Experimental Investigation on Carbon Fiber Composite during Processing with EDM based Hybrid Machining Process

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Abstract

In present scenario, advanced manufacturing sectors are more focused on development and processing of advanced engineering materials with improved properties. Recently, many advanced engineering materials such as super alloys, composite materials and reinforced materials are under consideration for replacing existing high cost materials. Carbon fibers are getting more popularity in area of aerospace, military, automobile and sports due to some remarkable properties such as low weight, high temperature tolerance, low thermal expansion, high stiffness and high tensile strength.

The present research paper shows the processing and experimental investigations during Electrical discharge diamond grinding (EDDG) process for carbon fiber composite. Electrical discharge diamond grinding (EDDG) is one of the hybrid machining processes developed for difficult to machine hard electrically conductive materials. EDDG has been developed by replacing the stationary electrode used in electrical discharge machining (EDM) with rotating diamond based disc. Electrical discharge grinding allows the machining of any type of conducting material regardless of its hardness. In the present experimental study carbon fiber composite selected as workpiece material due to its high applications in area of aerospace, medical and robotics. In EDDG process, the material is removed from the work surface due to combined effect of thermal and mechanical erosion. Sparking action of EDM is responsible for thermal erosion and mechanical erosion due to abrasion action of diamond abrasive grinding wheel. Due to thermal erosion action melting and vaporization takes place but large amount of molten material which is physically not removed but re-deposited in to the work surface, this re-deposited material form a layer which is known as recast layer (white layer). In the present experimental study experimentation have been done on self developed attachment of EDDG on EDM. The effect of input parameters viz pulse current, pulse-on-time and wheel RPM on output responses, namely MRR and average surface roughness (R_a) are investigated experimentally using full factorial design with three levels. The present work was also focused on the micro structure study of machined surface with the help of scanning electron microscopy (SEM).

Keywords: Grinding, SEM, Recast layer, Surface roughness, MRR

1. INTRODUCTION

Composite materials are extensively used for the manufacturing of body parts of aircrafts and robots due to their special characteristics like low weight and high strength. Composite materials are gaining popularity due to their broad application areas, therefore to choose the appropriate machining process which gives good surface finish and high material removal rate, is a big task. Machining of nonmetallic composite materials which are electrically conductive in nature using hybrid machining of EDM and conventional diamond grinding is the aim of our work, therefore composite material of carbon fiber is used as work material. Carbon fiber composite is an anisotropic material so its strength and thermal conductivity are directional dependent [1]. Due to directional dependency of thermal conductivity most of the heat is transferred in longitudinal direction so at higher current larger craters are formed in longitudinal direction as compared to transverse direction.

Machining of carbon fiber composite material from conventional machining gives poor surface finish and low material removal rate so we use non-conventional machining process i.e. EDM process. EDM process has poor machining efficiency, therefore hybrid machining process (HMPs) is used incorporating the advantages of EDM and conventional diamond grinding known electrical discharge diamond grinding (EDDG) process. EDDG have three different configurations i.e. electrical discharge diamond cut off grinding (EDDCG), electrical discharge diamond face grinding (EDDFG) and electrical discharge diamond surface grinding (EDDSG) [2]. We have used cut off mode of EDDG process for machining. In EDDCG process there are two electrodes (grinding wheel-cathode and workpiece-anode) [3]. There is a gap (IEG) between electrodes which is filled with dielectric. This dielectric act as flushing agent due to which at higher wheel speed we get smooth surface finish. During machining half portion of rotating grinding wheel dipped inside the dielectric, rotating wheel is fed downward using servo system. During on time of machining work surface is thermally soften by the heat generated due to sparking action EDM and soften material is removed by mechanical erosion i.e. grinding action.

In EDDCG process, the important task is to select machining parameters to achieve high machining performance. The performance of any machining process is measured in terms of response parameters i.e. material removal rate and surface roughness. The input process parameters which affect the responses are pulse-on-time, wheel speed and pulse current. EDDG process is very suitable for micro- fabrication due to its high accuracy and the good surface quality.

Kosy et al. [1996] studied the role of pulse current and wheel speed on material removal rate and concluded that the sparking action enhanced the grinding performance and diminish the grinding force and power. Yadava et al. [2008] did the finite element analysis of EDDG process and studied the effect of pulse current, pulse-on-time and duty cycle on temperature distribution and thermal stresses on workpiece. Many researchers have successfully implemented various

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configurations of electrical discharge diamond grinding process.

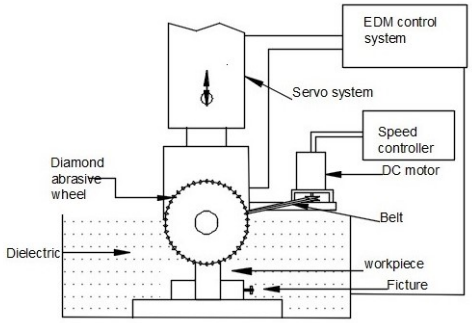

Fig. 1: Sketch of Experimental set-up of EDDCG

2. EXPERIMENTAL SETUP OF EDDG

The experiments were performed on ZNC EDM. A self-designed and fabricated cut off grinding setup is attached with it. The actual pictorial representation of EDDG setup is shown in Fig. 2. The setup consists of bronze-diamond abrasive grinding wheel, direct current motor, shaft, V-belt and bearing as shown in Fig.2, Diamond grinding wheel acts as anode and the workpiece as cathode. The workpiece is clamped by means of a fixture (vice). The components of the setup have been designed by taking the different important factor in to consideration. Every component has its own unique function like the function of the shaft is to rotate the grinding wheel. A direct current electric motor 0.25hp and 1500 rpm is used to drive the grinding wheel. The V-shaped belt of trapezoidal cross section is used to transmit power from driver to driven pulley. The DC motor speed can be controlled through a variac. Carbon fiber composite material (7.45µm fiber diameter and LLY-556 Epoxy resin as a bonding agent) is selected for experimental study. The wheel speed, pulse current and pulse-on-time are taken as input parameters while MRR and surface roughness are selected as response parameters.

Fig. 2: Setup of Electrical discharge diamond grinding

The range of input parameters is decided on the basis of preliminary experiments. The values of input parameters used in experimental study are shown in Table 1. Design of Experiments is based on full factorial design. As per full factorial design, the total number of experiments is given by k^n.

Where,
n= number of input variables
k= number of levels of each input variable

Table 1: Input parameters and their levels

Input parameters	Level I	Level II	Level III
Pulse current (A)	3	4.5	6
Wheel speed (rpm)	600	700	800
Pulse-on-time (µs)	4	8	12

Table 2: Grinding wheel specification

Description	Specification
Diamond Wheel Diameter	100mm
Thickness	5.7mm
Abrasive used	Diamond
Bore Diameter	32
Bonding material	Bronze

3. RESULTS AND ANALYSIS

Response surface methodology is the procedure for determining the relationship between different input parameters and output responses. Table 3 shows the experimental design matrix along with the data observed in terms of MRR and R_a. 'MINITAB 17' software (student version) is used for regression and graphical analysis of the data obtained. Taking into consideration nonlinearity of the responses, a second-order polynomial Eq. 1 was fitted to the observations.

$$y = b_0 + \sum_{i=1}^{n} b_i x_i + \sum_{i=1}^{n} b_{ii} x_i^2 + \sum_{i<j}^{n} b_{ij} x_i x_j \quad .....(1)$$

Where, y is response b_o, b_i, b_{ii} and b_{ij} are regression coefficients and x_i are parameters. The values of regression coefficients were calculated by using the experimental data and MINITAB 17 software, which gave Eqs. 2 and 3. ANOVA results are calculated to test the regression equations fitted for material removal rate and average surface roughness. ANOVA analysis is based on 95 % confidence level i.e. error would be 0.05. For material removal rate regression equation, the F_o has value of 21.65. The critical value of F for material removal rate regression equation at 95% confidence level is found to be 2.49, which is less than F_o. Also, in the case of average surface roughness regression equation, F_o has the value of 342.95, which is greater than the critical value of F (2.49). The P-value obtained from the ANOVA table should be less than the error chosen (0.05). In both the cases, P has values almost equal to 0. So we can conclude that both the regression equations are significant in explaining the relation between their respective responses (MRR and R_a). To get the significance of the regression equations (Eq. 2 & Eq. 3) responses MRR' & R_a' are calculated which are given in Table 3 now we can compare the values obtained through experiments and the values obtained through regression equations. Based on the observations, the main effects are presented in Fig. 3 and Fig. 4. Main effect plots for MRR and ASR (R_a) were obtained from MINITAB 17 software considering MRR as higher-the-better characteristics and ASR (R_a) as lower the better characteristics.

Table 3: Experimental and Theoretical values of Responses

Exp. No.	I (A)	T_{on} (μs)	N (rpm)	Experimental MRR (g/min)	Theoretical MRR' (g/min)	Experimental ASR(R_a) (μm)	Theoretical ASR'(R_a') (μm)
1	-1	-1	-1	0.00560	0.007422	1.240	1.25640
2	-1	-1	0	0.00580	0.004407	1.360	1.12950
3	-1	-1	1	0.00621	0.004972	1.390	0.93620
4	-1	0	-1	0.00610	0.004857	1.110	1.32835
5	-1	0	0	0.00630	0.004947	1.210	1.19003
6	-1	0	1	0.00767	0.008617	1.270	0.98531
7	-1	1	-1	0.00670	0.005532	0.950	1.38729
8	-1	1	0	0.00730	0.008727	0.970	1.23756
9	-1	1	1	0.01330	0.015502	0.973	1.02142
10	0	-1	-1	0.00890	0.01176	1.730	1.74161
11	0	-1	0	0.01200	0.01009	1.780	1.64529
12	0	-1	1	0.01380	0.012012	1.810	1.48257
13	0	0	-1	0.00980	0.010619	1.670	1.80414
14	0	0	0	0.01310	0.01206	1.690	1.69640
15	0	0	1	0.01400	0.01708	1.740	1.52226
16	0	1	-1	0.01100	0.01271	1.490	1.85367
17	0	1	0	0.01460	0.017264	1.530	1.73451
18	0	1	1	0.03167	0.02539	1.590	1.54895
19	1	-1	-1	0.01430	0.014138	1.890	1.86042
20	1	-1	0	0.01610	0.013849	1.930	1.79468
21	1	-1	1	0.01680	0.013849	1.970	1.66254
22	1	0	-1	0.01630	0.014421	1.770	1.91363
23	1	0	0	0.01750	0.017213	1.810	1.83637
24	1	0	1	0.02167	0.023585	1.860	1.69281
25	1	1	-1	0.01700	0.017944	1.660	1.95364
26	1	1	0	0.02100	0.023841	1.690	1.86506
27	1	1	1	0.03500	0.033318	1.710	1.71008

Regression Equation for MRR

$$MRR' = 0.01206 + 0.006133I + 0.003584T_{on} + 0.003231rpm - 0.00098I^2 + 0.00162T_{on}^2 + 0.00179rpm^2 + 0.001424I * T_{on} + 0.001351I * rpm + 0.003105T_{on} * rpm \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Regression Equation for R_a

$$R_a' = 1.6964 + 032317I + 0.04461T_{on} - 0.14094rpm - 0.1832I^2 - 0.0065T_{on} - 0.0332rpm^2 - 0.00942I * T_{on} + 0.03058I * rpm - 0.01142T_{on} * rpm \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Table 4: ANOVA for MRR regression equation

Source	DOF	SS	MS	F_o	P	$F_{(9,17,0.05)}$
Regression	9	0.001299	0.000144	21.65	0	2.49
Residual error	17	0.000113	0.000007			
Total	26	0.001412				

Table 5: ANOVA for roughness (R_a) regression equation

Source	DOF	SS	MS	F_o	P	$F_{(9,17,0.05)}$
Regression	9	2.4952	0.27725	342.95	0	2.49
Residual error	17	0.0137	0.00081			
Total	26	2.5090				

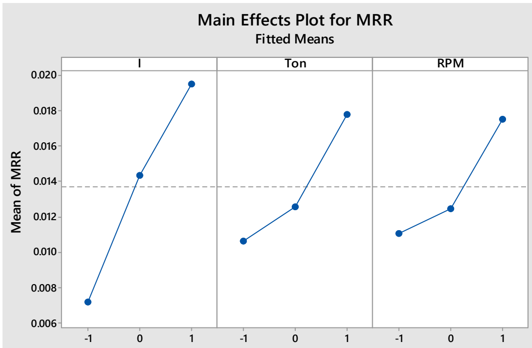

Fig. 3: Main effects plot for material removal rate

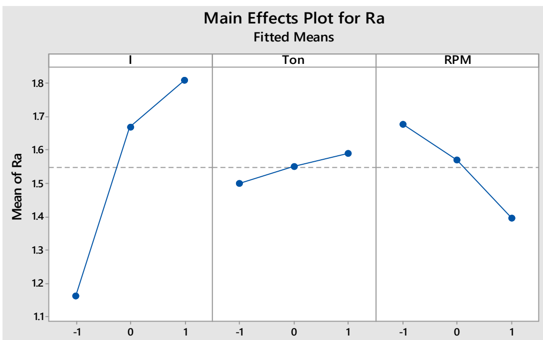

Fig. 4: Main effects plot for average surface roughness

3.1. Effect of pulse current

The effect of pulse current on MRR is shown in Fig. 3. It is observed that as the pulse current increases (I) the input energy (E=VIt) increases due which melting and evaporation of work material increases and hence the MRR and surface roughness both increases. Also as the pulse current increases, sparking action of EDM dominates over grinding. The main effects plots shows that current is the most dominant factor in increasing MRR as well as R_a.

3.2. Effect of wheel RPM

As wheel speed increases flushing action of dielectric fluid increases which decrease the rate of resolidificaton and hence increases the MRR and decreases the R_a. As wheel speed increases abrasive action of diamond abrasives increases which increase the MRR. Due to enhanced flushing action the thickness of recast layer (white layer) decrease and hence decreases R_a value.

3.3. Effect of pulse-on-time

Pulse-on-time is duration in which current is allowed per cycle, as pulse-on-time increases span of sparking action increases therefore the time for conduction of heat into to the work increases due to which softening of larger volume of workpiece takes place. The grinding force decreases due to softening of the workpiece which increase the protrusion height and also increases the depth of penetration, which results the increase in chip thickness and hence both MRR and surface roughness increases.

Surface plots for R_a and MRR shown in Fig. 5 and Fig. 6 respectively, which shows that as the pulse current increases, both R_a and MRR increases due to the fact that on increasing pulse current spark energy increases while as wheel rpm increases R_a decreases and MRR increases because of increased flushing action of dielectric fluid.

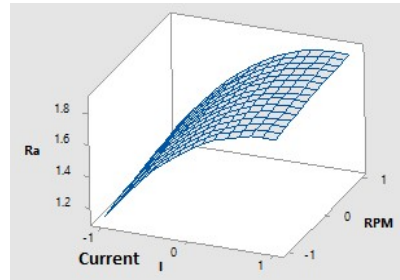

Fig. 5: Surface plot of R_a in terms of Current and wheel rpm

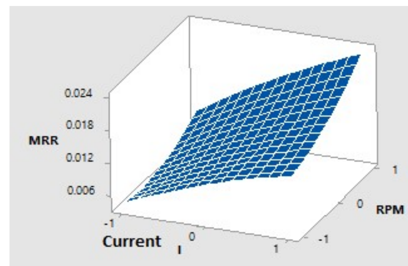

Fig. 6: Surface plot of MRR in terms of Current and wheel rpm

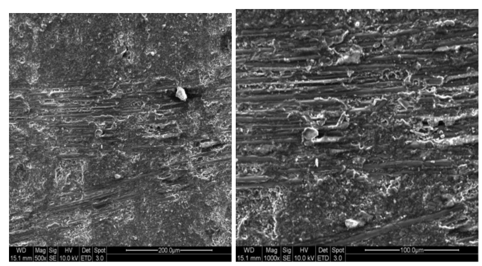

Fig. 7: Micro-structure of carbon fiber composite at 3A, 12µsTon and 800 rpm

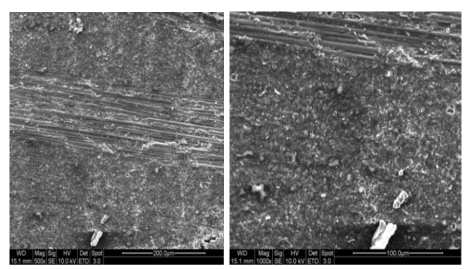

Fig. 8: Micro-structure of carbon fiber composite at 4.5 A, 12µsTon and 800 rpm

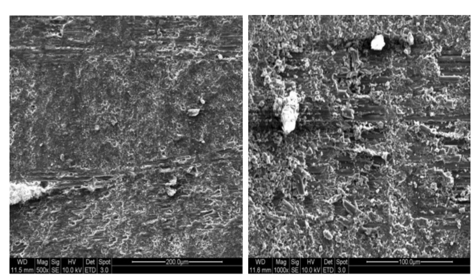

Fig. 9: Micro-structure of carbon fiber composite at 6A, 12µsTon and 800 rpm

The surface damage of the carbon fiber composite material at different value pulse currents are shown in the scanning electron micrographs. At a low current of 1A, the material removal rate was very low and the fibers were not disturbed. The severe melting of the composite surface was found at higher currents from 3A to 6A and the molten layer flowed into irregular patterns without distinction between the carbon fibers and the epoxy resin. In addition to melting, the high amount of heat generated at higher currents caused thermal expansion of fibers. The fibers expanded against one another. The resin were squeezed out and appeared as white boundaries surrounding the fibers. It must be emphasized that the surface produced by EDDG process at large currents was highly heterogeneous on the microscopic scale. This scanning electron micrograph reveals that the randomly distributed white layer and solid particles are resolidified and remain attached to the eroded surface. Moreover increasing the discharge energy causes high melting and vaporization.

4. CONCLUSIONS

In the present work, parametric analysis of the EDDG process has been based on experimental results and the process optimization was performed by Response surface method. Following conclusions can be drawn from the analysis of the results:

i Maximum value of MRR 0.03500 g/min is observed at 6A pulse current, 800 rpm wheel speed and the 12µs pulse-on-time.
ii Minimum value of average surface roughness 0.950 µm is observed at 3A pulse current, 800 rpm wheel speed and the 4µs pulse on-time.
iii Both MRR and R_a increases as pulse current increases. The value of pulse current for carbon fiber composite lie between 3-6A.
iv The value of surface roughness observed between 1.2 to 1.9 µm and the value of MRR between 0.006 to 0.02 g/min at given values of input parameters.

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