Regression Modeling of EDM Process for AISI D2 Tool Steel with RSM

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ABSTRACT

In this paper, Response Surface Method (RSM) is utilized to carry out an investigation of the impact of input parameters: electrode type (E.T.) [Gr, Cu and CuW], pulse duration of current (I_p), pulse duration on time (T_{on}), and pulse duration off time (T_{off}) on the surface finish in EDM operation. To approximate and concentrate the suggested second- order regression model is generally accepted for Surface Roughness Ra, a Central Composite Design (CCD) is utilized for evaluating the model constant coefficients of the input parameters on Surface Roughness (Ra). Examinations were performed on AISI D2 tool steel. The important coefficients are gotten by achieving successfully an Analysis of Variance (ANOVA) at the 5 % confidence interval. The outcomes discover that Surface Roughness (Ra) is much more impacted by E.T., T_{on}, T_{off}, I_p and little of their interactions action or influence. To predict the average Surface Roughness (Ra), a mathematical regression model was developed. Furthermore, for saving in time, the created model could be utilized for the choice of the high levels in the EDM procedure. The model adequacy was extremely agreeable as the constant Coefficient of Determination (R2) is observed to be 99.72% and adjusted R^2-measurement (R^2_{adj}) 99.60%.
Keywords: Response Surface Methodology, Electrical Discharge Machining, Central Composite Design, Analysis of Variance, Surface Roughness.

تحليل ونمذ جة معلمات التشغيل على خشونة السطح في عملية القطع بالشرارة الكهربائية للفولاذ العدة $AISI\ D_2$ بأستخدام منهجية أستجابة السطح

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الخلاصة

في هذا البحث، استخدمت طريقة استجابة السطح للتحقق من تاثير متغيرات التشغيل: نوع الالكترود (كرافيت، نحاس وتنكستن النحاس)، التيار النبضي، زمن تفريغ الشحنة وزمن توقف الشحنة على خشونة السطح في عملية التشغيل بالشرارة الكهربائية. لدراسة النموذج المقترح لخشونة السطح من الدرجة الثانية، استخدمنا التصميم المركب المركزي لتخمين معاملات النموذج للمتغيرات الاربعة سالفة الذكر على خشونة السطح. التجارب نفذت على فولاذ العدد D2 تم الحصول على المعاملات المؤثرة بتنفيذ تحليل التباين (ANOVA) عند مستوى من الاهمية مقداره 5% . النتائج بينت ان خشونة السطح تتأثر بمتغيرات التشغيل الاربعة وبعض تفاعلاتهم. النموذج الرياضي طور لتنبأ متوسط خشونة السطح في عملية التشغيل بالشرارة الكهربائية. كذلك يمكن استخدام النموذج الرياضي في اختيار مستويات في عملية الشرارة الكهربائية لتوفير وقت التشغيل. كفاءة النموذج الرياضي مقنعة جدا لان معامل التحديد 99.72 % والمعامل الاحصائي 99.60 %.
الكلمات الرئيسية: منهجية استجابة السطح، التشغيل بالشرارة الكهربنئية،التصميم المركب الوسطي،تحليل االتباين، خشونة السطح.

1. INTRODUCTION AND LITERATURE REVIEW:

Electrical discharge machining (EDM) process newly developed thermal non-conventional cutting techniques for difficult metals to machine such as ceramics, heat-resistant steels, tool steel, super alloy, composites, carbides, etc. These materials used either non-conventional materials with special features and properties or newly formed developed materials with high-achievement ability. Now today's especially manufacturing industry is confrontation from these modern and advanced "difficult-to-cut" materials, capital requirements wanted, (three dimensional (3D) complex shapes), high or great precision and high surface finish) and machining high cost. Developed materials engage and play a gradually important pivotal role in advanced industries. The properties of the material greatly improved (such as mechanical properties, heat resistance, corrosion resistance, and wear resistance) the economic interest to the especially manufacturing industries through get better product design and output product achievement. Non-conventional machining methods are unable to achieve machine product materials economically because traditional machining methods depend on removing materials rate by using cutting tools harder than the workpiece. But one of advanced processes using the material features and properties, such as melting, temperature, electrochemical equivalent, electrical conductivity, and thermal etc. **Puertas, et al., 2004**, anatomized the impact of (EDM) input parameters on material removal rate (MRR), electrode wear and surface quality inspection in tungsten carbide workpiece material. A quadratic mathematical model was amelioration for each one of the output parameter responses and it was noted that for material removal rate (MRR) and current intensity, the parameter was the most effective, followed by τ, the interaction, and Ton influence of the first just the two. The amount value of material removal rate (MRR) also increased, when intensity and τ were increased and decreased amount value with Ton.Therefore for the prediction of multi-regression mathematical models and surface roughness finish, empirical equation models are applied and utilized**. Patel, et al., 2007**, verify the machining general characteristics, such as the mechanism of material removal rate (MRR) and surface integrity of AL_2O_3-SiC-Tic material with (EDM). The final result refers to the white layer (recast layer) and surface roughness (Ra) increase with a pulse on time and current. Material removal rate (MRR) for the reasons of the evaporation, decomposition, some extent oxidization, and dissolution or separation melting at lower current and thermal spelling at higher current, **Kuppan, et al., 2007.** In this study, strong mathematical model for average surface roughness (Ra) and material removal rate (MRR) of deep hole drilling form of Inconel 718 was obtained. The set of experiments were planned and designed using central composite design (CCD) and response surface methodology (RSM) was used to the same model. It appears that material removal rate (MRR) is very affected by peak current, duty factor and the input operating parameters were making the best (optimized) for maximum material removal rate (MRR) with the required surface roughness Ra. **Chiang, 2008,** had explained the influences of Ip, Ton, τ and voltage on the responses; MRR, electrodes wear ratio and Ra. The experiments were planned according to a CCD and the influence of parameters and their interactions were investigated using ANOVA. A mathematical model was developed and claimed to fit and predict MRR accurately with a 95% confidence. Results show that the main two significant factors affecting the response are the Ip and the τ.). **Biswas, and Pradhan,**

2008, displayed Adaptive Neuro-Fuzzy Interence Systems (ANFISs) model to predict and forecast material removal rate (MRR) of workpiece AISI D2 tool steel with Ip, duty cycle (τ) and Ton as operating parameters. All experimental results were found to be in agreement and very good approval with the mathematical model predictions. **Kanagarajan, et al., 2008,** selection, Ton, Ip, electrode rotation flushing and pressure as design input operating parameters to research the (EDM) process accomplished such as material removal rate (MRR) and surface roughness (Ra) on Tungsten carbide. The most effective input operating parameters for decreasing the surface roughness (Ra) have been specified using the response surface methodology (RSM) and experimentally make sure by conducting affirmation experiments. **Pradhan, et al., 2009,** also suggested just the two artificial neural networks (ANNs) mathematical models for the prediction of surface roughness (Ra) with the similar workpiece material and operating parameter and then estimate the experimental results. It is supposed that the mathematical models could predict surface roughness (Ra) they successfully accomplished. In **Rao, et al., 2010**, a central composite design (CCD) is applied and utilized to conduct the output response surface final approach and set of experiments are utilized for the improvement of analysis of surface roughness (Ra) with E.T., I_p, and T_{off} , T_{on} as input operating factors and a second-order polynomial model. **Medfai, et al., 2011,** studied the influence of the cutting conditions on machining operation by EDM of steel materials 42CD4-42 CrM04 on surface layer quality by the development of a regression model. The results show that the surface layer quality and the volume of the removal influence considerably with nature of the electrode used and the different materials machined by EDM. In, **Khalid Hussain Syed, et al., 2013,** paper, tool electrode materials used are electrolytic copper and W300 die steel respectively, concentration powder, pulse on- time and pulse peak current are taken as input operating parameters. The output response parameter is white layer (WLT) or thickness recast material. Mathematical or empirical model is developed for output white layer by utilizing response surface methodology(RSM) to research the influence of process operating parameters. In this research study, a central composite design is applied research to conduct the response surface approach and a experiment is utilized for the software development of a second-order polynomial model and analysis of surface roughness SR with input parameters as (Ip, E.T, Toff and Ton).

2. EXPERIMENTATION

The set of experiments have been achieved to study the influence of different characteristics machining input operating parameters on Ra of tool steel. This work has been pledged to realize the influence of process operating parameters.T. E, I_p, T_{off} and T_{on} on surface roughness (Ra)**.** The number of experiments was carried out on a die sinking type EDM computer numerical control (CNC) machine model (CHMER EDM). The kind of workpiece material utilized in this work was AISI D2 tool steel, with dimensions (35×35×3) mm and surface roughness Ra (2 μm) to be formed or machined. The chemical composition of the workpiece material is shown in **Table 1.** In this study, the electrolytic copper cylindrical shaft is selected as the tool electrode with dimensions (100 mm long and 30 mm diameter) were mounted axially at positive polarity. The working gap between the workpiece and electrode the is (0.20 mm). The grade oil was used as dielectric fluid with pressure (0.3) Kg/cm^2 for cleaning and flushing. Description of each workpiece surface layer condition was achieved traceable of the surface roughness (Ra) profile measurement on a wide variety of surface. A portable surface roughness tester (type Pocket Surf III/ PMD 90101) was used to measure the Ra of AISI D2 tool steel. At the beginning of measuring surface roughness (Ra), any specimen was washed and cleaned in liquid type(acetone) and then dried with hot air blower. To obtain validity period and accuracy, five observed value times of surface roughness was measured along five different directions. Then finding the mean value for each treatment combination, the cutoff length was 0.8 mm **Fig.1** shows a picture of the measuring .and **Fig.2** shows a picture of the EDM machine type (.CM 323C+50N).

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3. RESPONSE SURFACE METHODOLOGY (RSM)

The method response surface methodology (RSM) is a collection of mathematical model and statistical techniques method, it can be used for, improvement, development, and optimisation of processes in order to solve the problems of engineering, **Boopathi and Sivakumar, 2014.** Design of Experiments (DOE) as a scientific method utilized to exact convergent value and without the knowledge of function for which only a few quantity of values are calculated. These relationships are the product by utilizing many designs such as least square error or a mistake fitting of the response surface. The very popular one is the Central Composite Design (CCD) is utilizing because it gives a relatively more accurate forecast or prediction of all response parameter median with reference to amounts measured during this period of experimentation**, Mason, et al., 2003**. A Central Composite Design (CCD) displays the feature that a certain amount of modification is suitable and be able to utilize in the two-step chronological age response surface methodology. In these type of scientific methods, there's a probability that the set of experiments may be finished or stop with any runs and be decided that the prediction regression model is acceptable. In Central Composite Design CCD, the end boundary or limits of the set of experimental range to learn are understood and are well made as great to the full extent able to be done to get an evident output response from the empirical model. Operating parameters (E.T., Ip, Ton, and Toff) are carefully chosen as being the more significant for this general investigation. The various levels were taken for this research show or represent in **Table 2**. The result of arranging in the behavior of the experiments utilize a Central Composite Design CCD with input operating parameters, the important points utilized are sixteen points formed a cube, six center points position and eight axial points, in the overall of 30 work s in three blocks**.** The average rate of change value in surface roughness (Ra) is shown in **Table 3**. The second-order response surface model is usually utilized when the response cumulative distribution function is non-linear. In this study, a second-order response surface model has been used to explains the behavior of the system and relation between the input operating parameters and output parameters response. The second-order response surface model in Eq.(1), **2003**.

$$\mathbf{Y} = \beta_o \sum_{i=1}^{k} \beta_i X_i + \sum_{i=1}^{k} \beta_{ii} X_i^2 + \sum_{\mathrm{i}<j=2}^{k} \beta_{ij} X_i X_j \pm \varepsilon \qquad (\mathbf{1})$$

where Y is the congruent output expected for the response, X_i is the input operating parameters, $X_i X_j$ and X^2_{ii} are the interaction terms and squares, of these operating parameters. The unbeknown regression coefficients to be estimated are β_o, β_i, β_{ij} and β_{ii} and the error or noise observed in the response surface model is indicated that ε.

The unbeknown coefficients are found and be specified from the set of experimental data as given in **Table 4**. The used or accepted as normal or average mistakes in the evaluation of the correlation coefficients are arranged (data) in tabular form in the column، constant SE coif. The F-value is a test to determine main influences are significant and interaction, are studied at the level 95% of confidence and the operating parameters having p-value the probability of obtaining more than 0.05 are insignificant or unimportant (shown with * in p-column). For the suitable fitting of surface roughness Ra, by the backward elimination operation, the non-significant terms are eliminated. The regression model is evaluated again or differently by determining or limit the not known coefficients, which are arranged (data) in tabular form in **Table 5**. The new mathematical model made to clarify surface roughness Ra describe that electrode type E.T., Pulse duration of current (I_p), Pulse duration on time (T_{on}), Pulse duration off time (T_{off}), Electrode type E.T..2, E. T. × Pulse duration on time(T_{on}), Electrode type E.T. × Pulse duration off time (T_{off}), Pulse duration of current (I_p) × Pulse duration off time (T_{off}) and Pulse duration on time(T_{on}) × Pulse duration off time (T_{off}) are the greatest extent influences operating parameters in order to do this of statistical significance. The last empirical model for surface roughness Ra is specified in Eq. (2).

$$\mathbf{Ra = 4.46833 - 0.70333\ E.T. + 0.14111\ Ip - 0.53389\ Toff + 0.45556\ Ton - 0.07375E.T - 0.16167\ E.T.2.\times Ton + 0.08625E.T.\times Toff - 0.1025Ip\times Toff - 0.055Ton\times Toff} \quad (2)$$

Since electrical discharge machining EDM method is non-linear behavior in the state of nature, a linear polynomial will not be capable prophesy the output parameter carefully, and for this reason, the second-order response surface model or quadratic mathematical model have set up to be strong enough modeling the EDM method. The analysis of variance (ANOVA) display in table for the reduced or shorten quadratic mathematical model **Table 6** describe an estimation of the present value of the constant coefficient of determination, (R2) as far as 99.75%, which is an indication of how much a change or difference in the output parameter is clarified or explained by the mathematical model. The higher level constant coefficient of determination (R2), denotes the suitable or get the better fitting of the empirical mathematical model with the technical information.

The empirical mathematical model sufficiency examination contains the placement test for the importance of the empirical mathematical model, lack of fit and model coefficients, which is achieved when utilizing analysis of variance (ANOVA) on the shorten empirical mathematical model **Table 6**. The overall mistake or error of regression models collect the total of mistakes or errors in interaction terms, and linear square (18.49148 + 0.43095 +0.191964=19.114394). The residual value mistake is the collect of lack-of-fit and pure mistakes. The fit abstract recommends that the quadratic mathematical model statistically results in information important influence for data analysis of surface roughness (Ra). In the table, p-value for the lack-of-fit about 0.094, which is tenuous influence, so the mathematical model is surely enough. On the other hand, the mean square mistake of refined error is even less than that of lack-of-fit. The final report for empirical mathematical model measures to check tested for (ANOVA) (F-test) refers that the being sufficiency of the test report is decided. The calculated set of values of output parameters, model charts and graphs are created for the more content analysis in another part. A total residual value analysis has been achieved for improving the charts and graphs output and response are shown below in **Fig.3**. When the normal conditional probability plot of residuals expose that set of experimental information and data are propagation approximately condition along the direct straight line, corroborative a useful connection between a set of experimental and predicted values level for the output parameter is shown below in **Fig. (3 - a)**. In the scheme of residuals against a completely fitted set of values are shown below in **Fig. (3 - b)**, only too small amount difference can be visually seen. The generating histogram of residuals is shown below in **Fig. (3 - c)** as well display a Gaussian probability distribution in which is favored, and at last, in residuals versus the required order of a set of experimentations are shown below in **Fig. (3- d)** both of them positive and negative residues are clearly visible, indicating that nothing special direction which is deserved across from a statistical information analysis from this point of view. As a total, all the models do not really show any weakness.

.4. RESULTS AND DISCUSSION

Fig. 4 displays the greater influence and make plans to carry out of the four input operating parameters which under control on surface roughness Ra. It is comprehensible that all input parameters have great effect and strong impacts on surface roughness Ra which is confirming by a consequence, are shown below in **Table 6**. Specifically designed, change the electrode type (E. T) alone or only one for a Gr to Cu then CuW, while conservation the other operating parameters constant at their middle amount levels, can be reduced in surface roughness (Ra) by percentage 28% about (4.93μm - 3.55 μm), which is a great variance interval or space than those produced by another input operating factors. This is because the least removal of debris reached for that material, which means a result is brought that minimum and of little depth or shallower craters were made in the workpiece surfaces with CuW. In addition to this, the surface roughness (Ra) increased change by percentage 5 % about (4.41 μm - 4.61 μm), with pulse current (Ip) become greater or make increases about (24 Amp - 36 Amp). In other words the greater or increase in pulse current (Ip) for various reasons happened elevated level of surface roughness (Ra) accordingly the pulse current (Ip) is greater or increases, electrostatic discharge make a sudden stoppage on the superficial layers of the workpiece very strong, intensely and creates a sensation an effective force on the liquefied by heat metal in a large or small crater, due to exceedingly molten metal to be pushed outside of the large or small crater, and the surface roughness (Ra) of machine leading to superficial layers increases, **Shabgard, et al., 2011.** At the same surface roughness (Ra) change increased by percentage 23 % (4.02 μm - 4.92 μm) such as the pulse on time (Ton) increased change from low to high of different level at constant middle amount of set of values of other input operating factors Long pulse on time(Ton) lead to the high performance in heat transfer inside the dielectric fluid and workpiece, the is capable to remove the molten or liquid metal, such as make flushing of dielectric pressure in constant certain amount. In another statement, during the time that the pulse on time (Ton) is increased change, the melting isothermals permeate moreover into the interior design of the reference material, and the liquid material or molten effect region extends most or extra into the material and this produces a greater extent recast or white thick layer. Consequently, such as the pulse on time(Ton) increases change the surface roughness (Ra) increases that can be corroborated by **Hascalık and Caydas, 2007.** At the end, the direction of pulse off time (Toff) is similar to electrode type (E.T.) where applicable reduction in surface roughness (Ra) by percentage 23 % (5.04 μm - 3.89 μm) when pulse off time (Toff) increases (25 μsec - 75 μsec), reduce levels out of (Toff) form the higher up than frequency range that output yields less than (Ra). Moreover, for a long time period of (Toff) output yields lowered metal removal (MR) for this reason get least or smaller and little depth of craters are obtain. The longtime period of (Toff) supplies best refrigeration influence and required time to straight flush out away or subtract the molten material molten material which liquefied by heat and fragments and debris from the working spark gap or distance between the workpiece and electrode. Thus, a longer period of (Toff) attends low (Ra) **Jahan, et.al, 2011. Fig. 5** displays the synchronous influence of electrode type(E.T.) and pulse on time (Ton) on the surface roughness (Ra), (a) and (b) in three-dimensional (3D) surface and two-dimensional (2D) contour interval format. It is clearly able to be seen that smaller surface roughness (Ra) be able to get selected a great level of electrode type (E.T.) less pulse on time (Ton). That is referred to carrying capacity of debris away far by CuW electrode as well as possible with the reduction in pulse on time (Ton), the extremely weak spark become a shorter period, which makes small craters, temperature and hence good surface finish. The group influence of pulse off time (Toff) and electrode type (E.T.) at a constant level (middle amount of value) of a pulse on time (Ton) and pulse current (Ip) there has been a performance display in Fig.5 in two and three-dimensional surface with the contour format shape. It is able to be complimented that the decrease surface roughness (Ra) is accomplishable at the upper part right zone of the contour plot region where the pulse off time (Toff) and electrode type (E.T.) are their highest amount levels. This unnatural phenomenon happens and is able to refer to a feature of carrying capacity debris away far by CuW electrode as well as possible the refrigeration influence on workpiece and electrode with long pulse off time (Toff) hence decreasing the surface roughness (Ra). **Fig. 6** clarifies the together influence of pulse off time (Toff) and pulse current (Ip) over surface roughness (Ra). It is clearly visible that more smoothly achieved without bitterness surfaces can be marks obtained specifying when high value pulse off time (Toff) and low pulse current (Ip) which is accomplishable at the uppercase level left zone of the contour plot region. This is due to the discharge sparking hits the surface layer of the specimen less value of intensely with lower pulse current (Ip) and, as mentioned over, the refrigeration influence on workpiece and electrode with long period pulse off time (Toff) and as a consequence reducing the surface roughness (Ra). **Fig. 7** describes the contour plot and surface of surface roughness (Ra) with regard to pulse off time (Toff) and pulse on time (Ton). From this, it is strongly recommended to stratify get low pulse on time with a considerable pulse off time (the upper class left portion of **Fig. 7 (b)**) to create much more smooth or polished or refined work surfaces. This is because a medium as the dielectric fluid influenced which is qualified for pure or clear away the molten or liquefied material with low level pulse on time (Ton) and the refrigeration influence above-mentioned with long pulse off time. From the (ANOVA) analysis of variance (Table 6), the interaction of pulse current and pulse off time is the very considerable (significant) influence on surface roughness (Ra), followed by electrode type (E.T.) × pulse off time (Toff), electrode type (E.T.) × pulse on time(Ton) and then pulse on time(Ton) × pulse off time (Toff).

5. CONCLUSION

The main conclusions achieved can be summarized as follows:

1. The operating parameters have more significant effect on Ra surface roughness were the. Electrode type E.T., Pulse duration off time (T_{off}) and Pulse duration on time (T_{on}), E. T.^{2}, Electrode type E.T.. × Pulse duration on time(T_{on}), Electrode type E.T. × Pulse duration off time (T_{off}), Pulse duration of current (I_p) × T_{off} and Pulse duration on time(T_{on}) × Pulse duration off time (T_{off}) with the estimate the worth of a parameter a confidence specified range (level) of 95%.
2. The final test result refers that with a view to getting a low amount of value of surface roughness Ra during the work period of this research, Pulse duration of current (I_p) and Pulse duration on time (T_{on}) must be stable as less as much as possible to be done, whereas the T. E. and T_{off} should be stable as high as possible to be done.
3. The improved mathematical regression model for the surface roughness Ra is able and influential used for the optimal or best option of the (EDM) drilling work in process operating factors to accomplish high surface finish of AISI D2 tool steel material of workpieces.
4. Although the (EDM) drilling work in process input operating factors on AISI D2 tool steel workpieces are extremely interconnected system stochastic nature and due their inherently complex, however, the practical approach of response surface methodology coupled can usefully help recognizing process good behavior and determine suitable (EDM) operating conditions meeting all accomplishment search criteria in accept compromise in such a manner.
5. This study assists researchers and industries in developing productivity a strong, trustworthy knowing range and prediction based on evidence of surface roughness (Ra) without a doubt achieve more experiments with an (EDM) drilling work in process for AISI D2 tool steel workpieces.

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Table 1. Chemical composition of the AISI D2 tool steel workpiece [wt. %].

Material	C	Si	Mn	Mo	Cr	Ni	V	Co	Fe
Wt.%	1.5	0.3	0.3	1.0	12.0	0.3	0.8	1.0	Balance

Figure 1. Set up for surface roughness measurement.

Figure 2. shows a picture of the EDM machine.

Table 2. Different variables used in the experiment and their levels.

Variable	Unit	Coded/Actual level		
		-1	**0**	**1**
Electrode type E.T.	-	Gr	Cu	CuW
Pulse duration of current (I_p)	Amp.	24	30	36
Pulse duration on time(T_{on})	μsec.	50	100	150
Pulse duration off time (T_{off})	μsec.	25	50	75

Table 3. Design layout with experimental results and predictions for AISI D2 tool steel work piece.

Exp. No.	Pt Type	Blocks	E. Sh.	Ip (Amp.)	Ton(µsec.)	Toff(µsec.)	Ra(µm)	Ra(Fit) Calculated (Regression)	Residual
1	1	1	-1	-1	1	-1	6.501	6.542	-0.041
2	1	1	-1	-1	-1	1	4.257	4.239	0.018
3	1	1	-1	1	1	1	5.39	5.419	-0.029
4	0	1	0	0	0	0	4.884	4.915	-0.031
5	1	1	1	-1	-1	-1	3.784	3.734	0.050
6	1	1	1	-1	1	1	3.828	3.814	0.014
7	1	1	1	1	-1	1	3.168	3.128	0.040
8	1	1	1	1	1	-1	5.181	5.178	0.003
9	1	1	-1	1	-1	-1	5.83	5.845	-0.015
10	0	1	0	0	0	0	4.906	4.915	-0.009
11	1	2	-1	1	-1	1	4.411	4.376	0.035
12	1	2	-1	1	1	-1	7.205	7.130	0.075
13	0	2	0	0	0	0	4.928	4.915	0.013
14	1	2	1	1	1	1	3.883	3.847	0.036
15	1	2	-1	-1	1	1	5.324	5.282	0.042
16	1	2	1	1	-1	-1	4.191	4.217	-0.026
17	1	2	1	-1	-1	1	3.058	3.095	-0.037
18	1	2	-1	-1	-1	-1	5.258	5.256	0.002
19	0	2	0	0	0	0	4.95	4.915	0.035
20	1	2	1	-1	1	-1	4.675	4.695	-0.020
21	-1	3	0	1	0	0	5.071	5.070	0.001
22	-1	3	0	0	0	1	4.279	4.328	-0.049
23	-1	3	0	0	1	0	5.412	5.416	-0.004
24	-1	3	0	0	-1	0	4.422	4.414	0.008
25	-1	3	-1	0	0	0	5.423	5.511	-0.088
26	0	3	0	0	0	0	4.895	4.915	-0.020
27	-1	3	0	-1	0	0	4.851	4.760	0.091
28	-1	3	0	0	0	-1	5.544	5.502	0.042
29	0	3	0	0	0	0	4.84	4.915	-0.075
30	-1	3	1	0	0	0	3.905	3.964	-0.059

Table 4. Estimated Regression Coefficients for Ra (Before elimination).

Term	Coef.	SE Coef.	T-value	P-value
Constant	4.506408	0.017109	266.0088	0.000
Block 1	-0.0022	0.012726	-0.17473	0.865
Block 2	0.011938	0.012726	0.012726	0.365
E. T.	-0.71036	0.010686	-67.1387	0.000
I_p (Amp.)	0.142521	0.010686	13.47037	0.000
T_{on} (µsec.)	0.460116	0.010686	43.48656	0.000
T_{off} (µsec.)	-0.53923	0.010686	-50.9646	0.000

E. T.×E. T.	-0.22113	0.028452	-7.84871	0.000
I_p (Amp.)×I_p (Amp.)	0.051571	0.028452	1.83012	0.093**
T_{on} (µsec.)×T_{on} (µsec.)	0.011171	0.028452	0.39693	0.701**
T_{off} (µsec.)×T_{off} (µsec.)	0.006121	0.028452	0.21715	0.833**
E. T.×I_p (Amp.)	-0.02399	0.011332	-2.13716	0.054**
E. T.×T_{on} (µsec.)	-0.07449	0.011332	-6.63772	0.000
E. T.×T_{off} (µsec.)	0.087113	0.011332	7.76286	0.000
I_p (Amp.)×T_{on} (µsec.)	0.00505	0.011332	0.45046	0.663**
I_p (Amp.) ×T_{off} (µsec.)	-0.10353	0.011332	-9.22534	0.000
T_{on} (µsec.) ×T_{off} (µsec.)	-0.05555	0.011332	-4.95001	0.000
	R^2 = 99.86% $R^2_{(adj.)}$ = 99.69%			

Table 5. Estimated Regression Coefficients for Ra (After backward elimination).

Term	Coef.	SE Coef	T-value	P-value
Constant	4.47883	0.01674	267.507	0.000
E. T.	-0.70333	0.01199	-58.661	0.000
Ip (Amp.)	0.14111	0.01199	11.769	0.000
T_{on} (µsec.)	0.45556	0.01199	37.995	0.000
T_{off} (µsec.)	-0.53389	0.01199	-44.529	0.000
E. T. ×E. T.	-0.17917	0.02322	-7.717	0.000
E. T. ×T_{on} (µsec.)	-0.07375	0.01272	-5.799	0.000
E. T. ×T_{off} (µsec.)	0.08625	0.01272	6.782	0.000
Ip (Amp.) ×T_{off} (µsec.)	-0.10250	0.01272	-8.060	0.000
T_{on} (µsec.) ×T_{off} (µsec.)	-0.05500	0.01272	-4.325	0.000
	R^2= 99.72% $R^2_{(adj.)}$ = 99.60%			

Table 6. Analysis of Variance for Ra (µm).

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	9	19.11439	19.11439	2.123824	817.377	0.000
Linear	4	18.49148	18.49148	4.622854	1779.166	0.000
E.T.	1	9.082284	9.082284	9.082284	3495.428	0.000
I_p	1	0.365568	0.365568	0.365588	140.6988	0.000
T_{on}	1	3.810312	3.810312	3.810271	1466.423	0.000
T_{off}	1	5.233314	5.233314	5.233283	2014.092	0.000
Square	1	0.191964	0.191964	0.191944	73.8684	0.000
E.T. × E.T.	1	0.191964	0.191964	0.191944	73.8684	0.000
Interaction	4	0.43095	0.43095	0.107753	41.4732	0.000
E.T. × T_{on}	1	0.08874	0.08874	0.08876	34.1598	0.000
E.T. × T_{off}	1	0.12138	0.12138	0.1214	46.7262	0.000
I_p × T_{off}	1	0.171462	0.171462	0.171462	65.994	0.000
T_{on} × T_{off}	1	0.049368	0.049368	0.049368	19.0026	0.000
Residual	20	0.05304	0.05304	0.002652		

Error						
Lack-of-Fit	15	0.04692	0.04692	0.003131	2.6316	0.151
Pure Error	5	0.006018	0.006018	0.001214		
Total	29	19.114394				

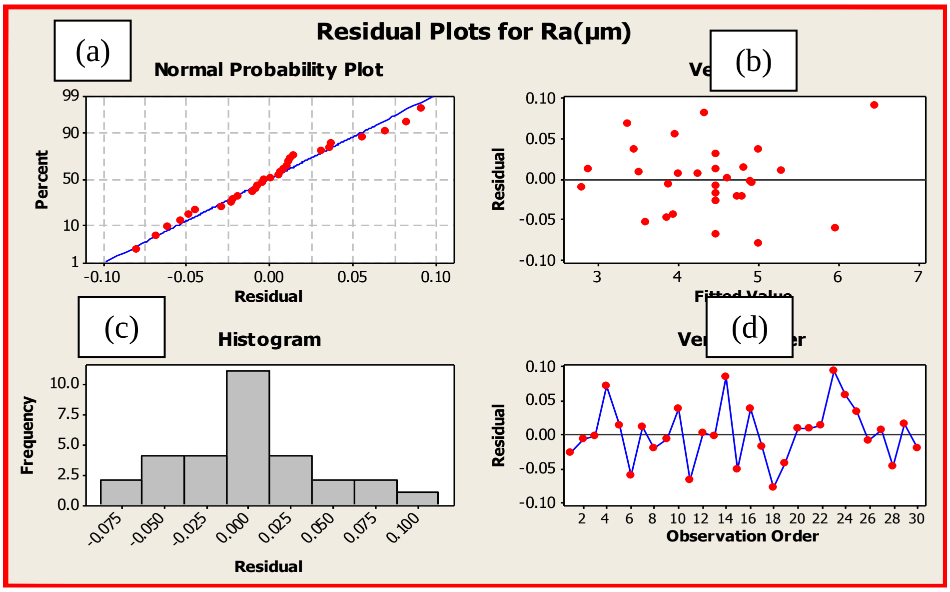


Figure 3. Residual Plot for Ra (µm).

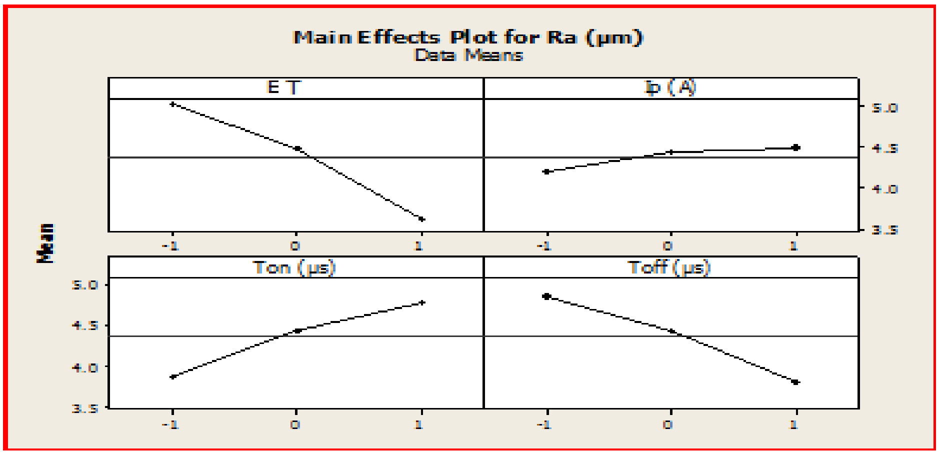
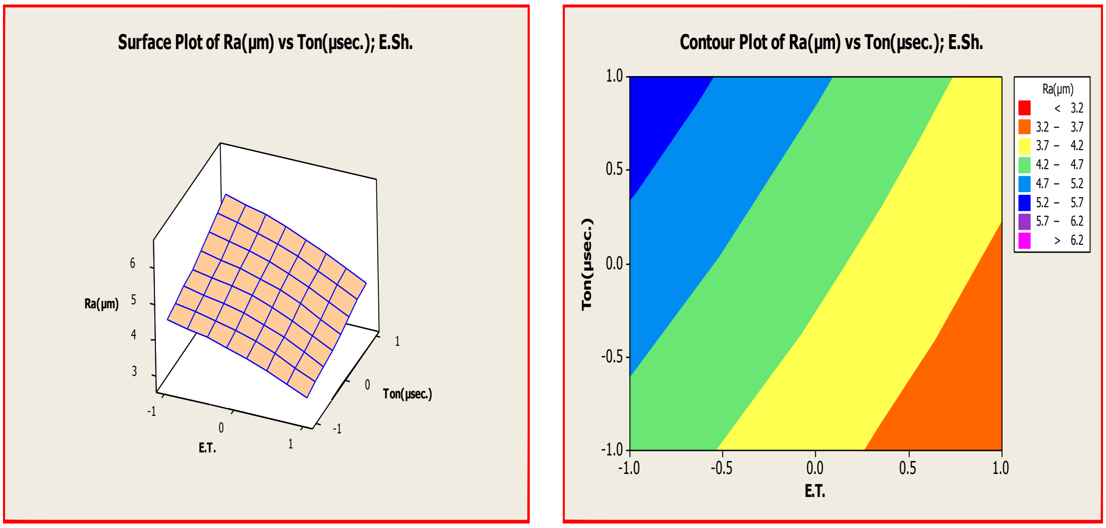
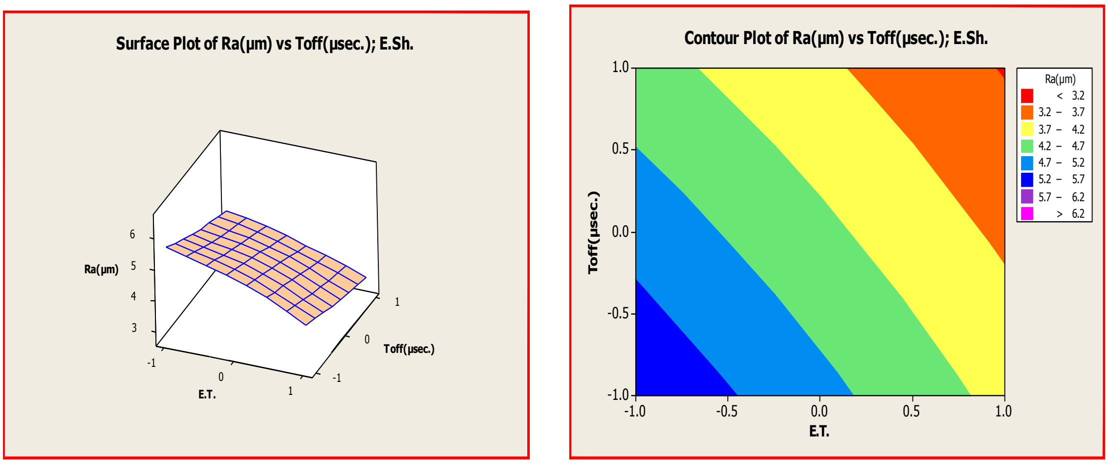


Figure 4. Main effect plots for Ra (µm).



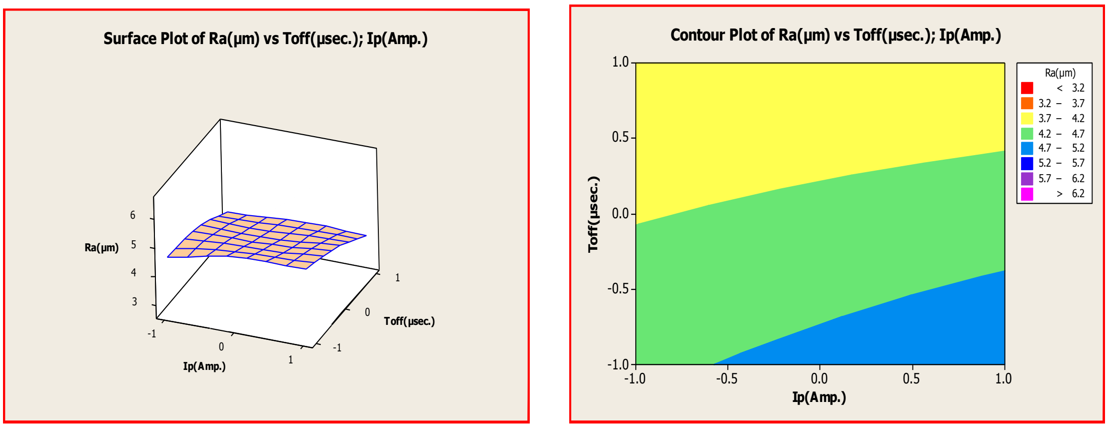
(a) (b)

Figure 5. Response surface plot (a) and contour plot (b) of Ra versus electrode shape (E.T.) and pulse on time (T_{on}).



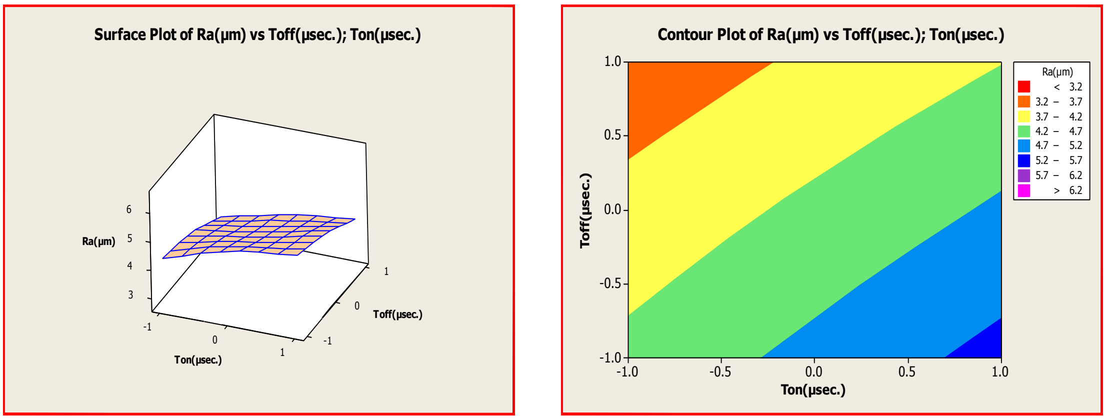
(a) (b)

Figure 5. Response surface plot (a) and contour plot (b) of Ra versus electrode shape E.T. and pulse off time(T_{off}).



(a) (b)

Figure 6. Response surface plot (a) and contour plot (b) of Ra versus pulse current (I_p) and pulse off time(T_{off}).



(a) (b)

Figure 7. Response surface plot (a) and contour plot (b) of Ra versus pulse on time(T_{on}) and pulse off time(T_{off}).