International Journal of Engineering & Technology
CENTRE OF PROFESSIONAL RESEARCH PUBLICATIONS
ISSN 2049-3444

International Journal of Engineering and Technology Volume 2 No. 4, April, 2012

Prediction of Surface Roughness in Wire Electric Discharge Machining (WEDM) Process based on Response Surface Methodology

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ABSTRACT

This paper presents an investigation on WEDM of pure titanium (grade-2). An attempt has been made to model the response variable i.e. surface roughness in WEDM process using response surface methodology. The experimental plan is based on Box-Behnken design. Six parameters i.e. pulse on time, pulse off time, peak current, spark gap voltage, wire feed and wire tension has been varied to investigate their effect on surface roughness. The surface roughness has been optimized using multi-response optimization through desirability. The ANOVA has been applied to identify the significance of developed model. The test results confirm the validity and adequacy of the developed RSM model. Finally, the optimum parametric setting has been designed for the optimization of process.

Keywords: *WEDM,Titanium, Response surface methodology, Box-Behnken design, Desirability function*

1. INTRODUCTION

WEDM process is one of the most widely used non-traditional machining processes in current manufacturing. It involves the removal of metal by discharging an electrical current from a pulsating DC power supply across a thin inter-electrode gap between the tool and the work piece. It is most commonly used for machining hard and difficult to machine materials with very close tolerances. Generally, WEDM is perceived to be an extremely actuate process and there are various reasons for this perception. Firstly, in WEDM, no direct contact takes place between the cutting tool (electrode) and the work piece; as a result, the adverse effects such as mechanical stresses, chatter, and vibration normally present in traditional machining are eliminated. Secondly, the wire used as a cutting tool has high mechanical properties and small diameter 0.076 to 0.30 mm that produces very fine, precise, clean cuts. Finally, in WEDM, the movements of the work piece during cutting are controlled by a highly accurate CNC system (with positioning accuracy up to ±0.5 µm) [1]; as a result, the effects of positioning errors present in conventional machining are significantly diminished.

2. LITERATURE REVIEW ON WEDM PROCESS

Titanium and its alloys are used extensively in aerospace. This is due to their excellent combination of high specific strength maintained at elevated temperature, their fracture resistant characteristics and exceptional resistance to corrosion. Also these are being used increasingly in other industrial and commercial applications such as aerospace industry, mainly in airframe construction, petroleum refinery, nuclear reactors, surgical implants and marine applications. Other applications include compressor blades, rocket cases and offshore pressure vessels. The machining of titanium and its alloys is generally cumbersome owing to several inherent properties of the material. Titanium is very chemically reactive and therefore, has a tendency to weld to the cutting tool during machining thus, leading to premature tool failure [2]. Its low thermal conductivity increases the temperature at the tool-work interface thus, affecting the tool life adversely.

Additionally, its high strength maintained at elevated temperature further impairs the machinability. Owing to all these problems, it is very difficult to machine titanium and its alloys by conventional machining processes and moreover, by conventionally used tool materials. Non-traditional machining methods such as EDM and LBM have been applied to the machining of titanium and its alloys during recent times. However, these processes have some limitations; particularly in machining of small and deep holes in titanium and its alloys. With EDM process, one problem is that the debris in machining gap cannot be eliminated easily, and the machining status is unstable during the process [3]. Another reason is that titanium has a low heat conduction efficiency and high tenacity. LBM can be applied for machining of titanium, but even this process has its own problems in forming pear shaped holes, tapering of holes and holes with straight profile.

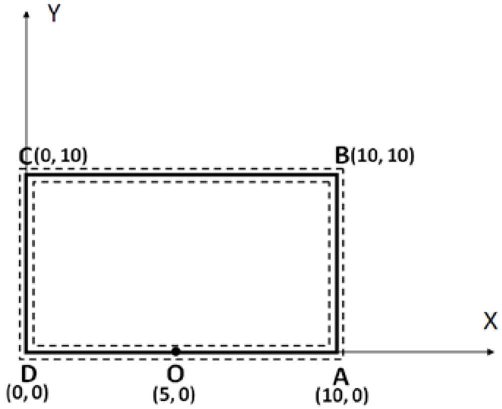
Recast layer is a common phenomenon in EDM that cause some problems. Certain materials melt and re-solidify on the base materials, giving rise to surface coating in which the properties are different from those of the original material. The HAZ also alters the performance of the work piece material [4]. In this regard, the machinability of WEDM for titanium needs to be explored. Almost little attempt has been reported regarding the feasibility of using an unconventional machining process such as WEDM for machining of titanium. There is a critical need for optimization of process parameters while using WEDM. Sarkar et al. [5, 6] presented an approach to select the optimum cutting condition with an appropriate wire offset setting in order to get the desired surface roughness and dimensional accuracy for machining of γ-titanium aluminide alloy. The process has been modeled using additive model in order to predict the response parameters i.e. cutting speed, surface roughness and dimensional deviation. Hseigh et al. [7] investigated WEDM characteristics of Ti Ni X ternary shape memory alloys. It was that surface roughness of machined Ti Ni X alloy increased with growing pulse duration. The hardness of each specimen was reported 875 and 807 HV for WEDMed Ti Ni Zr and Ti NiCr alloys. Hewidy et al. [8] has been investigated the WEDM performance on Inconel 601 by using response surface methodology (RSM). They have confirmed that surface roughness increase with the increase of peak current and decrease with increase of duty factor and wire tension. Mahapatra and Patnaik [9]; Yuan and Chiang [10] used coated wire electrode to investigate WEDM machining performance. Coated brass wire can perform at higher cutting speed as compared to brass wire electrode. Coated brass wire can also produce exceptional surface finish. Porous et al. [11] developed the model of efficiency of cutting by application of dimensional analysis. The developed semi-empirical model enables analysis of the influence of the most important process parameters and properties of machined materials on volumetric efficiency of cutting. Kuriakose et al. [12] optimized the WEDM process for titanium alloys by non-dominated sorting genetic algorithm. It was found that there was no single optimal combination of cutting parameters, as their influences on the cutting velocity and the surface finish were quite opposite. The sorting procedure employed a fitness assignment scheme, which prefers non-dominated solutions and used a sharing strategy, which preserves diversity among the solutions. In addition, none of the solution in the pareto-optimal set was better than any other solution in the set. Liao et al. [13] studied the effect of specific discharge energy on WEDM characteristics of Ti-6Al-4V and Inconel 718. A quantitative relation between machining characteristics and machining parameters was derived. It was observed that two most significant factors affecting the discharge energy (η) are discharge-on time (pulse on time) and servo voltage. Moreover, discharge-on time and work piece height have a significant effect on machined groove width. Spedding and Wang [14] have arrived at the optimal combination of parameters for maximum cutting speed, keeping the surface roughness and waviness within the required limits, but the optimization method is not specified. Scott et al. [15] proposed a factorial design model to measure the process performance as a function of different control setting. The process was further optimized by introducing the concept of a non-dominated point. Tarang et al. [16] developed a feed-forward neural network to associate cutting parameters with cutting performances. A simulated annealing (SA) algorithm was then applied to the neural network to solve for the optimal cutting parameters. Liao et al. [17] developed a mathematical model by means of regression analysis and then solved the optimization problem by a feasible direction method. Manna and Bhattacharyya [18] optimized the machining parameters using the Taguchi and Gauss elimination method. The test results were analyzed for the selection of an optimal voltage and pulse on period was the most significant and influencing parameters for controlling the metal removal rates. Wire tension and wire feed rate were the most significant and influencing parameters for the surface roughness. Ramakrishnan and Karunamoorthy [19] used multi response optimization method using Taguchi’s robust design approach for WEDM. Each experiment had been performed under different cutting conditions of pulse on time, wire tension, delay time, wire feed speed and ignition current intensity. Three responses namely material removal rate, surface roughness and wire wear ratio had been considered for each approach. It was observed that the Taguchi’s parameter design is a simple, systematic, reliable and more efficient tool for optimization of the machining parameters. It was indentified that the pulse on time and ignition current had influenced more than the other parameters. Sarkar et al. [20] modeling and optimization of wire electrical discharge machining of γ-TiAl in trim cutting operation.

A second-order mathematical model, in terms of machining parameters, was developed for surface roughness, dimensional shift and cutting speed using RSM. Singh and Khanna [21] investigated the effect of parameters on cutting rate of cryogenic-treated D-3 steel in WEDM. It was observed that cutting rate decreases with increases in pulse width, time between two pulses and servo voltage. Rong tai yang et al. [25] analyzed the variations in metal removal rate (MRR) and quality performance of roughness average (R_a) and corner deviation (CD) depending on parameters of wire electrical discharge machining (WEDM) process in relation to the cutting of pure tungsten profiles. A hybrid method including response surface methodology (RSM) and back-propagation neural network (BPNN) integrated simulated annealing algorithm (SAA) were proposed to determine an optimal parameter setting. Furthermore, the field-emission scanning electron microscope images show that many built-edge layers were presented on the finishing surface after the WEDM process. Finally, the optimized result of BPNN with integrated SAA was compared with that obtained by an RSM approach. Comparisons of the results of the algorithms and confirmation experiments show that both RSM and BPNN/SAA methods are effective tools for the optimization of parameters in WEDM process.

From the literature review, it was concluded that limited work has been done on WEDM of pure titanium (grade-2). Therefore, it was needed to carry out the present research work for pure titanium (grade-2). The pure titanium is extensively used for sea water piping’s, reactor vessels and heat exchangers. The present work explores the machinability of pure titanium (grade-2) using WEDM process. The six parameters i.e. pulse on time, pulse off time, peak current, spark gap voltage, wire feed and wire tension were varied to investigate their effect on surface roughness. In addition, a second order mathematical model, in terms of machining parameters has been developed for machining rate, surface roughness, and dimensional deviation using response surface methodology. The experiments have been performed based on the Box-Behnken design. These responses are optimized using multi-response optimization through desirability. The ANOVA has been used to identify the significance of the process parameters involved during machining. The test results confirm the validity and adequacy of the developed RSM model.

3. EXPERIMENTATION

The experiments were performed on a four-axis CNC type WEDM (Electronica Sprintcut 734) shown in Figure.1b. The six parameters i.e. pulse on time, pulse off time, peak current, spark gap voltage, wire feed and wire tension were varied to investigate their effect on surface roughness. The parameters kept constant during machining are work piece (pure titanium), electrode (brass wire with 0.25mm diameter), thickness of material 26mm and dielectric pressure 7kg/cm^2. The chemical composition of work material taken for experimentation work as follows: C: 0.10% N: 0.03% O_2: 0.25% H_2:0.015% Fe: 0.30% and Ti: 99.03%. The work material in the form of square plate having dimensions 148mm × 148 mm × 26 mm has been taken for the experimentation work. The surface roughness of machined surface was measured in µm. The measurements were taken three times using the Mitutoyo's SURFTEST (SJ-301). The average of the measurements was taken for the analysis of results. Figure.1 (a) shows the work path profile during machining. The reference point taken was O (5, 0). The wire tool will trace the OA-AB-BC-CD-DO. The CNC program for machining was generated using ELAPT software. During machining the wire offset was set at zero. The Table 1 presents the factors and their levels. The pulse on time and pulse off time was measured in µs and wire tension in grams.



(a) Work-path profile

(b) WEDM machine tool

(c) Presentation of machining

Figure. 1. Job profile and experimental setup of WEDM machine tool. (a) Work-path profile (b) WEDM machine tool (c) Presentation of machining

Table 1: Factors and their Levels

S.No.	Symbols	Input factors	Level I	Level II	Level III	Units
1.	A	Ton	112	116	120	µs
2.	B	Toff	44	50	56	µs
3.	C	IP	120	160	200	Ampere
4.	D	SV	40	50	60	Volt
5.	E	WF	4	7	10	m/min
6.	F	WT	500	950	1400	grams

Experimental Design

The experiments were performed using Box- Behnken design. The pilot experimentation was done for the selection of process parameters levels during machining. Table 2 presents the experimental matrix (54 experiments run order).

4. RESULTS AND DISCUSSION

Response surface modeling of WEDM process

Response surface methodology is a collection of statistical and mathematical methods that is useful for modeling and analysis of engineering problems. In this technique, the main objective is to optimize the response surface that is influenced by various process parameters. The RSM has been applied for modeling and analysis of machining parameters in the WEDM process in order to obtain the relationship to the surface roughness. In the RSM, the quantitative form of relationship between desired response and independent input variables is represented as follows:

$$Y=f\,(Ton, Toff, Ip, SV, WF, WT) \qquad (1)$$

Table 2. Design of Experiments Matrix and Results

	Factors						Response Variable
Standard Run no.	**Pulse on time T_{on} (µs)**	**Pulse off time T_{off} (µs)**	**Peak current Ip (Ampere)**	**Spark gap voltage SV (Volt)**	**Wire Feed WF (m/min)**	**Wire Tension WT (grams)**	**Surface Roughness (µm)**
1	120	50	200	50	7	500	3.22
2	116	56	160	50	4	500	2.48
3	112	50	160	60	4	950	2.23
4	116	44	120	50	10	950	2.75
5	116	50	120	60	7	500	2.47
6	120	50	160	40	4	950	2.93
7	116	56	160	50	10	1400	2.48
8	116	50	160	50	7	950	2.65
9	116	44	160	50	4	500	2.81
10	120	50	160	40	10	950	2.94
11	120	56	160	40	7	950	2.91
12	120	50	160	60	4	950	2.83
13	116	44	160	50	10	500	2.79
14	116	50	160	50	7	950	2.61

15	112	50	120	50	7	500	2.49
16	116	50	160	50	7	950	2.68
17	116	50	120	60	7	1400	2.49
18	112	56	160	40	7	950	2.32
19	116	56	120	50	10	950	2.31
20	116	50	200	40	7	1400	2.89
21	116	50	200	60	7	500	2.69
22	116	56	200	50	10	950	2.57
23	116	50	120	40	7	1400	2.71
24	112	50	120	50	7	1400	2.51
25	116	56	200	50	4	950	2.56
26	120	50	160	60	10	950	2.82
27	120	50	120	50	7	500	2.77
28	112	50	160	40	10	950	2.35
29	112	50	200	50	7	500	2.48
30	112	44	160	40	7	950	2.70
31	112	50	200	50	7	1400	2.51
32	116	50	160	50	7	950	2.65
33	116	44	200	50	4	950	2.88
34	116	50	160	50	7	950	2.65
35	120	44	160	40	7	950	3.28
36	116	44	200	50	10	950	2.98
37	116	50	200	40	7	500	2.84
38	112	50	160	40	4	950	2.33
39	116	56	160	50	10	500	2.50
40	116	50	160	50	7	950	2.69
41	120	56	160	60	7	950	2.66
42	112	44	160	60	7	950	2.60
43	116	50	200	60	7	1400	2.68
44	116	44	120	50	4	950	2.75
45	112	50	160	60	10	950	2.28
46	120	50	120	50	7	1400	2.75
47	112	56	160	60	7	950	2.15
48	116	44	160	50	4	1400	2.85
49	116	50	120	40	7	500	2.78
50	120	44	160	60	7	950	3.00
51	116	56	120	50	4	950	2.29
52	120	50	200	50	7	1400	3.12
53	116	44	160	50	10	1400	2.82
54	116	56	160	50	4	1400	2.49

Where, Y is the desired response and f is the response function (or response surface). For the analysis purpose, the approximation of Y was proposed using the fitted second order polynomial regression model which is called as the quadratic model. The quadratic model of Y is written as follows:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j} \beta_{ij} x_i x_j \tag{2}$$

Where Y is the desired response and the x_i *(1, 2, k)* are the independent of k quantitative process variables. β_0 is constant and β_i, β_{ii}, β_{ij} are the coefficients of linear, quadratic and cross product terms.

Effect of Process Parameters on Surface Roughness

Eq. 3 represents the relationship between machining parameters and surface roughness, which is the result of proposed second-order polynomial model:

Surface Roughness = 10.87640 - 0.038333Ton - 0.12840Toff - 0.072771Ip - 8.66667E -003SV + 0.1247WF – 3.65432E-004WT + 9.72222E - 004Toff^2 *- 8.75000E - 003WF*^{2} *+ 1.91358E-007WT*^{2} *+ 6.48438E - 004TonIp (3)*

Based on analysis of variance as shown in Table 3 Ton, Toff, Ip, SV and one interaction (Ton Ip) is significant to surface roughness. In addition to this normal plot of residuals and residual versus predicted plots has also been drawn. The data is normally distributed. It has been observed from Figure.2 (b), all the experimental results are approximately very close to the predicted values. To fit the quadratic model for surface roughness appropriate, the non significant terms are eliminated by backward elimination. The *p*-value for lack of fit is 0.1173 suggesting that this model adequately fits the data. The "Pred R-Squared" of 0.9527 is in reasonable agreement with the " Adj R-Squared" of 0.9646. "Adeq Precision" measures the signal to noise ratio. From the main effect plots based on the Figure.2 (a), it has been observed that whenever Ton is increased from 112µs to 120µs, the value of surface roughness also increased significantly. The increment of surface roughness was approximately 2.40 to 2.93µm. Meanwhile, a reverse result was observed for SV effect showed roughness was about 2.75 to 2.58µm.When Toff decreased from 56 to 44µs and Ip increased from 120 to 200A showed the most significant effect on surface roughness i.e. 2.51 to 2.89µm and 2.57 to 2.76µm. In order to obtain better surface roughness during WEDM of pure titanium, the optimum parameter combination obtained is Ton=112µs, Toff=56µs, Ip=120A,SV = 60V, WF = 7m/min and WT = 980 grams. The percent contributions of various factors have been shown in Figure. 2(d). The percentage contribution of Ton: 55%, Toff: 28%, Ip: 8%, SV: 6% and error: 3%.

Table 3: Analysis of Variance for Surface Roughness

Source	SS	DOF	MS	F-Value	P>F	Remarks
Model	3.08	10	0.31	145.26	<0.0001	significant
A	1.64	1	1.64	775.10	<0.0001	significant
B	0.84	1	0.84	396.22	<0.0001	significant
C	0.23	1	0.23	108.54	<0.0001	significant
D	0.18	1	0.18	85.03	<0.0001	significant
B^2	0.013	1	0.013	6.36	0.0155	significant
E^2	0.068	1	0.068	32.18	<0.0001	significant
F^2	0.019	1	0.019	8.90	0.0047	significant
AC	0.086	1	0.086	40.62	<0.0001	significant
R^2=0.9712						
R^2 Adjusted=0.9646						
Predicted R^2=0.9527						

Determination on Interaction Effects on Surface Roughness

Based on Table 3, single interaction involved (Ton Ip) is shown in Figure. 2(c). The "Prob>F" value of was <0.0001. Ton was increased from 112 to 120µs and keeps Ip constant of 120A then surface roughness increased from 2.41 to2.72µm. When Ton was set from 112 to120µs with Ip of 200A, then surface roughness increased from 2.40 to 3.13µm. The surface roughness increased when Ton and Ip increased due to the longer time for machining which lead to the higher possibility of "double sparking" and localized sparking to occur. In the other words, double sparking or re-sparking can cause poor surface finish since only the initial phase sparks contributed to the material removal, while the following sparks were poorly distributed along the surface, debris and removed particles.

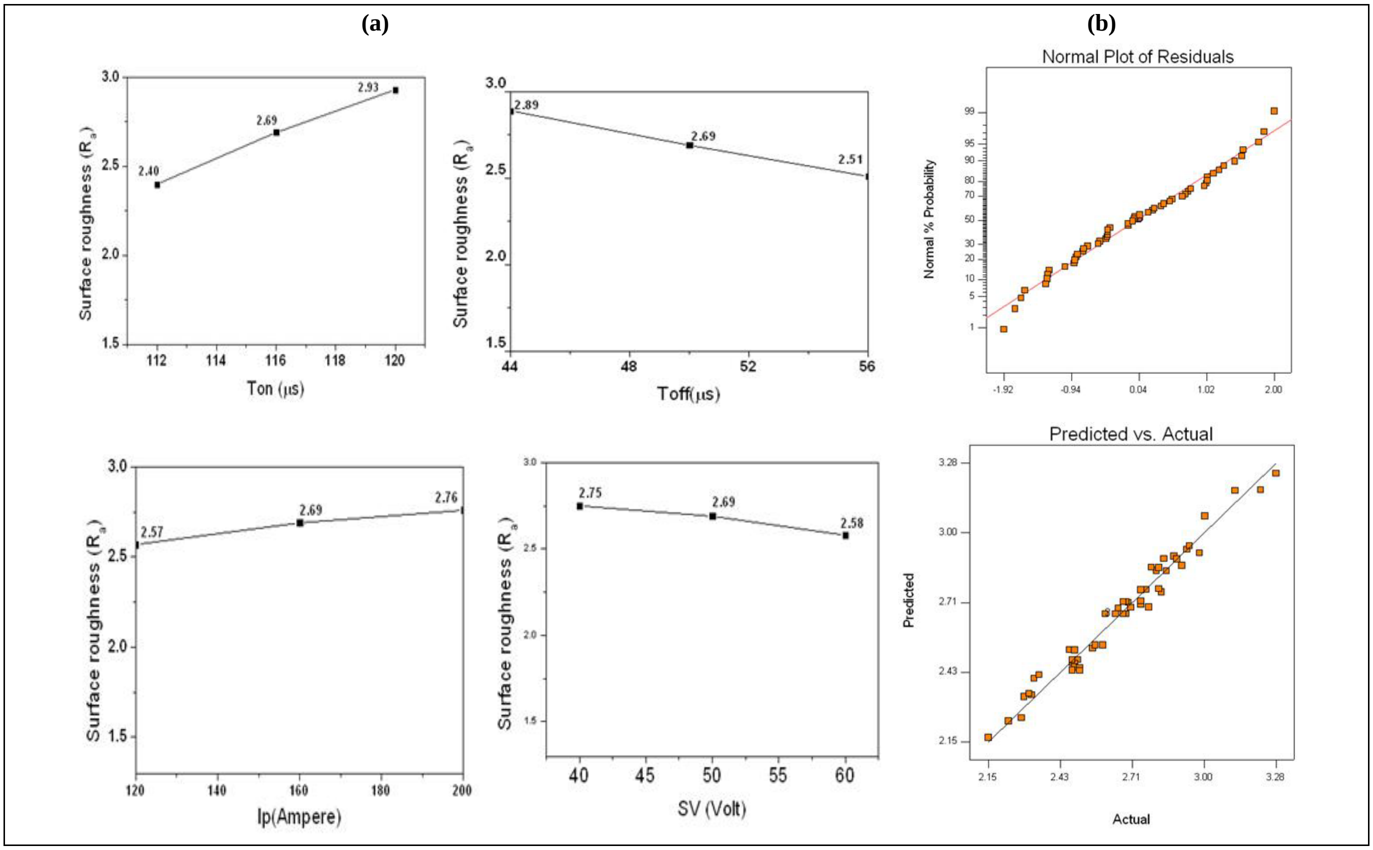
Multiresponse Optimization through Desirablity

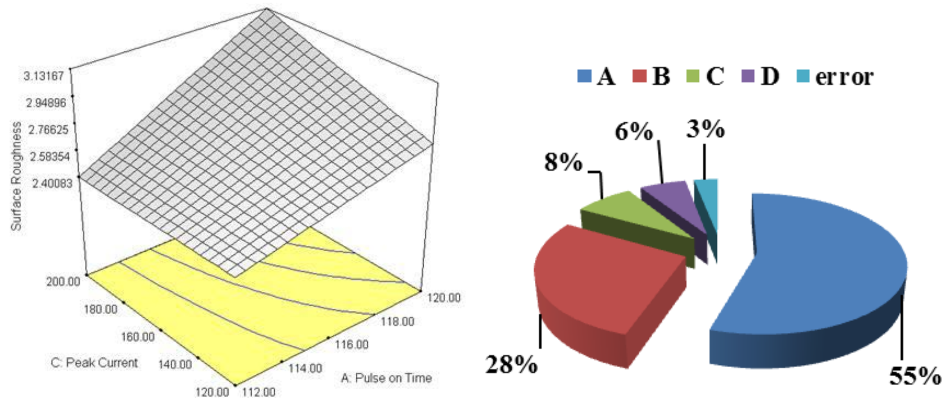
Optimum selection of process parameters combinations is needed for obtaining minimum surface roughness as well as dimensional accuracy. This is obtained by apply the multi-objective optimization technique.

Optimization through Desirability Function Approach

One of the useful approaches to optimization of multiple responses is to use the simultaneous optimization technique developed by (Derringer and Suich, 1980). This approach includes the concept of desirability functions. The general approach is to first convert each response (yi) into an individual desirability function (di) and varied over the range ≤di≤1.Where if the response yi is at its goal or target, then (di=1). The response is outside an acceptable region (di=0). The weight of the desirability function for each response defines its shape. For each response, weights are assigned (ri) to emphasize or de-emphasize the target. Finally, the individual desirability functions are combined to provide a measure of the overall desirability of the multi-response system. This measure of composite desirability is the weighted geometric mean of the individual desirability for the responses. The optimal operating conditions determined by maximizing the composite desirability (Montgomery, D.C, 1997). In the present investigation, the response parameters machining rate, surface roughness and dimensional deviation are chosen to maximize the overall desirability. The factor settings with maximum total desirability are considered to be the optimal parameter conditions. The simultaneous jective function is a geometric mean of all transformed responses:

$$D=(d_1 \times d_2 \times d_3 \times \ldots\ldots\ldots\ldots \times d_n)^{1/n}=\left(\prod_{i=1}^{n} di\right)^{1/n} \tag{4}$$





(c) (d)

Figure 2: Main effects of residuals and interaction plots for surface roughness (a). Process parameters effect (b). Residuals plots (c). interaction plots between TonxIp (d). Contribution of signifcant factors

Where, n is the number of responses in the measure. If any of the responses or factors falls outside the desirability range, the overall function becomes zero. It can be extended to reflect the possible difference in the importance of different responses, where the weight wi satisfies and $0<wi<1$ *and* $w_1+w_2+\dots\dots\dots + w_n = 1$.

$$D=(d_1^{w1} \times d_2^{w2} \times \dots\dots\dots\dots d_n^{wn})^{1/n} \quad (5)$$

Desirability is an objective function that ranges from zero outside of the limits to one at the goal. The numerical optimization finds a point that maximizes the desirability function. The characteristics of a goal may be altered by adjusting the weight or importance. For several responses and factors, all goals get combined into one desirability function. For simultaneous optimization each response must have a low and high value assigned to each goal. The "Goal" field for responses must be one of five choices: "none", "maximum", "minimum", "target", or "in range". Factors will always be included in the optimization, at their design range by default, or as a maximum, minimum of target goal. The meanings of the goal parameters are:

Maximum

$di = 0$ if response < low value
$1 \leq di \leq 0$ as response varies from low to high
$di = 1$ if response > high value

Minimum:

$di = 1$ if response < low value
$1 \geq di \geq 0$ as response varies from low to high
$di = 0$ if response > high value

Target:

$di = 0$ if response < low value
$0 \leq di \leq 1$ as response varies from low to target
$1 \geq di \geq 0$ as response varies from target to high
di = 0 if response > high value

Range:

$di = 0$ if response < low value
$di = 1$ as response varies from low to high
$di = 0$ if response > high value

The *di* for "in range" are included in the product of the desirability function *"D"*, but are not counted in determining *"n"*: $D=(\prod di)^{1/n}$

Table 4: Desirability Analysis for Surface Roughness

Parameters	Target	Lower limit	Upper limit	Lower weight	Upper weight	Importance
Ton		112	120	1	1	3
Toff		44	56	1	1	3
Ip		120	200	1	1	3
SV		40	60	1	1	3
WF		4	10	1	1	3
WT		500	1400	1	1	3
Surface roughness	minimum	2.15	3.28	1	1	3

Modeling for Surface Roughness

In the present study, Design Expert 6.0 has been used to optimize the response variables. The objective is to minimize the surface roughness and dimensional deviation within the desired limit. Hence, the upper limit for the surface roughness is set at 3.28µm with a target of 2.15µm. The ranges and targets of input parameters viz. pulse on time, pulse off time, spark gap voltage, peak current, wire feed and wire tension and the response characteristics viz. surface roughness is given in Table 4. The values of upper weight and lower weight are identical for surface roughness. The objective is to choose an optimal setting to maximize the desirability function. The objective of optimization is to determine the optimum conditions. The RSM model has been used to predict the forty seven optimal desirability solutions for surface roughness as shown in Table 5. It has been observed that within the given parametric range, surface roughness varies between 2.41 µm and 2.74 µm .

The experimental test data set and corresponding RSM model prediction are shown in Table 6. Prediction error in the table has been defined as a follows (Sarkar et al., 2008).The main effect plot for predicted and experimental values is shown in Figure 3.

$$\textit{Prediction error (\%)} = \left| \textit{Experimental results-Predicted results} / \textit{Experimental results} \right| x100 \qquad (8)$$

It has been determined that the percentage of prediction errors is very less and hence the prediction performance of the model is quite satisfactory. Seven confirmatory experiments have been performed to verify the validity of response surface equations.

Table 5: Optimal Solution for Surface Roughness

Exp. no.	**Factors**						**Response Variable**	
	T_{on} (µs)	**T_{off} (µs)**	**Ip (Ampere)**	**SV (Volt)**	**WF (m/min)**	**WT (grams)**	**Surface Roughness (um)**	**Desirability**
1	115.61	56.00	199.74	60.00	10.00	726	2.43	0.563
2	115.44	56.00	199.77	59.98	9.96	770	2.40	0.562
3	115.78	56.00	195.10	59.98	9.85	875	2.44	0.557
4	115.44	56.00	200.00	60.00	4.23	787	2.40	0.557
5	115.51	56.00	199.97	60.00	7.43	536	2.49	0.556
6	116.37	56.00	200.00	59.99	9.13	600	2.53	0.556
7	115.34	56.00	199.80	60.00	7.02	788	2.47	0.556
8	115.65	56.00	200.00	60.00	4.80	808	2.47	0.555
9	115.33	56.00	200.00	58.74	4.01	831	2.39	0.554
10	115.45	56.00	200.00	59.19	6.10	641	2.47	0.554
11	114.51	56.00	199.66	60.00	9.57	858	2.37	0.552
12	115.16	56.00	199.94	55.98	10.00	971	2.41	0.552
13	115.13	56.00	199.81	59.16	7.09	935	2.45	0.551
14	116.52	55.96	200.00	60.00	4.41	815	2.51	0.551
15	116.00	56.00	199.50	60.00	4.02	788	2.44	0.551
16	115.83	55.68	200.00	60.00	4.03	1075	2.43	0.550
17	115.16	55.96	200.00	59.58	6.36	1057	2.48	0.550
18	116.02	56.00	199.99	60.00	4.18	1348	2.45	0.550
19	116.21	56.00	190.97	60.00	10.00	1341	2.45	0.549
20	115.47	55.69	200.00	60.00	9.66	1400	2.43	0.548
21	115.01	55.98	200.00	53.99	10.00	1338	2.43	0.545
22	116.73	56.00	188.99	60.00	10.00	1392	2.49	0.544
23	115.25	56.00	199.91	56.81	4.47	1174	2.43	0.544
24	115.96	56.00	200.00	59.97	8.94	1313	2.53	0.541
25	114.88	56.00	200.00	54.22	6.74	1230	2.47	0.541
26	116.42	55.39	200.00	60.00	6.28	1309	2.60	0.537
27	114.75	56.00	200.00	48.13	10.00	1207	2.47	0.536
28	117.68	55.99	174.23	60.00	9.94	1085	2.55	0.532
29	116.98	55.99	179.86	60.00	4.97	1400	2.55	0.531
30	114.74	56.00	200.00	44.06	10.00	1395	2.48	0.527
31	114.12	56.00	200.00	43.92	7.70	1306	2.53	0.525
32	112.00	44.04	139.05	40.00	9.84	1400	2.69	0.523

33	112.00	44.00	153.71	40.01	10.00	1150	2.67	0.522
34	112.00	44.00	153.04	40.00	9.69	930	2.68	0.520
35	112.00	44.15	134.70	40.00	4.00	1249	2.66	0.518
36	112.00	44.06	139.08	40.01	4.07	1342	2.67	0.518
37	112.01	44.00	141.51	43.41	10.00	1001	2.63	0.518
38	112.00	44.00	157.87	40.31	5.21	1380	2.71	0.512
39	112.04	44.00	156.31	43.91	9.74	934	2.63	0.511
40	112.00	44.00	120.02	46.51	9.55	1400	2.61	0.508
41	112.00	44.02	120.00	50.14	9.96	1151	2.56	0.504
42	112.00	44.27	120.00	45.14	6.60	1357	2.70	0.503
43	112.00	44.00	177.12	40.00	4.00	968	2.63	0.500
44	112.00	44.00	127.32	48.58	4.61	500	2.59	0.495
45	112.12	44.00	120.00	51.05	4.00	759	2.54	0.495
46	112.00	44.00	198.99	40.03	7.74	901	2.74	0.495
47	113.13	44.00	156.94	54.93	10.00	1400	2.58	0.488

Table 6: Prediction Performance of RSM Model

Exp. No.	Experimental Results	RSM predicted Vaules	Prediction error(%)
1.	2.533	2.642	4.303
2.	2.625	2.681	2.133
3.	2.593	2.659	2.545
4.	2.649	2.722	2.755
5.	2.812	2.870	2.062
6.	2.683	2.739	2.087
7.	2.481	2.604	4.957

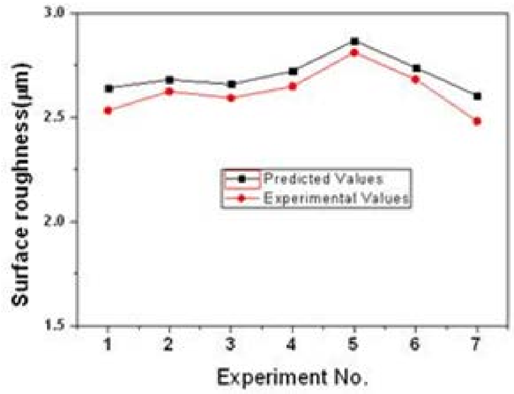


Figure 3: Plots for Predicted and Experimental Values Surface Roughness

5. CONCLUSIONS

In this investigation, quadratic models for the machining rate, surface roughness and dimensional deviation have been developed to correlate the dominant machining parameters: pulse on time, pulse off time, peak current, spark gap voltage, wire feed and wire tension, in the WEDM process of pure titanium(grade-2). An experimental plan of the Box-Behnken based on the RSM has been applied to perform the experimentation work. The machinability evaluation in the WEDM process has been analyzed according to the developed mathematical models to obtain the following conclusions:

1. WEDM is an adequate process to machine high strength temperature resistant (HSTR) pure titanium (grade-2) with good surface finish and dimensional accuracy.
2. The surface roughness was ranged from 2.48µm to 2.62µm during WEDM of pure titanium. The minimum surface roughness was obtained for the process parameter combination given by Ton=112µs, Toff=56µs, Ip=120A, SV=60V, WF = 7m/min and WT = 980 grams. The percentage contribution of input parameters given by Ton: 55%, Toff: 28%, Ip: 8%, SV: 6% and error: 3%.
3. From the results of ANOVA it has been determined that the quadratic models developed for machining rate, surface roughness and dimensional deviations were fairly well fitted with the experimental results with 95% confidence level. The most significant parameters with respect to the response variables are found to be pulse on time, pulse off time, peak current and spark gap voltage according to the ANOVA and *F*-test analysis. The R^2 value of the proposed surface roughness was 0.9712.

4. During WEDM of pure titanium, wire feed and wire tension found to be insignificant to the output process parameters.

ACKNOWLEDGMENT

The authors acknowledge Prof. V.K. Jain (IIT Kanpur) for providing their technical advice and guidance during the research work. Also highly thankful to General Manager, Central tool room (CTR), Ludhiana, Punjab, India, for providing the necessary wire electric discharge machine set-up and other facilities during the research work.

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