width is only 210 μm at the blind part of slicing. It is also clear that the surface of the micro sliced section has continuous uncut fibres. Overall, slicing surface finish is very poor at micron level. It may be due to the not circulation of electrolyte. It may overcome by proper flashing of electrolyte during slicing.

Figure 9 shows a SEM photograph of a micro slice section of e-glass fiber epoxy composite workpiece sliced by developed WECSM setup. This SEM graph shows the actual condition of the micro cutting surface. The micro slicing shown in Fig. 9 is the result of continuous 60 min machining with 200 μm diameter brass wire electrode at 0.25 m/min wire speed, 50 V D.C supply, 150 g/l electrolyte concentration, 110 mm gap between tool and anode and 1.8 A supply current. From SEM graph Fig. 9, it is clear that micro slicing proceeds in uniform pattern. The surface of the micro slicing is showing continuous undissolved fibres adhered with matrix. Overall, slicing surface finish is poor at micron level. Slicing width at the entry is 253 μm, but after that, the micro slicing width maintained as 222 μm (Fig. 9). Some uncut and

Table 3 ANOVA for MR

S/No	Control parameters	Sum of squares	Degree of freedom	Variance	F-test	% age of contribution
1	A: DC supply voltage	0.07483	3	0.02494	376.49*	29.94
2	B: Electrolyte concentration	0.16324	3	0.05441	821.32**	65.33
3	C: Wire speed	0.00390	3	0.0013	19.6	1.56
4	D: Gap between wire and auxiliary electrode	0.00512	3	0.00171	25.77	2.05
5	E: Supply current	0.00065	3	0.00022	3.25	0.26
6	Error	0.00212	32	0.00007	–	0.85
7	Total	0.24985	47	–	–	100

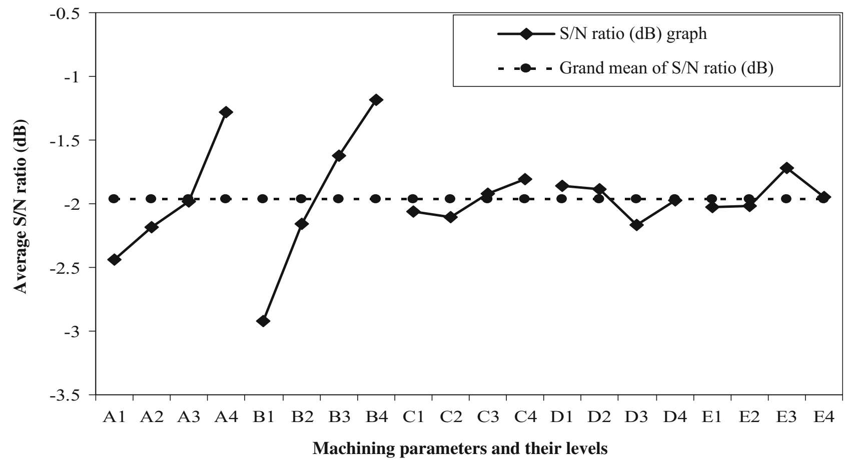

Fig. 10 S/N ratio for material removal (MR, mg)

undissolved fibres adhere with matrix are also observed during cutting in either sides of the sliced surface. It may be due to the not flow of electrolyte. Hence, proper flashing during micro slicing can enhance the quality of slicing that may be required to be investigated.

5 Optimization of WECSM parameters

Taguchi method based L_{16} (4^5) orthogonal array, analysis of variance (ANOVA), 'F-test' and S/N ratio are employed for experimental investigation and analysis of acquired data. Table 2 represents the developed WECSM parameters considered for detail experimental investigation and optimization of process parameters.

Table 3 represents the ANOVA and F-test value with percentage of contribution, i.e. effectiveness of the individual machining parameter on material removal (MR, mg). This ANOVA table is constructed based on experimentally acquired data during micro cutting of electrically nonconductive e-glass fiber epoxy composite on developed WECSM setup. From ANOVA Table 3, it is clear that the electrolyte concentration (X_2, g/l) and DC supply voltage (X_1, volt) have most significant parameters on material removal with 65.33 and 29.94 % contributions, respectively. From Table 3, it is also clear that the F-test value corresponding to the parameter, D (gap between wire and auxiliary electrode) and parameter, C (wire speed) is higher than the standard tabulated value; hence, these parameters cannot be ignored while assessing the significance of process parameter for material removal.

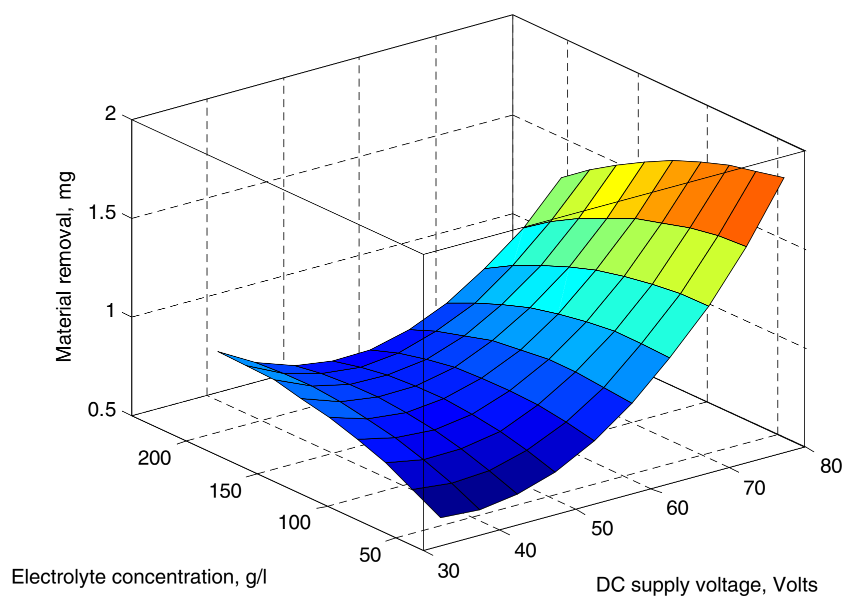

Fig. 11 Effect of DC supply voltage and electrolyte concentration on MR (mg)

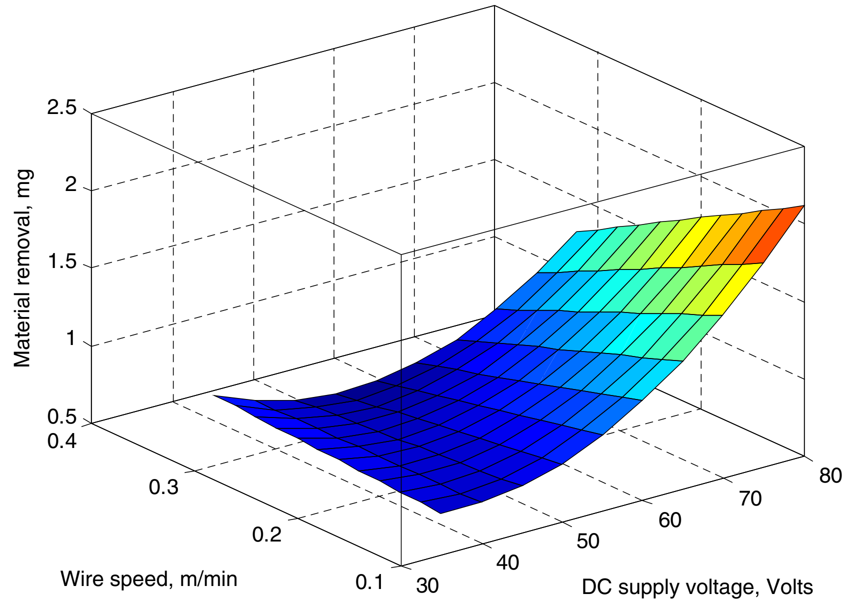

Fig. 12 Effect of D.C. supply voltage and wire speed on MR (mg)

The utilized acquired data S/N ratio (dB) has been calculated. Figure 10 shows the S/N ratio (dB) graph for MR (material removal). From Fig. 10, it is concluded that the optimal parametric combination for higher MR is $A_4B_4C_4D_1E_3$.

Figure 11 shows the effect of DC supply voltage (Volt) and electrolyte concentration (g/l) on MR. From Fig. 11, it is clear that the MR increases with increase in electrolyte concentration. It is also clear that the MR increases with increase in DC supply voltage. It reveals that the MR is higher at higher setting value of electrolyte concentration (e.g. 200 g/l) and DC supply voltage (e.g. 70 V). It is because high voltage supply creates higher potential difference between wire and auxiliary electrode, which may discharge more electrons per unit area of wire electrode. At the same time, dissolution rate of ions from the anode increases with high electrolyte concentration. It may be due to strong dissolution effect at higher current density.

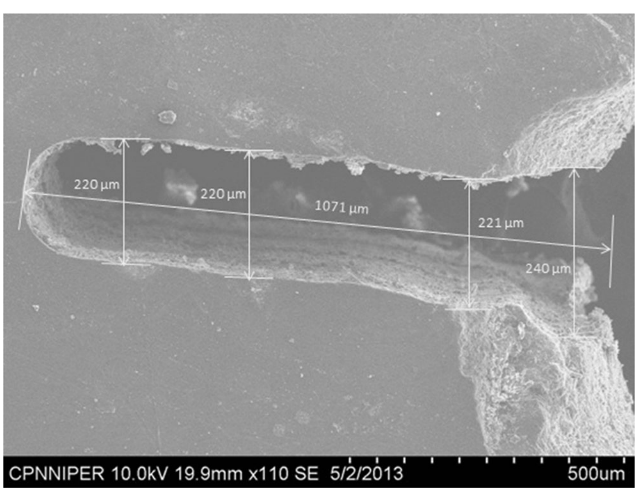

Fig. 13 SEM of a micro sliced section with 200 μm diameter brass wire

Figure 12 shows the combined effect of DC supply voltage and wire speed on MR. From Fig. 12, it is clear that the material removal increases with increase in DC supply voltage and wire speed. It is also clear that the MR marginally increases with increase in wire speed. It is because higher voltage supply creates higher potential difference between wire electrode and auxiliary electrode that enhances discharge of more electrons per unit area. At the same time, high wire speed also increases the formation of crater and large size bubbles; in due course, the bubbles are collapsed and increased electrolyte conductivity, thereby increasing material removal.

Figure 13 shows a SEM photograph of a micro slice section of e-glass fiber epoxy composite workpiece sliced by developed WECSM setup. The SEM graph shows the actual condition of the micro cutting surface. The micro sliced Fig. 13 is the result of continuous 50 min machining with 200 μm diameter brass wire at 0.25 m/min cutting speed, 50 V D.C supply voltage, 200 g/l electrolyte concentration, 1.4 A supply current and 80 mm gap between wire and auxiliary electrode. From SEM photograph Fig. 13, it is clear that micro slicing proceeds perfectly straight in nature. This SEM photograph also reveals that the surface of the micro slicing is far better than surface produced shown in Figs. 7, 8 and 9. Slicing width at the entry is 240 μm, but after that, the micro width is uniform throughout the cutting, i.e. 220 μm. Some irregularities are also observed at the beginning of cutting in either sides of

Table 4 Parametric conditions utilized for confirmation test

Exp. no.	Developed TW-ECSM parameters				
	X_1 : DC supply voltage (Volt)	X_2 : Electrolyte concentration (g/l)	X_3 : Wire speed (m/min)	X_4: Gap between wire and auxiliary electrode (mm)	X_5: Supply current (A)
1	65	75	0.225	100	1.5
2	55	125	0.175	70	2.2
3	75	175	0.275	130	1.9

the sliced surface. However, the overall surface finish is good; it may be due to higher concentration of electrolyte, which increases the dissolution strength, thereby uniform dissolution of fibres. During micro slicing, it is also observed that some gas bubbles and foam are generated, which later on make a barrier to flow of electrons and decrease the chemically dissolution strength of the electrolyte and hence reduces material removal rate.

6 Mathematical model for material removal (MR, mg)

A mathematical model has been developed considering the following WECSM parameters such as D.C. supply voltage (X_1, volt), electrolyte concentration (X_2, g/l), wire speed (X_3, m/min), gap between wire and auxiliary electrode (X_4, mm) and supply current (X_5, A) for material removal (MR, mg). This developed mathematical model can be utilized for effective micro cutting of e-glass fiber epoxy composite on WECSM. The additivity test results show that the predicted values utilizing developed mathematical models make a good agreement with the experimental results.

$$\begin{aligned} Y_{MRR} = & -0.00027 + 0.02046\,X_1 + 0.00421\,X_2 + 0.00012\,X_3 + 0.004115\,X_4 + 0.000012\,X_5 - \\ & 0.000116\,X_1X_2 - 0.094146\,X_1X_3 - 0.000158\,X_1X_4 - 0.022536\,X_1X_5 + 0.029706\,X_2X_3 - \\ & 0.000046\,X_2X_4 + 0.00175\,X_2X_5 + 0.0000101\,X_3X_4 + 0.000011\,X_3X_5 + 0.009647\,X_4X_5 + \\ & 0.000\ 756\,X_1^2 - 0.0000\ 138\,X_2^2 + 0.000010\ 4\,X_3^2 - 0.0000\ 45\,X_4^2 - 0.0\ 7638\,X_5^2 \end{aligned} \tag{1}$$

$R^2 = 0.99$

Where

- X_1 DC supply voltage (volts)
- X_2 Electrolyte concentration (g/l)
- X_3 Wire speed (m/min)
- X_4 Gap between wire and auxiliary electrode (mm)
- X_5 Supply current (A)

6.1 Additivity test

Table 4 represents the parameters and their levels considered for conducting the additivity test to validate the developed mathematical model.

Table 5 represents the comparison of the experimentally obtained results and calculated values utilizing developed mathematical model (Eq. 1) for MR during micro slicing of electrically nonconductive e-glass fiber epoxy composite on developed WECSM. From Table 5, it is clear that the error is always less than 4.1 %; hence, the developed model is appropriate and makes a good agreement with the experimentally acquired data.

Table 5 Additive test for MR

Exp. no.	Material removal (MR, mg)		% of Error
	Experimental	Developed Eq. 1	
1	1.742	1.784	2.35
2	4.163	4.337	4.02
3	1.103	1.138	3.04

7 Conclusions

Based on the experimental results during slicing of electrically non-conductive e-glass fibre epoxy composite on developed wire electro chemical spark machining (WECSM) setup, the following conclusions are drawn:

(i) The developed WECSM setup can be effectively used for machining of non conductive e-glass fibre epoxy composite.

(ii) The parameters, electrolyte concentration and DC Supply voltage have been identified as most significant and significant parameters on material removal with 65.33 and 29.94 % contributions, respectively.

(iii) The optimal parametric combination for higher MR is $A_4B_4C_4D_1E_3$.

(iv) At the beginning of micro cutting, the width of the micro slice is slightly higher than the width of continuous cutting. The surface of the micro slicing is irregular and poor if experiments are performed without plan.

(v) Undissolved fibres along the cutting surfaces are observed that may be due to the adhering of small particles scattered from the workpiece surface during cutting. It is due to not flow of electrolyte during machining. The uncut fibres are also noticed along the surface of micro cutting. However, from the experimental results, it is clear that the very fine micro slicing is possible. The generation of high surface texture also can be possible by optimization of machining parameters.

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