Investigation and Modeling of Electrical Discharge Machining Process Parameters for AISI 4340 steel

N. Annamalai[#1], V. Sivaramakrishnan[*2], B. Suresh kumar[#3], N.Baskar[*4]

[#1]Department of Mechanical Engineering, Mookambigai College of Engineering, Pudukkottai, Tamilnadu, India – 622502

[1]nannamalai1966@gmail.com

[* 2]Department of Mechanical Engineering, Roever Engineering College, Perambalur, Tamilnadu, India – 621212

[2]vsmp1967@yahoo.com

[#3,*4] Department of Mechanical Engineering, M. A. M. College of Engineering, Tiruchirappalli, Tamilnadu, India – 621152

[3]bsureshcvl@yahoo.com,[4]baskarnaresh@gmail.com

***Abstract*: - Investigation of machining parameters on Electrical Discharge Machining (EDM) is important for manufacturing industries for achieving higher productivity and product quality. so, this work investigated the effect of machining parameters on machining of AISI 4340 steel in spark erosion process on electric discharge machine with electrolytic copper electrode. In response, the input parameters considered for the experimental work is Pulse on time, Peak Current and Pulse off Time. However, the main objective of this work is to investigate the effects of input parameters on material removal rate (MRR) and Surface Roughness. Subsequently the Box behnken design of response surface methodology (RSM) is used to plan the experimental design. In addition, the ANOVA technique is used for identifying the parameter influences and interaction effect of process parameters on MRR and surface roughness. Finally, the results show that the MRR and surface roughness are mainly affected by pulse on time, peak current and pulse off time. Based on the statistical investigation the regression models were developed and the developed regression models are compared with experimental values.**

Keywords- Electrical Discharge Machining, Material Removal Rate, Surface Roughness, Response Surface Methodology

I. INTRODUCTION

Now a day's modern manufacturing industries utilize the nontraditional machining processes for achieving high accuracy on difficult to machine materials. For that purpose lot of machining operations such as EDM, electrochemical machining, laser beam machining etc., were introduced in materials manufacturing industries. In sense the EDM is playing a vital role due to its simplicity, compactness and ease to produce the components with economically rather than other nontraditional machining processes. Simultaneously machining of miniaturized parts without any distortions can be done in EDM which is a contactless process and does not exert significant forces. Generally EDM is used to produce complex shapes that would otherwise be difficult to produce with conventional cutting tools. In that Electric Spark erosion is one of the techniques used to remove the materials from work piece by using electrical energy in EDM .The general process parameters to control the machining operation in EDM are the pulse on time, the pulse off time, the peak current and gap voltage. Subsequently the MRR, Surface finish, EWR and overcut are the important responses to decide the productivity and product quality [1, 2]. Hence the pulse on time, peak current and pulse off time are the predominant parameters for attaining the higher material removal rate and better surface finish [3]. This work finding is based on the following procedure, first the analysis of input parameter effects on material removal rate and surface roughness are carried out by ANOVA technique and then the regression models were developed for making relationship between input parameters and responses through response surface methodology.

The present study has been conducted with AISI 4340 steel used in automobile components where strength and toughness are fundamental design requirements. The chemical analysis of the material used in this research indicates accordance with specifications [4]. AISI 4340 is a high strength low alloy steel material chosen based on its application in automobile and machine tool parts such as axle shafts, main shafts, spindles, gears, power transmission gears and couplings [5]. The machined components used in these applications require a high dimensional accuracy and good surface quality. However, from machining view point, these are 'difficult-to-machine' materials. They generate lot of heat during machining primarily due to their low thermal conductivity

[6]. The effectiveness, efficiency and overall economy of machining any work material by given tool depend largely only on the machinability characteristics of the tool–work material under the recommended condition [7].

In previous, few researchers have considered optimizing material removal rate, tool wear and overcut with Taguchi methodology but not surface roughness [8]. So this work considers MRR and surface roughness. Some researchers were concentrated about presence and absence of dielectric fluid for achieving accuracy and crater dimensions [9]. MRR is more influenced by duty factor and peak current while machining AISI 4140 grade alloy steel in EDM [2]. In dielectric fluid the silicon powder particle is suspended in powder mixed electro-discharge machining and observed that it increases machining efficiency and surface finish significantly [10]. Pulse on time, duty cycle, peak current and concentration of the silicon powder added into the dielectric fluid of EDM are used as process parameters to study the process performance in terms of material removal rate and surface roughness [11]. The debris evacuation efficiency and low work piece conductivity posed a challenge of low material removal rate and using design of experiments peak current, duty ratio, gap voltage and pulse duration were studied and analysis of variance was conducted to achieve higher MRR [12].

The Shortage in quality of finished surface in austenitic stainless steel was found due to localized corrosion resistance when it was machined in EDM [13] and found that it has to be annealed before machining to achieve better surface finish. Matrix nano composite of Al 7075 reinforced with 0.5 wt% SiC nano particles is machined in electrical discharge machining with copper electrode using face-centered central composite design of response surface methodology and mathematical model was developed for MRR, EWR and SR .The experimental values fitted with a 95% confidence interval [14]. The effects of discharge current, pulse on time, duty factor and open discharge voltage were used to analyze the performance characteristics of material removal rate , electrode wear ratio and surface roughness in the EDM process of Al2O3+TiC mixed ceramic[15].

AISI 4340 is a heat treatable, low alloy steel containing nickel, chromium and molybdenum. It is tough and has high strength in the heat treated condition. AISI 4340 is machined in annealed and tempered condition. Due to its high strength conditions machining is preferred in EDM. Research work on machinability of AISI 4340 on EDM is not dealt much. Few researches had been done on EDM but with different materials. This research work strive out the empirical relations of material removal rate and surface finish with AISI 4340 and copper as work material and electrode material respectively.

II. EXPERIMENTAL WORK

The parameter influence and interaction effect of controlling parameters such as pulse on time, peak current and pulse off time on material removal rate and surface roughness is examined through design of experiments.

A. Work piece and Electrode material

AISI 4340 is the work material which is a low alloy medium carbon steel used for large size parts which requires high strength and toughness. It offers a very good balance of strength, toughness and wear-resistance. The electrode material is copper. The chemical composition of AISI 4340 is given in table I.

TABLE I
Chemical Composition of AISI 4340

ELEMENT	C	Mn	P	S	Si	Cr	Ni	Mo
WEIGHT %	0.38-0.43	0.60 - 0.80	0.035 (max)	0.04 (max)	0.15 - 0.30	0.70 - 0.90	1.65 – 2.00	0.20 - 0.30

B. Characteristics

This nickel-chromium- molybdenum alloy steel possesses increased ductility and toughness and much deeper hardenability. The advantages of AISI 4340 are realized principally where high strength is required in heavy sections. It is ideal for all highly stressed parts in the most severe conditions because of its high fatigue strength. It has good wear resistance and may be used in both elevated and low temperature environments.

C. Typical Applications of AISI 4340

Typical applications include aircraft landing gear, power transmission gears and shafts and other structural parts, high strength machine parts, heavy-duty shafting, high tensile bolts and studs, gears, axle shafts, crankshafts, boring bars and down-hole drilling components.

D. Experimental Set up

Elektra Puls SE35 ZNC Electric Discharge machine manufactured by Electronica Machine Tools is the machine used to carry out this experiment. The size of the work table is 500 x 300 mm. When the material removal is less than 0.5 mm it is termed as micromachining for which the peak current must be between 3 to 10 amps. The input parameters considered for process optimization are T_{on} Pulse on time, I_p Peak current and T_{off} Pulse off time. The various levels of input parameters are given in table II.

Fig 1: SE 35 ZNC EDM

TABLE II
Process Parameters and their levels

Parameter	Description	Unit	Level 1	Level 2	Level 3
T_{on}	Pulse on time	μ sec	20	50	100
I_p	Peak current	Amp	3	6	10
T_{off}	Pulse off time	μ sec	150	200	250

The other standard settings are work time potentiometer T_w for the sparking amplitude, antiarc sensitivity pot to set the spark gap voltage to enable antiarc control, duty cycle, gap control potentiometer to set the sparking gap voltage and sensitivity pot to vary the speed of Z axis. The die electric used is EDM oil. Through pressure flushing the product of spark erosion is removed from the work gap. EDM oil under pressure of 0.80 kg/cm^2 is admitted in the vicinity of the spark area and the debris is carried away. The response surface methodology is analyzed to maximize MRR and to minimize SR.

E. Measurement Procedure

An electronic weighing scale is used to measure the weight of work piece before and after trial. The digital timer is used to measure the period of trial in minutes. SURFCORDER, a surface roughness measuring instrument is used to measure the surface roughness Ra in terms of μm

1) Measurement of MRR

$$MRR = \frac{(w_i - w_f)x1000}{7.8xt} \quad mm^3/\text{min}$$

Where w_i = weight of work piece in grams before trial

w_f = weight of work piece in grams after trial

t = period of trial in minutes

7.8 = density of steel in gms/cc

2) *Measurement of Surface Finish*

The surface finish is measured on a surface test recorder, SURFCORDER of Kosaka Laboratory Ltd,Japan.

Stroke length : 4 mm

Stylus Speed : 2 mm/sec

Cut – off value : 0.8 mm

Arithmetic mean of Surface Roughness Ra is recorded in terms of μm.

III. MATHEMATICAL MODELING

Mathematical models are developed on the basis of experimental data. The experimental planning is done based on Design of Experiments. The Box behnken design was used to find the quadratic response surfaces to construct the second order polynomial models.

A. *Design of Experiments*

Design of Experiments (DOE) is a method used to obtain useful information about a process by conducting only minimum number of experiments. Each controllable variable (T_{on},I_p,T_{off}) can be set on EDM machine at three consecutive levels and hence the design consisting of 17 experiments based on Box behnken design was generated.

As per the Box Behnken Design of Response Surface methodology for 17 runs the various input parameters and the results obtained are shown in the table III.

TABLE III
Plan of Experiments and Output Responses

Sl. No.	***Pulse ON time (*** μ **sec)**	***Peak current (amp)***	***Pulse OFF time (*** μ **sec)**	***MRR (mm^3/min)***	***SR*** **(μm)**
1	20	3	200	0.323	1.49
2	100	3	200	0.312	1.78
3	20	10	200	3.619	3.60
4	100	10	200	5.222	6.68
5	20	6	150	4.106	3.53
6	100	6	150	4.342	5.16
7	20	6	250	2.952	3.96
8	100	6	250	2.957	5.72
9	50	3	150	0.329	1.68
10	50	10	150	5.133	5.35
11	50	3	250	0.259	1.72
12	50	10	250	3.746	5.71
13	50	6	200	4.203	4.77
14	50	6	200	4.931	4.79
15	50	6	200	4.060	4.85
16	50	6	200	4.103	5.10
17	50	6	200	4.563	5.33

Regression analysis for MRR indicates that the individual and higher order effects of variables, such as I_p,T_{off} and higher order effect of $T_{on}$and I_p have significant contributions in MRR model since these P-values are less than 0.05. Hence the equation for calculating the approximate MRR is

$$MRR = -13.05567 + 0.032718 x T_{on} + 2.84774 x I_p + 0.065230 x T_{off} + 2.91488E-003 x T_{on} x I_p - 4.70741E-005 x T_{on} x T_{off} - 1.76239E-003 x I_p x T_{off} - 2.98260E-004 x T_{on}^2 - 0.15895 x I_p^2 - 1.54043E-004 x T_{off}^2$$

The values stated below in table IV indicates ANOVA results for MRR .

TABLE IV
Anova Results for MRR

Source	Sum of Squares	Df	Mean Square	F Value	p - value Prob > F
Model	50.52902	9	5.614336	43.21957	< 0.0001
A-PULSE ON TIME	0.528782	1	0.528782	4.070606	0.0834
B-PEAK CURRENT	34.68576	1	34.68576	267.0135	< 0.0001
C-PULSE OFF TIME	2.186004	1	2.186004	16.82802	0.0046
AB	0.693742	1	0.693742	5.340476	0.0541
AC	0.036552	1	0.036552	0.281382	0.6122
BC	0.384252	1	0.384252	2.958003	0.1291
A^2	0.815929	1	0.815929	6.28108	0.0406
B^2	15.15613	1	15.15613	116.673	< 0.0001
C^2	0.624254	1	0.624254	4.805555	0.0645
Residual	0.909318	7	0.129903		
Lack of Fit	0.36246	3	0.12082	0.883738	0.5213
Pure Error	0.546858	4	0.136715		
Cor Total	51.43834	16			
Std Dev	0.06			R-Squared	0.9823
Mean	0.36			Adj R-Squared	0.9596
C.V.%	3.24			Pred R-Squared	0.8663
PRESS	6.88			Adeq Precision	18.414

Regression analysis for Surface Roughness indicates that the individual and higher order effects of variables such as $T_{on}$and I_p and higher order effect of T_{on} and I_p and interactive terms of $T_{on}$and I_p have significant contributions in Surface Roughness model since these P-values are less than 0.05. Hence the equation for calculating the approximate Surface Roughness is

$$SR = -5.18238 + 0.027995 x T_{on} + 1.86190 x I_p + 9.81413E-003 x T_{off} + 4.63971E-003 x T_{on} x I_p + 2.48665E-005 x T_{on} x T_{off} + 3.91892E-004 x I_p x T_{off} - 3.40737E-004 x T_{on}^2 - 0.12854 x I_p^2 - 2.53903E-005 x T_{off}^2$$

The values stated below in table V indicates the ANOVA results for Surface Roughness .

TABLE – V
Anova Results for Surface Roughness

Source	Sum of Squares	Df	Mean Square	F Value	p –value Prob > F
Model	42.24889	9	4.694321	63.48634	< 0.0001
A-PULSE ON TIME	6.268578	1	6.268578	84.7767	< 0.0001
B-PEAK CURRENT	28.52985	1	28.52985	385.8398	< 0.0001
C-PULSE OFF TIME	0.262626	1	0.262626	3.551775	0.1015
AB	1.757674	1	1.757674	23.77091	0.0018
AC	0.0102	1	0.0102	0.137939	0.7213
BC	0.019	1	0.019	0.256953	0.6278
A^2	1.064885	1	1.064885	14.40158	0.0068
B^2	9.911944	1	9.911944	134.0499	< 0.0001
C^2	0.016959	1	0.016959	0.229361	0.6466
Residual	0.517596	7	0.073942		
Lack of Fit	0.284014	3	0.094671	1.621217	0.3184
Pure Error	0.233581	4	0.058395		
Cor Total	42.76649	16			
Std Dev	0.27			R-Squared	0.9879
Mean	4.19			Adj R-Squared	0.9723
C.V.%	6.49			Pred R-Squared	0.8786
PRESS	5.19			Adeq Precision	26.910

IV. RESULTS AND DISCUSSIONS

Pulse On time,Peak current and Pulse off time are the three parameters which are used as conrolling parameters.Its effect of Material removal rate and Surface roughness is discussed.

A. Material Removal Rate

The effect of peak current,pulse on time and pulse off time on material removal rate is shown in graphical representation.

1) Effect of Peak Current

The fig 2 indicates that *MRR* is 0.323 mm^3/min when the peak current is 3 amps. It increases to 4.931 mm^3/min when the peak current is 6 amps. It reaches 5.222 mm^3/min when the peak current is increased to 10 amps. The pulse off time is kept constant as 200 µsec.

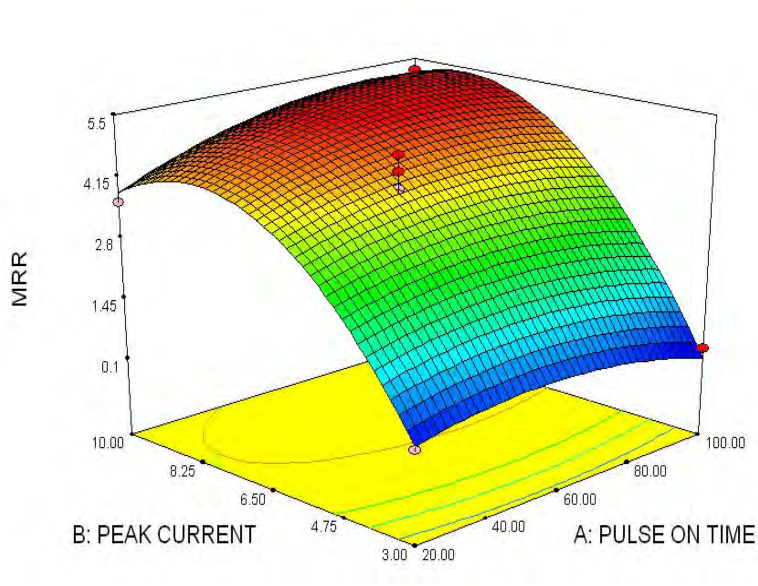

Fig 2.Effect of peak current on MRR

2) Effect of Pulse on time

The MRR increases from 0.259 to 5.222 mm^3/min when the pulse on time increases from 20 µsec to 100 µsec.The fig 3 indicates the change in MRR when the peak current is kept constant at 6.5 amp.

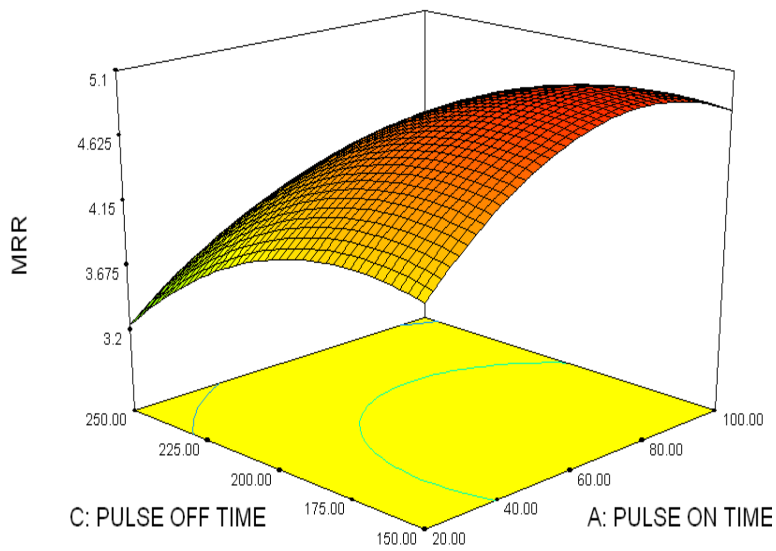

Fig 3.Effect of pulse on time on MRR

3) Effect on Pulse off time

There is no much changes on MRR when the pulse off time increases from 150 µsec to 250 µsec.The fig 4 indicates the change in MRR when the pulse on time is kept constant at 60 µsec.

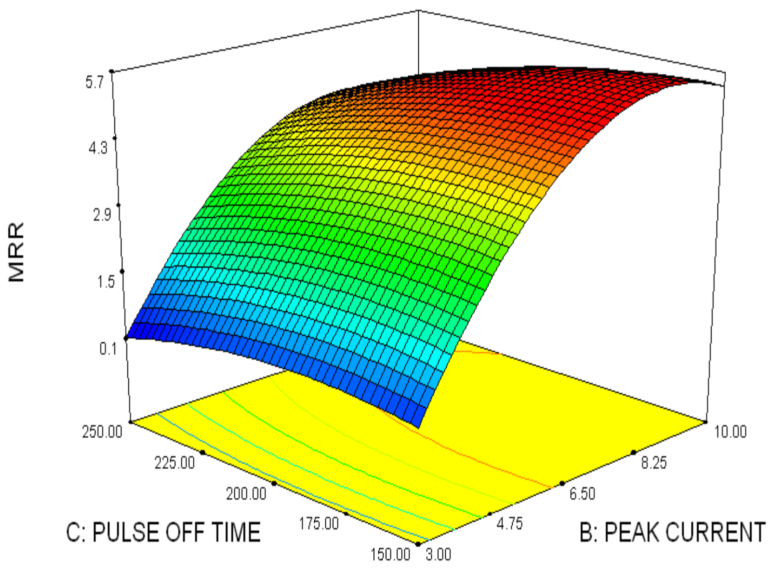

Fig 4.Effect of pulse off time on MRR

B. Surface Roughness

The effect of peak current,pulse on time and pulse off time on surface roughness is shown in graphical representation.

1) Effect of Peak Current

The surface roughness is 1.49 µm when the peak current is 3 amps,increases to 5.10 µm when the peak current is 6 amps and finally reaches 6.68 µm when the peak current is 10 amps. The fig 5 indicates the change in surface finish while keeping pulse off time in 200 µsec as constant.

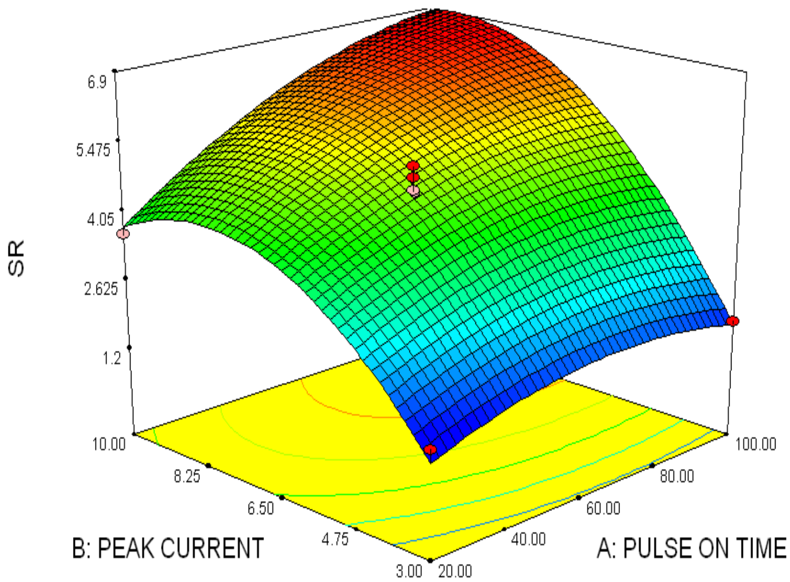

Fig 5.Effect of peak current on surface roughness

2) Effect of Pulse on Time

The surface roughness increases from 1.49 µm to 6.68 µm when the pulse on time increases from 20 µsec to 100 µsec.The fig *6* indicates the change in surface finish while keeping peak current as constant in 6.5 amps.

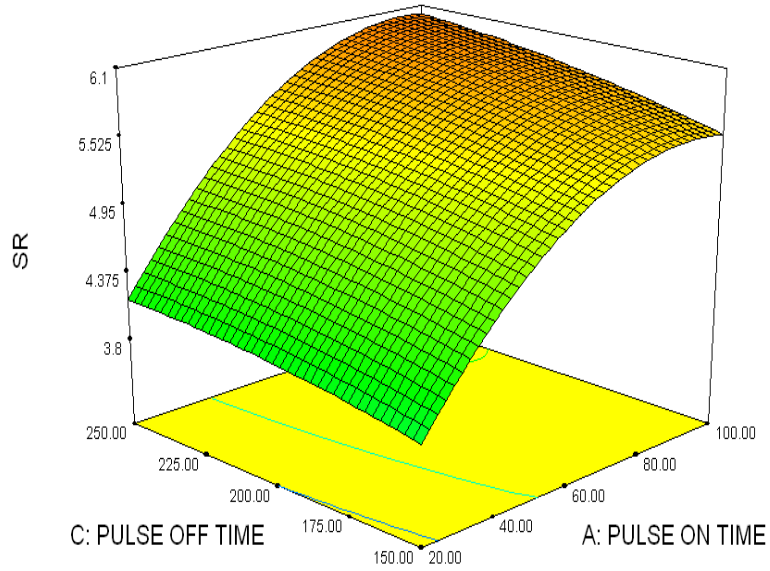

Fig 6.Effect of pulse on time on surface roughness

3) Effect of Pulse off time

The fig *7* indicates that there is no impact or change on surface roughness when the pulse off time increases from 150 µsec to 250 µsec.

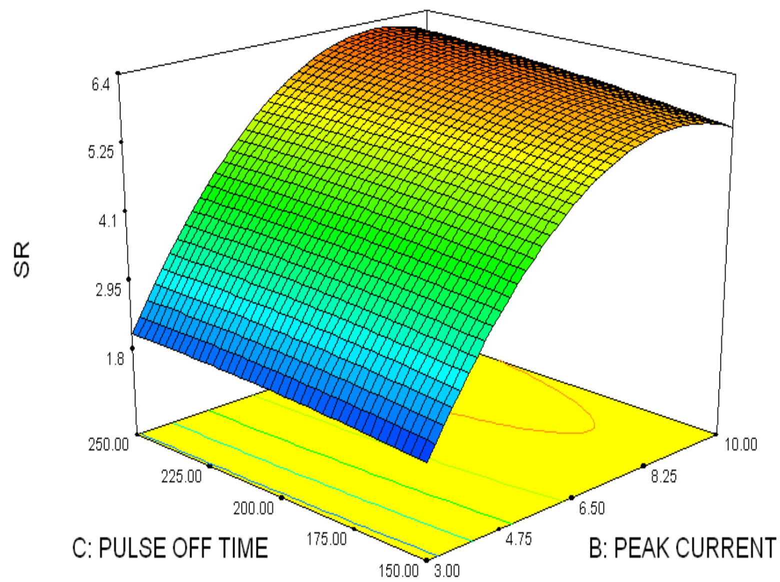

Fig 7.Effect of pulse off time on surface roughness

V. CONCLUSIONS

This work deals with the RSM – based investigations on material removal rate and surface roughness while machining AISI 4340 in EDM. Through Boxbehnken design of DOE the experiments were done and mathematical models were developed in second order to establish the relationship between input parameters (peak current, pulse on time and pulse off time) and the responses (MRR and SR). The following conclusions have been derived.

- The increase in peak current increases the material removal rate significantly.
- The increase in pulse on time increases the material removal rate whereas there is no much impact when pulse off time is increased.
- The surface roughness values in µm increases when there is increase in peak current.So the peak current must be kept optimum for minimum Ra value.
- When the pulse on time increases the roughness average values also increases.So for better surface finish,the pulse on time must be optimum.
- There is no change in Ra value when the pulse off time is increased.

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