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DOI:
10.1016/j.procir.2018.08.284

Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 77 (2018) 195–198

www.elsevier.com/locate/procedia

8th CIRP Conference on High Performance Cutting (HPC 2018)

A feasibility study on wire electrical discharge machining of carbon fibre reinforced plastic composites

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Abstract

This paper details preliminary experimental work to investigate the wire electrical discharge machining (WEDM) of unidirectional carbon fibre reinforced plastic (CFRP) composites using a high tensile strength zinc rich coated brass wire (0.25 mm diameter). A fractional factorial L18 Taguchi experimental design was employed to evaluate the influence of varying open gap voltage (120 and 140 V), ignition current (3 – 5 A) as well as pulse on-time (0.8 – 1 µs) and off-time (4 – 8 µs) on material removal rate (MRR), top (W_t) and bottom (W_b) kerf widths as well as workpiece edge damage. The ignition current and pulse off-time were found to be statistically significant factors affecting MRR based on an analysis of variance, with percentage contribution ratios (PCR) of 48.5% and 24.3% respectively. It was observed that MRR, which ranged between 0.43 and 2.41 mm^3/min, increased with both ignition current and pulse on-time due to the higher discharge energy generated in the machining gap. No signs of workpiece damage in terms of delamination or surface burning was apparent, despite the higher MRR. Conversely, the larger open gap voltage surprisingly led to reductions in MRR, which was likely due to unstable gap conditions caused by greater levels of residual melted resin within the gap or re-deposition on the workpiece surface. In terms of kerf width, ignition current was revealed as the sole significant factor with respect to the top surface (up to ~ 0.28 mm) having a PCR of 56.6%, while none of the variable parameters had a major effect on the bottom kerf width.

Keywords: Composite; Electrical discharge machining (EDM); Material removal; Kerf

1. Introduction

Carbon fibre reinforced plastic (CFRP) composites are used extensively in various industrial sectors such as aerospace, automotive, textile and sporting equipment due to its outstanding attributes including high strength to weight ratio (~785 kN.m/kg), high modulus of elasticity (75-105% of steel), low thermal expansion/shrinkage and good resistance to wear, corrosion and fatigue [1-4]. Currently, CFRP constitutes up to ~50% of weight in modern civil aircraft such as the Airbus A350XWB and Boeing 787, which has a marked influence in reducing their operational fuel consumption [5]. The machinability of CFRP however is generally considered to be poor, particularly when employing conventional processes such as drilling and milling, as they are prone to low tool life and adverse workpiece surface integrity with defects such as delamination, fibre pullout, matrix melting/burn and cracking being commonly prevalent [6-8]. This is largely due to the highly abrasive nature of the carbon fibres as well as the anisotropy/heterogeneity of the material. Various non-conventional cutting processes including laser beam, abrasive waterjet and vibration assisted machining have been evaluated as potential alternatives [9], with each showing benefits as well as limitations in terms of productivity, process complexity and workpiece damage. Another non-traditional machining process that has been investigated is electrical discharge machining

10.1016/j.procir.2018.08.284

(EDM), where material removal is not hindered by workpiece mechanical properties such as hardness and strength. However, the relatively low bulk electrical conductivity of CFRP is currently a major barrier to EDM being an effective option.

The majority of published literature regarding the EDM of CFRP has focused on die-sink based operations with scant information involving the wire EDM (WEDM) configuration. Ichii et al. [10] investigated the effect of duty cycle, pulse width, electrode material (copper/graphite) and cut direction (parallel/perpendicular to fibre orientation) during EDM of unidirectional CFRP and SKD11 tool steel. When machining perpendicular to the fibre direction, material removal rate (MRR) was significantly higher for CFRP (up to ~5 mm^3/min using graphite electrode) compared to SKD11 (~0.1 mm^3/min) due to the rapid melting of the epoxy matrix. However, substantially rougher surfaces were evident on the CFRP workpieces (~50 µm Rz as opposed to ~9 µm Rz for SKD11). A similar study conducted on unidirectional and bidirectional/woven CFRP lay-ups showed that MRR was up to ~25% higher in the latter, as increased levels of the polymer matrix phase were present in the bidirectional CFRP composites [11]. In an investigation concerning EDM die-sinking of CFRP laminates, Hayakawa et al. [12] reported that the local material removal rate was greater in plies with fibres parallel to the electrode surface. This was attributed to the increased frequency of short-circuiting between the electrode and frayed/exposed fibres, which led to Joule heating of the resin matrix. By employing a thermal camera, Akematsu et al. [13] showed that the discharge energy during the EDM of CFRP was typically confined to flow along the longitudinal direction of fibres. Islam et al. [2] studied the use of EDM to deburr conventionally drilled holes in CFRP involving 4 different electrode materials. Productivity was highest when utilising copper electrodes (~6.3 mm^2/min) while no evidence of delamination or hole deformation was detected following EDM deburring. A comparative assessment between WEDM and laser machining of 2.5 mm thick CFRP workpieces showed that while considerably higher MRR was achieved in the latter (~95 mm^2/min as opposed to 12 mm^2/min); the former produced superior edge quality and lower workpiece damage [14].

The current paper details initial research aimed at assessing the influence of key process parameters on workpiece MRR, kerf width and surface damage when WEDM of CFRP composites.

2. Experimental work

2.1. Workpiece material and equipment

The workpiece material employed was unidirectional CFRP composite plates measuring 100 x 100 x 8.4 mm. Each of the plates comprised 32 prepreg layers laid up in a single direction (0°), which contained intermediate modulus carbon fibres impregnated within an epoxy resin (34% of weight). The key mechanical/physical properties of the carbon fibres are detailed in Table 1. All machining trials were conducted on a wire electrical discharge machine (AgieCharmilles Robofil FI 240 CC) equipped with a minimum damage generator. The diameter of the wire electrode utilised was 0.25 mm, which consisted of a brass core (80%Cu20%Zn) with a dual layer coating containing β (50%Cu50%Zn) and γ (35%Cu+65%Zn) phases. The wire composition provided high tensile strength (800 MPa) and electrical conductivity appropriate for machining high resistivity materials such as CFRP. The conductivity of the deionised water dielectric was maintained at ~5µS/cm, with the corresponding experimental setup shown in Fig. 1.

Table 1. Properties of the carbon fibre.

Parameter	Value
Fibre diameter	5 µm
Tensile modulus	294 GPa
Tensile strength	5880 MPa
Fibre areal weight	268 g/m^3
Density	1.8 g/cm^3
Thermal conductivity	70 W/m.K
Strain	2%

Machined kerf width was measured using an Alicona G5 InfiniteFocus microscope while the CFRP workpieces were weighed before and after each test using a digital precision scale (measurement range of 0.5 to 3500 g) to record the mass of material removed. Optical micrographs of workpiece surface damage were captured using a toolmakers microscope connected to a digital camera.

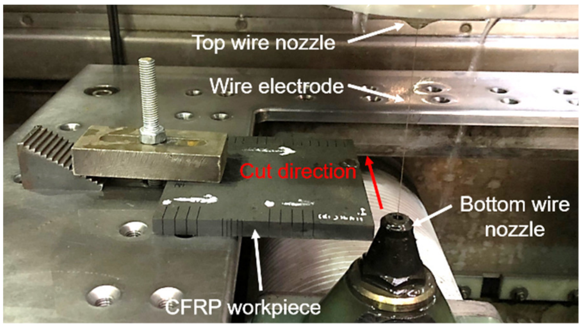

Fig. 1. Experimental setup

2.2. Design of experiment and test procedures

Experiments were undertaken according to a Taguchi fractional factorial L18 orthogonal array involving variation in open gap voltage at 2 levels together with ignition/peak current, pulse on-time and off-time, each at 3 levels as detailed in Table 2. Fixed parameters included wire tension (13 N), wire speed (10 m/min), flushing pressure (16 bar) and servo voltage (15 V). The operating parameter values were selected following preliminary scoping trials to ascertain workable process windows. All tests involved straight cuts with machining performed parallel to the carbon fibre direction. The end of test criterion was a cut length of 12 mm with the associated machining time recorded using a stopwatch. The MRR was calculated based on the relationship in Eq. 1:

$$MRR = \frac{m_b - m_a}{\rho * t_m} \quad (1)$$

where m_b and m_a: mass of the workpiece before and after machining respectively (g), ρ: workpiece density (g/mm^3) and t_m: machining time (min).

Kerf widths for both the top (W_t) and bottom (W_b) surfaces of the workpiece were determined based on the mean of measurements at 9 positions (approximately equidistant) along the cut length.

Table 2. Variable machining parameter levels.

Machining parameter	Level 1	Level 2	Level 3
Open gap voltage, V_0 (V)	120	140	-
Ignition current, IAL (A)	3	4	5
On-time, A (µs)	0.8	0.9	1.0
Off-time, B (µs)	4	6	8

3. Results and discussion

3.1. Material removal rate and workpiece damage

All of the tests achieved the 12 mm cut distance with machining times varying from 13.3 to 49.1 minutes. This resulted in MRR's of between 0.43 and 2.41 mm^3/min for the range of tests performed. Corresponding analysis of variance (ANOVA) revealed that ignition current and pulse off-time were both statistically significant factors at the 5% level, with percentage contribution ratios (PCR) of 48.5% and 24.3% respectively. The main effects plot in Fig. 2 showed that MRR increased with ignition current and pulse on-time due to the greater discharge energy, whereas higher pulse off-times reduced MRR due to the lower spark efficiency/frequency. Surprisingly, operating at the larger open gap voltage level (140 V) generally led to a reduction in mean MRR. A possible reason for this was the rise in molten resin material in the gap caused by the elevated discharge energy leading to unstable machining.

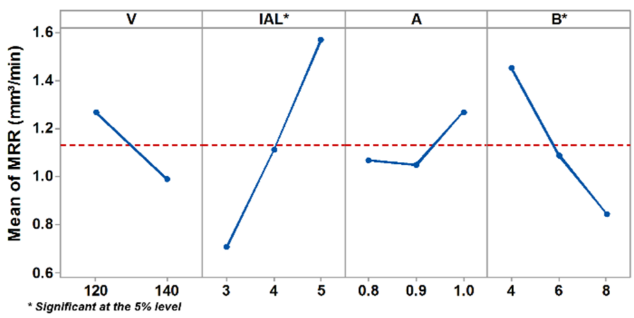

Fig. 2. Main effects plot for MRR.

Fig. 3 details optical micrographs of the machined kerf on the top and bottom of the workpiece from the test achieving the highest MRR. Aside from a relatively uneven edge profile, there was no evidence of major damage such as delamination, matrix burning or uncut fibres on the kerf periphery in any of the workpieces examined. There was however bronze coloured patches of suspected adhered debris/contamination visible around the bottom surface of the workpiece, see Fig. 3b, which may be deposits of re-solidified wire electrode material. This was possibly due to the differences in flushing efficiency/conditions between the top and bottom sides of the workpiece.

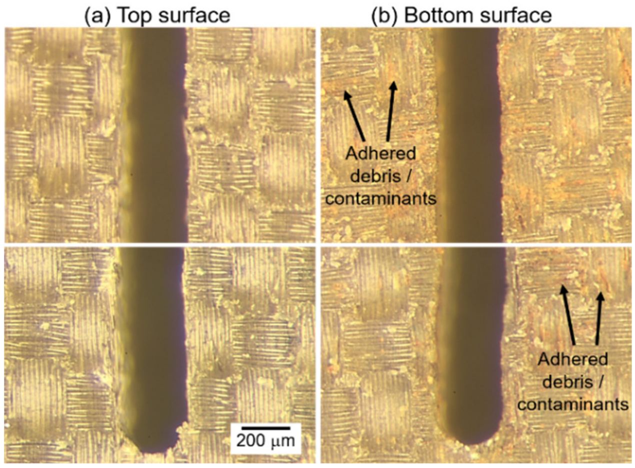

Fig. 3. Sample micrographs of machined kerf on the (a) top and (b) bottom surfaces from the test achieving the highest MRR.

3.2. Kerf width

The kerf width results highlighted discrepancies between measurements at the top and bottom surfaces of the CFRP workpiece. Average W_t was found to vary between ~256 and 289 µm while W_b was generally smaller, ranging from ~243 to 277 µm. The ANOVA shown in Table 3 for W_t demonstrated that the ignition current was the only significant factor with a corresponding PCR of 56.6%, while none of the variable parameters were found to be statistically significant with respect to the bottom kerf width. The main effects plot in Fig. 4 revealed that mean W_t decreased with increasing current and pulse off-time whilst increasing voltage enlarged the kerf width as expected due to the larger spark gap generated. In terms of W_b, both open gap voltage and pulse off-time exhibited similar effects compared to the top kerf, however the trends for ignition current and pulse on-time were reversed as shown in Fig. 5.

Table 3. ANOVA table for top kerf width.

Source	DF	Seq. SS	Adj. MS	F	P	PCR%
Voltage, V_0	1	40.18	40.18	1.91	0.197	4.1%
Current, IAL	2	559.73	279.78	13.31	0.002*	56.6%
On-time, A	2	32.19	16.10	0.77	0.490	3.3%
Off-time, B	2	146.65	73.33	3.49	0.071	14.8%
Residual error	10	210.21	21.02			21.3%
Total	17	988.97				100%

*Significant at the 5% level

The relatively smaller mean W_b (~261 µm) compared to W_t (~282 µm) when operating at the lowest current level of 3 A was possibly due to greater machining instability at the bottom side of the workpiece. However, the disparity between the top and bottom kerf width was found to reduce significantly as ignition current increased to 5 A, which suggests that the wire advanced more uniformly through the workpiece, most likely as a result of the higher discharge energy.

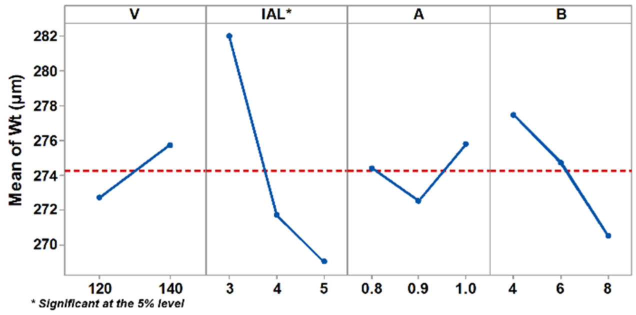

Fig. 4. Main effects plot for top kerf width.

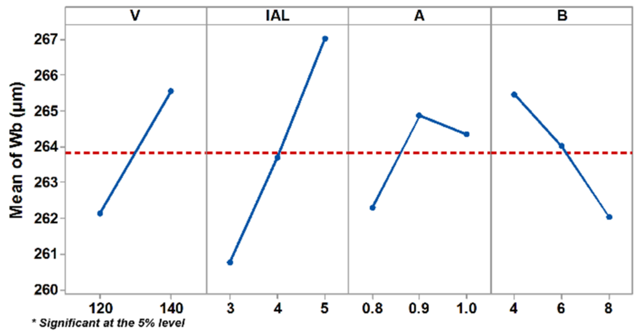

Fig. 5. Main effects plot for bottom kerf width.

3.3. Confirmation tests

Confirmation trials were carried out to validate the preferred combination of operating parameter levels to achieve maximum MRR and minimum top/bottom kerf widths. Although the recommended parameter combinations for MRR and Wt were undertaken as part of the orthogonal array, confirmation trials for all 3 responses were carried out to verify the results. Table 4 details the predicted and experimental values of the mean and signal to noise (S/N) ratio for the respective confirmation trials. The percentage error between the experimental and predicted data did not exceed 5% for all of the responses evaluated, which indicates that the accuracy of the Taguchi experiment was acceptable.

Table 4. Predicted and experimental values of mean and S/N ratio.

Response	Mean		S/N ratio (dB)		Error %
	Pred.	Exp.	Pred.	Exp.	
MRR	2.17	2.28	7.79	7.16	4.95
W_t	262.14	263.67	-48.37	-48.42	0.58
W_b	255.72	262.97	-48.15	-48.43	2.75

4. Conclusions

- All of the trials were successfully completed to a cut length of 12 mm. This suggests that the process parameters and electrode material selected were suitable for enabling the wire electrical discharge machining of unidirectional CFRP composites.
- The highest MRR of 2.41 mm^3/min was achieved when utilising an ignition current of 5 A, pulse on-time of 1 µs, open gap voltage of 120 V and pulse off-time of 4 µs.
- Ignition current and pulse off-time were statistically significant factors with regard to MRR while current was the sole parameter influencing the kerf width on the top surface. The difference in measured kerf width between the top and bottom surfaces of the workpiece was possibly due to the variation in flushing conditions/efficiency at the respective locations.
- None of the machined workpieces showed any indications of thermal damage or serious defects around the vicinity of the kerf, apart from rough edges and some minor adhered debris on the bottom surface of the workpiece.

Acknowledgements

The authors wish to thank the Egyptian Cultural Bureau for funding a research studentship and GF Machining Solutions for providing the WEDM machine for the tests.

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