CIRP Annals - Manufacturing Technology 68 (2019) 169–172

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Pulse electrochemical discharge machining of glass-fiber epoxy reinforced composite

Murali Sundaram[a,*], Yu-Jen Chen[a], K. Rajurkar (1)[b]

[a] Department of Mechanical and Materials Engineering, University of Cincinnati, Cincinnati, OH, USA
[b] Department of Mechanical and Materials Engineering, University of Nebraska-Lincoln, Lincoln, NE, USA

ARTICLE INFO

Keywords:
Composite
Machining
Surface analysis
Thermal effects

ABSTRACT

The effect of pulse current and tool immersion depth on gas film formation and its consequences on machining quality in the pulse electrochemical discharge machining (PECDM) of glass-fiber epoxy reinforced composite are studied. The frequency and duty cycle of the pulse current were controlled for discharging at no more than single spark per cycle. As compared to ECDM with DC current, the PECDM results in smaller hole diameter and smaller heat affected zone (HAZ). Also, lower tool immersion depth results in thinner gas film and smaller HAZ in the workpiece.

1. Introduction

Advanced materials such as glass, ceramics, and composites have numerous aerospace, biomedical, healthcare, and MEMS applications. However, these materials, in general, are difficult to machine due to their high material strength, brittleness, nonconductivity, inertness, and complex structure. Electrochemical discharge machining (ECDM) is capable of machining such hard and brittle nonconductive materials [1–8]. While several studies are available on the machining of glass and ceramics [8–11], the literature on the ECDM of composite materials such as fiber-reinforced composites is rather limited [12,13]. Mechanical machining of composites has challenges such as delamination and chipping caused by residual stresses and strain [14,15]. Thermal machining such as laser beam machining is proposed as an alternative to mechanical machining. However, in the thermal machining of composites made of a matrix of fibers and resin, such as glass-fiber epoxy reinforced composite, the melting point of the epoxy poses machinability challenges due to the thermal damages to the fiber structure caused by the melting of the resin during the process [16]. The energy required to melt the glass fibers is much higher than melting the resin. Additionally, due to the nonconductive nature of glass-fiber epoxy reinforced composites, electrical machining processes such as electrochemical machining (ECM) or electro discharge machining (EDM) are less effective, if not unsuitable, to machine these advanced materials. Though ECDM, as mentioned earlier, has a great potential to machine these materials, issues such as wrinkling may cause certain surface integrity challenges [17]. In a study of machining glass-fiber-epoxy composite by ECDM, a poor surface quality was reported due to heat effect [12]. Therefore, to mitigate the thermal defects in the machining glass-fiber epoxy reinforced composites by ECDM, the feasibility of controlling the discharging energy needs to be investigated.

Most of the ECDM studies are performed with DC power supply. An inevitable heat affected zone (HAZ) occurs in the process and damages the surface quality of the material. Applying a pulse current instead of the usual direct current (DC) causes a reduction in the surface damage and HAZ in glass machining [18,19]. It has been reported that smaller duty cycle decreases the surface roughness due to the reduction in the ratio of time that the discharges are occurring [18]. In addition to the duty cycle, pulse frequency also can affect the discharge energy in ECDM with a change on the critical voltage [20]. Increasing pulse voltage decreases the film formation time, which is a key factor that reflects in the energy of discharges. A recent study demonstrated that the discharging energy is related with the gas film thickness and the gas film stability [21]. A more stable gas film can be obtained by decreasing the level of the electrolyte and electrolyte concentration used in ECDM. In the present study, the effect of the duty cycle of the pulse current and tool immersion depth (or electrolyte level) on the gas film formation and its consequence on machining quality in the pulse electrochemical discharge machining (PECDM) of glass-fiber epoxy reinforced composite is studied.

2. Experimental method

An in-house built pulse ECDM experimental setup used in this study is shown in Fig. 1. A pulse width modulator is connected to a DC power supply (0–3 A, 0–120 V) to provide a pulse voltage output. A 760 μm thick non-conductive glass-fiber epoxy reinforced composite is used as work material. Table 1 lists other experimental parameters used in this study.

A tapered tungsten tool (the cathode) was prepared using an in-house-built electrochemical setup [22]. Using of tapered tool helps in

* Corresponding author.
E-mail address: murali.sundaram@uc.edu (M. Sundaram).

https://doi.org/10.1016/j.cirp.2019.04.113
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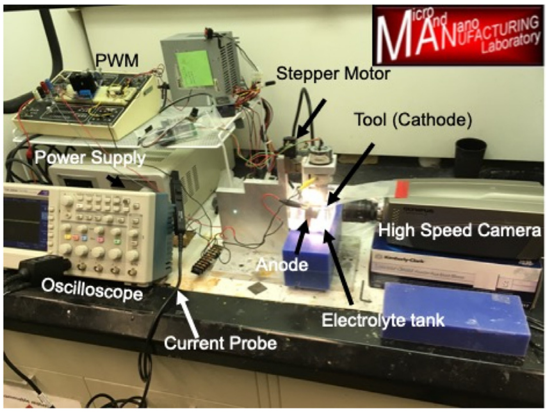

Fig. 1. PECDM experimental setup.

Table 1
Experimental parameters.

Parameters	Values
Work Piece	Glass-fiber epoxy reinforced composite
Tool	Tapered WC
Applied voltage	45 V
Pulse duty cycle	33%; 66%; 100% (DC)
Pulse frequency	100 Hz
Electrolyte	1M NaOH
Electrolyte level	2–6 mm
Tool rotation speed	1200 rpm
Machining time	1 min

focussing the sparks at a specific location [23]. Sparks mostly occur at the rims of the tool which may be due to a higher current density at these locations [23]. A high-speed camera is used to capture the images of the gas film formation process. A current probe is connected to the circuit with an oscilloscope to read the current values during PECDM. The frequency of the pulse voltage was adjusted to where the 66% duty cycle will be sparking with around one or a few in each cycle (each pulse). The quality of a machined hole (i.e., the diameter of the hole and the HAZ) was studied with an optical microscope and scanning electron microscope (SEM).

3. Results and discussion

3.1. Hole diameter

The diameter of the machined hole is studied using an optical microscope. Representative results are shown in Fig. 2, and the values of the average hole diameter at different trails are shown in Fig. 3.

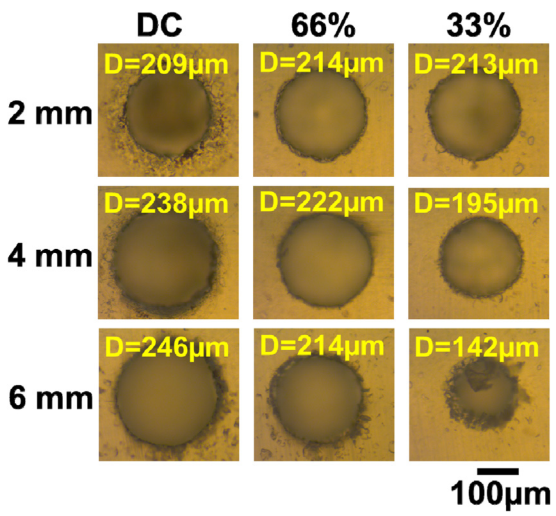

Fig. 2. Optical microscope image of the machined hole with 2–6 mm electrolyte level (or tool immersion depth) and 33%, 66%, 100%(DC) duty cycle.

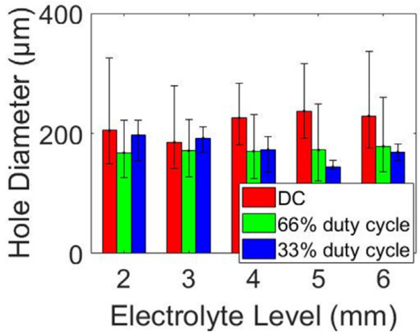

Fig. 3. Hole diameter at different electrolyte level and duty cycle.

Two observations can be made from Fig. 2. Decreasing the duty cycle typically decreases the diameter of the machined hole. Secondly, this trend was found to be even more pronounced as the electrolyte level/ tool immersion depth increases as can be seen in Fig. 3. Also, as the level of the electrolyte increases, the hole diameter increases when ECDM is performed with DC current as shown in the first column in Fig. 2. This is due to the increase in the peak current at higher electrolyte level. This larger peak current can be related to higher gas film thickness. That is, as the electrolyte level increases, the correspondinggas film thickness also would increase [21]. Higher spark energy is required to break this thicker gas film and thus produces larger holes at higher electrolyte level in ECDM using DC.

However, with pulsed ECDM, this trend was found to reverse. At 66% duty cycle, the hole diameter seldom varies with the electrolyte level (middle column in Fig. 2), and more interestingly, at 33% duty cycle, the diameter of the hole decreases with increasing electrolyte level (last column in Fig. 2). This can be reasoned with the observations made on the gas bubble generation and gas film formation using a high-speed camera (Fig. 4). In Fig. 4, the first row (a)–(c) and the second row (d)–(f) show the gas film for different duty cycles at a 3 mm and at 6 mm electrolyte levels respectively. The gas film was clearly observed for ECDM with DC current (first column in Fig. 4) but not for any of the ECDM trails with a pulsed current. This is because of the higher level of turbulence caused in pulsed ECDM where the gas film is more likely to collapse frequently during the pulse off-time. This causes more gas bubbles surrounding the tool to diffuse into the electrolyte (2nd and 3rd columns in Fig. 4) in pulsed ECDM. Thus, the gas film thickness with lower duty cycles could be inferred to be thinner. The increase in tool immersion depth for pulsed ECDM with a small duty cycle causes longer gas film formation time as can be seen from the current signal shown in Fig. 5. The gas film formation time is much longer with a 6 mm electrolyte level than a 3 mm level (indicated by the green arrow in Fig. 5). Therefore, in pulsed ECDM, the spark frequency and hence the hole diameter decreases with the increase in electrolyte level.

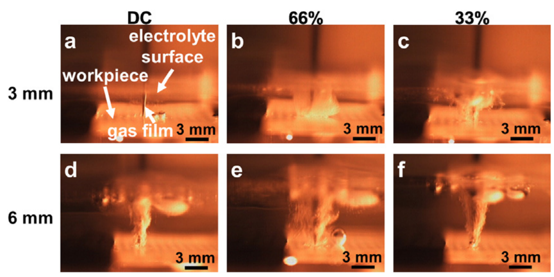

Fig. 4. Gas film images captured at the 10th second with 60 fps using a high-speed camera. The electrolyte level is (a)–(c) 3 mm and (d)–(f) 6 mm. (a) and (d) is a DC current; (b) and (e) 66% duty cycle; (c) and (f) 33% duty cycle.

If the gas bubbles are unable to coalesce into a film within the pulse on-time (6.6 and 3.3 ms for 66% and 33% duty cycles respectively), a gas film is less likely to be built up in pulsed ECDM. Thus, the chances of gas film formation, and hence the probability of sparking decreases at lower duty cycles. Also due to the longer

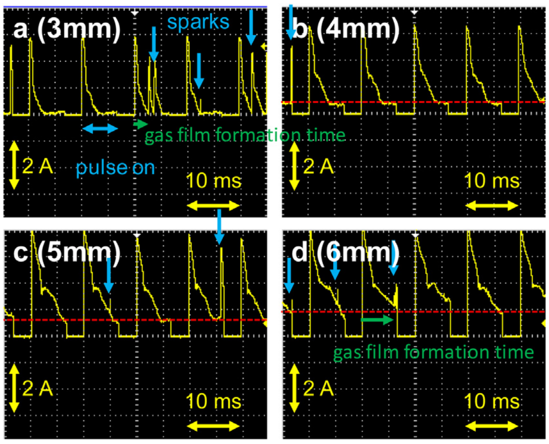

Fig. 5. Current signals of 66% duty cycle recorded at different electrolyte levels. (a) shows a shorter gas film formation time for 3 mm tool immersion depth where the current peaks are observed after the current reaches zero i.e. sparks occur after the tool is totally insulated with gas film. (b)–(d) shows a longer gas film formation time for 4–6 mm tool immersion depth where current peaks (i.e. sparks) are observed within the film formation time.

pulse off-time in lower duty cycles, more gas bubble will escape from the electrolyte and no new gas bubbles are generated during the pulse off-time. This results in a reduction of discharging frequency and the hole diameter at lower duty cycles.

In summary, increasing the electrolyte level increases the gas film formation time, the gas film thickness, the discharging energy of each spark, and produces larger hole diameters. However, in pulsed ECDM, the need for longer gas film formation time at higher electrolyte levels would decrease the frequency of sparking, especially at a lower duty cycle wherein during the longer period of pulse off time the gas bubbles leave the tool and go into the electrolyte.

3.2. Heat affected zone

The heat affected zone with a different duty cycle at various electrolyte levels and the corresponding values of mean current observed are shown in Fig. 6. Optical images of maximum and minimum HAZ observed are shown in Fig. 7(a) and (b) respectively where the green line indicates the edge of the hole, and a red dash line shows the edge of the HAZ.

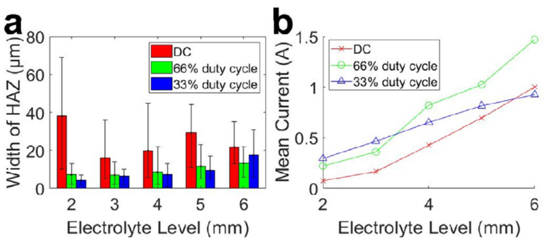

Fig. 6. (a) Width of HAZ at different electrolyte level and duty cycle. (b) Mean current different electrolyte level and duty cycle.

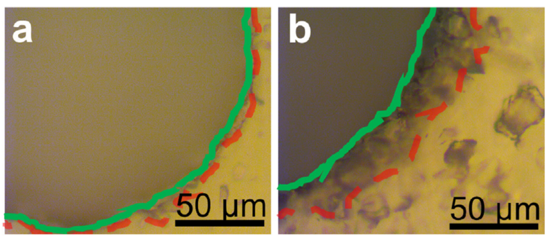

Fig. 7. HAZ observed at (a) 33% duty cycle, 2 mm electrolyte level; (b) DC current, 6 mm electrolyte level. The green line indicates the edge of the hole. The red dash line indicates the end of the HAZ.

The tendency of the HAZ can be compared with the hole diameter values shown in Fig. 3. The HAZ increases as the electrolyte level increases. This can be related to the increasing gas film thickness and the consequently increasing energy of each spark. However, in the case of ECDM with DC current, at 2 mm electrolyte level, an unexpected high HAZ was observed. A similar observation has also been reported in the literature and the reason has been attributed to the occurrence of highly concentrated sparks at a low electrolyte level [24].

Though the mean DC current values are lower than that of pulsed ECDM (Fig. 6(b)), the ECDM with DC current is showing a much greater HAZ than with pulse ECDM (Fig. 6(a)) due to the continuous high-energy sparking as explained before.

ECDM with pulse current minimizes the HAZ. This can be reasoned with the explanation in the previous section that the thinner gas film formation in pulsed ECDM results in less sparking energy that reduces HAZ.

Monitoring the current signal (Fig. 8) reveals the reason for the mean current in ECDM with DC to be lower than that of pulsed ECDM with 33% and 66% duty cycles (Fig. 6(b)). Due to the absence of pulse off-time in ECDM with DC, there is a significant period of time during which the coalescence of gas bubbles into a gas film formation and tool insulation occurs. In this time, the enveloping gas film is too thick to generate a spark and no current flows. In the absence of current flow, obviously no new gas bubbles are formed at this stage and as a consequence, the thickness of gas film would gradually decrease due to gas bubbles escaping continuously at the surface of the electrolyte. Discharges (shown with blue arrows in Fig. 8) occur only when the gas film thickness decreases to a critical film thickness where the applied voltage can break through the gas film causing sparks. Therefore, the mean value for DC current is lower than pulse current.

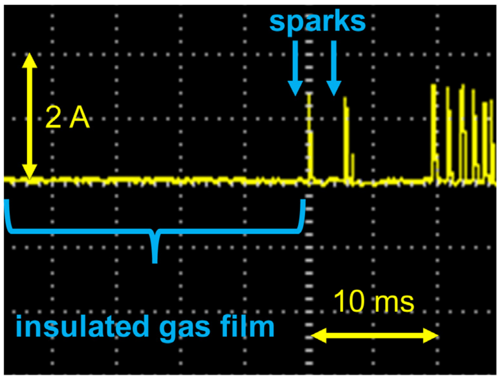

Fig. 8. Current plot observed with DC current at a 2 mm electrolyte level.

Finally, it can be noticed from Fig. 3 and Fig. 6(a) that the hole diameter and HAZ follow a tend with the increase in the electrolyte level. However, this trend changes when the tool immerses beyond 5 mm electrolyte level. The possible reason for this phenomenon can be understood by observing the minimum (non-zero) current limit in ECDM. In Fig. 5 this lower current limit is shown in red line. Sparking is occurring before the current value drops to zero (when the gas film fully insulates the tool). At this level, the current is relatively higher, and the gas bubbles surrounding the tool merge to form a gas film. As the gas film no longer is coalesced at zero current, this will increase the frequency of the gas film formation (i.e., the current does not need to drop to zero to form a gas film) and also the gas film thickness (i.e., a portion of the departure gas bubbles merge back into a gas film) during pulse ECDM. Therefore, both the diameter and the HAZ will increase.

In summary, decreasing the electrolyte level decreases the gas film thickness, and discharge energy of each spark, which will result in a smaller HAZ. Also, pulse ECDM produces smaller HAZ. Therefore, it is recommended to perform pulse ECDM with lower electrolyte level to achieve better machining quality.

4. Micro hole drilling

As discussed in the earlier section, HAZ is minimum for pulse ECDM at an electrolyte level of 3 mm. To validate these findings, confirmation tests were performed on a 762 μm thick glass-fiber epoxy reinforced composite at 3 mm electrolyte level. Four micro holes were drilled in the composite at a feed rate of 1.5 μm/s with 33%, 66% and DC duty cycles. Fig. 9 shows the SEM cross-section images of the four machined holes under each machining condition. As compared to the ECDM with DC current, the HAZ is greatly reduced in pulsed ECDM. Fig. 9(d) shows the glass fibers that are exposed with no epoxy holding the fiber structures. This is due to the excessive sparking energy melting the epoxy while machining. This thermal damage is minimized in pulsed ECDM (Fig. 9(e)) and almost avoided at the lower duty cycle (Fig. 9(f)).

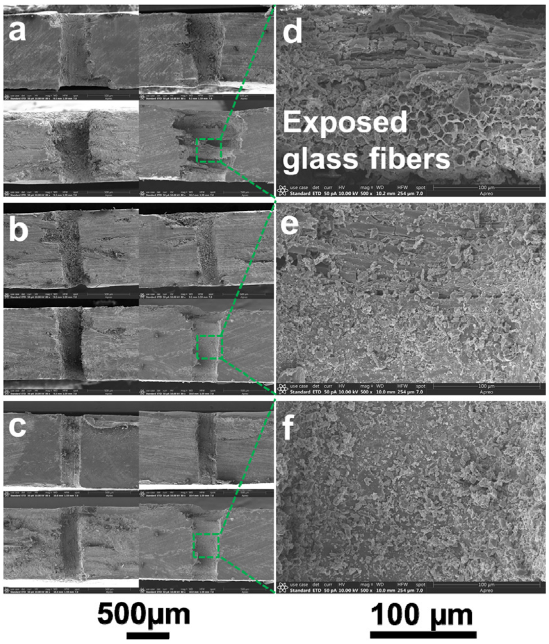

Fig. 9. SEM images of the ECDM drilled holes. (a) DC (b) 66% duty cycle (c) 33% duty cycle machined hole. (d)–(f) are zoomed in images of areas marked in green in (a)–(c).

5. Conclusions

Following conclusions can be drawn based on the results from this study:

Pulse ECDM with lowering duty cycle decreases the gas film thickness and increases the gas film formation time, which in turn decreases the sparking energy and sparking frequency respectively. This results in smaller hole diameter, especially for low duty cycle and smaller HAZ. An optimal combination of duty cycle and electrolyte level exists. Increasing the electrolyte level furthermore will decrease the hole diameter for low duty cycle but will increase the HAZ.

Acknowledgements

This material is based upon work supported by the National Science Foundation [Grant No. CMMI-1833112]. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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