Reason - A Technical Journal
ISSN 2277–1654
Vol - XII • 2013

PARAMETRIC ANALYSIS OF TRAVELLING WIRE ELECTROCHEMICAL DISCHARGE MACHINING PROCESS

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Manuscript received on : Ocotber 21, 2013, acceped after revision on : February 26, 2014.

Abstract : Travelling Wire Electrochemical Discharge Machining (TW-ECDM) process is a special type of Electrochemical Spark Machining (ECSM) process which has a greater effectiveness for machining of electrically non-conducting material like hylam based fiber reinforced plastics (FRP). The recent research paper focuses the parametric analysis on machining criteria such as material removal rate (MRR) and Overcut (OC) for slot cutting operation considering applied voltage, electrolyte concentration, feed rate of wire and pulse on time etc as process parameters. This paper shows the single and multi-objective optimization for determining the optimal parametric combination of TW-ECDM for maximum MRR and minimum OC based on response surface methodology (RSM). From the parametric analyses it is concluded that applied voltage has more significant effects on MRR and OC during TW-ECDM slot cutting operation.

Keywords : TW-ECDM, ECSM, MRR, OC, RSM

1. INTRODUCTION

Travelling Wire Electrochemical Discharge Machining (TW-ECDM) is an advanced hybrid machining process comprising the techniques of Electrochemical Machining (ECM) and Electro discharge Machining (EDM) [1,2]. This is a special type of Electrochemical Discharge Machining (ECDM) process. The process is important since it can machine a variety of electrically non-conductive materials like ceramics, composites, alumina and glass etc. The basic principle of Travelling Wire-ECDM is similar to that of ECDM. Wire-ECDM generally employs a continuously travelling wire electrode to slice the work piece. An electrically non-conducting work piece is placed in the closed vicinity of the electrical discharge and the material of the workpiece is melted, vaporized and eroded due to the transmission of spark energy to the work piece. The removal rate of material also depend on other machining parameters like concentration of electrolyte, feed rate of travelling wire and pulse on time etc. In the TW-ECDM process, the material removal takes place due to the combined effects of electrochemical (EC) reaction and electrical spark discharge (ESD) action. Since from its inception, TW-ECDM process is affected by various factors, researchers are trying to overcome these problems. Yang *et al*. [3] showed that by adding SiC abrasive to the electrolyte, over cut quality, surface roughness can be improve and the vibration of the wire in TW-ECDM strongly affect the shape accuracy. Han *et al.* [4] proposed a new method to improve the surface integrity and spark discharge distribution of wire electrochemical discharge machining (wire-ECDM) process by roughening the wire tool surface. Peng and Liao [5] used Traveling wire electrochemical discharge machining (TW-ECDM) to slice the small size (10–30 mm diameter) optical glass and quartz bars. The input power was modulated to obtain the appropriate frequencies and duty factors for machining glass and quartz materials. Sarkar *et al.* [6, 7] showed the effects of various process parameters during micro-drilling of silicon nitride ceramic using response surface methodology by electrochemical discharge machining (ECDM). Doloi *et al.* [8] investigated into traveling wire electrochemical discharge machining of non-conducting materials such as Hylum based fibre reinforced composite and analyzed only the effects of various process parameters but none has conducted any investigation to correlate various process parameters with different machining criteria and multi objective optimization of them during slot cutting of any electrically non-conducting materials with TW-ECDM process. Therefore, the objective of this paper are to study the effects of various process parameters such as voltage, electrolyte concentration, wire feed rate and pulse-on time on different machining characteristics *e.g.* material removal rate (MRR), overcut (OC) and establish a relationship between them so that optimized condition can be attained during cutting of Hylum based fiber reinforced composite materials with TW-ECDM process

2. EXPERIMENTAL

2.1 Experimental Set up

After proper understanding of the fundamentals of TW-ECDM process and also in order to meet all the objectives of the present research work TW-ECDM system has been developed. The system consists of several subsystems as follows.

a) Mechanical subsystem;

b) Electric Power supply unit and

c) Electrolyte supply unit etc.

The schematic diagram of experimental set-up of TW-ECDM is shown in Fig 1.

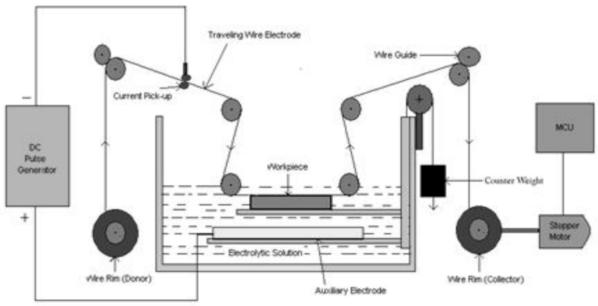

Fig.1 Schematic diagram of TWECDM Experimental setup

2.2 Experimental Planning Based on RSM

In the current research four process parameters were considered for conducting experiments on Travelling Wire-ECDM. The brass wire of 0.25 mm diameter was used as the tool electrode material and KOH is used as electrolyte. The experiments were carried out according to a design based on response surface methodology (RSM).

Response surface modelling was used to establish the mathematical relationship between the response (Y_u) and the various machining parameters [1]. The second order polynomial response surface mathematical model, which analyses the parametric influences on the various response criteria, can be described as follows:

$$Y_u = b_0 + \sum_{i=1}^{n} b_1 X_{iu} + \sum_{i=1}^{n} b_{ii} X_{iu}^2 + \sum_{i<j} b_{ij} X_{iu} X_{ju} + \varepsilon \quad (1)$$

Y_u = the corresponding response, e.g. MRR, OC

X_{iu} = the coded values of the ith machining parameters for uth experiment,

ε = the error

n = number of machining parameters and

b_i, b_{ii}, b_{ij} = second order regression coefficients

Also the different experimental conditions are exhibited in the Table 1. FRP is manufacture from Chlorosulponated polyethylene and containing a minimum 70% Hypalon 45 by volume of compound, PRO-STRUCT 795 two part gap filling mastic adhesive based on modified epoxy resin and hardener. Experimental test results and ANOVA analysis is shown in Table 2 and Table 3.

Table 1 Actual and coded values of parameters

Input factor	Level/code				
	-2	-1	0	1	2
Pulse on time, %	40	45	50	55	60
Electro. conc., wt%	10	15	20	25	30
Applied voltage, V	15	20	25	30	35
Feed rate, mm/min	60	75	90	105	120

Table 2 Experimental plan and test results

Expt. No.	**Pulse on time(%)**	**Electrolyte concen.(wt%)**	**Voltage(V)**	**Wire Feed rate(mm/min)**	**MRR (mg/h)**	**OC(mm)**
1	45	15	20	75	0.359	0.05585
2	55	15	20	75	0.368	0.05865
3	45	25	20	75	0.403	0.0715
4	55	25	20	75	0.4033	0.07055
5	45	15	30	75	0.4223	0.0855
6	55	15	30	75	0.452	0.09155
7	45	25	30	75	0.502	0.1502
8	55	25	30	75	0.480	0.14927
9	45	15	20	105	0.254	0.03335
10	55	15	20	105	0.276	0.03855
11	45	25	20	105	0.340	0.04535
12	55	25	20	105	0.3566	0.0525
13	45	15	30	105	0.3853	0.07855
14	55	15	30	105	0.4530	0.1254
15	45	25	30	105	0.502	0.15072
16	55	25	30	105	0.512	0.15834

Table 2 Contd/-...

Expt. No.	Pulse on time(%)	Electrolyte concen.(wt%)	Voltage(V)	Wire Feed rate(mm/min)	MRR (mg/h)	OC(mm)
17	40	20	25	90	0.454	0.10545
18	60	20	25	90	0.478	0.14041
19	50	10	25	90	0.295	0.03755
20	50	30	25	90	0.4616	0.1135
21	50	20	15	90	0.261	0.03575
22	50	20	35	90	0.5166	0.19015
23	50	20	25	60	0.465	0.06965
24	50	20	25	120	0.3533	0.04825
25	50	20	25	90	0.4633	0.1183
26	50	20	25	90	0.478	0.1182
27	50	20	25	90	0.4635	0.10545
28	50	20	25	90	0.4535	0.10815
29	50	20	25	90	0.4833	0.11325
30	50	20	25	90	0.4555	0.1062
31	50	20	25	90	0.472	0.12115

Table 3 Analysis of Variance for MRR and OC

Source	DF	SS		MSS		F		P	
		MRR	OC	MRR	OC	MRR	OC	MRR	OC
Regression	14	0.171143	0.052486	0.012224	0.003749	75.74	67.07	0.000	0.000
Linear	4	0.133056	0.040716	0.033264	0.010179	206.09	182.11	0.000	0.000
Square	4	0.029107	0.008408	0.007277	0.002102	45.08	37.61	0.000	0.000
Interaction	6	0.008979	0.003362	0.001497	0.000560	9.27	10.02	0.000	0.000
Lack-of-Fit	10	0.001830	0.000646	0.000183	0.000065	1.46	1.56	0.333	0.303
Pure Error	6	0.000752	0.000248	0.000125	0.000041				
Total	30	0.173725	0.053380						

3. RESULTS AND DISCUSSION

3.1 Experimental Results

Experimentation was conducted based on response surface methodology (RSM) using a developed TW-ECDM set-up and thus obtained experimental results are shown in the Table 2. Based on the experimental results second order non-linear models have been established and the influences of various process parameters such as pulse on-time (X_1), electrolyte concentration (X_2), voltage (X_3) and feed rate (X_4) on different machining criteria *i.e*. material removal rate (MRR) and overcut (OC) have been studied. Design of experiment (DOE) features of MINITAB software were utilized to obtain the second order rotatable central composite design and also to determine the coefficients of mathematical models.

3.2 Empirical Modelling on MRR and OC

A model has been developed to correlate the interaction and higher-order effects of the previously mentioned TWECDM process parameters on the overcut criteria, utilizing the relevant experimental data as observed during the course of machining. The empirical model on MRR of TW-ECDM has been established and expressed as Eq. 1 using MINITAB software.

$$Y(MRR) = 0.46701+0.00755X_1 +0.03594X_2 +0.06083X_3- 0.02225 X_4 – 0.00130X_1 X_1 - 0.02323X_2X_2 - 0.0206X_3X_3- 0.01551X_4X_4 - 0.00772X_1X_2 + 0.00234X_1 X_3 + 0.00621X_1 X_4 + 0.00234X_2X_3 + 0.00971X_2X_4 + 0.01892X_3X_4 \quad (2)$$

Also a mathematical model for OC of TW-ECDM has been established and expressed as Eq. 1 using MINITAB software and the relevant experimental data from Table 2.

$$Y(OC) = 0.11296 + .00599X_1 +0.01804X_2 +0.03633X_3 -.00388X_4 + .00181X_1X_1 - 0.01004X_2X_2-0.00069X_3X_3- 0.01419X_4X_4- 0.003X_1X_2+ 0.00284X_1X_3+ 0.00374X_1X_4+ 0.01088X_2X_3- 0.00118X_2X_4+ 0.00771X_3X_4 \quad (3)$$

3.3 Analysis of Variance (ANOVA) of developed models for MRR and OC

An ANOVA and F-ratio test were performed to justify the goodness of fit of the developed mathematical models. Since the calculated values of F-ratio for the lack of fit are found to be less than the standard F-ratio values (4.06) and P values (0.5) for MRR &OC, it can be ascertained that the second order regression models are adequate at 95% confidence level with five degrees of freedom to represent the relationship between MRR, OC and the machining parameters of the TWECDM process. Hence, the developed mathematical models, which link the various machining parameters with MRR and OC can adequately be represented through the response surface methodology. Estimated regression coefficients and analysis of variance for MRR and OC are shown in Table 3 suggesting that this model adequately fits the data. The values of adj-R^2 for MRR and OC are 98.5% and 98.3% respectively indicating the goodness of the models. In this term “variability” is defined as the sum of squares. There are equivalent expressions for R^2 based on analysis of variance decomposition. Adj-R^2 is modification of R^2 that adjusts for the number of terms in a model to improve the model expectation. The ANOVA test result for the developed models *i.e.* Eq. 2 & 3. R^2 may be expressed as following formula.

$$R^2 = \frac{SS_R}{SS_T}$$

3.4 Determination of optimized condition of TW-ECDM process

In this present experimental investigation the desired objective is to get maximized Material Removal Rate and minimum Over Cut for better cutting operations. Single objective optimization of MRR and OC are done separately using MINITAB software. It is observed that global optimum value of response for MRR is 0.5166 mg/h and the optimum value of MRR can be found out with the combination of pulse on time 60% ,concentration 30%, applied voltage 35 volt, wire feed rate 120 mm/min and OC is 0.033 mm.

Over Cut is very low then we can say it is perfect operations. If the value of OC is zero or near zero it is better. For minimum response of OC pulse on time is 60%, concentration of electrolyte 10%, voltage 25.811 volt and feed rate 60 mm/min. MRR is .5158 mg/h. Fig. 2 shows the microscopic view of the machined job for the minimum value of OC at optimum parametric combination.

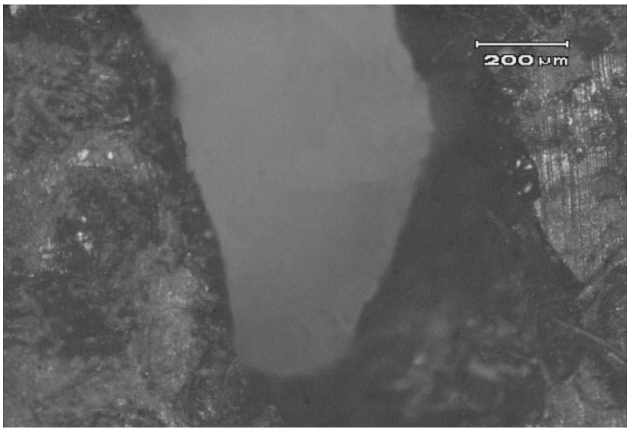

Fig 2 Photographic view of the machined job for the minimum value of OC

The optimal machining parametric combinations of the TW-ECDM process to maximize material removal rate as well as minimize overcut can be determined based on RSM models using MINITAB software. Based on the second order rotatable central composite design plan, the experimental region can be shifted to another set of machining parameter levels technique of RSM. Here, the set of machining parameters is chosen so that an optimum value of responses occurs. Considering our investigation, which is based on the developed mathematical model of MRR (Eq. 2), OC (Eq. 3) the optimal combinations of the machining parameters for maximizing MRR and minimizing OC is determined. To achieve the maximum MRR and minimum OC the parametric combination is pulse-on time as 50%, concentration 20%, voltage 21.64 V and feed rate 60 mm/min

3.5 Effects of process parameters on MRR & OC

MRR & OC is mostly influenced by applied voltage and electrolyte concentration, pulse on-time but wire feed rate has less effect on it during machining of FRP through TW-ECDM process. As shown in Fig. 3 it is observed that MRR increases as electrolyte concentration and applied voltage increase keeping the other parameters at constant value as pulse on time at 50% and wire feed rate at 90 mm/min. From Fig. 4 it is observed that MRR increases as pulse on time increases and wire feed rate decreases keeping other parameters constant value, as voltage 25 volt and electrolyte concentration 20%.

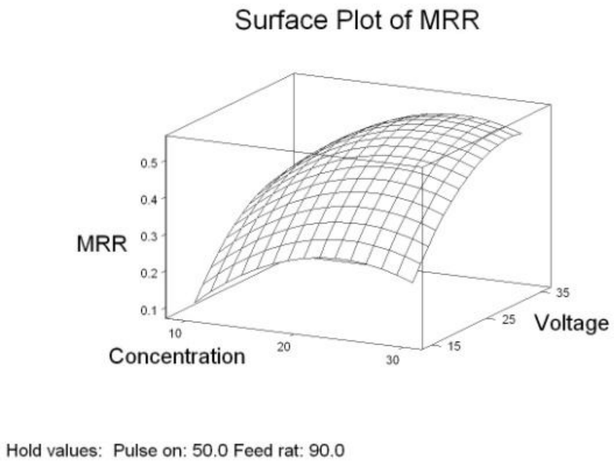

Fig. 3 Variation of electrolyte concentration and applied voltage on MRR

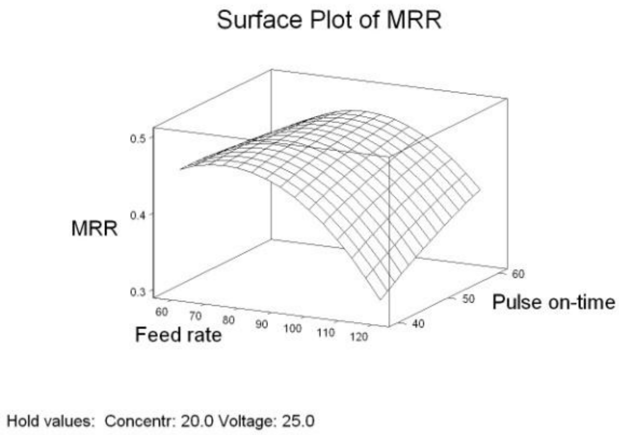

Fig. 4 variation of wire feed rate and pulse-on time on MRR

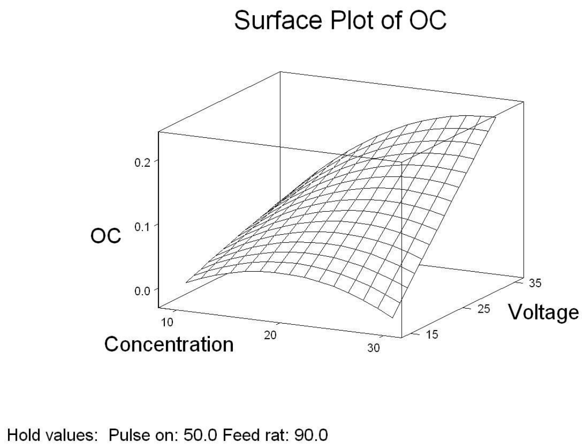

Fig. 5 Variation of electrolyte concentration and applied voltage on OC

The influence of the applied voltage and electrolyte concentration on OC in the TW-ECDM process were observed and are shown in Fig. 5. The variation of the OC with the applied voltage is similar to the effect of different electrolyte concentrations. The overcut during TW-ECDM operations increases with an increase in applied voltage because of the fact that at high voltage a large number of gas bubbles are generated at the tool sidewall. This may increase the possibility of stray sparking and thus cause more OC. The amount of OC for medium electrolyte concentrations is comparatively low due to the fact that a concentrated sparking takes place at these levels. Based on the non-linear model of OC established through the response surface methodology, the effect of applied voltage and electrolyte concentration on OC in TW-ECDM processes was evaluated during the cutting operation of FRP. The variation of OC with the wire feed rate and pulse on time is shown in Fig. 6. But at high wire feed rate and low pulse on time the OC is low due the decreased amount of current flow.

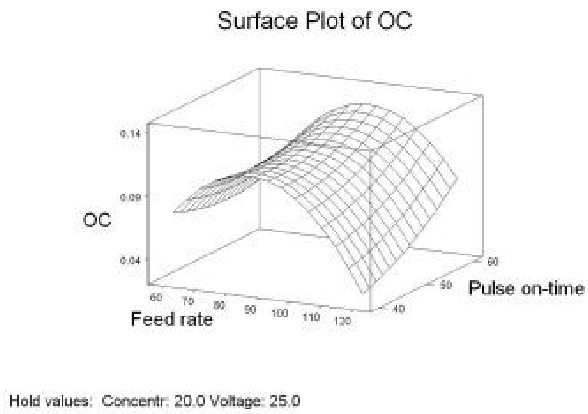

Fig. 6 Effect of feed rate and pulse-on time on OC

4. SINGLE OBJECTIVE OPTIMIZATION OF TW-ECDM PROCESS

In this present experimental investigation the desired objective is to get maximum Material Removal Rate and minimum Over Cut for better cutting operations. Single objective optimization of MRR and OC are done separately using MINITAB software based on RSM models.

4.1 Maximization of MRR

The maximum value of MRR and parametric combination are shown. in the fig.7.

4.2 Minimizations of OC

Over Cut is very low then we can say it is perfect operations. If the value of OC is zero or near zero it is better. In fig.8, The minimum value of OC and parametric combination are shown.

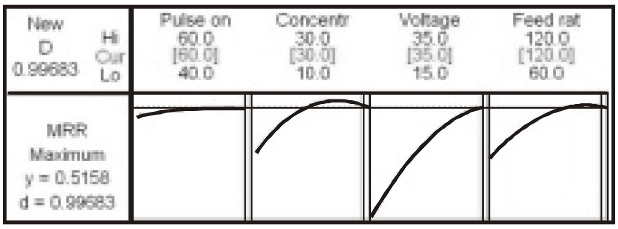

Fig. 7 Graphical plots of results of single objective optimization MRR

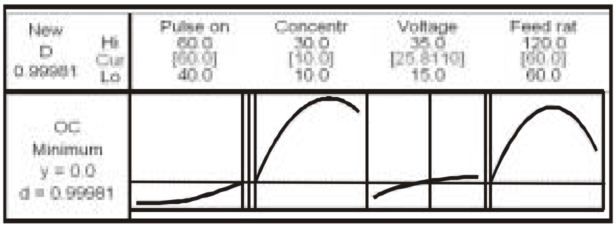

Fig. 8 Graphical plots of results of single objective minimization MRR

5. MULTI OBJECTIVE OPTIMIZATION OF BOTH MRR AND OC IN TW-ECDM

The optimal machining parametric combinations of the TW- ECDM process to maximize material removal rate as well as minimize overcut can be determined based on RSM models using MINITAB software. In fig.9 represents the results of multi objective optimization of MRR and OC.

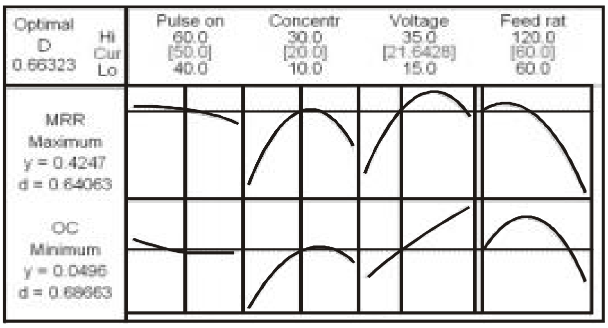

Fig.9 Graphical plots of results of multi objective optimization MRR and OC

6. CONCLUSIONS

Finally it can be concluded that the developed empirical models are adequate to determine the MRR and OC at different combinations of important process parameters of TW-ECDM process during machining of FRP composites.

Maximum MRR is obtained at 60% pulse on time/35V/120mm/min,/30wt% and minimum OC at pulse on time 60%/25V/60mm/min,/ 10wt% based on RSM. For achieving multi-objective optimization both MRR and OC, the optimal parametric combination is pulse on time of 50%, applied voltage 20 volt, feed rate 60 mm/min and electrolyte concentration of 20% based on RSM models.

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