Experimental Investigation for Quality of Micro-holes Machined Using Electrochemical Discharge Machining Process

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1 Introduction

The leading-edge materials such as glass, composites and ceramics have attracted the interest of research society owing to their foremost chemical and mechanical properties. The machining of these materials with conventional machining processes is challenging to researchers due to damages during machining, such as chipping, delamination and cracks. In advanced machining processes, the electrochemical discharge machining (ECDM) has risen as a fabulous machining process for the processing of difficult to cut materials regardless of their properties [1]. More importantly, the ECDM process has extremely endeavoured for processing of non-conductive materials. The basic ECDM set-up includes two electrodes: (1) cathode, (2) anode and named as tool electrode and auxiliary electrode, respectively, as shown in Fig. 1. While machining, the workpiece is dipped in electrolyte, and tool electrolyte is partially immersed in an electrolyte. A DC power source is used for supply of voltage to cathode and anode electrodes of ECDM set-up. The regulation of voltage supply to respective electrodes yields the electrolysis process. This tends to generate hydrogen bubbles in the vicinity of the tool electrode and combines to form a thin gas layer which acts as insulation in between the tool electrode and electrolyte [2]. When the applied potential surpasses, the critical value of gas film and spark is produced in front of the tool and sides of the tool electrode. The heating and thermal energy of

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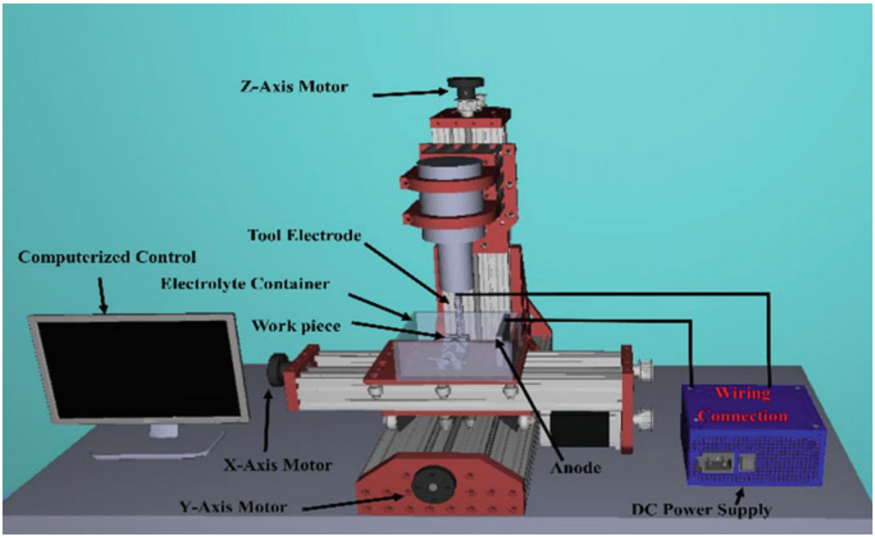

Fig. 1 Schematic of ECDM set-up installed on CNC machine

sparking at the tool electrode tip tends to machine workpiece material. In the beginning period, the ECDM procedure is used for machining of glass, and later on, the machining of ceramics, composites and alloys was effectively performed. Wuthrich et al. [3] characterized the micro-drilling of glass into two phases; (1) discharge regime with depth up to 300 μm, (2) hydrodynamic regime with a depth higher than 300 μm. The machining features of the second phase of the regime were outrageous due to limited supply and flushing of machined products at greater machining depth.

Chak and Rao [4] studied the trepanning of Al_2O_3 ceramic using abrasive particles coated tool electrode. They concluded that incorporation of abrasive particles coated tool electrode yields superior results in terms of machining quality in comparison with the copper tool. The abrasive particles coated tool electrode produces spark in front of tool electrode irrespective to sides of the tool electrode. Therefore, the side cutting is successfully eliminated with the use of particles coated tool in ECDM process. Liu et al. [5] studied machining behaviour of metal-based composite with the incorporation of diamond particles coated tool during ECDM. The diamond particles coated tool provides superior results in comparison with without coating tool electrode. The surface integrity of the machined sample is significantly improved due to additional grinding action. The morphology of machined holes exhibits HAZ and cracks around the periphery of holes. Sundaram et al. [6] explored the machining features of fibre epoxy-based composite using pulsed ECDM process. They concluded that the input of low pulsed supply reduced the diameter of the machined hole due to the reduction of gas layer size. The higher electrolyte level disperses the gas layer formed during machining and causes more diameter of the hole.

Moreover, there exists the best grouping of pulsed supply and electrolyte level for the generation of a precise hole with minimum HAZ. Kang and Tang [7] investigated the machining mechanism for ceramic coated Ni-based super-alloy using ECDM process. Based on the current waveform, the authors concluded that machining of coating is occurred due to electrochemical discharge. At the same time, the super-alloy substrate is machined due to the combination of electrochemical discharges and electrical discharges. Moreover, the surface roughness of the hole sidewall with ECDM is 5.6 μm as compared to 10.9 μm by EDM process. Singh et al. [8] explored the machinability of the silicon wafer during ECDM. They concluded that applied potential and tool travel rate are energetic input parameters which dominantly affect surface characteristics of a machined sample. Apart from these studies, the machining of carbon fibre-reinforced polymer (CFRP) composite is least reported in the literature using the ECDM process. Therefore, the present study describes the micro-manufacturing of holes on CFRP composite.

2 Methodology and Experimentation

The leading-edge materials such as glass and composites have attracted the interest of research fraternity due to their superior chemical and mechanical properties. The micro-manufacturing CFRP composite has been attempted using house in developed ECDM set-up attached to HY3040 CNC machine (Fig. 1). This machine provides accurate movements to machining platform in the X, Y and Z directions. Taguchi's L_9 orthogonal array was used to conduct the experiments with input parameters as applied voltage, electrolyte concentration and duty cycle. The experimental conditions are applied voltage of 50–70 V, the concentration of electrolyte from 20% to 40% and a duty cycle of 60–80%. The other experimental conditions include NaOH electrolyte, tool electrode, i.e. tungsten carbide drill bit of 450 μm and gap in between the tool and auxiliary electrode of 40 mm. The thickness of the surface damaged zone (TSDZ) was observed as response characteristics. Experimental results with several trails of Taguchi's L_9 orthogonal array are shown in Table 1. The TSDZ around the periphery of the machined hole is measured using a Zeiss optical microscope of high magnification. The TSDZ is measured as the difference between maximum hole diameter with damages and nominal hole diameter [9]. The maximum diameter with damages and a nominal diameter of the hole are represented in Fig. 2. The TSDZ is measured using this Eq. (1):

$$\mathrm{TSD} = (D_{\mathrm{max}} - D)/2 \tag{1}$$

where D_{max} stands for the maximum diameter of the hole with surface damages and D stands for the nominal diameter of the hole.

Table 1 Experimental results for TSDZ

S. No.	Voltage (V)	Electrolyte concentration (%)	Duty cycle (%)	TSDZ (mean) (μm)	S/N ratio
1	50	20	60	30.25	−29.6145
2	50	30	70	45.67	−33.1926
3	50	40	80	53.56	−34.5768
4	60	20	70	45.78	−33.2135
5	60	30	80	60.78	−35.6752
6	60	40	60	53.98	−34.6447
7	70	20	80	70.89	−37.0117
8	70	30	60	61.23	−35.7393
9	70	40	70	68.94	−36.7694

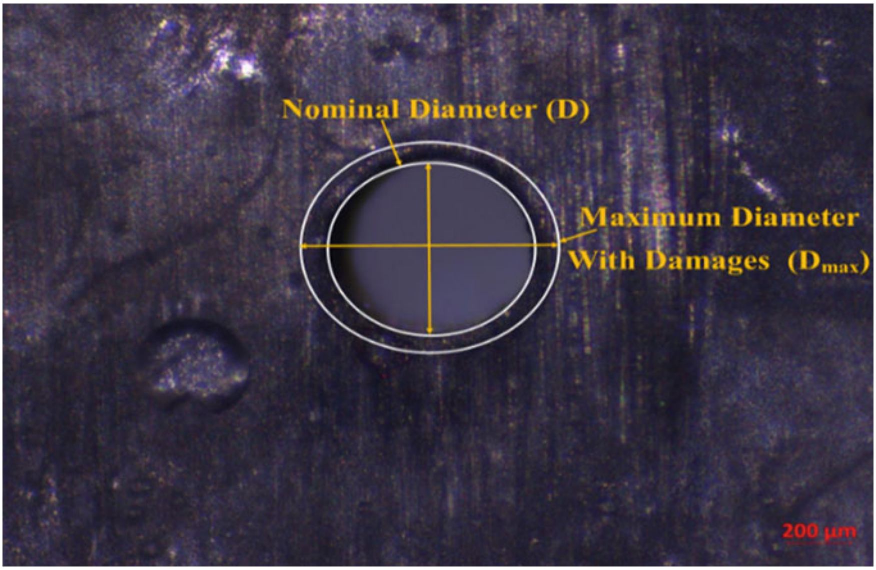

Fig. 2 Optical image for a description of maximum and the nominal diameter of the hole

3 Results and Discussions

The behaviour of input parameters such as applied voltage, electrolyte concentration and duty cycle on the thickness of surface damage zones (TSDZ) is presented in Fig. 3. It is concluded that the TSDZ increases with the increase of applied potential. The TSDZ increases from 43.16 to 67.02 μm with the rise in applied potential from 50 V (V1) to 70 V (V3). The higher voltage of the ECDM process boosts the spark intensity and generates an excess amount of thermal energy in the machining regime.

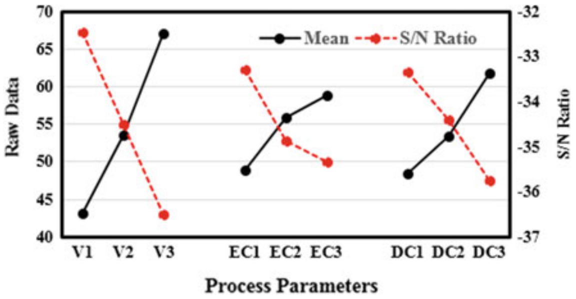

Fig. 3 The behaviour of process parameters on TSDZ

The excess thermal energy tends to produce heat-affected area around the periphery of the hole. The excess heat conducted to composite material produces uneven streaks on the surface of the machined sample, as shown in Fig. 4. Moreover, the TSDZ is more severe in CFRP composite material due to low-temperature resistant properties of epoxy. Likewise, the TSDZ significantly increases with the increase of electrolyte concentration of ECDM process. The TSDZ increases from 48.97 to 58.82 μm with an increase in the concentration of electrolyte from 20% (EC1) to 40% (EC3). The higher concentration of electrolyte promotes the kinetics of electrochemical reactions and causes ECM action is more dominating in the machining of ECDM. The

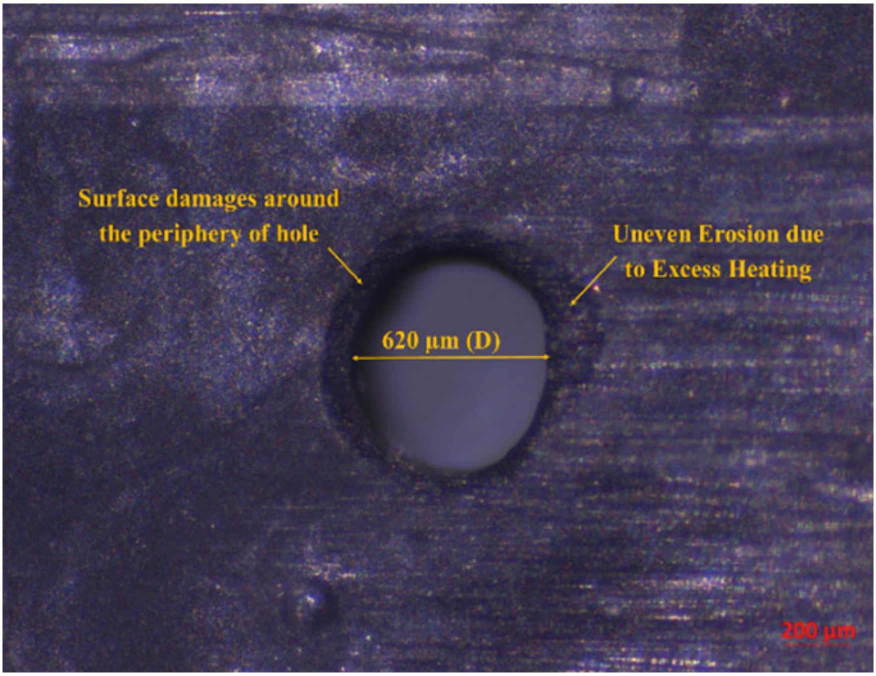

Fig. 4 Optical image of a micro-hole machined using ECDM

stepped-up electrochemical reactions produce intense heat in the machining zone. The generated heat is transferred to surrounding of machined hole and electrolyte by convection. Therefore, the transferred heat is responsible for uneven burn, surface damages and HAZs around the machined hole.

The TSDZ dominantly increases with the rise of the duty cycle of the ECDM process. TSDZ increases from 48.48 to 61.74 μm with an increase of duty cycle from 60% (DC1) to 80% (DC3). The duty cycle is incorporated to promote the cooling of machining products and electrolyte solution during the machining mechanism. At higher duty cycle, i.e. 80%, the time for cooling of machining products and the electrolyte solution is minimum. Therefore, the excess heat generated during machining is transferred to machined sample and produces uneven melting and HAZs around the periphery of the hole. On the other hand, at a low duty cycle, i.e. 60%, the excess heat generated is cooled down due to the availability of a long time for the next spark to have occurred. Therefore, the low duty of ECDM process produces better quality machined surface with least TSDZ.

According to S/N ratio, the optimal process parameters for TSDZ have applied voltage of 50 V (V1), the concentration of electrolyte, i.e. 20% (EC1) and duty cycle of 60% (DC1). The analysis of variance (ANOVA) for TSDZ is represented in Table 2 and concluded that TSDZ is dominantly affected by the applied voltage and followed by duty cycle and electrolyte concentration. The statistical analysis of input parameters on TSDZ is presented in Fig. 5. These results are justified from previous

Table 2 Analysis of variance for TSDZ

Source	DF	Adj SS	Adj MS	*F* value	*P*-value	% contribution
Voltage	2	858.92	429.4	36.55	0.027	66
Electrolyte concentration	2	153.58	76.79	6.54	0.133	12
Duty cycle	2	269.06	134.53	11.45	0.080	20
Error	2	23.50	11.75			2
Total	8	1305				

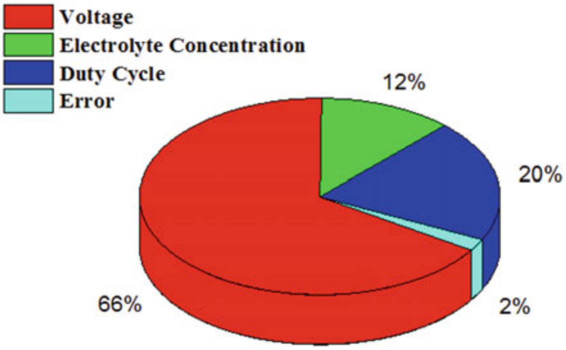

Fig. 5 Statistical analysis of process parameters on TSDZ

research in machining behaviour of the epoxy-based composite using ECDM process [10].

4 Conclusions

The conclusions explored from the findings of the present research problem were observed as

- The thickness of the surface damaged zone (TSDZ) during ECDM of CFRP composite was significantly affected by an applied voltage, electrolyte concentration and duty cycle of the ECDM process.
- The micro-images of machined hole signify the presence of TSDZ and uneven erosion of material around the periphery of the hole.
- The optimal process parameters for TSDZ have applied voltage of 50 V, concentration of electrolyte, i.e. 20% and duty cycle of 60%.
- The ANOVA analysis of TSDZ reveals the percentage contribution of applied voltage of 66%, duty cycle of 20%, electrolyte concentration of 12% and an error of 2%.
- The ECDM process is an imperious machining process for micro-machining of polymer matrix-based composites.

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