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ANALYSIS OF TRAVELING WIRE ELECTROCHEMICAL DISCHARGE MACHINING OF HYLAM BASED COMPOSITES BY TAGUCHI METHOD

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ABSTRACT

Precision machining of electrically non-conducting engineering ceramics and composites etc. is an immediate need of the present industries. For cutting these materials Traveling wire electrochemical discharge machining (TW-ECDM) process is a useful process. TW-ECDM which is a complex combination of ECM and wire-EDM, has a good application for machining advanced non-conducting ceramic materials like zirconia, alumina, silicon nitride, diamond, glass, ruby and composites like FRP etc. The present research paper includes a hybrid approach of Taguchi method and principal component analysis (PCA) for multi response analysis of traveling wire electrochemical discharge machining process during cutting of groove on Hylam based fiber reinforced composite work-piece. Optimal combinations of operating parameters viz. pulse on time as a percentage of total time, frequency, applied voltage, concentration of electrolyte and wire feed rate were observed for optimal values. Initially Taguchi methodology based single response optimization was performed. The signal to noise ratios obtained from Taguchi methods have been further used in principal component analysis for multi response optimization. The responses at predicted optimum parameter level are in good agreement with the results of confirmation experiment.

KEYWORDS: TW-ECDM Cutting, Taguchi Method, Principle Component Analysis, Fiber Reinforced Composites, Multi Parametric Optimization

INTRODUCTION

In order to face the challenge of machining new materials such as engineering ceramics and composites like fiber reinforced plastic (FRP) etc., the researchers are urgently looking for advanced machining techniques. Hylam, a mixture of cellulose adhesive based on modified epoxy resin and hardener, has important properties like impact resistance, scratch resistance, abrasion resistance and corrosion resistance. Fiber reinforced composites are being accepted in structural and non-structural applications like household goods, switch boards and control panels. Although fiber reinforced composites can be machined by traditional machining process but accuracy is less and surface finish are rough. In addition more complex shapes, low rigidity structures and micro mechanical components with tight tolerances and fine surface finish are often needed. The laminated structure of FRP is damaged and the insulating property of the material is also affected by conventional machining.

The manufacturing scientists are making use of combined hybrid machining process so that the adverse effects of individual processes are reduced. ECDM is an example. Bhattacharyya et al (Bhattacharyya, 1999) highlighted the modular mechatronic features of indigenously developed ECDM setup to carryout experiments. NaOH solutions with varying concentrations were taken as electrolyte. A pulsed DC electric supply had been utilized for drilling operation on ceramic work samples. Basak and Ghosh (Basak, 1997) proposed a theoretical model of electrochemical discharge machining to predict the characteristic of material removal rate for varying input parameters and also done experiments on a developed set up to support the proposed model. Jain et.al [3] applied electrochemical spark machining process successfully for cutting of quartz, quartz using a controlled feed and wedge edged tool using both cathode and anode as tool i.e by using both straight polarity and reverse polarity. Chak and Rao [4] had shown the possibility of drilling large size holes in aluminum oxide by trepanning during electrochemical discharge machining. Jain et.al [5] have investigated into the effect of applied voltage and electrolyte concentration on material removal rate and diametral over-cut during cutting of glass epoxy and Kevlar epoxy composites by travelling wire electrochemical spark machining (TW-ECSM) while NaOH salt solution was used as electrolyte. Tsuchiya et al [6] proposed a new method of cutting diamond, glass and ruby in two dimensional and complicated contours. The method was a combination of ECDM and Wire-EDM Glass and ceramics were slotted successfully. Singh et.al [7] devised a travelling wire traveling wire electrochemical spark machining (TW-ECSM) for cutting piezoelectric ceramic and carbon fiber epoxy composites with wire in vertical position and perpendicular to the work-piece.

The feasibility study of machining FRP with electrochemical spark machining (ECSM) was made using response surface methodology and it was concluded that ECSM is a viable solution for cutting FRP [9]. An experimental set up was devised to study the influence of external circuit parameters on the discharge process of electrochemical discharge machining (ECDM) [10]. A model similar to arc discharge valve was developed to explain the electrochemical discharge phenomenon and many experimental results were explained by this model [11]. Machining of non-conducting materials such as alumina and glass is always a difficult problem. With electrochemical spark abrasive drilling [12] better results were obtained than ordinary drilling. In order to reveal the basic mechanism and temperature rise an attempt was made to measure the time varying current during ECSM [13]. Spark assisted chemical engraving (SACE) of glass had been investigated using current voltage measurements and photographs [14]. Mediliyegedara et al [15] developed an intelligent pulse discrimination system to develop a control strategy for ECDM process. A feed forward neural network was trained to classify the pulses with various activation functions. Skrabalak et al [16] presented a model for estimation of current of electrochemical dissolution and electro discharge machining in ECDM. Based on the model an attempt was made to adopt a fuzzy logic controller for ECDM system. Bhondwe et al. [17] developed a thermal model for the calculation of material removal rate of ECDM.

Very few attempt was made to determine the dominant parameters of the process in order to reduce the cost and to improve the quality. Further fiber reinforced plastic is a new material and TW-ECDM of FRP is a challenge. This fact is considered and the present paper deals with Taguchi Method based parametric analysis during TW-ECDM cutting of groove of flat surfaces of hylam based fiber reinforced composite work piece. Pure engineering judgement is often used to deal with multiple quality characteristics in process optimization. This is very subjective in nature and brings uncertainty in decision making. It was suggested that normalized quality loss in Taguchi Method can be used for optimizing the multiple quality characteristics simultaneously. But due to possible correlations among the multiple quality characteristics an uncertainty is always possible in the selection of weighing factor. This uncertainty has been overcome by using hybrid approach of Taguchi Method and Principal Component Analysis (PCA).

FUNDAMENTALS OF TW-ECDM

The Traveling Wire Electrochemical Discharge Machining process is a complex combination of electrochemical machining and travelling wire electrical discharge machining. In TW-ECDM, pulsed D.C power is applied between the wire and the auxiliary electrode. In this process the conducting wire is always in contact with the non-conducting work piece material The diameter of the conducting wire varies from 0.03 to 0.3 mm and the material for conducting wire may be copper, brass, tempered steel, tungsten, molybdenum, brass-coated or multi-coated super alloy. The work piece material which can be machined is in general electrically non-conducting materials like zirconia (ZrO_2), alumina (Al_2O_3), silicon nitride (Si_3N_4), diamond, glass, ruby and composites like fiber reinforced plastic (FRP) etc. The electrolyte used here is the solution of NaOH, NaCl, $NaNO_3$ or KOH salt. In this process wire is used as cathode and auxiliary electrode is used as anode. As pulsed D.C power is applied, hydrogen and vapor bubbles are formed and accumulated near the wire surface. With the further increase of applied voltage sparking from the wire takes place. The electric discharge occurs between the wire and electrolyte across the insulating layer of gas bubbles. As the job surface is kept in the sparking zone, material is removed mainly due to melting and vaporization of the work piece material. For machining of composites this is witnessed by the presence of globules (i.e resolidified material) on the protruding fibers and heat affected or thermally damaged zone. The mechanism is shown in figure 1.

EXPERIMENTAL SET-UP AND PLANNING FOR EXPERIMENTATION

The developed experimental set up has been utilized to study the traveling wire electrochemical discharge machining process. The set up consists mainly of main machining chamber, auxiliary electrode and job positioning unit, wire feeding unit, electrolyte flow control unit, electrical power supply unit and control unit of wire feeding. The auxiliary electrode and job positioning unit consists of job holding unit, job feeding unit and auxiliary electrode positioning unit. Wire feeding unit consists of dead spool unit, power spool unit, wire tension adjusting mechanism and guide pulley and wire positioning unit. The wire positioning unit in turn consists of wire guide unit and wire guide positioning unit. The schematic diagram of the set up is shown in figure 2 and photograph of the set up is shown in figure 3.

In the present paper two qualities such as material removal rate and radial over-cut have been optimized simultaneously during traveling wire electrochemical discharge machining operation of Hylam based fiber reinforced composites with hybrid approach of Taguchi Method and Principal Component Analysis.

The control factors taken are: pulse on time (%), frequency (Hz), applied voltage (V), concentration of electrolyte (%) and wire feed rate (mm/sec). The work piece material is 3mm thick Hylam based fiber reinforced composite. The electrolyte used here was KOH solution. The inter electrode gap was kept constant at 45 mm and the effective wire length was fixed at 35 mm. Using the micro controller based stepper motor drive unit feed rate of the wire can be set from 0.05 mm/sec to 0.4 mm/sec. The rpm of the stepper motor can be varied from 1 to 80. The input voltage to the stepper motor is 12V and the input current to the stepper motor is 4A.

The traveling wire electrochemical discharge machining system demands for voltage of 5V to 150V, current 0A to 7A and frequency of 50Hz to 2000Hz depending on the rate of material removal and other machining criteria. A pulsed D.C power supply provides the supply voltage from 0V to 100V. The different process parameters (control factors) taken are pulse on time as a percentage of total time, frequency of the power supply, applied voltage, concentration of electrolyte and wire feed rate. Considering the required properties like 0.25 mm diameter were chosen as cathode or tool. Hylam based fiber reinforced composite of 3 mm thickness were used as work piece. Five levels of each control factor have been selected without considering the interaction effect.

The numerical values of control factors at different levels are shown in table 1. An exhaustive pilot experiment has been conducted to decide the parameter range for thorough cutting of Hylam based fiber reinforced composite sheet. The initial setting of parameters was pulse on time = 50%, frequency = 55 Hz, applied voltage = 30 V, concentration of electrolyte = 10%, wire feed rate = 50 mm/sec. The quality characteristics analyzed are material removal rate and radial over cut. For each experiment time taken is 10 minutes. The weight of the job before and after machining was measured and the difference was divided by machining time to get the material removal rate. The weight of the work piece before and after machining was measured by SARTORIUS GC 103 digital balance, in which minimum measurable weight is 1 mg and maximum measurable weight is 25 grams. The radial over cut was determined using the following formula:

$$ROC = (W - d)/2$$

Where W= Width of the cut and d = wire diameter.

Olympus STM6 optical measuring microscope was used to measure the radial over cut. The minimum length that can be measured with it is 0.5 micron. Each experiment is replicated for three times to observe 3 readings of material removal rate and radial over cut and averages of the 3 values are taken.

Initially the experiments were performed by using $L_{25}(5^5)$ orthogonal array to obtain the results of single objective optimization for material removal rate and radial over cut respectively. The signal to noise ratios of each characteristic has been further used in PCA to optimize the MQC. Finally the analysis of variance (ANOVA) was used to find out the most influential machining parameter for multiple responses.

ANALYSIS OF EXPERIMENTAL OBSERVATION

In this system, the results of single objective optimization using Taguchi Method and multi-objective optimization by hybrid approach of Taguchi Method and principal component analysis have been discussed. The verification results obtained on suggested optimum parameter levels have also been reported.

Orthogonal Array Experiments

The degree of freedom has been calculated without considering the interaction effect among different control factors.

The d.f. due to grand total sum of squares = no. of experiments = 25. Hence d.f due to total sum of squares = (25 – 1) = 24. But d.f for each factor = (5-1) = 4. Therefore d.f for error = 24 – (4X5) = 4. As the d.f for total sum of squares without considering error is (5-1) X 4 +1 = 21, the nearest larger set of experiments is taken one of which is $L_{25}(5^5)$ orthogonal array. The observed quality values for each quality characteristics viz. material removal rate (mg/min) and radial over cut (mm) in different trials have been tabulated in table 2.

Single Objective Optimization Using Taguchi Method

The S/N ratio values for material removal rate and radial over cut have been calculated from experimental values of each quality characteristics. The S/N ratio corresponding to each experimental run is given in table 3. The factor effect of a parameter at any level is computed by taking the average of all S/N ratios at the same level. The effects of various factors at different levels for the responses are shown in table 4. Also the signal to noise ratio at different factor levels are shown in figure 4 and figure 5.

From S/N ratios it is observed that for achieving maximum MRR the optimal parametric setting is $A_5B_5C_5D_4E_1$ i.e. pulse on time as 70% of the total pulse duration, pulse frequency of 75 Hz, applied voltage of 50V, electrolyte concentration of 25% by weight and wire feed rate of 50mm/sec. For achieving minimum radial over cut optimal parametric setting is $A_1B_1C_1D_1E_4$ i.e. pulse on time as 50% of the total pulse duration, pulse frequency of 55 Hz, applied voltage of 30V, 10% by weight concentration of electrolyte and wire feed rate of 225 mm/sec.

Analysis of variance (ANOVA) helps to estimate quantitatively the relative contribution that each control factor or parameter makes on the overall measured response. The relative significance of factors is often represented by F-ratio or in percentage contribution. The results of ANOVA for material removal rate and radial over cut are shown in table 5. The results show that for material removal rate the effects of pulse on time, applied voltage and concentration of electrolyte are significant at 99% confidence level and for radial over cut at 90% confidence level. The contribution of factors in decreasing order for material removal rate is applied voltage, pulse on time, concentration of electrolyte, wire feed rate and frequency of power supply; for radial over cut is applied voltage, concentration of electrolyte, wire feed rate, pulse on time and frequency.

Multi-Objective Optimization Using Hybrid Approach of Taguchi Method and Principal Component Analysis

The normalized S/N ratios for each quality characteristics material removal rate and radial over cut against different experimental runs have been calculated are shown in table 6. The correlation coefficient array obtained is shown in table 7. The eigen values and eigen vectors computed from the correlation coefficient matrix using MINITAB are 1.6905, 0.3095 and [0.707, 0.707], [-0.707, 0.707] respectively. The two principal components PC1, PC2 and their integrated TPCI for each experimental run have been computed and tabulated in table 8. The factor effect at each parameter levels have been computed by taking the average of all TPCI at that level and are given in table 9.

Graphical plots for factor effects at different levels for material removal rate and radial over cut are shown in figure 6 and figure 7 respectively. The optimum parameter level for multiple quality characteristics corresponds to maximum average TPCI for a control factor which is $A_5B_4C_5D_5E_1$ i.e. pulse on time as 70% of the total pulse duration, 85 Hz frequency, applied voltage of 50V, 30% by weight concentration of electrolyte and wire feed rate of 50 mm/sec.

The ANOVA given in table 10 shows the contribution of different parameters in descending order as applied voltage, concentration of electrolyte, pulse on time, wire feed rate and frequency. The graphical representation of factor effects at different levels for TPCI are shown in figure 8 and contribution of different control factors on TPCI is shown in figure 9. The improvement in predicted TPCI at the optimum level is found to be 1.093 dB as compared with the initial parametric setting.

The value of material removal rate and radial over cut at the optimum level are found to be 0.67 mg/min and 0.0780 mm respectively, after conducting the verification experiment. The microscopic view of the groove cut on the machined work piece at optimal parametric setting condition of TW-ECDM is shown in figure 10. The results of confirmation experiment show that there is an improvement.

CONCLUSIONS AND DISCUSSIONS

Fibre reinforced plastic is a recently used material and traveling wire electrochemical discharge machining of fibre reinforced plastic is a challenge. This challenge was overcome by developing an indigenous setup with a lot of constraints and proper planning of experiments helped in extracting maximum amount of inferences from minimum number of experiments.

The difficulties of dealing with multiple quality characteristics have been overcome using the hybrid approach of Taguchi method and principal component analysis. The following concluding remarks can be summarized as follows—

- The single objective optimization using Taguchi Method applied voltage, pulse on time and concentration of electrolyte are the significant factors for material removal rate and applied voltage, concentration of electrolyte and wire feed rate are significant for radial over cut.
- The optimum parameter levels predicted in single objective optimization for maximum value of material removal rate is $A_5B_5C_5D_4E_1$ and for minimum value of radial over cut is $A_1B_1C_1D_1E_4$.
- As compared to initial parameter setting the multiple quality characteristics has been improved by using hybrid approach of Taguchi Method and principal component analysis. The optimum value of control factor for overall improvement in MQC are pulse on time as 70% of total pulse duration, 85 Hz frequency, applied voltage of 50V, 30% by weight concentration of electrolyte and wire feed rate of 50 mm/sec.
- The contribution of different control factors on multiple quality characteristics is pulse on time – 14.99%, frequency – 2.07%, applied voltage – 41.56%, concentration of electrolyte – 22.36% and wire feed rate – 10.39%. The applied voltage is found to be the most significant parameter in the operating range.
- In multi-objective optimization the loss in some quality characteristics is always possible as compared to single objective optimization but over all quality is improved. The value of material removal rate and radial over cut at the optimum level are found to be 0.67 mg/min and 0.0780 mm respectively.

Finally if the results of this set of experiment can be followed properly then precision machining of fibre reinforced plastic will become possible which will be of tremendous help in future for application purpose.

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APPENDICES

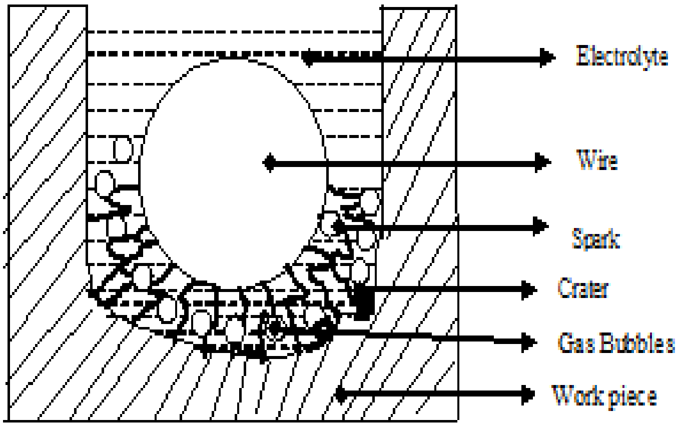
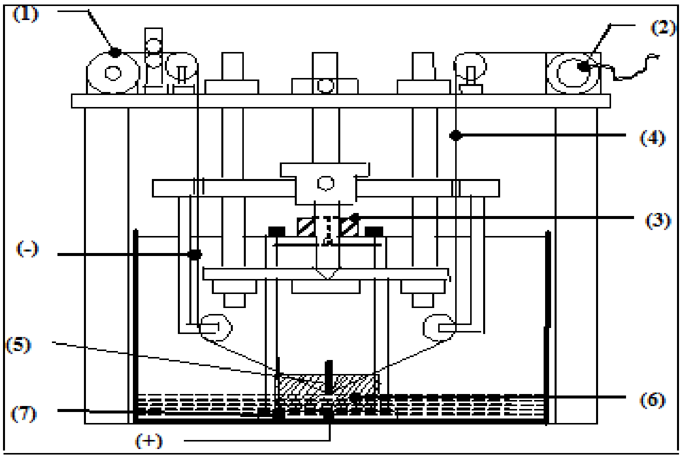


Figure 1: Spark Generation Process in TW-ECDM



Legends: (1) Input Spool, (2) Output Spool with Stepper Motor, (3) Pulley for Gravity Feed Mechanism, (4) Wire Electrode (Cathode), (5) Work-Piece in Vertical Position, (6) Work-Piece Holding Perspex Piece, (7) Auxiliary Electrode (Anode)

Figure 2: Schematic Diagram of TW-ECDM Set up

Figure 3: TW-ECDM System Set up

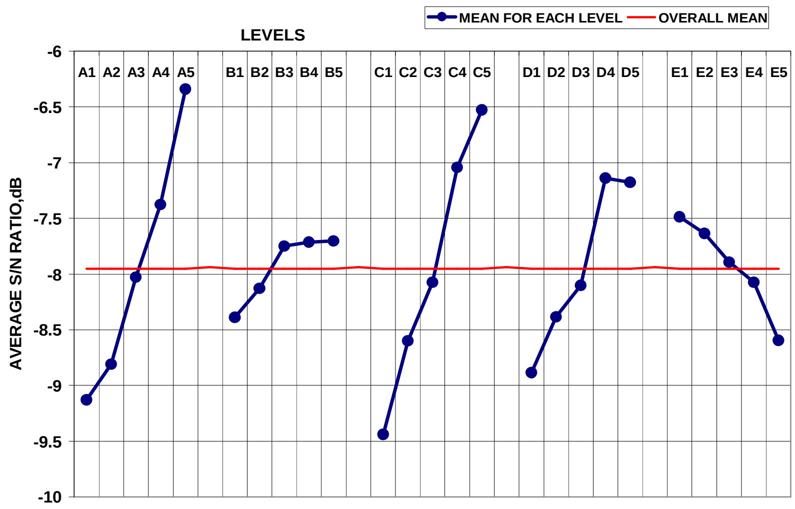


Figure 4: S/N Ratio Plot for MRR

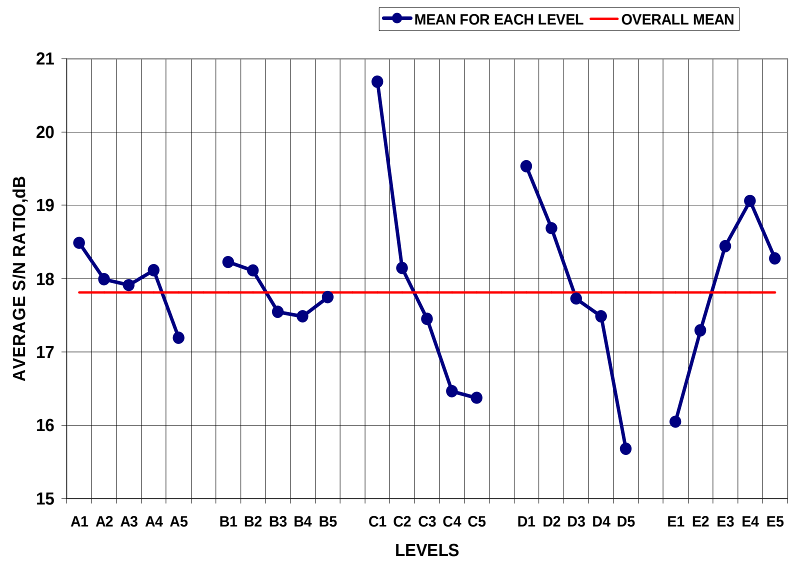


Figure 5: S/N Ratio Plot for ROC

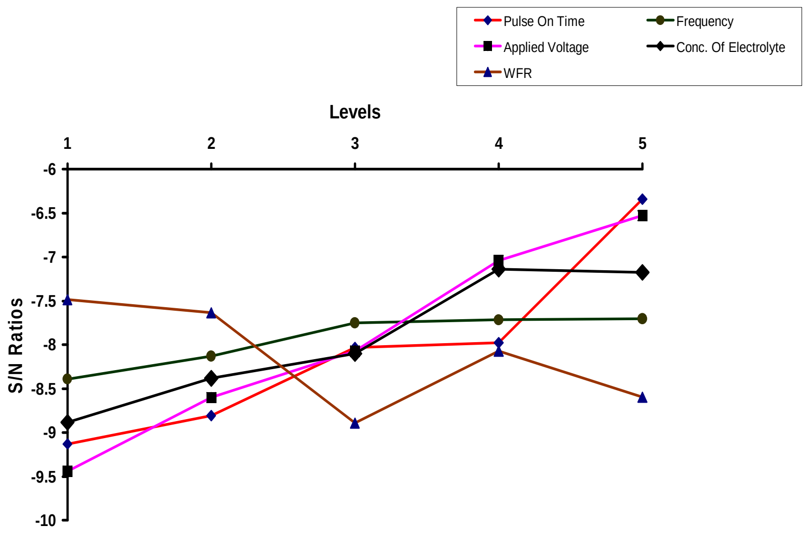


Figure 6: Factor Effects at Different Levels for MRR

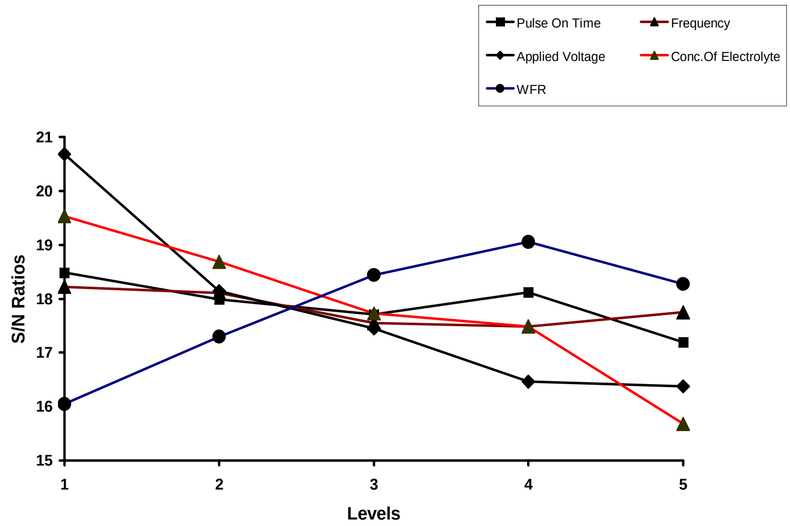


Figure 7: Factor Effects at Different Levels for ROC

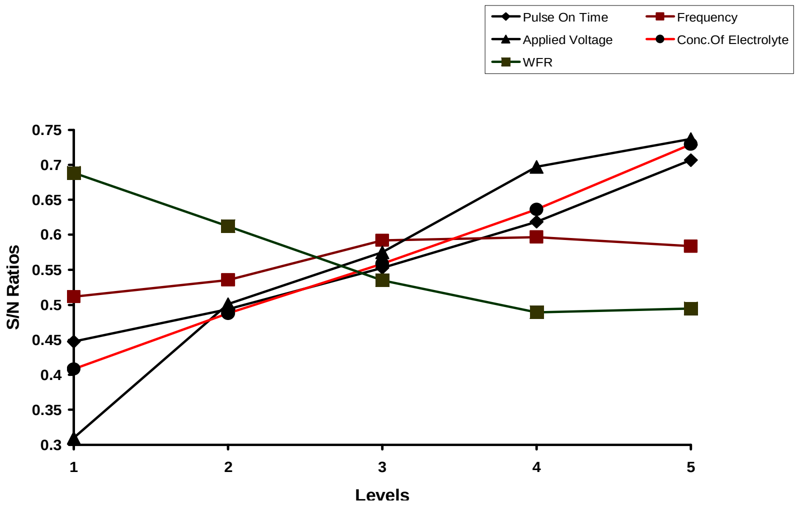


Figure 8: Factor Effects at Different Levels for TPCI

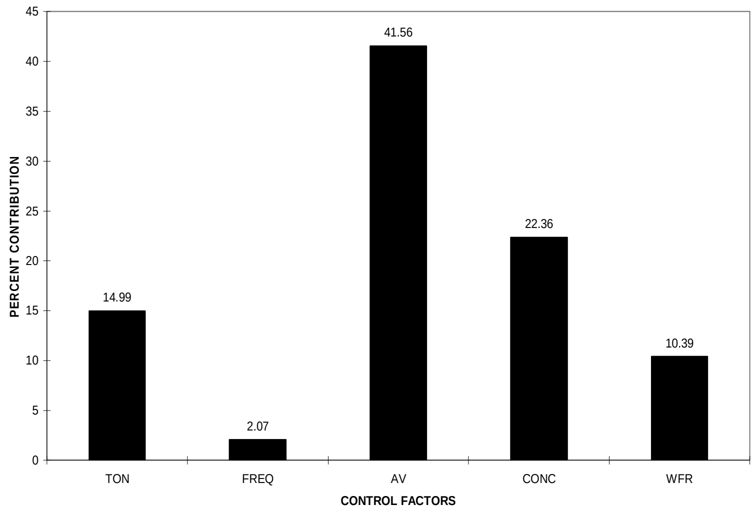


Figure 9: Contribution of Different Control Factors on TPCI of Multiple Quality Characteristics

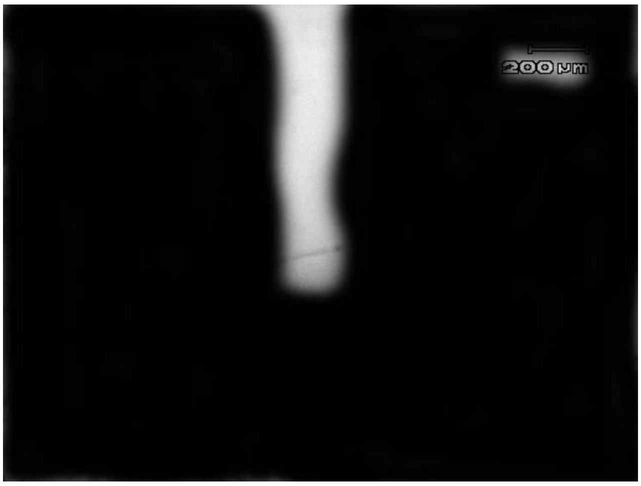


Figure 10: Microscopic View of Machined Work-Piece

Table 1: Control Factors and Their Levels Used in the Experiment

Symbol	Factors	Unit	Level1	Level2	Level3	Level4	Level5
A	Pulse on time	%	50	55	60	65	70
B	Frequency	Hz	55	65	75	85	95
C	Applied Voltage	V	30	35	40	45	50
D	Concentration	%	10	15	20	25	30
E	Wire feed rate	mm/min	50	125	175	225	300

Table 2: Experimental Layout Using L_{25} Orthogonal Array

Trial No.	Factor Level					MRR (mg/min)	ROC (mm)
	A	B	C	D	E		
1	1	1	1	1	1	0.26	0.071
2	1	2	2	2	2	0.31	0.138
3	1	3	3	3	3	0.35	0.121
4	1	4	4	4	4	0.43	0.112
5	1	5	5	5	5	0.43	0.180
6	2	1	2	3	4	0.31	0.106
7	2	2	3	4	5	0.35	0.108
8	2	3	4	5	1	0.47	0.308
9	2	4	5	1	2	0.41	0.135
10	2	5	1	2	3	0.30	0.066
11	3	1	3	5	2	0.42	0.148
12	3	2	4	1	3	0.39	0.115
13	3	3	5	2	4	0.44	0.105
14	3	4	1	3	5	0.31	0.118
15	3	5	2	4	1	0.44	0.158
16	4	1	4	2	5	0.40	0.128
17	4	2	5	3	1	0.51	0.162
18	4	3	1	4	2	0.42	0.114
19	4	4	2	5	3	0.44	0.137
20	4	5	3	1	4	0.38	0.129
21	5	1	5	4	3	0.59	0.195
22	5	2	1	5	4	0.43	0.107
23	5	3	2	1	5	0.38	0.092
24	5	4	3	2	1	0.49	0.174
25	5	5	4	3	2	0.55	0.151

Table 3: S/N Ratios for Material Removal Rate and Radial over-Cut

Expt. No.	S/N Ratio (dB)	
	MRR	ROC
1	-11.7005	22.9748
2	-10.1728	17.2024
3	-9.1186	18.3443
4	-7.3306	19.0156
5	-7.3306	14.8945
6	-10.1728	19.4939
7	-9.1186	19.3315
8	-6.5580	10.2290
9	-7.7443	17.3933
10	-10.4576	23.6091
11	-7.5350	16.5948
12	-8.1737	18.7860
13	-7.1309	19.5762
14	-10.1728	18.5624
15	-7.1309	16.0269
16	-7.9588	17.8558
17	-5.8486	15.8097
18	-7.5350	18.8619
19	-7.1309	17.2656
20	-8.4043	17.7882
21	-4.5830	14.1993
22	-7.3306	19.4123
23	-8.4043	20.7242
24	-6.1961	15.1890
25	-5.1927	16.4205
Overall Mean	**-7.9375**	**17.8106**

Table 4: S/N Response Table for Material Removal Rate and Radial over-Cut

Symbol	Factors	Mean S/N Ratios(Db)				
		Level1	Level2	Level3	Level4	Level5
MRR A	Pulse On Time	-9.1306	-8.8103	-8.0297	-7.3755	-6.3413
B	Frequency	-8.3900	-8.1299	-7.7494	-7.7149	-7.7032
C	Applied Volts	-9.4393	-8.6023	-8.0745	-7.0438	-6.5275
D	Concentration	-8.8864	-8.3892	-8.1011	-7.1396	-7.1770
E	Wire feed rate	-7.4868	-7.6360	-8.8938	-8.0738	-8.5970
ROC A	Pulse On Time	18.4863	17.9916	17.9093	18.1162	17.1891
B	Frequency	18.2237	18.1084	17.5451	17.4852	17.7478
C	Applied Volts	20.6841	18.1426	17.4496	16.4614	16.3746
D	Concentration	19.5333	18.6865	17.7262	17.4870	15.6792
E	Wire feed rate	16.0459	17.2946	18.4409	19.0572	18.2737

Table 5: Results of ANOVA for Material Removal Rate and Radial over Cut

Symbol	Factors	d.f	SS	MS	F	Contribution
MRR A	Pulse on Time	4	25.2875	6.3219	13.1378	35.9804
B	Frequency	4	1.9085	0.4771	0.9915	2.7155
C	Applied Volts	4	27.5150	6.8788	14.2951	39.1498
D	Concentration	4	11.7040	2.9260	6.0806	16.6531
E	Wire feed rate	4	3.7470	0.9368	1.9468	5.3314
Error		4	0.1193	0.0298	---	0.1698
Pooled Error		12	5.7748	0.4812	---	8.2170
Total		**24**	**70.2813**	**2.9284**	**---**	**100.0000**

Table 5: Contd.,

ROC A	Pulse on Time	4	4.8940	1.2235	0.2436	2.5509
B	Frequency	4	2.1930	0.5483	0.1092	1.1430
C	Applied Volts	4	61.8995	15.4749	3.0857	32.2634
D	Concentration	4	41.9480	10.4870	2.0877	21.8642
E	Wire feed rate	4	27.7315	6.9329	1.3802	14.4543
Error		4	53.1908	13.2977	---	27.7242
Pooled Error		12	60.2778	5.0232	---	31.4181
Total		**24**	**191.8568**	**7.9940**	**---**	**100.0000**

Table 6: Normalized S/N Ratios for Material Removal Rate and Radial over Cut

Expt. No.	MRR	ROC
1	0.0000	0.0474
2	0.2146	0.4788
3	0.3628	0.3985
4	0.6140	0.3433
5	0.6140	0.6513
6	0.2146	0.3076
7	0.3628	0.3197
8	0.7225	1.0000
9	0.5558	0.4646
10	0.1746	0.0000
11	0.5852	0.5242
12	0.4948	0.3605
13	0.6420	0.3014
14	0.2146	0.3772
15	0.6420	0.5667
16	0.5257	0.4300
17	0.8222	0.5829
18	0.5852	0.3548
19	0.6420	0.4741
20	0.4631	0.4350
21	1.0000	0.7033
22	0.6140	0.3137
23	0.4631	0.2156
24	0.7734	0.6293
25	0.9143	0.5373

Table 7: Correlation Coefficient among the Targeted Quality Characteristics

Correlation Coefficient	Material Removal Rate	Radial over Cut
Material Removal Rate	1.0000	0.6898
Radial Over Cut	0.6898	1.0000

Table 8: Principal Component Scores and Their Integrated TPCI

Expt. No.	PC1	PC2	TPCI
1	0.0335	0.0335	0.0335
2	0.4895	0.1861	0.4425
3	0.5382	0.0252	0.4588
4	0.6768	- 0.1914	0.5424

Table 8: Contd.,

5	0.8946	0.0264	0.7602
6	0.3692	0.0658	0.3222
7	0.4825	- 0.0305	0.4031
8	1.2178	0.1962	1.0597
9	0.7214	- 0.0645	0.5998
10	0.1234	- 0.1234	0.0852
11	0.7843	- 0.0431	0.6563
12	0.6047	- 0.0950	0.4964
13	0.6670	- 0.2408	0.5265
14	0.4184	0.1150	0.3714
15	0.8546	- 0.0532	0.7141
16	0.6757	- 0.0677	0.5607
17	0.9934	- 0.1692	0.8135
18	0.6646	- 0.1629	0.5365
19	0.7891	- 0.1187	0.6486
20	0.6350	- 0.0199	0.5337
21	1.2042	- 0.2098	0.9854
22	0.6559	- 0.2123	0.5215
23	0.4798	- 0.1750	0.3785
24	0.9917	- 0.1019	0.8225
25	1.0263	- 0.2665	0.8262

Average ($\overline{P}$) = 0.5640

Table 9: Response Table for TPCI

Symbol	Factors	Level1	Level2	Level3	Level4	Level5	(Max -Min)	Rank
A	Pulse on Time	0.4475	0.4340	0.5529	0.6186	0.7068	0.2593	3
B	Frequency	0.5116	0.5354	0.5920	0.5969	0.5839	0.0853	5
C	Applied Volts	0.3096	0.5012	0.5749	0.6971	0.7371	0.4275	1
D	Concentration	0.4084	0.4875	0.5584	0.6363	0.7293	0.3209	2
E	Wire feed rate	0.6887	0.6123	0.5349	0.4893	0.4948	0.1994	4

Table 10: Results of ANOVA for TPCI

Symbol	Factors	d.f	SS	MS	F	Contribution (%)
A	Pulse on Time	4	0.2100	0.0525	2.1341	14.99
B	Frequency	4	0.0290	0.0073	0.2967	2.07
C	Applied Volts	4	0.5820	0.1455	5.9146	41.56
D	Concentration	4	0.3132	0.0783	3.1829	22.36
E	Wire feed rate	4	0.1455	0.0364	1.4797	10.39
Error		4	0.1208	0.0302	---	8.63
Pooled Error		12	0.2953	0.0246	---	21.09
Total		**24**	**1.4005**	**0.0584**	**---**	**100.00**