EXPERIMENTAL INVESTIGATION OF MRR, SURFACE ROUGHNESS AND OVERCUT OF AISI 304 STAINLESS STEEL IN EDM

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By

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Under the Guidance of

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CERTIFICATE

This is to certify that the thesis entitled, “**EXPERIMENTAL INVESTIGATION OF MRR, SURFACE ROUGHNESS AND OVERCUT OF AISI 304 STAINLESS STEEL IN EDM**” submitted by Mr. AYUSH PODDAR in partial fulfillment of the requirements for the award of *Bachelor of Technology* Degree in Mechanical Engineering at National Institute of Technology, Rourkela is an authentic work carried out by him under my supervision and guidance.

To the best of my knowledge, the matter embodied in this thesis has not been submitted to any other university/ institute for award of any Degree or Diploma.

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ABSTRACT

EDM has become an important and cost-effective method of machining extremely tough and brittle electrically conductive materials. It is widely used in the process of making moulds and dies and sections of complex geometry and intricate shapes. The workpiece material selected in this experiment is AISI 304 Stainless steel taking into account its wide usage in industrial applications. In today's world 304 stainless steel contributes to almost half of the world's production and consumption for industrial purposes. The input variable parameters are current, pulse on time and duty cycle. Taguchi method is applied to create an L_{27} orthogonal array of input variables using the Design of Experiments (DOE). The effect of the variable parameters mentioned above upon machining characteristics such as Material Removal Rate (MRR), Surface Roughness (SR) and Overcut (OC) is studied and investigated. The tool material is copper.

The results obtained showed that current was the most significant parameter followed by pulse on time and the least significant was the duty cycle for the entire three responses namely Material removal rate, Surface roughness and overcut. With the increase in current and duty cycle MRR increased but for pulse on time it increased only up to 100 µs and then started to decrease. SR increased significantly with the increase in current; for pulse on time it increased up to 100 µs and after that there was no significant increase; and in case of duty cycle SR increased up to 70% and then started to decrease. OC increased with the increase in current and pulse on time but in different fashion and in case of duty cycle, OC increased up to 70% and then started decreasing.

ABBREVIATIONS AND SYMBOLS

A	Ampere
V	Voltage
µs	Micro second
µm	Micro meter
mm	Millimeter
ASEN	Anti-arc sensitivity
DF	Degree of freedom
DOE	Design of experiment
EDM	Electro Discharge Machining
Ip	Discharge current
MRR	Material Removal Rate
OC	Overcut
R^2	Amount of variation
SR	Surface Roughness
SEN	Sensitivity
S	Stander error of deviation
T_{on}	Pulse on time
T_{off}	Pulse off time
T_w	Tool work time
$T\uparrow$	Tool lift time

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CHAPTER 1 INTRODUCTION

1.1 History of EDM

The erosive effect of electrical discharges was first studied by an English scientist, Joseph Priestley in 1770.However it was not until 1943 when two scientists from Russia invented the EDM process. In the process of utilizing the erosive effects of an electrical discharge, they created a controlled process for machining of materials.

1.2 Introduction of EDM

Electrical Discharge Machining, commonly known as EDM is a non-conventional machining method used to remove material by a number of repetitive electrical discharges of small duration and high current density between the workpiece and the tool. EDM is an important and cost-effective method of machining extremely tough and brittle electrically conductive materials. In EDM, since there is no direct contact between the workpiece and the electrode, hence there are no mechanical forces existing between them. Any type of conductive material can be machined using EDM irrespective of the hardness or toughness of the material.

1.3 Principle of EDM

In this process the material is removed from the workpiece due to erosion caused by rapidly recurring electrical spark discharge between the workpiece and the tool electrode. There is a small gap between the tool and the workpiece. The workpiece and tool both are submerged in dielectric fluid, commonly used are EDM oil, deionized water, and kerosene.

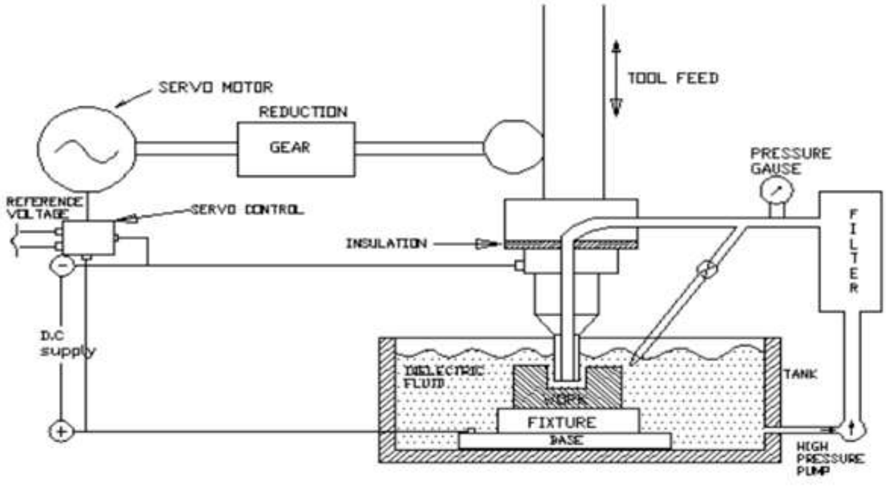

Fig. 1.1 Experimental setup [16]

1.4 Types of EDM

Basically there are two types of EDM: Die-sinking EDM and Wire-cut EDM

a. **Die-sinking EDM-**
   Die-sinking EDM, also known as Volume EDM or cavity type EDM consists of an electrode and a workpiece which is submerged in an insulating fluid such as oil or other dielectric fluids.

b. **Wire-cut EDM-**
   Wire-cut EDM, also known as Spark EDM is mostly used when low residual stresses are required, as it does not needs high cutting forces for removal of material.

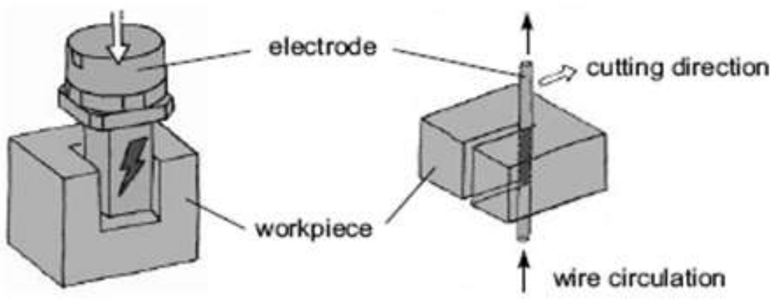

Fig.1. 2 Die sinking & wire cut EDM Process [16]

1.5 Important Parameters of EDM

a. **Spark on-time (T_{on}):** The duration of time (µs) the current is allowed to flow per cycle.
b. **Spark off-time (T_{off}):** the duration of time in between the sparks generated. During this time the molten material gets removed from the gap between the electrode and the workpiece.
c. **Voltage (V):** It is the potential difference applied between the electrode and the workpiece.
d. **Discharge Current (Ip):** It is the current flowing through the electrode and is measured in amp.
e. **Duty cycle (τ):** It is the ratio of T_{on} divided by total cycle time (T_{on}+T_{off}).

1.6 Advantages of EDM

a. Any electrically conductive material can be machined using this process.
b. Materials which are super tough can be machined without any deformation.
c. There are no mechanical forces present between the workpiece and tool.
d. Complex and intricate shape sections can be easily produced.

1.7 Limitations of EDM

a. The workpiece has to be electrically conductive so that electric sparks can be generated.
b. The measure of the gap that is the distance between the electrode and the workpiece is not always easily predictable, especially in case of complex geometries.
c. The material removal rate is rather low in case of EDM; hence it is limited to the production of certain sections.
d. The electrical parameters used in the EDM process have to be optimized for best results.

CHAPTER 2 LITERATURE REVIEW

In this chapter, some selected research papers have been discussed related to Electrical Discharge Machining. The studies carried out in these papers are mainly concerned with the EDM parameters such as current, voltage, pulse on time, duty cycle, etc. and how these affect the machining characteristics like MRR, SR, OC, etc.

B.S. Reddy et al. [1] carried out a study on the effect EDM parameters over MRR, TWR, SR and hardness. Mixed factorial design of experiments and multiple regression analysis techniques had been employed to achieve the desired results. The parameters in the decreasing order of importance for; MRR: servo, duty cycle, current and voltage; TWR: current, servo and duty cycle; SR: current; HRB: servo only. M.M. Rahman et al. [2] investigated the effect of the peak current and pulse duration on the performance characteristics of the EDM. The conclusions drawn were: the current and pulse on time greatly affected the MRR, TWR and SR, the MRR increases almost linearly with the increasing current, the SR increases linearly with current for different pulse on time, TWR increased with increasing peak current while decreased when the pulse on time was increased.

I. Puertas et al. [3] carried out results which showed that the intensity and pulse time factor were the most important in case of SR while the duty cycle factor was not significant at all. The intensity factor was again influential in case of TWR. The important factors in case of MRR were the intensity followed by duty cycle and the pulse time. S.H. Tomadi et al. [4] investigated the machining of tungsten carbide with copper tungsten as electrode. The full factorial design of experiments was used for analyzing the parameters. In case of SR, the important factors were voltage and pulse off time while current and pulse on time were not significant. For MRR the most influential was pulse on time followed by voltage, current and pulse off time. Finally in case of TWR the important factor was pulse off time followed by peak current.

Iqbal and Khan [5] concluded that the voltage and rotational speed of the electrode are the two significant parameters for EDM milling. Optimization is concerned with maximizing the MRR and minimizing EWR along with an optimum R_a. Norliana Mohd Abbas et al. [6] studied the research trends in dry wire EDM, EDM in water, EDM with powder additives, EDM on ultrasonic vibration and modeling techniques in predicting EDM performances. For every method that was introduced and employed in EDM process, the objectives were the same: to improve the capability of machining performances, to get improved output product and to create better technologies to machine new materials.

Singh and Maheshwari [7] found that the input parameters such as current, pulse on time, voltage applied and the workpiece material greatly influences overcut. It increases with the increase of current but only up to a certain limit. It also depends on the gap voltage. Kiyak and Cakir [8] found that SR of workpiece and electrode were influenced by current and pulse on time, higher values of these parameters increased the surface roughness. Lower current and pulse time and higher pulse off time produced a better surface finish.

B. Bhattacharyya et al. [9] observed that peak current and pulse on time significantly influenced different criteria of surface integrity such as surface crack density, surface roughness and white layer thickness. S Dhar et al. [10] came to the following conclusions: with increase in peak current MRR, TWR and ROC increased significantly in a nonlinear fashion; MRR and ROC increased with the increase in pulse on time and gap voltage was found to have some effect on the three responses.

Aim of the project

1. To estimate the material removal rate, surface roughness and overcut of AISI 304 SS with copper tool

CHAPTER 3 EXPERIMENTATION

In this chapter we will discuss about the experimental work formulated prior to execution of work. It consists of an L-27 orthogonal array using Taguchi design, selection of workpiece, experimental set-up, tool design and calculation of Material Removal Rate, Surface Roughness and Overcut.

3.1 Experimental set up

The experiments were conducted using the Electric Discharge Machine, model ELECTRONICA -ELECTRAPLUS PS 50ZNC (die sinking type) the polarity of the electrode was set as positive while that of workpiece was negative. The dielectric fluid used was EDM oil (specific gravity-0.763). The EDM consists of the following parts:

i. Dielectric reservoir, pump and circulation system.
ii. Power generator and control unit.
iii. Working tank with work holding device.
iv. X-Y working table
v. The tool holder
vi. The servo system for feeding the tool.

Fig. 3.1 Dielectric reservoir [16]

Fig. 3.2 Control unit of EDM machine [16]

3.2 Selection of the workpiece

AISI 304 Stainless Steel is one of the most widely used materials in all industrial applications and accounts for approximately half of the world’s stainless steel production and consumption. Because of its aesthetic view in architecture, superior physical and mechanical properties, resistance against corrosion and chemicals, weldability, it has become the most preferred material over others. Many conventional and non-conventional methods for machining AISI 304 stainless steel are available.

3.3 Tool Design

The tool material used in Electro Discharge Machining can be of a variety of metals like copper, brass, aluminium alloys, silver alloys etc. The material used in this experiment is copper. The tool electrode is in the shape of a cylinder having a diameter of 21mm.

Fig. 3.3 Machined workpiece and Tool

3.4 Mechanism and Evaluation of MRR

MRR is the rate at which tha material is removed the workpiece. Electric sparks are produced between the tool and the workpiece during the machining process. Each spark produces a tiny crater and thus erosion of material is caused.

The MRR is defined as the ratio of the difference in weight of the workpiece before and after machining to the density of the material and the machining time.

$$\text{MRR} = \frac{\text{Wi}-\text{Wf}}{\text{t x } \rho}$$

Where W_i = initial weight before machining

W_f = final weight after machining

T = machining time = 15 min

ρ is the density of AISI 304 stainless steel = 8000 kg/m^3

3.5 Mechanism and Evaluation of Surface Roughness

Surface Roughness is the measure of the texture of the surface. It is measured in µm. If the value is high then the surface is rough and if low then the surface is smooth. It is denoted by R_a. The values are measured using Portable style type profilometer, Talysurf (Model: Taylor Hobson, Surtronic 3^+)
The arithmetic mean of three readings is taken as the final value.

3.6 Mechanism and Evaluation of Overcut

It is the measure of cut produced exceeding the diameter of the tool. The impression created while EDM process is generally slightly larger than the original diameter of the tool electrode. This is because the spark is generated from along the side of the tool and hence erosion takes place in that direction also. OC is calculated as half the difference of the diameter of the hole produced to the tool diameter as shown in the equations below:

$$\text{Overcut Diameter} = \frac{Di-Do}{2}$$

Where D_i is the diameter of the hole and D_o is the diameter of the tool

3.7 Design of Experiments Analysis

Genichi Taguchi developed some statistical methods to improve the qualities of manufactures goods known as Taguchi methods. This design provides a potential and efficient method for designing different products that can operate consistently over a wide range of conditions. Minitab provides both static and dynamic response experiments. The design of experiments is used to find the best combination of input variables in an orthogonal array.

In this experiment the input parameters considered are current, T_{on}, and τ. Since three factors are chosen the design becomes a 3 level 3 factorial Taguchi design. L_{27} orthogonal array was chosen for the experiments to be conducted.

Fig. 3.4 Spark produced during machining

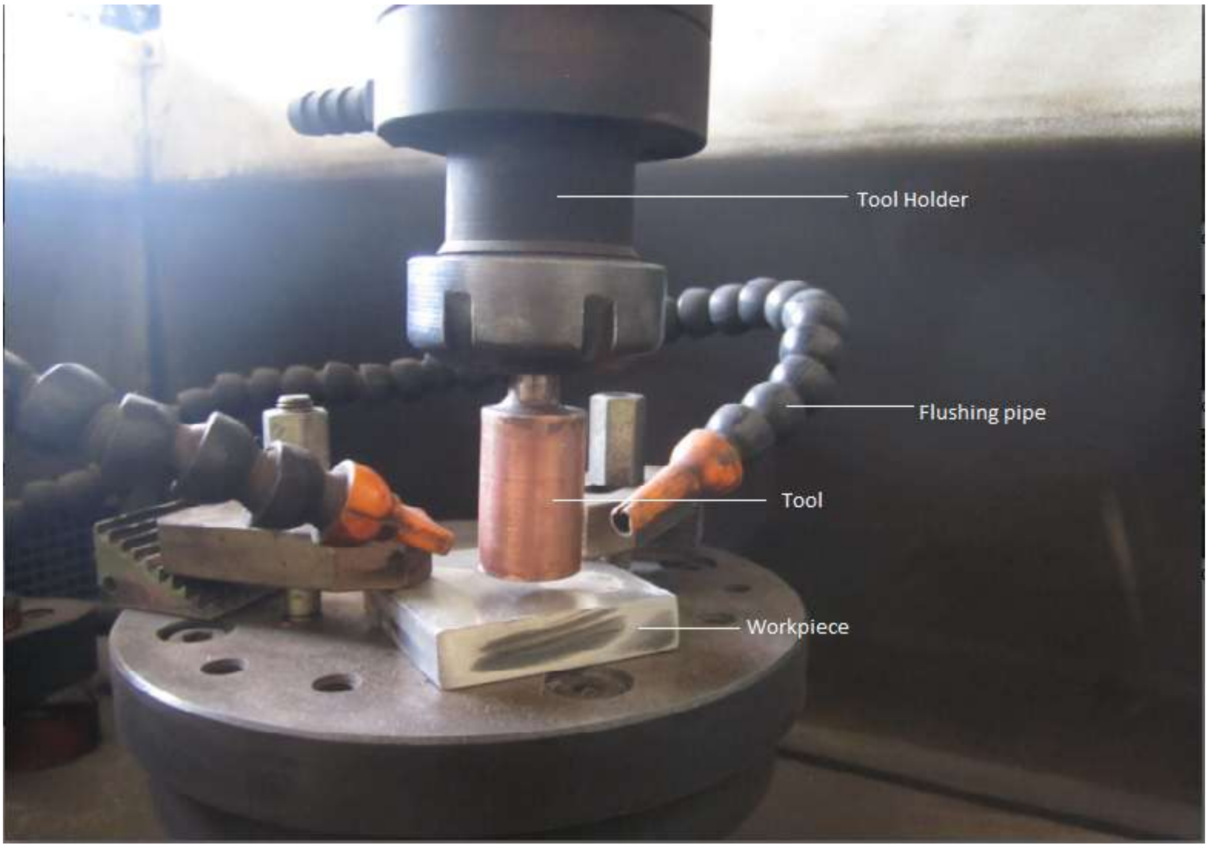

Fig. 3.5 Workpiece and tool setup

Table 3.1 Machining parameters and their levels

Machining Parameter	**Symbol**	**Unit**	**Levels**		
			1	2	3
Current	I_p	A	2	5	8
Spark on time	T_{on}	µs	50	100	150
Duty cycle	τ	%	60	70	80

Table 3.2 Fixed Parameters

SEN	**ASEN**	**Voltage**	**Tw**	**T↑**	**Flushing Pressure (kg/cm$^{2)}$**
6	3	45	0.6	0.1	0.25

CHAPTER 4 RESULT AND DISCUSSION

In this chapter we will discuss the results obtained and along with that find out the influential parameters that affect each of the MRR, Surface Roughness and Overcut.

Table4. 1 Observation Table

Run No.	Ip (A)	T_{on} (μs)	τ (%)	MRR (mm^3/min)	SR (μm)	OC (mm)
1	2	50	70	1.5438	5.267	0.012
2	2	50	80	2.3063	5.330	0.018
3	2	50	90	1.3125	4.130	0.016
4	2	100	70	1.7938	4.400	0.086
5	2	100	80	2.0625	4.530	0.056
6	2	100	90	2.1500	4.130	0.068
7	2	150	70	1.9000	4.670	0.096
8	2	150	80	2.1188	4.600	0.086
9	2	150	90	2.1250	4.067	0.096
10	5	50	70	7.3500	6.000	0.106
11	5	50	80	8.3167	6.530	0.130
12	5	50	90	8.7968	6.200	0.048
13	5	100	70	8.1917	7.330	0.082
14	5	100	80	9.2250	7.200	0.144
15	5	100	90	9.4250	7.867	0.084
16	5	150	70	7.6580	6.867	0.096
17	5	150	80	9.1750	7.800	0.195
18	5	150	90	9.5080	7.930	0.182
19	8	50	70	14.2417	6.600	0.181
20	8	50	80	17.1000	6.930	0.174
21	8	50	90	17.5167	7.530	0.158
22	8	100	70	15.8417	8.867	0.189
23	8	100	80	18.8670	10.000	0.225
24	8	100	90	20.4670	10.130	0.200
25	8	150	70	14.5875	10.000	0.201
26	8	150	80	16.9875	9.800	0.204
27	8	150	90	19.3500	10.000	0.226

4.1 Analysis and Discussion of MRR

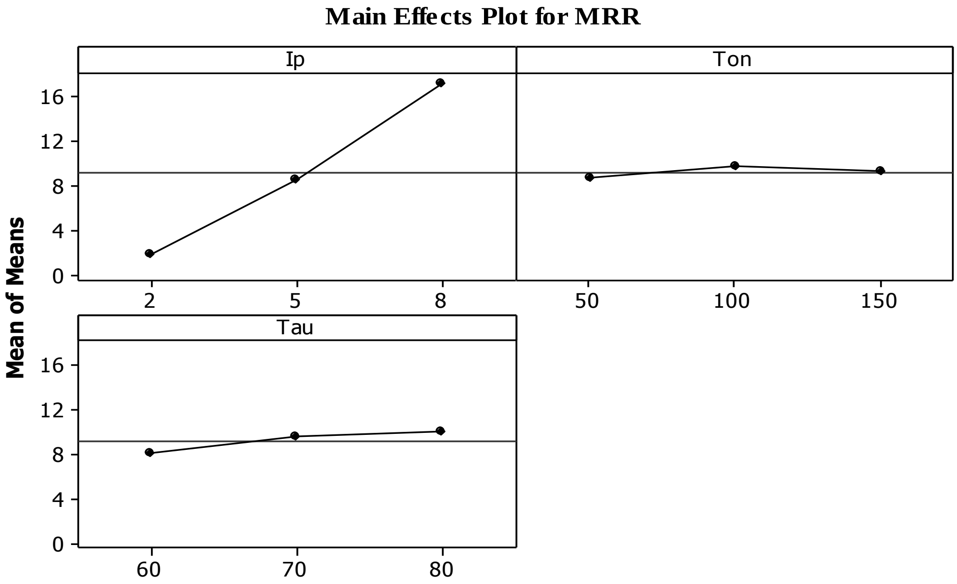

Fig. 4.1 Main Effects Plot for MRR

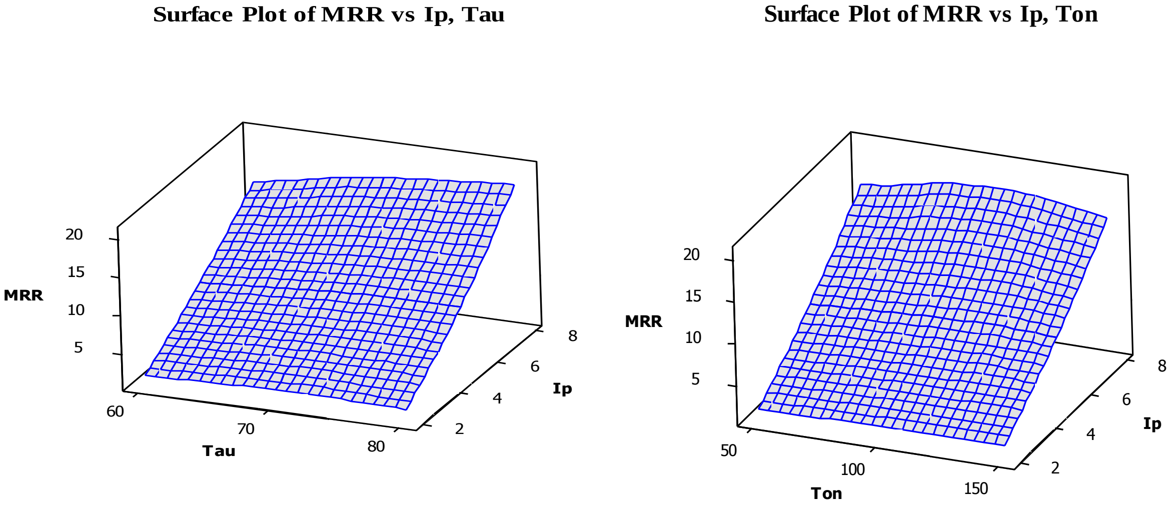

Fig.4. 2 Surface Plot for MRR

The MRR increases as the current increases throughout the entire range. In case of pulse on time, the MRR first slightly increases up to 100 µs and then decreases in a similar fashion till 150 µs. The MRR increases linearly along with the increase in duty cycle within the range but the magnitude of increase is not very large.

Table 4.2 Analysis of Variance for Means of MRR

Source	**DF**	**Seq SS**	**Adj MS**	**F**	**P**	**% cont.**
Ip	2	1057.93	528.963	4893.21	0.000	96.231
T_{on}	2	5.06	2.529	23.39	0.000	0.4602
τ	2	18.45	9.227	85.36	0.000	1.6782
I_p*T_{on}	4	3.10	0.774	7.16	0.009	0.282
I_p*τ	4	13.16	3.291	30.44	0.000	1.1971
T_{on}*τ	4	0.80	0.200	1.85	0.213	0.072
Residual Error	8	0.86	0.108			0.078
Total	26	1099.36				
S = 0.3288			R-Sq = 99.9%		R-Sq(adj) = 99.7%	

Table 4.3 Response Table for Mean of MRR

Level	**I_p**	**T_{on}**	**τ**
1	1.924	8.720	8.123
2	8.627	9.780	9.573
3	17.218	9.268	10.072
Delta	15.294	1.060	1.949
Rank	1	2	3

In table 4.1 1 column 1 represents variable sources such as current, pulse on time, duty cycle and the interactions between these three factors. Subsequently in the following columns degree of freedom (DF), Sum of squares (Seq SS), adjusted mean of square (Adj MS), F distribution and Probability are calculated respectively.

The standard deviation of errors in the modeling, S=0.3288. R^2=99.9% which indicates that the model is capable of predicting the response with a high accuracy.

From this table it can be concluded that all the factors except for the interaction between T_{on}* τ are significant as the value of $p<0.05$. The value of p for T_{on}* τ is 0.213 and hence the interaction is not significant. From the response table it can be seen that the most significant factor is Ip followed by T_{on} and the least significant being Tau.

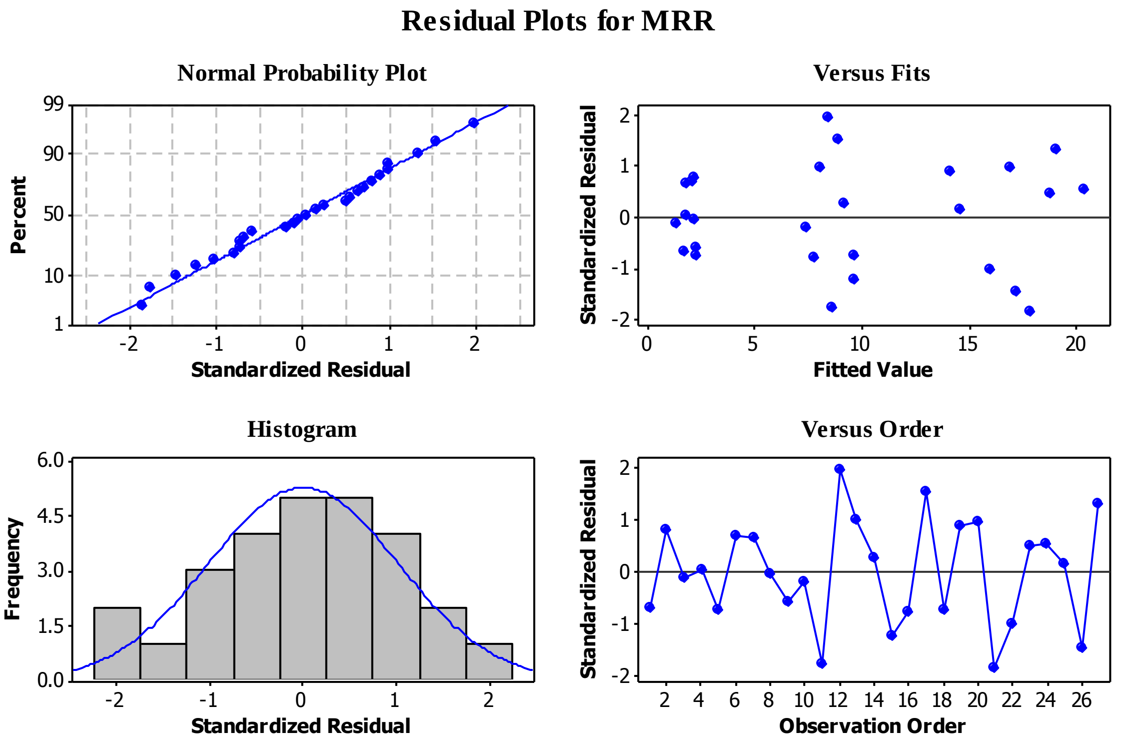

Fig.4. 3 Residual Plots for MRR

The residual plot of MRR is shown in Fig. 4.2. This layout is necessary to check whether the model meets the expectation of the analysis. The interpretation of the residual plots is as follows:

i. Normal probability plot indicates that the data are distributed normally. It can be seen that the standardized residue lies between -2 and 2

ii. Versus Fits graph indicate the variance is constant and a nonlinear relationship exists as well as no outliers exist in the data.

iii. Histogram of the data forms a desired skew shape.

iv. Versus order graph shows that there are systematic effects in the data.

The interaction plot of MRR is shown in Fig. 4.3. This plot shows the interactions between the three input variables taken in this experiment. The significant interactions can be seen in the plot (* marked). It can also be confirmed from the ANOVA table.

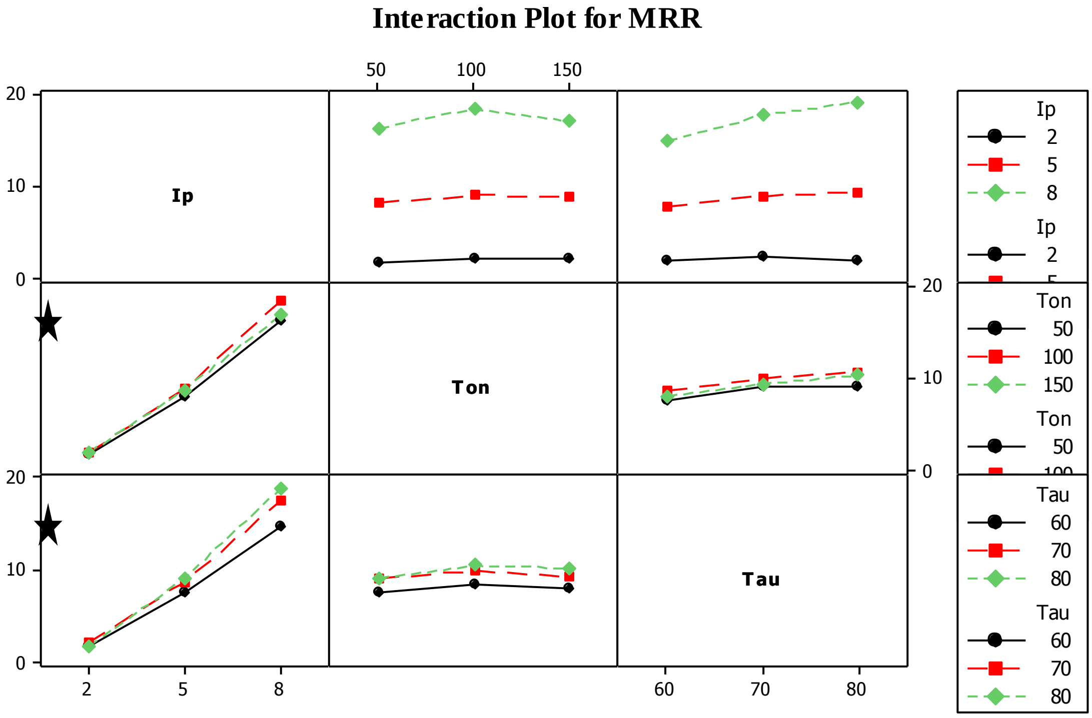

Fig.4. 4 Interaction Plot for MRR

4.2 Analysis and Discussion of Surface Roughness

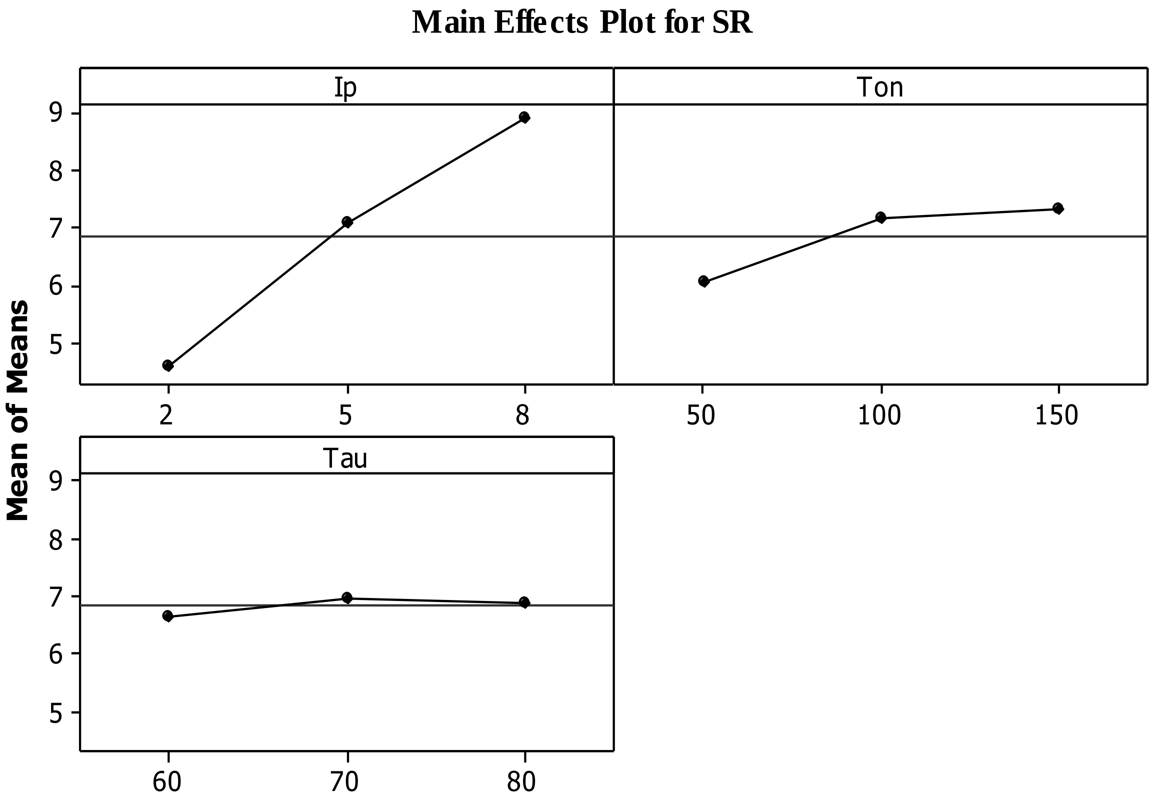

Fig. 4.5 Main Effects Plot for SR

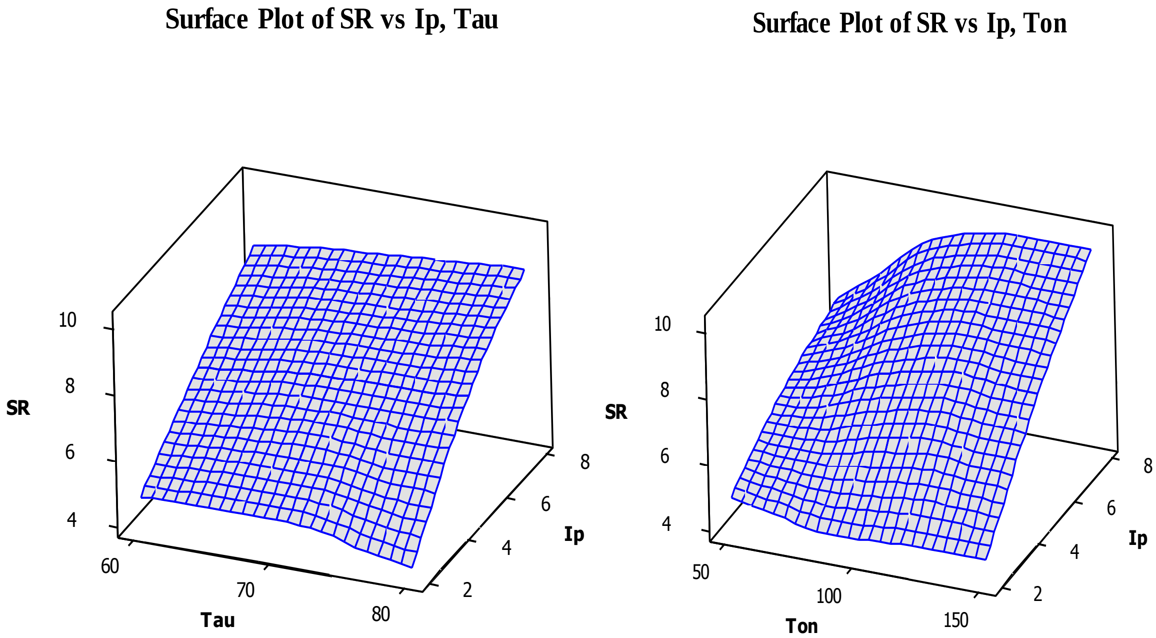

Fig.4. 5 Surface Plot for SR

The Surface Roughness increases along with the increase in current within the range of experimental conditions. In case of pulse on time SR increases up to 100µs and then the increment is very slight. With respect to duty cycle, SR first increases up to 70% and then decreases after that.

Table 4.4 Analysis of Variance for Means of SR

Source	DF	Seq SS	Adj MS	F	P	% cont.
I_p	2	84.121	42.0607	300.05	0.000	78.553
T_{on}	2	8.378	4.1890	29.88	0.000	7.8234
τ	2	0.440	0.2198	1.57	0.266	0.411
I_p*T_{on}	4	10.873	2.7182	19.39	0.000	10.153
I_p*τ	4	1.906	0.4765	3.40	0.066	1.7798
T_{on}*τ	4	0.248	0.0621	0.44	0.775	0.2316
Residual Error	8	1.121	0.1402			1.0468
Total	26	107.088				

S = 0.3744 R-Sq = 99.0% R-Sq(adj) = 96.6%

Table 4.5 Response Table for Mean of SR

Level	I_p	T_{on}	τ
1	4.569	6.057	6.667
2	7.080	7.162	6.969
3	8.873	7.304	6.887
Delta	4.304	1.246	0.302
Rank	1	2	3

From the ANOVA table it can be seen that the significant factors are Ip and T_{on} as their value of $p<0.05$. Also the interaction between Ip and is significant. Here it can be somewhat assumed that the interaction between Ip and τ may be slightly significant as $p=0.066$ is just greater than 0.05. The standard deviation of error $S=0.3744$ and $R^2= 99.0\%$.The most significant parameter is the current followed by T_{on} and Tau being the least significant. The residual and the interaction plot are shown below. The normal probability plot shows the data to be equally distributed within the range and the histogram also follows a skew shape. The graphs of Ip and T$_{on}$ can be seen intersecting in the interaction plot as it is the significant interaction.

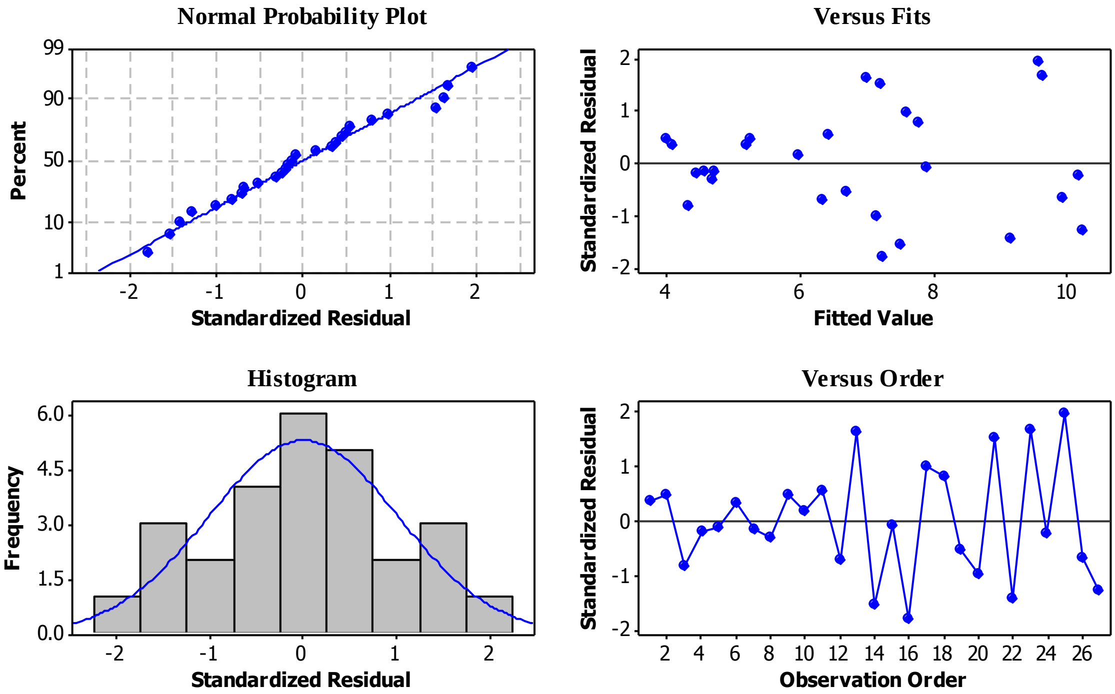

Fig.4. 7 Residual Plots for SR

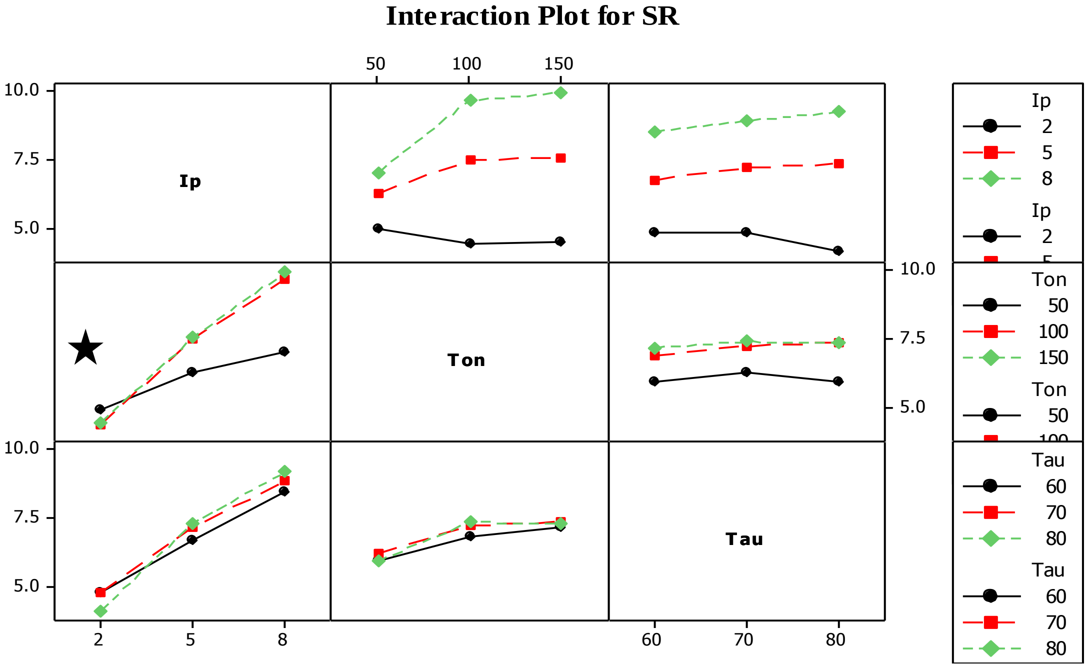

Fig.4. 8 Interaction Plot for SR

4.3 Analysis and Discussion of Overcut

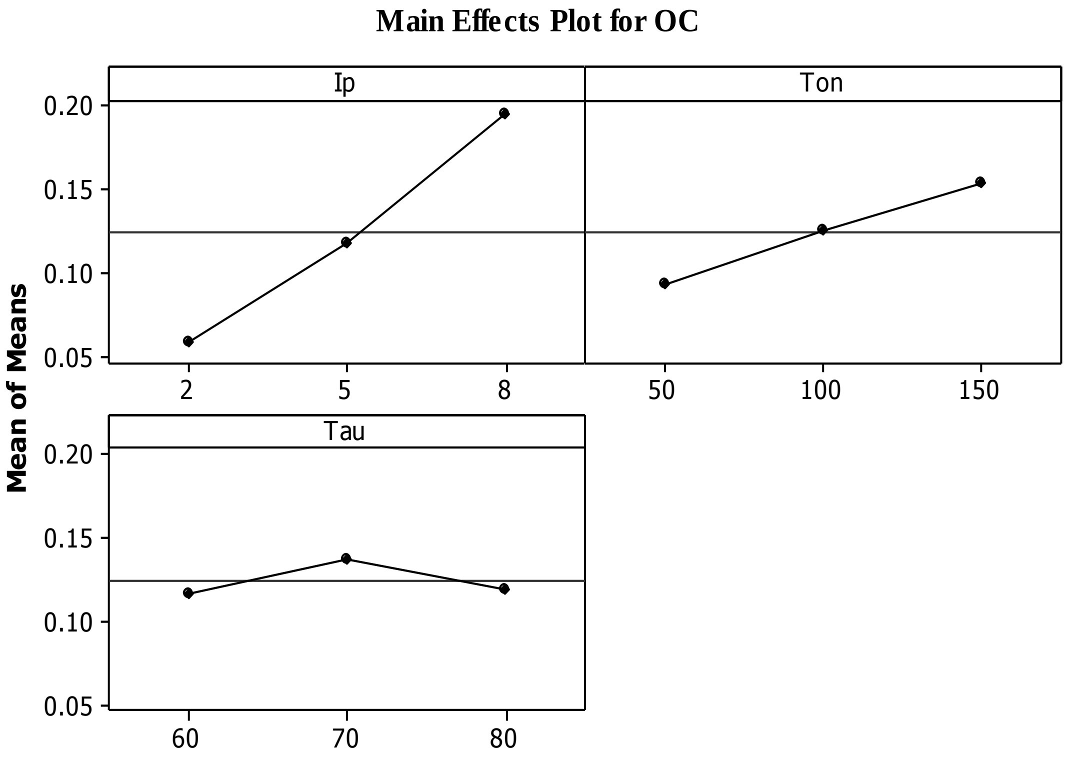

Fig. 4.9 Main Effects Plot for OC

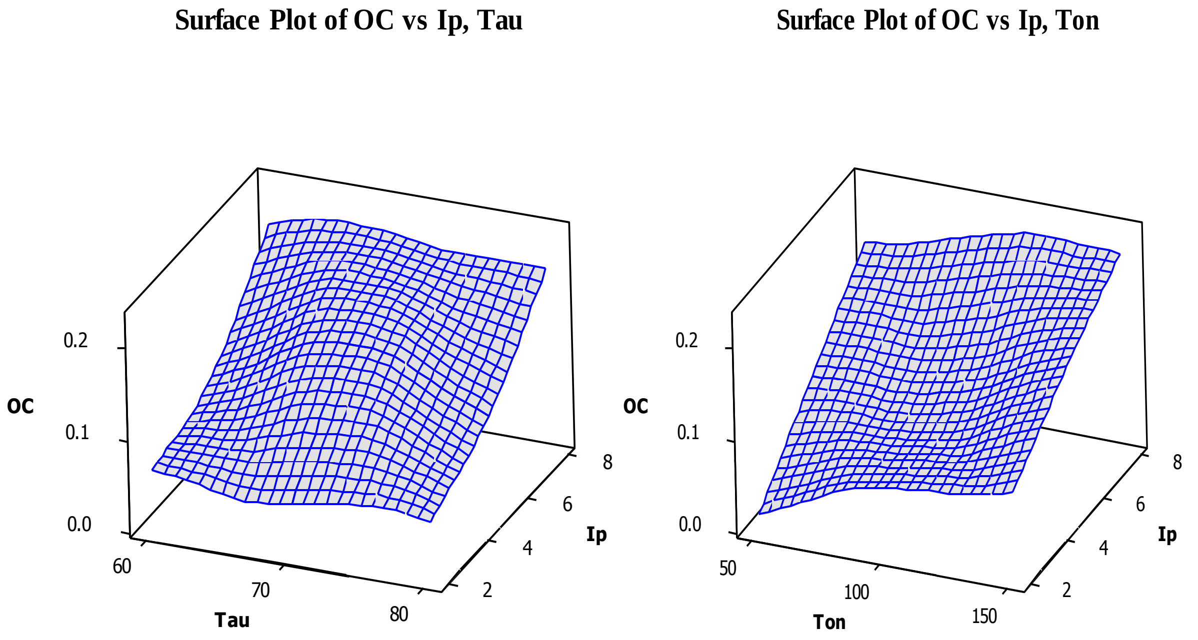

Fig.4. 10 Main Effects plot and Surface plot for OC

The overcut increases with the increasing current within the given range of values. The OC increases linearly with the increase in T_{on}. But in case of τ the OC first increases up to 70% and then decreases.

Table 4.6 Analysis of Variance for Means of OC

Source	DF	Seq SS	Adj MS	F	P	% cont.
I_p	2	0.083694	0.041847	92.43	0.000	71.787
T_{on}	2	0.016174	0.008087	17.86	0.001	13.873
τ	2	0.002150	0.001075	2.37	0.155	1.844
I_p*T_{on}	4	0.003017	0.000754	1.67	0.250	2.5878
I_p*τ	4	0.004790	0.001197	2.64	0.113	4.1085
T_{on}*τ	4	0.003137	0.000784	1.73	0.236	2.6907
Residual Error	8	0.003622	0.000453			3.1067
Total	26	0.116585				
S = 0.02128			R-Sq = 96.9%		R-Sq(adj) = 89.9%	

Table 4.7 Response Table for Mean of OC

Level	I_p	T_{on}	τ
1	0.05933	0.09367	0.11656
2	0.11856	0.12600	0.13689
3	0.19533	0.15356	0.11978
Delta	0.13600	0.05989	0.02033
Rank	1	2	3

From the ANOVA table it can be seen that current and pulse on time are the significant parameter. Also there are no significant interactions. The standard deviation of error S=0.02128 and R^2= 89.9%. The residual plots and the interaction plots for the overcut are shown in the graphs below. From the graph it can be seen that no interactions are significant.

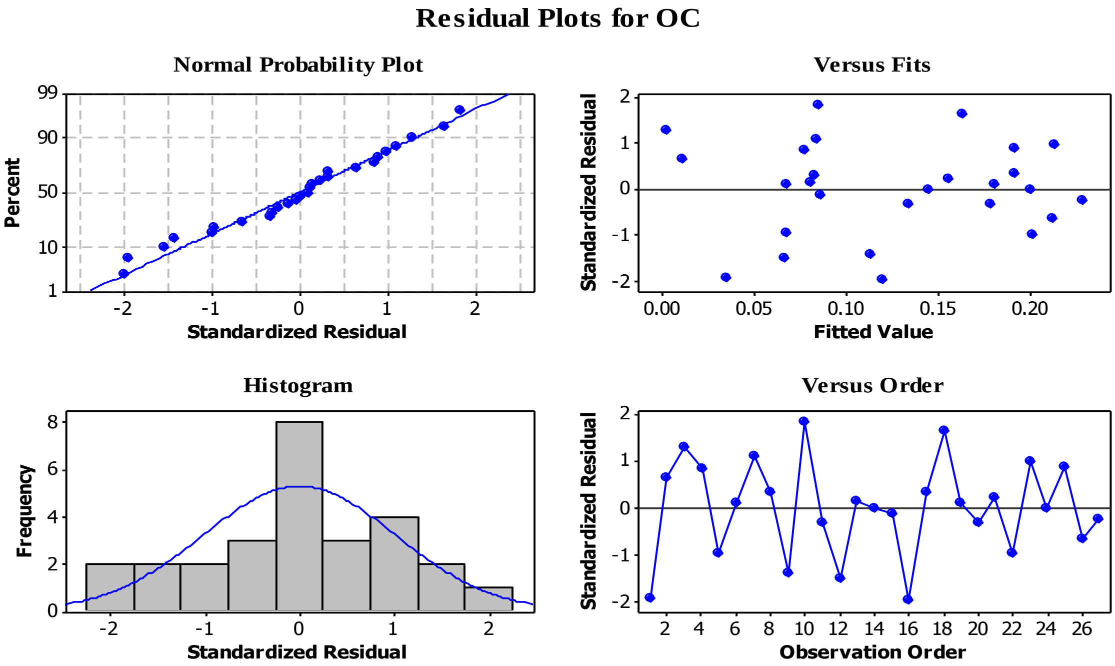

Fig. 4. 11 Residual Plots for OC

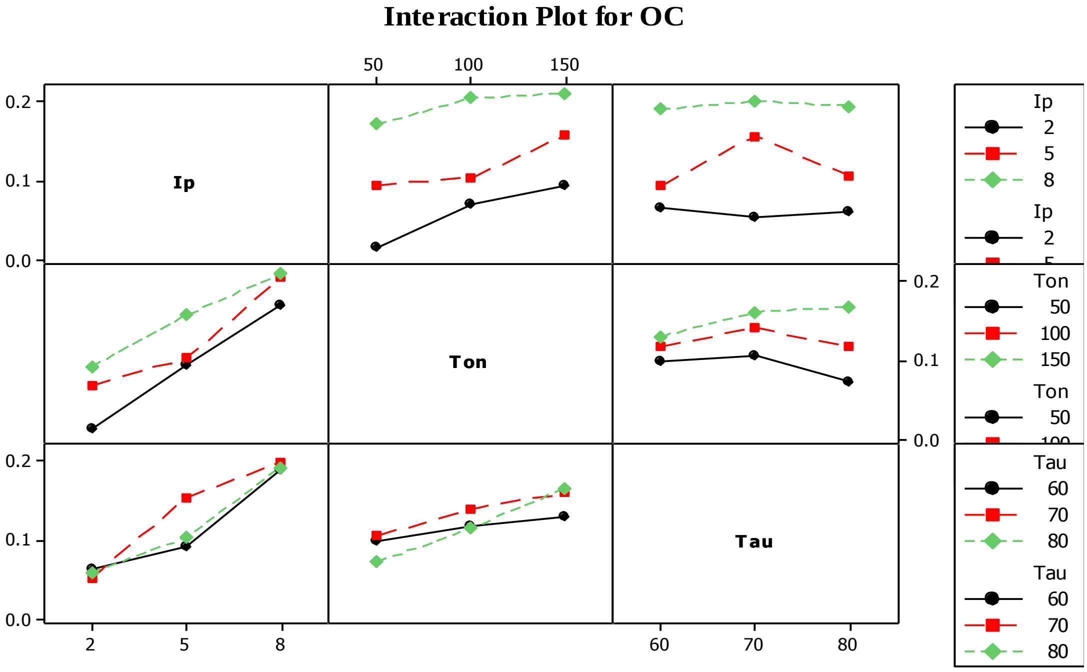

Fig. 4. 12 interaction Plot for OC

CHAPTER 5 CONCLUSION

In this study the experiment was conducted by considering three variable parameters namely current, pulse on time and duty cycle. The objective was to find the Material Removal Rate, Surface Roughness and Overcut and to study the effects of the variable parameters on these characteristics. The tool material was taken as copper and the workpiece was chosen as AISI 304 stainless steel. Using the Taguchi method an L_{27} orthogonal array was created and the experiments were performed accordingly. The following conclusions were drawn:

1. For MRR the most significant factor was found to be peak current followed by pulse on time and the least significant was duty cycle. The MRR increased nonlinearly with the increase in current. For T_{on} the MRR first increased till 100 µs and then decreased. With increase in duty cycle, MRR increased insignificantly.
2. For SR the most significant factor was again current followed by pulse on time and lastly the duty cycle. SR increased significantly with the increase in current in a nonlinear fashion. For increase in pulse on time SR increased up to 100 µs and then there was no significant increase. In case of duty cycle, SR first increased up to 70% and then started to decrease.
3. For OC the most significant factor was current followed by pulse on time and duty cycle respectively. OC increased along with the increase in current. For increase in pulse on time, OC increased linearly. Finally for duty cycle, OC increased but only up to 70% and then started decreasing.

CHAPTER 6 APPENDIX

In this chapter we will discuss about the machines and equipment used while conducting the experiments.

1. Experiments were conducted using this machine model ELECTRONICA-ELECTRAPULS PS 50ZNC (die-sinking type) with servo-head (constant gap).

Figure 6.1 Die Sinker EDM Model: PS 50ZN 2

2.

Fig. 6.2 Tool maker microscope

This machine was used to measure the overcut. This Tool maker microscope Make: Carl Zeiss, Germany and Accuracy: 0.001 mm.

3. Precision balance was used to measure the weight of the workpiece. This machine capacity is 300 gram and accuracy is 0.001 gram and Brand: SHINKO DENSHI Co. LTD, JAPAN, and Model: DJ 300S

Fig. 6.3 Weight balance

4. The values of surface roughness were measured using this Portable style type profilometer, Talysurf (Model: Taylor Hobson, Surtronic 3^{+})

Fig. 6.4 profilometer Talysurf

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