Electrochemical discharge machining of glass fiber-reinforced epoxy composites: a challenging approach

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Abstract. In this paper, a hybrid machining method called electrochemical discharge machining (ECDM) has been applied for making micron size holes in glass/epoxy composites. Initially, pilot experiments were conducted to check the feasibility of ECDM method for making a micro hole in glass/epoxy composites which is nonconductive in nature. Then the parametric investigations were conducted to analyse the influence of different parameters on the process performance. The influence of (i) applied voltage and (ii) pulse-on-time on (a) material removal rate (MRR) and (b) thickness of the heat-affected zone (THAZ) has been studied. It was identified that the ECDM method is a viable solution for making micron size holes in glass/epoxy composites.

1. Introduction
The polymer composites are important engineering materials as these materials possess multifunctional properties like (a) high-strength, (b) low-weight, (c) high resistance to corrosion, etc. [1, 2]. These materials have widespread applications in aerospace, marine, and automobile industries. The machining behaviour of polymer composites is quite different than that of monolithic materials. The machinability of polymer composites depends on many factors such as type of fibre and matrix, bonding strength between the fibre and matrix, orientation of fibre, volume fraction of fibre etc. [3]. The traditional machining of composites causes rapid wear of the tool due to the abrasive nature of fibres. Also, damages produced in terms of delamination, fibres pull-out, splintering, spalling and poor surface finish during traditional machining of polymer composites poses a major threat to the structure [4, 5]. These types of damages mainly occur due to the physical interaction between the cutting tool and work during traditional machining. Therefore, non-traditional machining has drawn the attention of many researchers as there is no physical interaction among the tool and work during removal of material. The non-traditional machining methods can be used as a potential alternative to the traditional machining methods because non-traditional machining of polymer composites results in less damage to the machined surface as cutting forces are not generate during the machining operation. But it is also pertinent to mention that all non-traditional machining is not suitable for machining of polymer composites. For instance, the laser beam machining method has been tried for machining of polymer composites. But the heat generated during laser beam machining of polymer composites...
causes severe thermal damage to the machined part [6]. Other non-traditional machining methods namely (i) electric discharge machining and (ii) electrochemical machining are also not suitable due to the nonconductive nature of most of the fibres (glass, aramid etc.) [7]. Therefore, ECDM method which is a hybrid machining method has been developed for machining of both conductive and non-conductive materials. Therefore, an attempt has been made to produce micro-holes in glass/epoxy composite which is nonconductive in nature using ECDM method. The main focus of the present work is to analyze the influence of two different parameters (voltage and pulse-on-time) on the MRR and THAZ during ECDM of glass/epoxy composites.

2. Materials and Methods

2.1. Composite fabrication

E-glass fibre (Young’s modulus: 80 GPa and Density: 2.62 g/cm³) was used as reinforcing material in the form of woven mat. Whereas epoxy resin Araldite AW106 (Density: 1.15-1.25 g/cm³ at 25°C) and hardener Araldite HV953 (Density: 0.95 g/cm³ at 25°C) were used as matrix material. The composite plate was manufactured using hand layup method. A cast iron mould having flat surface of 200 mm × 200 mm was used for manufacturing of composite plate. The resin and hardener were mixed in equal amount and stirred until the mixture becomes uniform. A thin polymer sheet was placed on the bottom mould plate and a layer of resin-hardener mixture was applied to it. The glass fibre mat is then placed over it and resin mixture was applied. An alternative layer of fibre mat is then placed and the resin mixture was applied again over it. The process is repeated until the required thickness (2 mm) of the composite is achieved. Finally, another polymer sheet was placed and the top mould plate was placed over it. A compression load of 15 ton was applied over the mould setup which helps in proper adhesion between the fibre mats and resin without leaving any air bubbles or voids.

2.2. Experimental setup

The major components of the developed machining setup are shown in Fig. 1. It consists of an electrolyte reservoir in which electrodes are immersed. Two electrodes used were (i) graphite plate and (ii) tool electrode. The plate electrode was connected to the anode while the tool electrode was connected to the cathode. DC pulse programmable power supply was applied between these two electrodes. The DC power supply provides better surface integrity when micro-holes are produced in electrically nonconductive materials [8]. Sodium hydroxide (NaOH) was used as electrolytic solution for obtaining higher MRR [9]. In ECDM, chemical etching and melting of the workpiece occur due to the discharge of electrical energy at the tool tip during electrolysis [10, 11].

![Figure 1. ECDM setup.](image-url)
2.3. Experimental condition

One-factor-at-a-time (OFAT) method was followed to perform the experiments. The feed rate, tool diameter, electrolyte concentration, electrolyte temperature, and type of electrolyte were kept constant during the experimentation. The machining was performed by changing the voltage and pulse-on-time as given in Table 1. The influence of input variables on the MRR and THAZ has been investigated. At least three samples were tested at each parameter setting and the average value of the output responses are presented in the paper. Fig. 2 shows a specimen of glass/epoxy composites machined by means of ECDM. The weight difference of specimen before and after machining was measured using micro balance having the accuracy of 0.0001 gm. The HAZ was considered as blackish surface at the hole periphery (Fig. 3). The HAZ surrounding the hole was measured using an optical microscope at higher magnification. The THAZ was measured using the following equation:

\[
THAZ \ (in \ \mu m) = \frac{D_{max} - d}{2}
\]

Where,

\(d\) = nominal diameter of the hole, and
\(D_{max}\) = maximum diameter of the HAZ

| Parameters          | Values                                |
|---------------------|---------------------------------------|
| Applied voltage     | 55, 60, 65, and 70 V                  |
| Pulse-on-time       | 1, 2, 3, 4, and 5 ms                  |
| Machining time       | 5 minutes                             |
| Diameter of the tool| 800 µm                                |
| Tool material        | SS                                    |
| Cathode and anode   | Tool and graphite plate               |
| Electrolyte         | Sodium hydroxide                      |
| Concentration       | 20 %                                  |

Figure 2. Micro-hole drilled specimen.
3. Results and Discussion

3.1. Material removal rate
The variation in MRR with respect to voltage and pulse-on-time is shown in Fig. 4. In ECDM, the voltage plays a vital role in controlling the thermal energy which is required for material removal. The applied voltage needs to be controlled during ECDM because the slightest variation in applied voltage may change the dynamics of the electrolysis process [12]. It is evident in the figure that MRR increases as the applied voltage during ECDM of glass/epoxy composites is increased from 55 to 70 V. The figure also shows that the increase in MRR is quite high with the higher level of voltage when compared one-on-one with lower level of voltage. The higher applied voltage leads to higher discharge energy. This phenomenon leads to a higher rate of melting of composite constituents (glass fibre and epoxy matrix) and subsequently higher MRR. The increase in applied voltage also results in the generation of more and larger size hydrogen bubbles [13]. The bubbles coalesce and form a thick film leading to infrequent but high intensity discharge. The increase in pulse-on-time also results in increased MRR. The duration of discharge energy increases with pulse-on-time which results in increased MRR [14]. The discharge phenomenon mainly occurs during pulse-on-time and it is considered as heat input stage. The increased MRR can be attributed to increased heat input with pulse-on-time.

3.2. Heat affected zone
The variation in THAZ with voltage and pulse-on-time is shown in Fig. 5. It is quite clear from the figures that THAZ increases with both the input parameters considered for the purpose of
investigation. During ECDM of glass/epoxy composites, heat is produced at the inter-electrode gap. Some percentage of heat is transferred to the electrolyte by convection, some amount of heat is radiated to atmosphere and remainder is conducted to the composite specimen. A HAZ is formed around the hole due to conduction of the heat to the composite specimen. Both higher voltage and higher pulse-on-time result in the higher magnitude of thermal energy for longer duration. A significant amount of heat is thermally conducted to the composite specimen during machining when the voltage and pulse-on-time are higher. This results in thermal degradation of composite constituents which subsequently results in higher THAZ. The epoxy resin used as matrix material in composites is very sensitive to temperature rise. The heat resistant capacity of epoxy resin is quite low when compared one-on-one with conventional metals and alloys. The epoxy resin becomes soft when the temperature conducted to the composite specimen reaches to the glass transition temperature of the epoxy resin. With further increase in temperature, the epoxy resin starts to degrade physically and a HAZ is created at the hole periphery which is clearly visible as blackish shades around the machined hole.

![Figure 5. Variation in THAZ with (a) voltage and (b) pulse-on-time.](image)

4. Conclusions
From the present work, it can be concluded that the ECDM can be a viable alternative for machining of micron size holes in fibre reinforced composites. This method does not involve cutting forces and consumes less power as compared to traditional machining methods. The results showed that the higher magnitude of the voltage and pulse-on-time results in higher MRR and THAZ. However, the influence of other machining parameters needs to be studied to understand the complete machining behaviour of polymer composites.

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