Asian Journal of Engineering and Applied Technology
ISSN: 2249-068X (P) Vol. 2 No. 2, 2013, pp. 19-24

DOI: https://doi.org/10.51983/ajeat-2013.2.2.687

Simultaneous Optimization of Multiple Quality Characteristics in Traveling Wire Electrochemical Spark Machining of Pyrex Glass

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Abstract - **A new way of promising hybrid process called as Traveling Wire Electrochemical Spark Machining (TW-ECSM) process which combines the characteristics of Electro-chemical Machining (ECM) and Wire Electrical Discharge Machining (WEDM) and uses for machining of electrically non-conductive materials. In this paper the simultaneous optimization of multiple quality characteristics during TW-ECSM of Pyrex glass has been presented using Taguchi method (TM). The experiments were conducted using L_{27} orthogonal array (OA) considering five process parameters such as applied voltage, pulse on-time, pulse off-time, electrolyte concentration and wire feed velocity and two performance characteristics namely material removal rate (MRR) and kerf width (K_w). The purpose of analysis of variance (ANOVA) is to investigate which input process parameters significantly affect the performance characteristics. Experimental results have shown that machining performance in the TW-ECSM process can be improved effectively through this approach.**

Keywords: **Traveling Wire Electrochemical Spark Machining, Pyrex Glass, MRR, K_w.**

I. Introduction

In current times, Pyrex glass is widely used in micro electro-mechanical systems (MEMS) because its thermal expansion coefficient is similar to that of silicon, yielding very low residual stress after anodic bonding. Due to its high material hardness and brittleness, Pyrex glass is one of the materials which are difficult to machine using conventional as well as unconventional machining methods. Recently, a new spark based machining method has been found an effective machining method suitable for machining of such type of hard and brittle electrically non-conducting materials. This new machining process combines the characteristics of electro chemical machining (ECM) and electro discharge machining (EDM) and known as Electro-Chemical Spark Machining (ECSM) method [1].

The ECSM process uses Electro-Chemical Discharge (ECD) phenomenon for generating heat for the purpose of removing work material by melting and vaporization. This was presented for the first time by Kurafuji as "Electrochemical Discharge Drilling (ECDD)" for creating microholes in glass workpiece [2]. ECSM process has been tried in many configurations, such as Die Sinking-ECSM, Hole Sinking-ECSM, Die Drilling-ECSM, Hole Drilling-ECSM, Wire Cutting-ECSM, Disc Cutting-ECSM, Cylindrical Grinding-ECSM, Surface Grinding-ECSM and Pocket Milling-ECSM. Success in the application of sinking and drilling ECSM has stimulated interest in studying the prospects of TW-ECSM.

Tsuchiya *et al.* [3] developed TW-ECSM setup in 1985 first time for machining of glasses and ceramics. Hofy and McGeough [4] introduced an experimental work showing the effects of mode of electrolyte flushing on metal removal rate during TW-ECAM of rectangular mild steel plate and recommended to use the coaxial mode of flushing for improving the machining action and accuracy. Peng and Liao [5] proposed Traveling Wire-Electro Chemical Discharge Machining (TW-ECDM) can be applied for slicing meso-size non-conductive brittle materials. They confirmed that pulsed DC power shows better spark stability and more spark energy than constant DC power. Nesarikar et al. [6] used TW-ECSM process for precision slicing of thick Kevlar-epoxy composite. They did comparison between the experimental and calculated values of MRR and average diametral overcut with the variations in electrolyte conductivity, applied voltage and specimen thickness. Jain et al. [7] conducted experiments on their self developed setup of TW-ECSM for cutting Glass epoxy and Kevlar epoxy composites using NaOH electrolyte. They observed that the wire wear rate and the over-cut follow a similar behavior as the machining rate but the wire wear rate was about two magnitudes smaller than the MRR. They have reported that there is an increase in MRR at higher voltage along with the presence of thermal cracks, large HAZ and irregular machined surfaces. They also studied the effect introducing some bubbles artificially into the process during machining and found that the MRR as well as the over-cut decreases slightly. Yang *et al.* [8] carried out the experimental study to improve the over-cut quality by adding SiC abrasive particles to the electrolyte. They have reported the effect of adding abrasives on surface roughness (R_a) and MRR due to TW-ECDM.

In this paper Taguchi methodology (TM) has been applied to study the optimum parameter settings for cutting of Pyrex glass during TW-ECSM process. The process input parameters (control factors) taken are applied voltage, pulse on-time, pulse off-time, electrolyte concentration and wire feed velocity whereas the quality characteristics analysed are MRR and K_w. Based on the robust design concept, an L_{27} orthogonal array (OA) has been used for conducting the experiments. These results are further used for optimization. Furthermore, analysis of variance (ANOVA) based on mean data and S/N ratio has been used to determine the percentage contribution of each input parameters on MRR and K_w.

II. Experimental Details

A. Process Parameters, Machine, Materials and Measurement

The experimental studies were performed on self developed TW-ECSM setup as shown in Fig. 1..

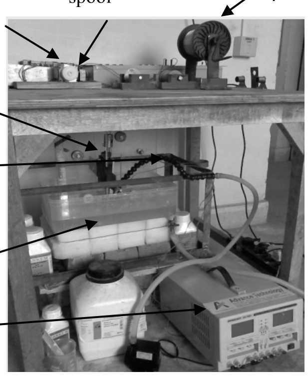

Fig. 1 Photographic view of the developed tabletop TW-ECSM setup

Different settings of input parameters such as applied voltage, pulse on-time, pulse off-time, electrolyte concentration and wire feed velocity were used in the experiments. Preliminary experiments were carried out in Pyrex glass workpiece material (40mm×35mm×2mm) with graphite rod (diameter 8mm, length 55mm) as anode and 0.25mm diameter of brass wire (tensile strength 800-1000MPa) as cathode. The material properties of Pyrex glass are given in Table I.

Table I Material Properties of Pyrex Glass

C_p (J/Kg K)	750
k (W/m K)	1.11
ρ (kg/m^3)	789
T_m (°C)	2,330

All the experiments were carried out using NaOH solution as electrolyte at 20ºC to 40ºC. The minimum linear feed rate to the workpiece which could be achieved using the present setup was 0.008mm/s. Each experiment was tested for about 10 to 12min., during which voltage and current were recorded on a voltmeter and ammeter. Based on the exhaustive pilot experimentation, parameters range have been decided. The considered process parameters and their levels are listed in Table II.

Table II Control Factors and Their Levels

Symbol	Control factors	Units	Level 1	Level 2	Level 3
A	Applied voltage	volt	70	75	80
B	Pulse on-time	μs	400	450	500
C	Pulse off-time	μs	350	400	450
D	Electrolyte concentration	g/l	200	250	300
E	Wire feed velocity	m/min	1.8	2.4	3.0

The MRR has been determined by finding the difference in weight of the specimen before and after the machining, by using a weighing digital microbalance (accuracy 10 µg, CAS India Private Limited). The optical measuring microscope (Sipcon Instrument Industries, India) was used for measuring K_w. In the present MRR and K_w are represented in MM^3/min and mm respectively.

B. Taguchi Method Based on Design of Experiments

In this article, a large number of control factors have been considered in order to increase the accuracy of the results. Since there are five control factors each with three levels in the experiment, a full factorial experimental design would have required a large number of experiments, making the study extremely time consuming and expensive. To reduce the number of experiments required, a Taguchi-based design of experiment was implemented [9]. The TM for robust design is a unique statistical experimental design technique, which greatly improves the engineering productivity. In this method the experiments are performed as per standard orthogonal array (OA) and the application of OA reduces the number of experiments for the particular process. OA is the especially constructed table which makes the design of experiments very easy and consistent. The selection of OA is based on the total degree of freedom (dof) of the process [10, 11]. Hence, orthogonal array L_{27} has been selected for conducting the experiments in present study. The results of experiments for responses MRR and K_w are shown in TableIII.

Table III The results of experiments for responses MRR and K_w

Expt. No.	Factor levels					MRR (mm^3/min)	K_w (mm)
	A	B	C	D	E		
1	1	1	1	1	1	0.1373	0.3521
2	1	1	1	1	2	0.1545	0.3106
3	1	1	1	1	3	0.1287	0.2781
4	1	2	2	2	1	0.1645	0.2983
5	1	2	2	2	2	0.1974	0.2852
6	1	2	2	2	3	0.1116	0.3154
7	1	3	3	3	1	0.1459	0.3596
8	1	3	3	3	2	0.1403	0.3448
9	1	3	3	3	3	0.3605	0.3061
10	2	1	2	3	1	0.1974	0.3559
11	2	1	2	3	2	0.1659	0.3499
12	2	1	2	3	3	0.1631	0.3485
13	2	2	3	1	1	0.2061	0.3206
14	2	2	3	1	2	0.1888	0.3187
15	2	2	3	1	3	0.1731	0.2945
16	2	3	1	2	1	0.2146	0.3361
17	2	3	1	2	2	0.2516	0.3612
18	2	3	1	2	3	0.3777	0.3315
19	3	1	3	2	1	0.3262	0.3368
20	3	1	3	2	2	0.2747	0.3028
21	3	1	3	2	3	0.2575	0.3446
22	3	2	1	3	1	0.2661	0.3199
23	3	2	1	3	2	0.2232	0.3462
24	3	2	1	3	3	0.2489	0.3093
25	3	3	2	1	1	0.3691	0.3712
26	3	3	2	1	2	0.2689	0.3495
27	3	3	2	1	3	0.2615	0.3285

III. Optimization Using Taguchi Methodology

In TM, a loss function is used to calculate the deviation between the experimental value and the desired value. This loss function is further transformed into a signal-to-noise (S/N) ratio. There are several S/N ratios available depending on type of characteristics; smaller is the better (SB), nominal is the best (NB) and higher is the better (HB). In TW-ECSM, kerf width is the smaller-the-better (SB) type and MRR is the higher-the-better (HB) type was selected for obtaining optimum machining performance characteristics. For "SB" and "HB", the definitions of the loss function (L) for machining performance results y_1, y_2, y_3…..y_i are the experiments (responses) and n is the number of repetitions of y_i.

$$L_{SB} = (y12+y22+y32+\ldots\ldots)/n = \frac{1}{n}\sum_{i=1}^{n} y_i^2 \quad (1)$$

$$L_{HB} = (1/y12+1/y22+1/y32+\ldots\ldots)/n = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2} \quad (2)$$

Before calculating the MSNR, it is important to normalize the quality loss of each quality characteristics because the unit of each quality characteristics may be different. The normalized quality loss can be computed using the following formula:

$$yij = \frac{L_{ij}}{L_i^*} \quad (3)$$

Where, yij is the normalized quality loss associated with the ith quality characteristics at jth experimental run and it varies from a minimum of zero to maximum of one. L^{ij} is the quality loss for the ith quality characteristic at the jth run, and L_{i*} is the maximum quality loss for ith quality characteristic among all the experimental runs. For computing the total normalized quality loss (Y_j) corresponding to each run, we must assign a weighing factor for each quality characteristic considered in the optimization process. If wi represents the weighing factor for the ith quality characteristic, p is the number of quality characteristics then Y_j can be computed using:

$$Y_j = \sum_{i=1}^{p} w_i y_j \quad (4)$$

After finding the total normalized quality loss, the next step is to calculate the MSNR (η_j) at each experimental condition as given below:

$$\eta_j = -10\log_{10}(Y_j) \quad (5)$$

The aim is always to maximize the MSNR. The average value of all MSNR when a process parameter is at different distinct level is used to describe the effect of a process parameter on quality characteristics at that level. A parameter level corresponding to the maximum average MSNR is called as the optimum level for that parameter. The predicted value of MSNR (η_p) at optimum parameter levels is calculated by using following formula [11]:

$$\eta_p = \eta_m + \sum_{i=1}^{k}(\eta_i - \eta_m) \quad (6)$$

Where, k is the no. of factors, ηm is the mean value of multiple S/N ratios in all experimental runs and η_i is the multiple S/N ratios corresponding to optimum factor levels. Some verification experiments are conducted at suggested optimum parameter levels to confirm the predicted response [9]. The analysis of variance was used to establish statistically significant machining parameters and the percentage contribution of these parameters on the MRR and K_w.

IV. Results and Discussion

The observed and calculated values of desired responses MRR and K_w using L_{27} OA have been shown in Table 3. The quality loss values for each quality characteristics against different experimental runs are calculated using the Eqs. (1) and (2). The results are given in Table IV.

The normalized quality loss, total normalized quality loss (TNQL) and MSNR for both quality characteristics have been calculated using equations (3), (4) and (5) as shown in Table V.

For calculating the total normalized quality loss, two unequal weights such as w_1=0.7 and w_2=0.3 for both MRR and Kw have been assumed. The effect of different cutting parameter levels on MSNR is shown in Table VI. In the present work, MRR is HB type and Kw is SB type. Therefore, higher weighting factor has been assigned to MRR. The optimum levels of different control factors are applied voltage at level 3 (80 volt), pulse on-time at level 3 (500µs), pulse off-time at level 1 (350µs), electrolyte concentration at level 2 (250g/l) and wire feed velocity at level 1 (1.8m/min). The graphical representation of factor effect at different levels on multiple quality characteristics i.e. MRR and K_w are shown in Fig. 2.

Table IV Quality Loss for MRP and K_w.

Expt. No.	Quality loss values	
	MRR	K_w
1	53.0468	0.1239
2	41.8932	0.0965
3	60.3730	0.0773
4	36.9546	0.0889
5	25.6629	0.0813
6	80.2919	0.0995
7	46.9774	0.1293
8	50.8025	0.1189
9	7.6947	0.0937
10	25.6629	0.1267
11	36.3335	0.1224
12	37.5917	0.1215
13	23.5420	0.1028
14	28.0541	0.1016
15	33.3738	0.0867
16	21.7140	0.1129
17	15.7971	0.1305
18	7.0098	0.1099
19	9.3979	0.1134
20	13.2520	0.0917
21	15.0815	0.1187
22	14.1225	0.1023
23	20.0729	0.1199
24	16.1417	0.0957
25	7.3403	0.1378
26	13.8299	0.1222
27	14.6237	0.1079

Table V Normalized Quality Loss, Total Normalized Quality Loss (TNQL) Values of MRR and K_w and Their Multiple S/N Ratios (MSNR)

Expt. No.	Normalized quality loss values		TNQL	MSNR (dB)
	MRR	K_w		
1	0.6607	0.8991	0.2697	5.6912
2	0.5218	0.7003	0.5754	2.4003
3	0.7519	0.5609	0.6946	1.5827
4	0.4603	0.6451	0.5157	2.8760
5	0.3196	0.5899	0.4007	3.9718
6	1.0000	0.7221	0.9166	0.3782
7	0.5851	0.9383	0.6911	1.6046
8	0.6327	0.8628	0.7017	1.5385
9	0.0958	0.6799	0.2710	5.6703
10	0.3196	0.9194	0.4995	3.0146
11	0.4525	0.8882	0.5832	2.3418
12	0.4682	0.8817	0.5923	2.2746
13	0.2932	0.7460	0.4290	3.6754
14	0.3494	0.7373	0.4658	3.3180
15	0.4157	0.6292	0.4798	3.1894
16	0.2704	0.8193	0.4351	3.6141
17	0.1967	0.9470	0.4218	3.7489
18	0.0873	0.7975	0.3004	5.2230
19	0.1170	0.8229	0.3288	4.8307
20	0.1650	0.6655	0.3152	5.0141
21	0.1878	0.8614	0.3899	4.0905
22	0.1759	0.7424	0.3459	4.6105
23	0.2499	0.8701	0.4359	3.6061
24	0.2010	0.6945	0.3491	4.5705
25	0.0914	1.0000	0.3639	4.3902
26	0.1722	0.8868	0.3866	4.1274
27	0.1821	0.7830	0.3624	4.4081
Mean MSNR (η_m)				3.5467

TABLE VI EFFECT OF FACTOR LEVELS ON MSNR

Symbol	Control factors	Mean of multiple S/N ratios (dB)		
		Level 1	Level 2	Level 3
A	Applied voltage	2.8571	3.3778	4.4053*
B	Pulse on-time	3.4712	3.3551	3.8139*
C	Pulse off-time	3.8941*	3.0869	3.6591
D	Electrolyte concentration	3.6425	3.7497*	3.2479
E	Wire feed velocity	3.8119*	3.3408	3.4875

*Optimum parameter level

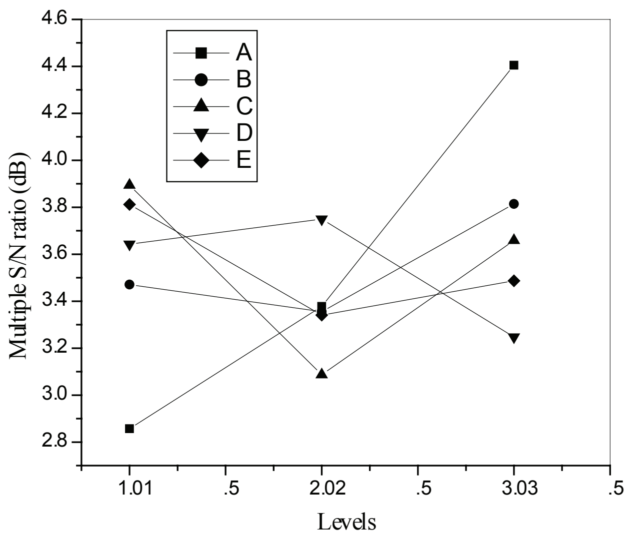

Fig. 2 Effect of control factors on multiple S/N ratios

A better feel for the relative effect of the different factors can be obtained by the decomposition of the variance, which is commonly called analysis of variance (ANOVA). It is a computational technique to estimate quantitatively the relative significance (F-ratio), and also the percentage contribution (PC) of each factor on quality characteristics. The sum of squares (SS) and mean sum of squares or variance (V) for each factor, and error (EP) obtained by pooling of factor B and E is calculated and then evaluate the F value and PC. The ANOVA given in Table 7 shows the percentage contribution of different control factors on multiple quality characteristics (MRR and Kw) in ascending order as: pulse on-time (5.82), wire feed velocity (5.94), electrolyte concentration (7.13), pulse off-time (17.63) and applied voltage (63.48). It may be also observed that applied voltage, pulse on-time, pulse off-time, electrolyte concentration and wire feed velocity are the significant control factors under more than 99% confidence level.

TABLE VII RESULTS OF ANOVA FOR MRR AND K_w

Factor	SS	dof	V	F	PC (%)
A	11.173	2	5.586	10.784	63.48
B	1.024#	2	0.512	-	5.82
C	3.102	2	1.551	2.994	17.63
D	1.257	2	0.628	1.212	7.13
E	1.046#	2	0.523	-	5.94
EP	2.07	4	0.518		
Total	14.3307	10			100

Pooled error

V. CONFIRMATION EXPERIMENT

The confirmation of experiment is performed by conducting a test using a combination of the cutting parameters and levels previously calculated. This is the final step of optimization procedure to predict and verify the improvement of the performance characteristics as shown in Table 8. The improvement in MSNR at the optimum level has been found to be 2.7609dB. The value of MRR and Kw at the optimum level are 0.3026mm3/min and 0.3108mm against the starting cutting parameter setting of 0.1373mm3/min and 0.3521mm respectively.

TABLE VIII RESULTS OF CONFIRMATION EXPERIMENT

	Initial setting	Optimum values	
		Prediction	Experiment
Level	$A_1B_1C_1D_1E_1$	$A_3B_3C_1D_2E_1$	$A_3B_3C_1D_2E_1$
MRR (mm^3/min)	0.1373	-	0.3026
K_w (mm)	0.3521	-	0.3108
MSNR (dB)	5.6912	5.4881	8.4521

Improvement of S/N ratio= 2.7609dB

VI. CONCLUSIONS

In the present study, MRR and Kw have been optimized simultaneously by using Taguchi quality loss function during TW-ECSM of Pyrex glass. The following conclusions have been made from the present work:

1. The preferred operating levels of TW-ECSM parameters for maximum MRR and minimum K_w are applied voltage at 80V, pulse on-time at 500µs, pulse off-time at 350µs, electrolyte concentration at 250g/l and wire feed velocity at 1.8m/min.

2. Applied voltage, pulse off-time and electrolyte concentration significantly affect the MRR and Kw in the present operating conditions whereas pulse on-time and wire feed velocity have negligible effect on output quality characteristics.

3. It has been observed that MRR improved by 120% and K_w decreased by 13% from the initial value. Hence, it can be concluded that the quality loss will always be possible during simultaneous optimization of multiple quality characteristics. Therefore, the careful selection of weighting factor for different quality characteristics is more important.

4. The percentage contributions of factors in multi-objective optimization of MRR and Kw in increasing order are pulse on-time (5.82%), wire feed velocity (5.94%), electrolyte concentration (7.13%), pulse off-time (17.63%) and applied voltage (63.48%).

Acknowledgement

The authors want to sincerely express their gratitude to the financial support for this work has been granted by the Council of Scientific and Industrial Research (CSIR), Government of India, New Delhi through project no. 22/(0486)/09/EMR-II entitled "Experimental and Numerical Study of Traveling Wire Electrochemical Spark Machining of Advanced Engineering Materials".

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