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PARAMETRIC STUDY FOR WIRE CUT ELECTRICAL DISCHARGE MACHINING OF SINTERED TITANIUM

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Abstract: In 21st century, it has been observed that Wire Cut Electrical Discharge Machining (WEDM) has evolved as one of the most important non-traditional machining process. The popularity and its success lies because of its uniqueness towards producing different components which are very difficult to machine like titanium, tungsten carbide, Inconel materials etc and provides a platform in producing intricate complex shape which in many cases become impossible to machine by traditional machining methods. Pure sintered titanium bears very high specific strength, abrasion and corrosion resistances and thus machining this type of materials by conventional techniques becomes very difficult though this material finds immense applications in bio-plant and aerospace components. In the present work, WEDM on pure sintered titanium is studied. The different input parameters of WEDM like, pulse on time, pulse off time, wire tension and wire feed have been varied to investigate the output response like MRR, Surface Roughness (Ra), Kerf Width and Over Cut. A response surface methodology (4 factors 3 level) design of experiment (DOE) has been applied in this context to examine the machining ability of pure sintered titanium and results are found to be satisfactory and verified by confirmatory test. The machining parameters like pulse on time, pulse off time, wire tension and wire feed shows immense effect on the output responses and present study provide an optimal conditions of these input parameters to get the best output responses through RSM

KEYWORDS: WEDM; titanium; input parameters; output response; response surface methodology.

1 Introduction

Today's Mechanical Engineering world demands materials which have high hardness, toughness, impact resistance, excellent strength to weight ratio, light weight, excellent corrosion resistance and much more. Such materials like alloy ceramic composites, alloy materials or hard materials like Titanium, Tungsten Carbide are also evolving to meet today's demand. With the inception of these materials major concern is coming to machine these types of materials because such materials are difficult to be machined by traditional machining methods. Hence, non-traditional machining methods like electrochemical machining, ultrasonic machining, abrasive jet machining, electrical discharging machine (EDM) etc. are used to machine such complicated to machine materials. Wire electrical discharge machining (WEDM) is a widely accepted non-traditional material removal process used to manufacture components with intricate shapes and profiles. WEDM process uses a thin wire as an electrode for transforming electrical energy to thermal energy for cutting materials. It is considered as a unique adaptation of the conventional EDM process which use a continuously wire as tool (electrode) made of thin copper, brass or tungsten of diameter 0.05mm-0.3mm to machine alloy steels, conductive ceramics and aerospace materials irrespective of their hardness and toughness. As WEDM is capable of producing a fine, precise, corrosion and wear resistant surfaces, it has been taken into consideration in the present research work. Pure Titanium has been considered as the base material in the present

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research work because of its excellent properties which is relevant to meet present world needs. The primary attributes that make titanium an attractive material include an excellent strength-to-weight ratio, providing weight savings attractive to the aerospace and petrochemical industries; corrosion resistance, particularly appealing to the aerospace, chemical, petrochemical and architectural industries; and biological compatibility, of interest to the medical industry. Titanium has the highest strength to weight ratio of all metals. The feed rate of a milling machine for aluminium or steel and the thickness of chips will be approximately equal but Titanium due to its strength will have chips about half as thick as the feed rate which made it difficult to machine in conventional machining setup. Another reason titanium is difficult to machine is as the tool cuts it generates significantly more heat than aluminium or steel and this heat will heat-treat the titanium making it much harder than carbide cutting tools, resulting in breakage of the tool. In annealed condition, the hardness of Titanium will be similar to stainless steel. All these reasons provide the platform for the present research to use Titanium as the material which can be machined by Wire Cut Electrical Discharge Machine (WEDM) process. ***Anish Kumar et al.*** [1] have focussed on the Wire Electric Discharge Machining process. In this research work the researchers' shows intensive study on the WEDM research involving the optimization of the process parameters surveying the influence of the various factors affecting the machining performance and productivity. ***G. Selvakumar et al.*** [5] aimed at the selection of the most optimal machining parameter combination for wire electrical discharge machining (WEDM) of 5083 aluminium alloy. ***S. K. Garg et al.*** [6] presents an experimental investigation of the machining characteristics and the effect of wire EDM process parameters during machining of newly developed Al / ZrO_2 particulate reinforced metal matrix composite material. ***N. Z. Khan et al.*** [7] carried out an investigation into wire electric discharge machining of high strength and low alloy (HSLA) steels. ***A. Goswami et al.*** [8] investigates the influence of machining parameters on cutting speed and material removal rate for machining of Nimonic 80A with brass wire as tool electrode during wire electrical discharge machining process. Statistical and regression analysis of kerf width using design of experiments has been proposed for WEDM operations by ***V. Parashar et al.*** [9] in their research work. Quadratic Mathematical models have been derived to represent the process behaviour of wire electrical discharge machining (WEDM) operation by ***S. Datta et al.*** [10] in their research work. The recent upgradation of newer and harder materials has made the machining task in WEDM quite challenging and thus for the optimum use of all the resources it is essential to make the optimum use of parameters to get the best output to increase the productivity which has been clearly explained in ***R.A. Shah et al.*** [11] research paper. ***A. K. Singh et al.*** [13] in this research paper describe about the importance of electrical discharge machining in modern times and also presented a detail report of wide acceptance of EDM process for machining of super alloys. Wire EDM is most progressive non-conventional machining process in mechanical industries and there are so many parameters that affect the performance of wire-EDM. ***S. V. Subrahmanyam et al.*** [16] in their research work demonstrate the optimization of Wire Electrical Discharge Machining process parameters for the machining of H13 hot die steel with multiple responses material removal rate (MRR), surface roughness (Ra) based on the Grey-Taguchi method. ***R. A. Shah et al.*** [17] in their research work review the various notable works in the field of WEDM and magnifies on effect of electrode material of some diameter on MRR, kerf width and surface roughness. ***Norliana Mohd Abbas et al***. [18] in their research paper reviews the research trends in EDM on ultrasonic vibration, dry EDM machining, EDM with powder additives, EDM in water and modelling technique in predicting EDM performances. Along with this they also give the fundamental knowledge about EDM process. ***K.H. Ho et al.*** [19] in their paper reviews the vast array of research work carried out from the spin-off from the EDM process to the development of the WEDM. The researchers also report on the WEDM research involving the optimisation of the process parameters surveying the influence of the various factors affecting the machining performance and productivity. This research paper also highlights the adaptive monitoring and control of the process investigating the feasibility of the different control strategies of obtaining the optimal machining conditions. A wide range of WEDM industrial applications are reported together with the development of the hybrid machining processes. The final part of the research paper discusses these developments and outlines the possible trends for future WEDM research. **Mu-Tian Yan et al.** [20] in their paper, a closed-loop wire tension control system for a wire-EDM machine is presented to improve the machining accuracy. Dynamic models of the wire feed control apparatus and wire tension control apparatus are derived to analyze and design the control system. PI controller and one-step-ahead adaptive controller are employed to investigate the dynamic performance of the closed-loop wire tension control system. In order to reduce the vibration of wire tension during wire feeding, dynamic absorbers are added to the idle rollers of wire transportation mechanism. Experimental results in this research paper not only demonstrate that the developed control system with dynamic absorbers can obtain fast transient response and small steady-state error than an open-loop control system, they also indicate that the geometrical contour error of corner cutting is reduced with approximately 50% and the vertical straightness of a workpiece can be improved significantly**. Aniza Alias et al.** [21] in their research paper highlights the importance of process parameters and different machining conditions on kerf width, MRR, surface roughness (Ra) and surface topography. Following a brief summary of the process, **J Simao et al** [22] in their research paper reviews published work on the deliberate surface alloying of various workpiece materials using EDM. Details are given of operations involving powder metallurgy (PM) tool electrodes and the use of powders suspended in the dielectric fluid, typically aluminium, nickel, titanium, etc. Following this, the research paper also contains experimental results which are presented on the surface alloying of AISI H13 hot work tool steel during a die sink operation using partially sintered WC / Co electrodes operating in a hydrocarbon oil dielectric. An L8 fractional factorial Taguchi experiment was used in this research paper to identify the effect of key operating factors on output measures (electrode wear, workpiece surface hardness, etc.). **Giovanna Gautier et al.** [23] in their paper investigates the interactions between common process parameters of WEDM and final quality of the generated surface, through analysis of variance (ANOVA) and regression models based on experimental results. In particular, the paper is focused on the effects of pulse on time, pulse off time, servo-reference voltage, and wire tension on the surface finish during the WEDM of a Ti-48Al-2Cr-2Nb (at. %) γ-TiAl alloy. In their research work results are discussed and compared with reference to the models available in literature. **C. Poletti et al** [24] in their work highlights that Titanium alloys exhibit high specific strength and stiffness that fit structural applications demanding lightweight construction. They also show in their work that Ceramic reinforcements can improve specific strength and stiffness, and also the wear resistance. Higher specific strength and Young's modulus is expected when reinforcing titanium by SiC particles compared to other reinforcements. The production of a SiC reinforced titanium alloy using conventional powder metallurgy methods (PM) yields porosity and silicides formation. PM processing methods are discussed in this research work with equal channel angular pressing, Spark plasma sintering, sintering using an induction oven and hot extrusion. **Daniel M. Madyira et al.** [25] focus on the Grade 5 titanium (Ti6Al4V) which is considered as the workhorse material when it comes to automotive and aerospace applications. According to their research Grade 5 Titanium (Ti6Al4V) is widely referred to as an aerospace alloy and is relatively a new engineering material and the main attraction of this material is its high strength to weight ratio when compared to such common engineering materials such as steel and aluminium alloys. The purpose of this research paper is to conduct a study on the effect of wire EDM on the fracture toughness of this aerospace material. Standard test procedure using compact tension (CT) specimen is used to measure the fracture toughness. Four specimens are produced using wire EDM. This includes the pre-crack which is usually produced by fatigue cycling. Obtained results in this research paper indicate a slight decrease in fracture toughness compared to that reported in literature. In addition to this the researchers also concluded in this paper that wire EDM can be used as an alternative to fatigue pre-cracking in fracture toughness testing of titanium alloys. **Himanshu Prasad Raturi et al.** [26] provide the information about the parametric study on a wire-cut electro discharge machine which was carried out by using Taguchi Method. A statistical analysis of variance (ANOVA) was performed in their research work to identify the process parameters that were statistically significant. The observation received in the present research paper that the MRR decreases with increase in the percentage weight fraction of SiC and Al2O3 particles in the MMCs and HMMCs, whereas, the surface roughness parameter increases with increase in the percentage weight fraction of SiC and Al2O3 particles due to the hardness of MMCs and HMMCs composites. **Moi Subhas Chandra et al. [27]** in their research paper explain about the Box-Behnken design of response surface methodology and the process of their employment to formulate the experimental plan to identify the effect of process parameters. **Srinivasa Rao Mallipudi et al. [28]** employed in their research work Response surface methodology (RSM) to construct a mathematical regression model. Three-factor five-level central composite design was adopted for experimentation and provides the information about the process design in their research work. RSM was successfully used to showcase their research work.

Within the scope of literature survey the researchers failed to find any conclusion about the machining characteristics of WEDM processes in terms of Material Removal Rate (MRR), Surface Roughness (Ra), Kerf Width and Over Cut when machining with Pure Titanium. Thus the present work has been initiated to machine sintered pure Titanium using non-conventional (WEDM) machining and study of machining characteristics and also optimization of machining parameters like Pulse on Time, Pulse off Time, Wire Feed and Wire Tension to get best machining condition in terms of MRR, Ra, Kerf Width and Over Cut for this sintered Pure Titanium. For this purpose 4 factors 3 levels experiments have been planned using response surface methodology (RSM) design matrix. Mathematical model has been developed on the experimental results. A Box–Behnken design (BBD) based on response surface methodology is employed for multi objective optimization.

2 Experimental Setup and Procedure

In the present experimental work, Material Removal Rate (MRR), Surface Roughness (Ra), Kerf Width and Over Cut have been considered for evaluating the machining performance. MRR, Ra, Kerf Width and Over-Cut are correlated with input machining parameters such as Pulse on Time, Pulse of Time, Wire Feed and Wire Tension. The experiments were conducted on a WT 355 JOEMARS (TAIWAN) CNC Wire cut EDM. Fig. 1 shows the used experimental setup attached with CNC WEDM machine. The wire Electrode material used in the WEDM process was made from brass with diameter 0.25 mm. During machining, de-ionised water was circulated as the dielectric fluid around wire and with side flushing technique. Pulse on time (T_{ON}), Pulse off time (T_{OFF}), Wire Feed (WF) and Wire Tension (WT) were variable and these chosen parameters and their limits are given in Table 1. These are chosen through reviews of experience, literature surveys and some preliminary investigations. The workpiece material used in these experiments is sintered pure Titanium metal fabricated from Alfa Aesar make Titanium powder -325 mesh, 99.5% (Metal basis) having CAS no 7440-32-6 by sintering process in tube furnace at 13500 C in pure Argon - Hydrogen gas mixture (Ar -97% & H2 - 3%) with a hold time of 2 hours. It can be classified as a difficult to cut material, not suitable for traditional machining. Twenty seven experiments have been conducted as per Box–Behnken designs (BBD) on sintered pure Titanium of diameter 50 mm and thickness 9 mm. The material removal rate is calculated using the relation MRR = (Thickness of the sample) X (Cutting Velocity) X (Kerf Width). The roughness average (Ra) for each specimen has been measured by Surface Roughness Tester (Talysurf Surtronic 3+, Taylor-Hobson, UK) shown in Fig 2. Each surface roughness value has been obtained by averaging five measurements. Twenty seven experiments have been conducted as per Box–Behnken designs (BBD) on sintered pure Titanium of diameter 50 mm and thickness 9 mm. Twenty seven experiments are used to cut down 9 square pieces from the sample and each square piece has been cut down using three different experiments on three faces of the square piece respectively to measure the surface roughness for each case. Twenty seven experiments are again used to cut straight slots on the sample to measure the kerf width using a profile projector which is important parameter to calculate the MRR. The measurement of kerf width taken through profile projector is shown in Fig.3.

Fig.1 CNC Wire cut EDM Experimental Setup

Fig. 2 Surface Roughness Tester Setup (Talysurf Surtronic 3+, Taylor-Hobson, UK)

Table.1. Process control parameters and their limits

INPUT PARAMETERS	LEVEL 1	LEVEL 2	LEVEL 3
PULSE ON TIME (TON)	6	8	10
PULSE OFF TIME (TOFF)	7	10	13
WIRE TENSION (WT)	6	8	10
WIRE FEED 9 (WF)	7	9	11

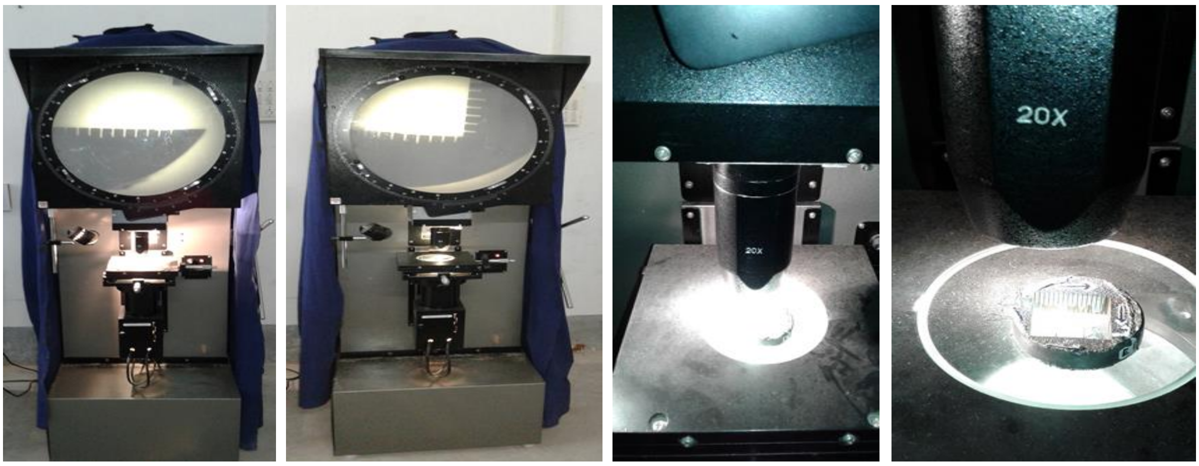


Fig. 3 Kerf Width measurement of the sample through Profile Projector setup

3 Results and Discussions

The measured values of responses i.e. Material Removal Rate (MRR), Surface Roughness (Ra), Kerf Width and Over-Cut corresponding to BBD design matrix are shown in Table 2. The effect of process parameters on MRR, Ra, Kerf Width and Over-Cut has been analysed by response surface and contour plots. Design expert 10 software has been used for this purpose.

Table 2. BBD design for actual factors and measured experimental results

Sl No	Input Parameters				Output Responses			
	PULSE ON TIME	PULSE OFF TIME	WIRE TENSION	WIRE FEED	Ra	MRR	Kerf Width	Over cut
1	8	13	10	9	2.06	10.93	0.37	0.12
2	6	10	8	7	2.58	7.66	0.38	0.13
3	6	10	6	9	2.46	7.42	0.39	0.14
4	8	10	10	11	2.34	8.97	0.34	0.09
5	6	13	8	9	2.13	7.81	0.42	0.17
6	8	13	8	11	2.31	10.20	0.43	0.18
7	8	13	6	9	2.31	9.17	0.39	0.14
8	6	10	8	11	2.08	7.31	0.36	0.11
9	8	10	8	9	2.17	10.16	0.39	0.14
10	8	7	8	7	2.60	10.97	0.40	0.15
11	10	7	8	9	2.75	11.28	0.40	0.15
12	8	10	10	7	2.54	10.15	0.40	0.15
13	8	7	8	11	2.34	9.32	0.34	0.09
14	8	10	6	7	2.39	7.60	0.30	0.05
15	8	10	8	9	2.28	9.68	0.39	0.14
16	6	10	10	9	2.32	6.68	0.32	0.07
17	8	7	10	9	2.71	9.39	0.37	0.12
18	6	7	8	9	2.61	6.82	0.35	0.10
19	8	7	6	9	2.34	9.45	0.34	0.09
20	10	10	10	9	2.91	11.04	0.38	0.13
21	10	10	8	7	2.68	9.18	0.32	0.07
22	8	10	6	11	2.43	9.90	0.37	0.12
23	8	13	8	7	2.14	8.34	0.36	0.11
24	8	10	8	9	2.11	11.44	0.40	0.15
25	10	10	8	11	2.73	11.92	0.38	0.13
26	10	10	6	9	2.51	8.18	0.28	0.03
27	10	13	8	9	2.67	10.06	0.34	0.09

4.1 Effect of the process parameters on Surface Roughness (Ra)

The 3-D response surface and contour plots for the effect of process parameters on surface roughness have been constructed according to the fitted model:

$$Ra = + 15.21917 - 1.67979 * T_{ON} - 0.29833 * T_{OFF} - 0.32333 * WT - 0.79458 * WF + 0.016667 * T_{ON} * T_{OFF} + 0.033750 * T_{ON} * WT + 0.034375 * T_{ON} * WF - 0.025833 * T_{OFF} * WT + 0.018333 * T_{OFF} * WF - 0.015000 * WT * WF + 0.063750 * T_{ON}^2 + 7.91667E-003 * T_{OFF}^2 + 0.029062 * WT^2 + 0.023750 * WF^2 \quad (1)$$

Table 3. ANOVA table for Surface Roughness (Ra)

Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**P-value Prob> F**	
Model	1.37	14	0.098	21.67	< 0.0001	Significant
A-Pulse on Time	*0.36*	*1*	*0.36*	*79.14*	*< 0.0001*	*Significant*
B-Pulse off Time	*0.25*	*1*	*0.25*	*55.92*	*< 0.0001*	*Significant*
C-Wire Tension	*0.016*	*1*	*0.016*	*3.58*	*0.0830*	*not significant*
D-Wire Feed	*0.040*	*1*	*0.040*	*8.79*	*0.0118*	*Significant*
AB	*0.040*	*1*	*0.040*	*8.87*	*0.0115*	*Significant*
AC	*0.073*	*1*	*0.073*	*16.16*	*0.0017*	*Significant*
AD	*0.076*	*1*	*0.076*	*16.76*	*0.0015*	*Significant*
BC	*0.096*	*1*	*0.096*	*21.30*	*0.0006*	*Significant*
BD	*0.048*	*1*	*0.048*	*10.73*	*0.0066*	*Significant*
CD	*0.014*	*1*	*0.014*	*3.19*	*0.0993*	*not significant*
A^2	*0.35*	*1*	*0.35*	*76.87*	*< 0.0001*	*Significant*
B^2	*0.027*	*1*	*0.027*	*6.00*	*0.0306*	*Significant*
C^2	*0.072*	*1*	*0.072*	*15.97*	*0.0018*	*Significant*
D^2	*0.048*	*1*	*0.048*	*10.67*	*0.0068*	*Significant*
Residual	0.054	12	4.512E-003			
Lack of Fit	*0.039*	*10*	*3.928E-003*	*0.53*	*0.7991*	*not significant*
Pure Error	*0.015*	*2*	*7.433E-003*			
Core Total	1.42	26				
R-Squared	0.9619			Pred R-Squared	0.8175	
Adj R-Squared	0.9175			Adeq Precision	16.112	

The Model F-value of 21.67 implies the model is significant. Values of "Prob> F" less than 0.0500 indicate model terms are significant. In this case A, B, D, AB, AC, AD, BC, BD, A^2, B^2, C^2, D^2 are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. The "Lack of Fit F-value" of 0.53 implies the Lack of Fit is not significant relative to the pure error. There is a 79.91% chance that a "Lack of Fit F-value" this large could occur due to noise. The "Pred R-Squared" of 0.8175 is in reasonable agreement with the "Adj R-Squared" of 0.9175; i.e. the difference is less than 0.2."Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable and in the present study the ratio of 16.112 indicates an adequate signal. This model can be used to navigate the design space.

Fig. 4 shows the predicted vs. actual response plot for surface roughness. It is observed that the predicted response points are very close to the actual experimental data. This confirms the good agreement between the predicted model and the experimental results.

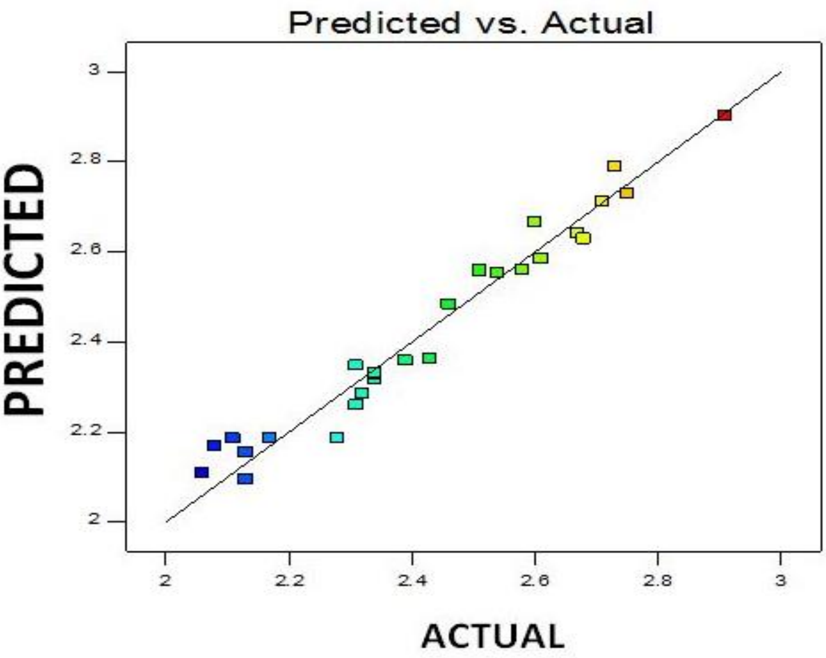
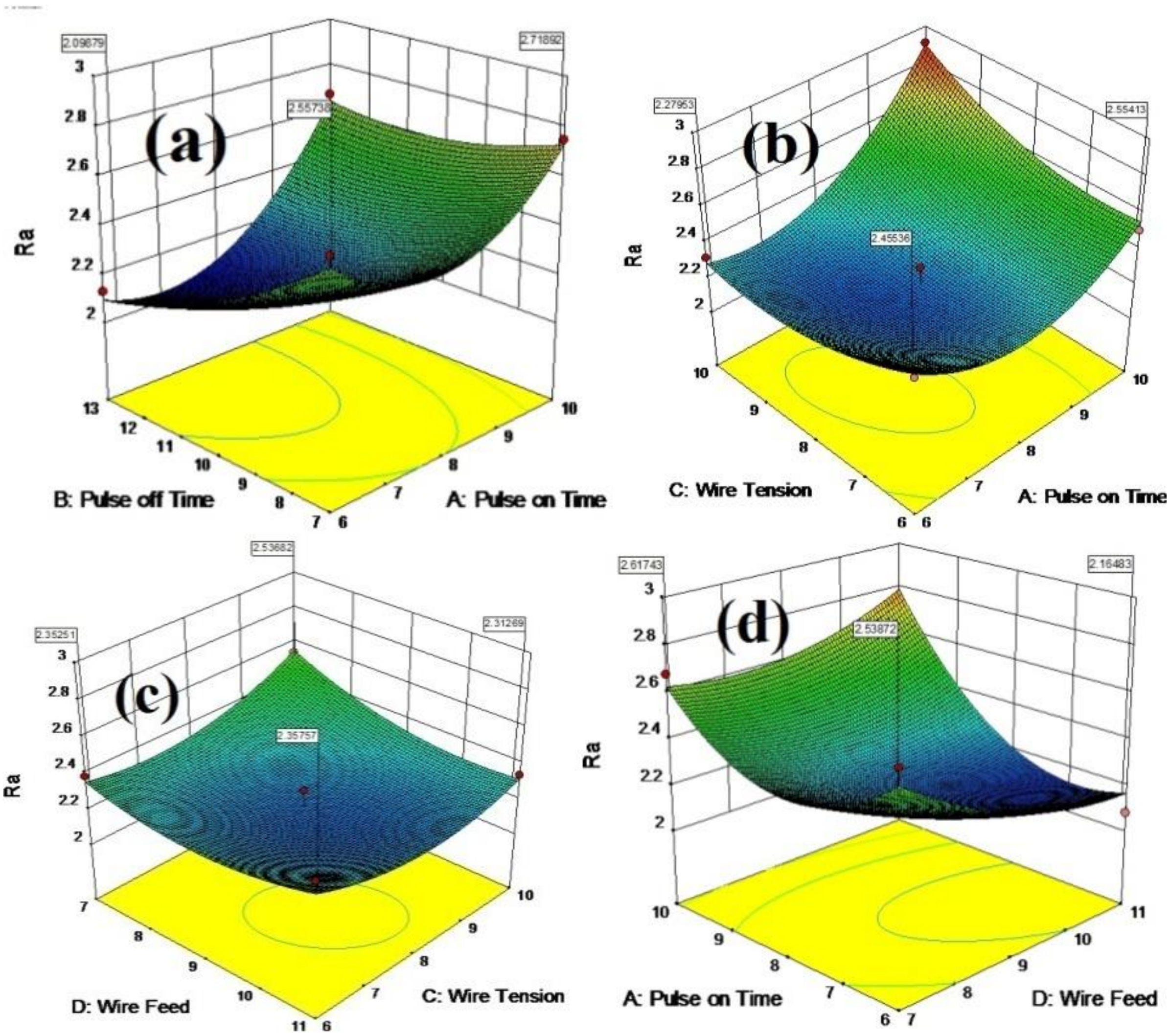


Fig.4. Actual vs. Predicted Graph for Ra



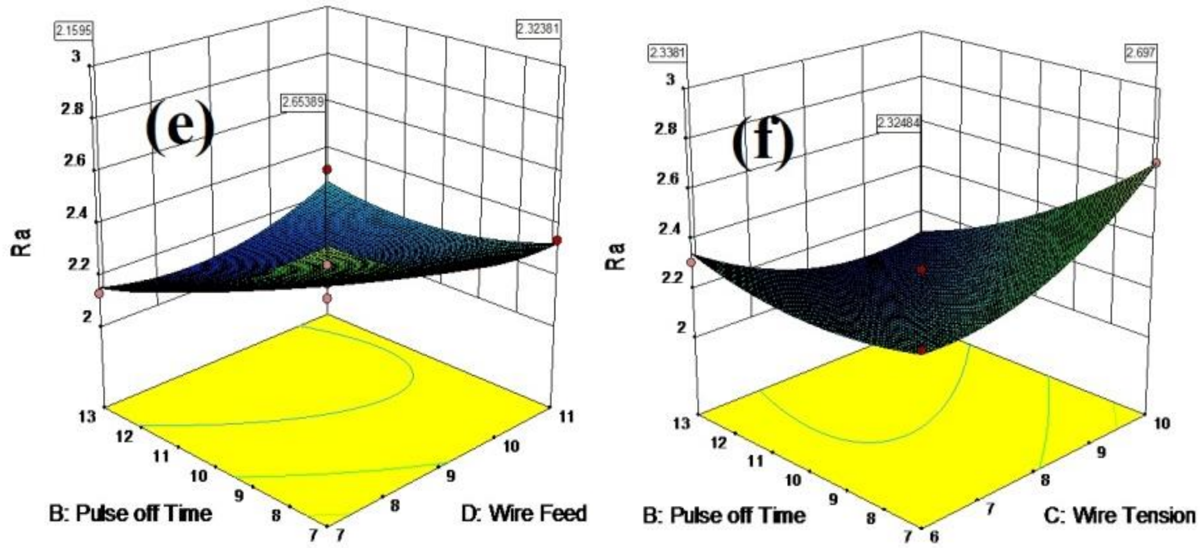


Fig. 5. Response surface and contour plots showing the interaction effects of (a) T_{ON} and T_{OFF} (b) T_{ON} and WT (c) WT and WF (d) WT and T_{ON} (e) WF and T_{OFF} (f) WT and T_{OFF} on the surface roughness (Ra) of sintered pure Titanium, while the other two parameters are at their respective center value

Fig. 5 show the plot with two variables kept constant at their respective centre value and other two within the limiting range. It is seen that with the increase of Pulse on Time in Fig 5 (a), Fig 5(b) and Fig 5(c) Surface Roughness also increases. By increasing the pulse on time the material removal rate increase and poor surface finish on the material surface results in increase of Surface Roughness. On the other hand with the increase of Pulse off Time in Fig 5(a) and Fig 5(e), Surface Roughness decreases and in Fig 5(f) Surface Roughness remains almost constant with its increase. With the increase of Pulse off Time surface quality improves and that's the reason of decreasing the value of surface roughness. Wire Tension increase in Fig 5(b) and Fig 5(c) shows decline graph of Surface Roughness and a slight increase of Surface Roughness is observed in Fig 5(f) with the increase of Wire Tension. Surface roughness shows a declination sign with increase of Wire Feed in Fig 5(d) and Fig 5(e) but a slight increase of Surface Roughness is observed in the Fig 5(c) with the increase of Wire Feed. With increase of Wire Feed, Cutting Speed, Metal Removal Rate, Spark Gap, Width of cut, Peak Surface Roughness and Surface Roughness firstly increases and afterwards decreases and thus both the results are reflected in the present experimental results showing its increase in some cases and its decrease in some other cases depending on different fixed parameters and variable parameters.

4.2 Effect of the process parameters on Material Removal Rate (MRR)

The 3-D response surface and contour plots for the effect of process parameters on material removal rate have been constructed according to the fitted model:

$$MRR = -15.79638 + 2.92938 * T_{ON} - 0.86829 * T_{OFF} + 2.66417 * WT + 0.82062 * WF - 0.092083 * T_{ON} * T_{OFF} + 0.22500 * T_{ON} * WT + 0.19313 * T_{ON} * WF + 0.075833 * T_{OFF} * WT + 0.14625 * T_{OFF} * WF - 0.21750 * WT * WF - 0.29990 * T_{ON}^2 - 0.016898 * T_{OFF}^2 - 0.18990 * WT^2 - 0.10740 * WF^2 \qquad (2)$$

Table 4. ANOVA table for Material Removal Rate (MRR)

Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**P-value Prob> F**	
Model	53.51	14	3.82	10.57	0.0001	significant
A-Pulse on Time	*26.88*	*1*	*26.88*	*74.32*	*< 0.0001*	significant
B-Pulse off Time	*0.043*	*1*	*0.043*	*0.12*	*0.7356*	*not significant*
C-Wire Tension	*2.47*	*1*	*2.47*	*6.82*	*0.0227*	significant
D-Wire Feed	*1.15*	*1*	*1.15*	*3.19*	*0.0994*	*not significant*
AB	*1.22*	*1*	*1.22*	*3.38*	*0.0910*	*not significant*
AC	*3.24*	*1*	*3.24*	*8.96*	*0.0112*	significant
AD	*2.39*	*1*	*2.39*	*6.60*	*0.0246*	significant
BC	*0.83*	*1*	*0.83*	*2.29*	*0.1561*	*not significant*
BD	*3.08*	*1*	*3.08*	*8.52*	*0.0129*	significant
CD	*3.03*	*1*	*3.03*	*8.37*	*0.0135*	significant
A^2	*7.67*	*1*	*7.67*	*21.22*	*0.0006*	significant
B^2	*0.12*	*1*	*0.12*	*0.34*	*0.5700*	*not significant*
C^2	*3.08*	*1*	*3.08*	*8.51*	*0.0129*	significant
D^2	*0.98*	*1*	*0.98*	*2.72*	*0.1249*	*not significant*
Residual	4.34	12	0.36			
Lack of Fit	*2.68*	*10*	*0.27*	*0.32*	*0.9094*	*not significant*
Pure Error	*1.66*	*2*	*0.83*			
Core Total	57.85	26				
R-Squared	0.9250		Pred R-Squared		0.6683	
Adj R-Squared	0.8374		Adeq Precision		10.825	

The Model F-value of 10.57 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. Values of "Prob> F" less than 0.0500 indicate model terms are significant. In this case A, C, AC, AD, BD, CD, A^2, C^2 are significant model terms. The "Lack of Fit F-value" of 0.32 implies the Lack of Fit is not significant relative to the pure error. There is a 90.94% chance that a "Lack of Fit F-value" this large could occur due to noise. The "Pred R-Squared" of 0.6683 is in reasonable agreement with the "Adj R-Squared" of 0.8374; i.e. the difference is less than 0.2."Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable and in the present study the ratio of 10.825 indicates an adequate signal. This model can be used to navigate the design space.

Fig. 6 shows the predicted vs. actual graph for Material Removal Rate. The actual value points have a good agreement with the predicted line and are very close to each other which validate the experimental results to be on the right track.

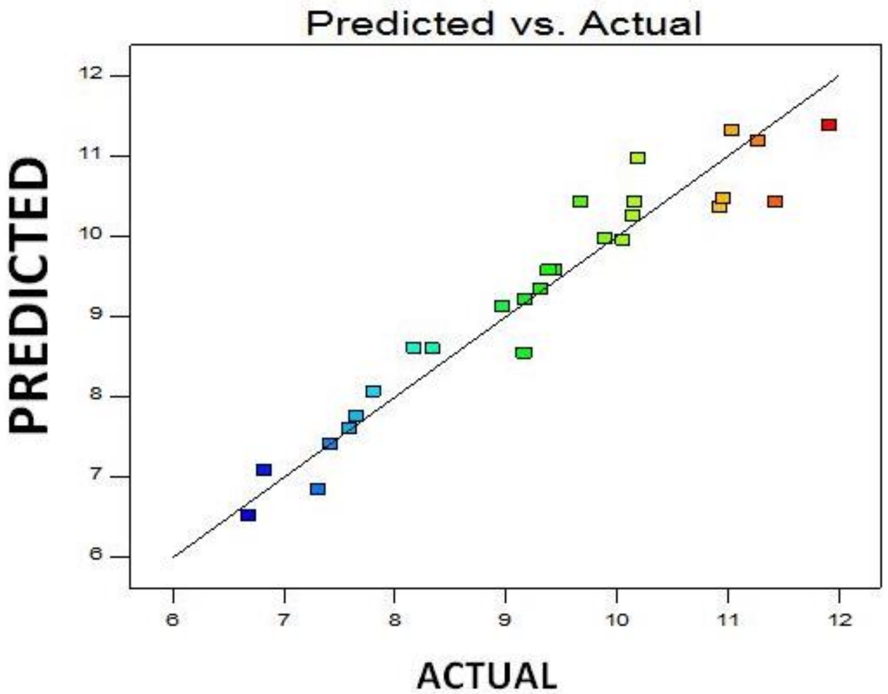
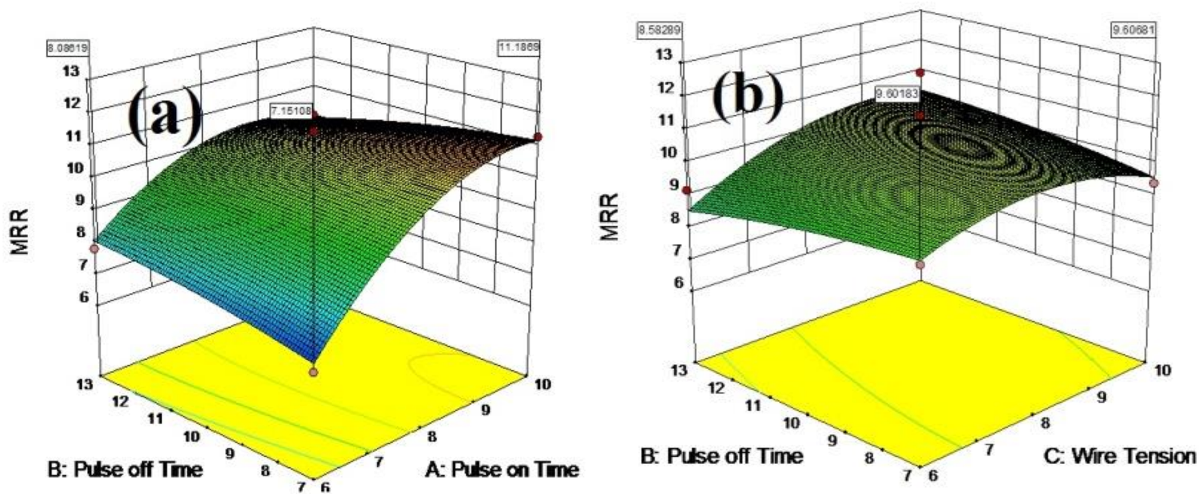


Fig 6. Predicted vs. Actual graph for MRR

Fig.7 show the plot with two variables kept constant at their respective centre value and other two within the limiting range. Pulse on Time has a greater impact on MRR and thus MRR always increases (irrespective of other parameters effect) with the increase of Pulse on Time as shown in Fig 7(a), 7(d) and Fig 7(e). Pulse Off-time is the time during which re-ionization of the dielectric take place. An insufficient off time can lead to erratic cycling and retraction of the advancing servo thereby slowing down the operation cycle and thus MRR decreases with its increase as shown in Fig 7(b) and Fig 7(f). Wire Tension depends on other parameters and thus with its increase MRR increases when Pulse on Time and Pulse off Time is constant at centre point in Fig 7(c), MRR decreases when Wire Feed and Pulse off time is at centre point as in Fig 7(e) and MRR remains constant when Pulse on time and Wire Feed is at centre point as in Fig 7(b). MRR decreases with the increase of Wire Feed as shown in Fig 7(d) and Fig 7(f) but MRR increases with its increase in Fig 7(c) as Wire Feed depends on other parameters and their respective positions.



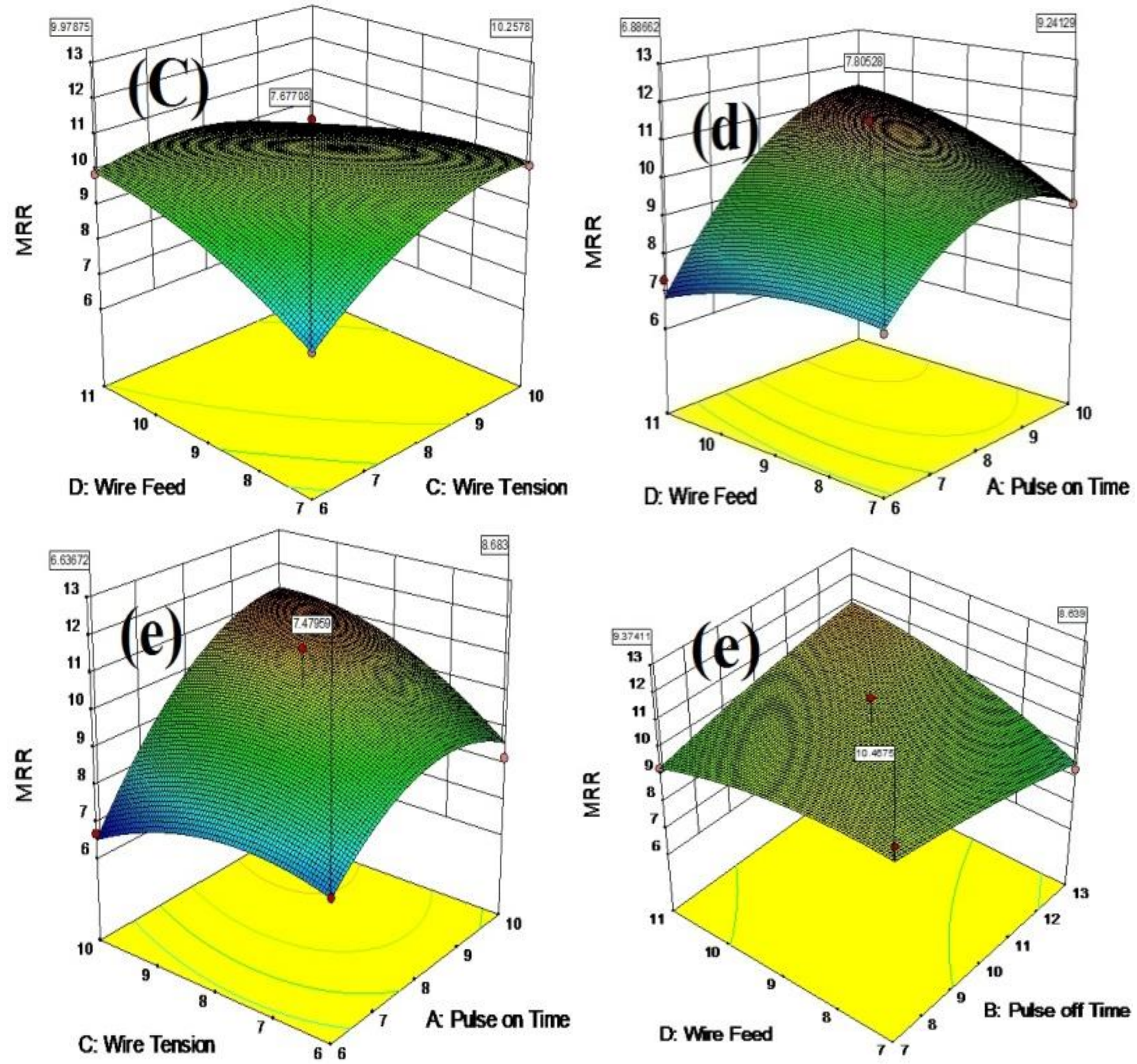


Fig. 7 Response surface and contour plots showing the interaction effects of (a) T_{ON} and T_{OFF} (b) WT and T_{OFF} (c) WT and WF (d) T_{ON} and WF (e) T_{ON} and WT (f)T_{OFF} and WF on the material removal rate (MRR) of sintered pure Titanium, while the other two parameters are at their respective center value

4.3 Effect of the process parameters on Kerf Width

The 3-D response surface and contour plots for the effect of process parameters on Kerf Width have been constructed according to the fitted model:

$$\text{Kerf Width} = -0.33175 + 8.33333E\text{-}004 * T_{ON} + 6.89815E\text{-}003 * T_{OFF} + 0.13021 * WT + 0.031458 * WF - 5.41667E\text{-}003 * T_{ON} * T_{OFF} + 0.010625 * T_{ON} * WT + 5.00000E\text{-}003 * T_{ON} * WF - 2.08333E\text{-}003 * T_{OFF} * WT + 5.41667E\text{-}003 * T_{OFF} * WF - 8.12500E\text{-}003 * WT * WF - 5.10417E\text{-}003 * T_{ON}^2 + 3.70370E\text{-}004 * T_{OFF}^2 - 7.29167E\text{-}003 * WT^2 - 3.22917E\text{-}003 * WF^2 \quad (3)$$

Table 5 shows the ANOVA table for Kerf Width where the Model F-value of 27.21 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. Values of "Prob> F" less than 0.0500 indicate model terms are significant. In this case A, B, C, AB, AC, AD, BC, BD, CD, A^2, C^2, D^2 are significant model terms. The "Lack of Fit F-value" of 2.88 implies the Lack of Fit is not significant relative to the pure error. There is a 28.56% chance that a "Lack of Fit F-value" this large could occur due to noise. The "Pred R-Squared" of 0.8311 is in reasonable agreement with the "Adj R-Squared" of 0.9338; i.e. the difference is less than 0.2. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable and in the present case the ratio found to be 21.533 indicates an adequate signal. This model can be used to navigate the design space.

Fig 8 indicates a close agreement of the predicted line with the actual values. The actual value points are very close to the predicted line which clearly provides the information that the experimental values are justifying the predicted results.

Table 5. ANOVA table for Kerf Width

Source	**Sum of Squares**	**DF**	**Mean Square**	**F Value**	**p-value Prob> F**	
Model	0.033	14	2.324E-003	27.21	< 0.0001	*significant*
A-Pulse on Time	*1.200E-003*	*1*	*1.200E-003*	*14.05*	*0.0028*	*significant*
B-Pulse off Time	*1.008E-003*	*1*	*1.008E-003*	*11.80*	*0.0049*	*significant*
C-Wire Tension	*1.008E-003*	*1*	*1.008E-003*	*11.80*	*0.0049*	*significant*
D-Wire Feed	*3.000E-004*	*1*	*3.000E-004*	*3.51*	*0.0855*	*not significant*
AB	*4.225E-003*	*1*	*4.225E-003*	*49.46*	*< 0.0001*	*significant*
AC	*7.225E-003*	*1*	*7.225E-003*	*84.59*	*< 0.0001*	*significant*
AD	*1.600E-003*	*1*	*1.600E-003*	*18.73*	*0.0010*	*significant*
BC	*6.250E-004*	*1*	*6.250E-004*	*7.32*	*0.0191*	*significant*
BD	*4.225E-003*	*1*	*4.225E-003*	*49.46*	*< 0.0001*	*significant*
CD	*4.225E-003*	*1*	*4.225E-003*	*49.46*	*< 0.0001*	*significant*
A^2	*2.223E-003*	*1*	*2.223E-003*	*26.03*	*0.0003*	*significant*
B^2	*5.926E-005*	*1*	*5.926E-005*	*0.69*	*0.4212*	*not significant*
C^2	*4.537E-003*	*1*	*4.537E-003*	*53.12*	*< 0.0001*	*significant*
D^2	*8.898E-004*	*1*	*8.898E-004*	*10.42*	*0.0073*	*significant*
Residual	1.025E-003	12	8.542E-005			
Lack of Fit	*9.583E-004*	*10*	*9.583E-005*	*2.88*	*0.2856*	*not significant*
Pure Error	*6.667E-005*	*2*	*3.333E-005*			
Core Total	0.034	26				
R-Squared	0.9695			Pred R-Squared	0.8311	
Adj R-Squared	0.9338			Adeq Precision	21.533	

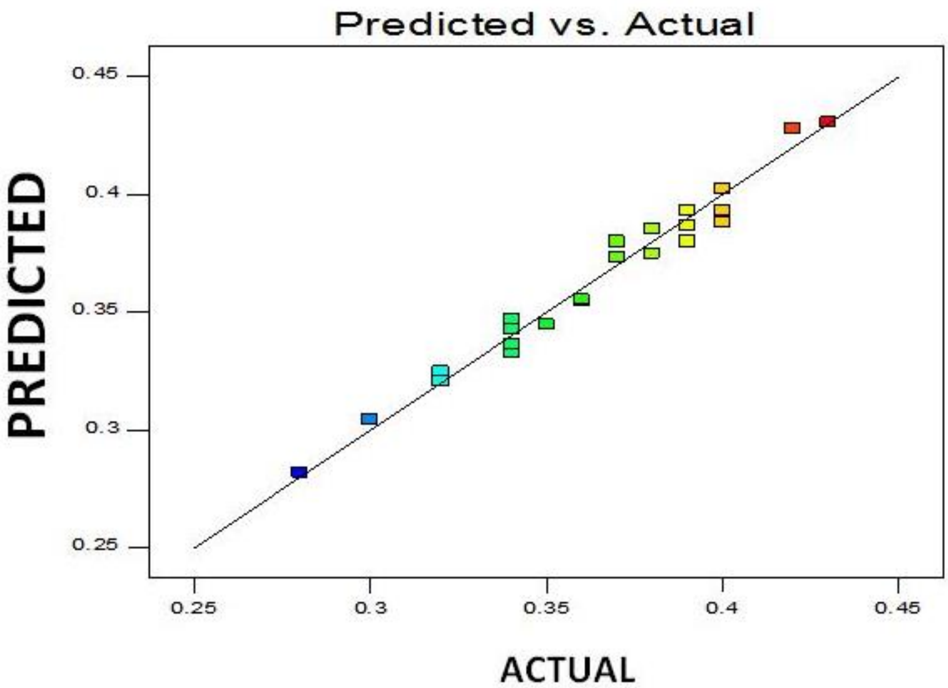
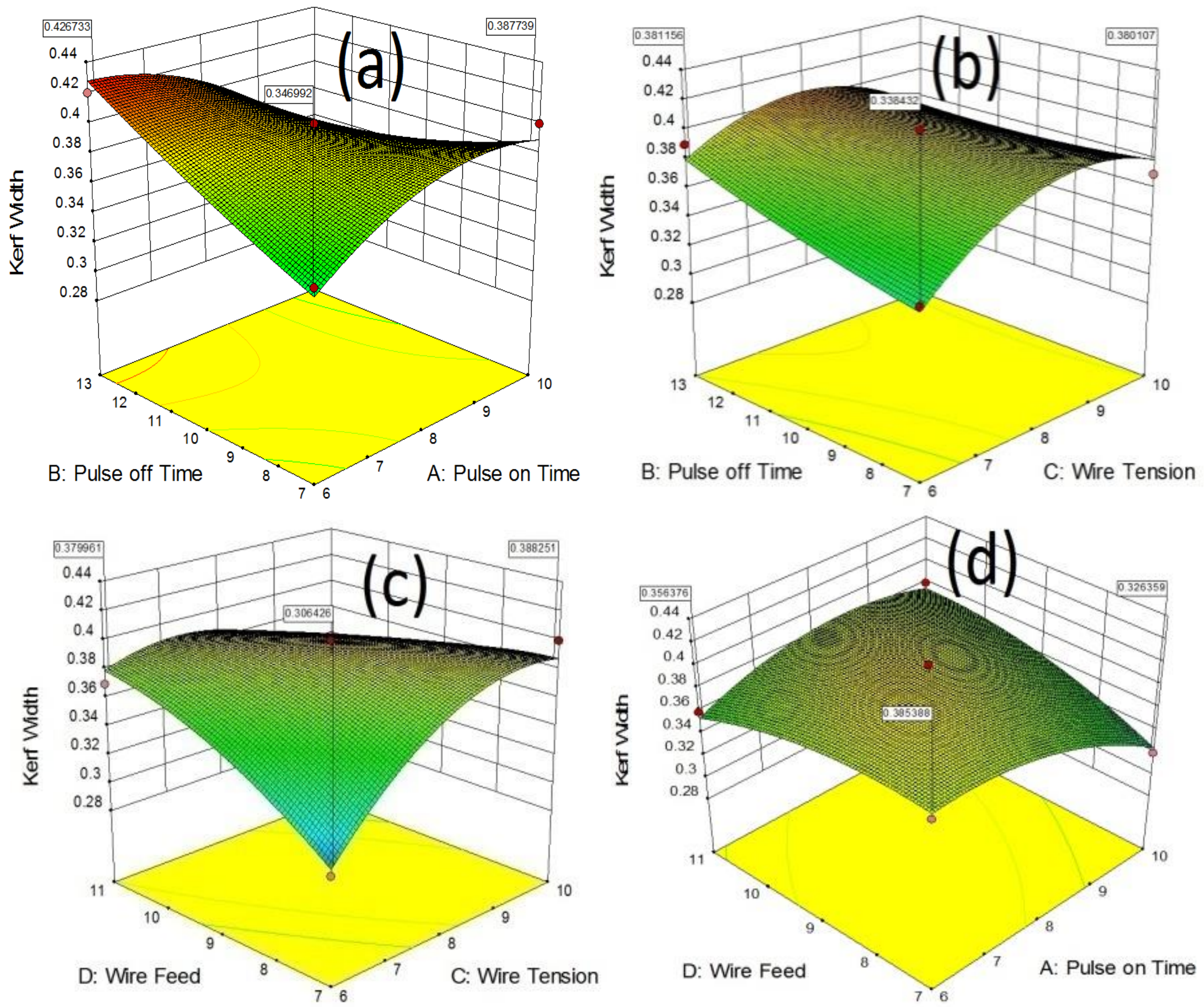


Fig. 8 Predicted vs. Actual graph for Kerf Width



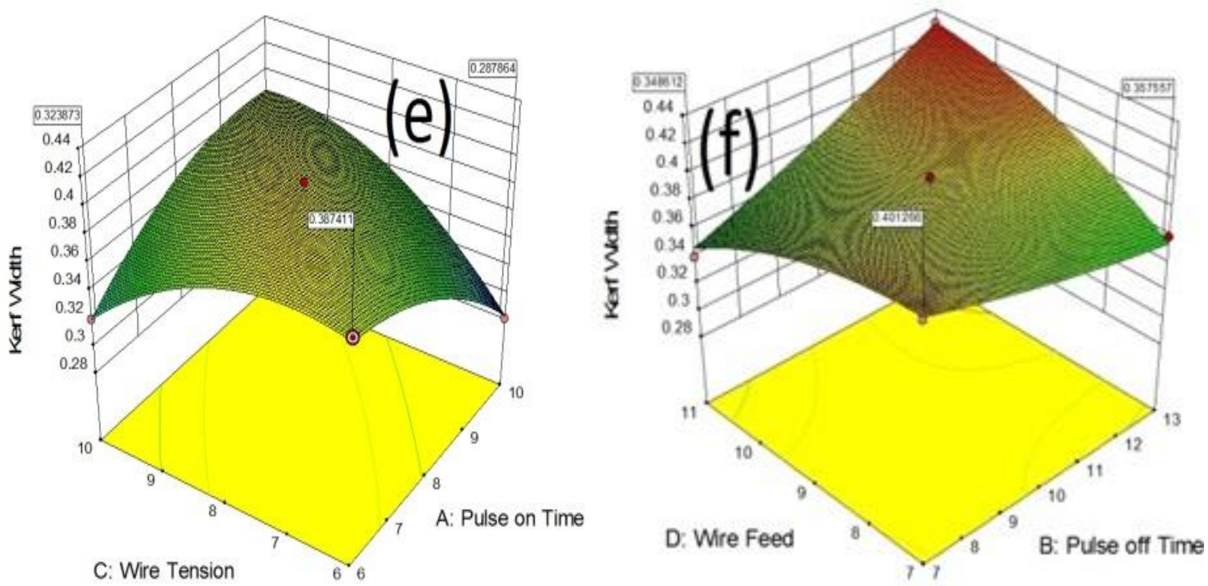


Fig. 9 Response surface and contour plots showing the interaction effects of (a) T_{ON} and T_{OFF} (b) WT and T_{OFF} (c) WT and WF (d) T_{ON} and WF (e) T_{ON} and WT (f)T_{OFF} and WF on the Kerf Width of sintered pure Titanium, while the other two parameters are at their respective center value

With the increase of Pulse on Time and Pulse off Time, Kerf Width also increases, when Wire Tension and Wire Feed remain constant as shown in Fig.9 (a). Similar observation is followed in Fig.9 (b) where Kerf Width increases with the increase of Wire Tension and Pulse off Time, when the other two factors Wire Feed and Pulse on Time remain constant. Fig 9(c) is also showing the same trend of incremental graph of Kerf Width as the Wire Feed and Wire Tension increases, when Pulse on Time and Pulse off Time remain constant. In Fig.9 (d), Fig. 9 (e) and Fig. 9 (f) shows opposite scenario. In Fig.9 (d), shows a detrimental graph of Kerf Width as Wire Feed and Pulse on Time increases, when Pulse off Time and Wire Tension remain constant. Similar observation observed in Fig.9 (e) where Kerf Width decreases considerably with the increase of Wire Tension and Pulse on Time, when Pulse off time and Wire Feed remain constant. Fig.9 (f) shows the same scenario of decrease of Kerf Width with the increase of Pulse off Time and Wire Feed, when factors like Pulse on Time and Wire Tension remain constant.

3.4 Effect of the process parameters on Over Cut

The 3-D response surface and contour plots for the effect of process parameters on Kerf Width have been constructed according to the fitted model:

$$\text{Over Cut} = -0.58175 + 8.33333E\text{-}004 * T_{ON} + 6.89815E\text{-}003 * T_{OFF} + 0.13021 * WT + 0.031458 * WF - 5.41667E\text{-}003 * T_{ON} * T_{OFF} + 0.010625 * T_{ON} * WT + 5.00000E\text{-}003 * T_{ON} * WF - 2.08333E\text{-}003 * T_{OFF} * WT + 5.41667E\text{-}003 * T_{OFF} * WF - 8.12500E\text{-}003 * WT * WF - 5.10417E\text{-}003 * T_{ON}^2 + 3.70370E\text{-}004 * T_{OFF}^2 - 7.29167E\text{-}003 * WT^2 - 3.22917E\text{-}003 * WF^2 \quad (4)$$

Table 6. ANOVA table for Over Cut

Source	Sum of Squares	DF	Mean Square	F Value	P-value Prob> F	
Model	0.033	14	2.324E-003	27.21	< 0.0001	significant
A-Pulse on Time	1.200E-003	1	1.200E-003	14.05	0.0028	significant
B-Pulse off Time	1.008E-003	1	1.008E-003	11.80	0.0049	significant
C-Wire Tension	1.008E-003	1	1.008E-003	11.80	0.0049	significant
D-Wire Feed	3.000E-004	1	3.000E-004	3.51	0.0855	not significant
AB	4.225E-003	1	4.225E-003	49.46	< 0.0001	significant
AC	7.225E-003	1	7.225E-003	84.59	< 0.0001	significant
AD	1.600E-003	1	1.600E-003	18.73	0.0010	significant
BC	6.250E-004	1	6.250E-004	7.32	0.0191	significant
BD	4.225E-003	1	4.225E-003	49.46	< 0.0001	significant
CD	4.225E-003	1	4.225E-003	49.46	< 0.0001	significant
A^2	2.223E-003	1	2.223E-003	26.03	0.0003	significant
B^2	5.926E-005	1	5.926E-005	0.69	0.4212	not significant
C^2	4.537E-003	1	4.537E-003	53.12	< 0.0001	significant
D^2	8.898E-004	1	8.898E-004	10.42	0.0073	significant
Residual	1.025E-003	12	8.542E-005			
Lack of Fit	9.583E-004	10	9.583E-005	2.88	0.2856	not significant
Pure Error	6.667E-005	2	3.333E-005			
Core Total	0.034	26				
R-Squared	0.9695		Pred R-Squared		0.8311	
Adj R-Squared	0.9338		Adeq Precision		21.533	

Table 6 represent the ANOVA table for the output response Over Cut where the Model F-value of 27.21 implies the model is significant. There is only a 0.01% chance that an F-value this large could occur due to noise. Values of "Prob> F" less than 0.0500 indicate model terms are significant. In this case A, B, C, AB, AC, AD, BC, BD, CD, A^2, C^2, D^2 are significant model terms. The "Lack of Fit F-value" of 2.88 implies the Lack of Fit is not significant relative to the pure error. There is a 28.56% chance that a "Lack of Fit F-value" this large could occur due to noise. The "Pred R-Squared" of 0.8311 is in reasonable agreement with the "Adj R-Squared" of 0.9338; i.e. the difference is less than 0.2. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable and in the present case the ratio of 21.533 indicates an adequate signal.

Fig.10 shows a good agreement of the actual values with the predicted line. The actual points are very close to the predicted line which confirms that the experimental values are justifying the predicted results.

Fig. 11 shows the 3D Response Surface and Contour Plots having the same trends observed in case of Kerf Width. This is because the plot or values obtained in overcut are derived from the kerf width results. The values of Kerf Width obtained are subtracted with the diameter of the wire which gives the final value of the overcut.

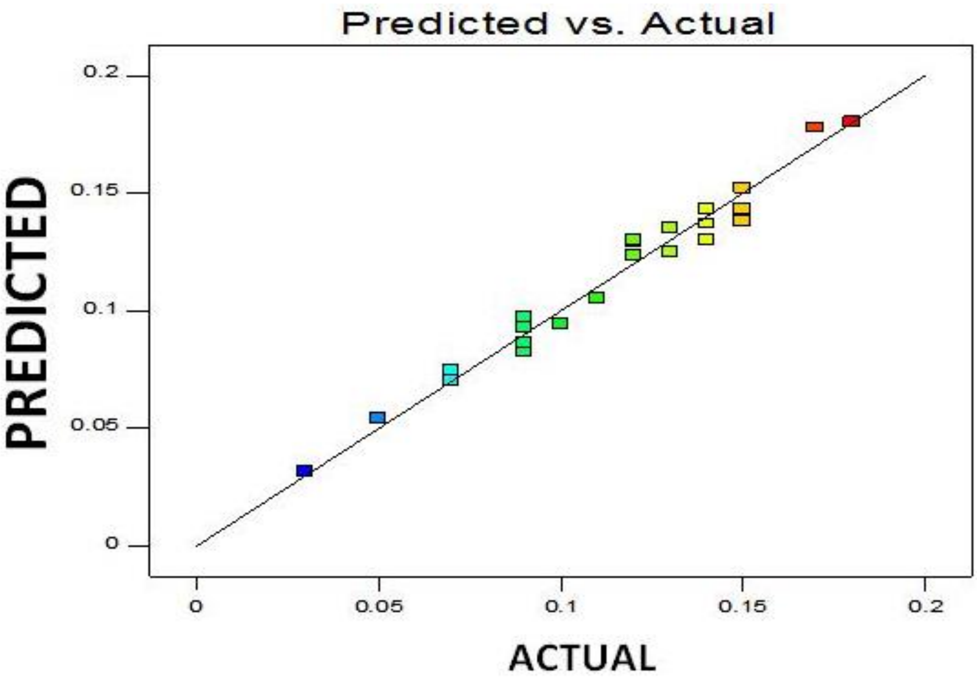
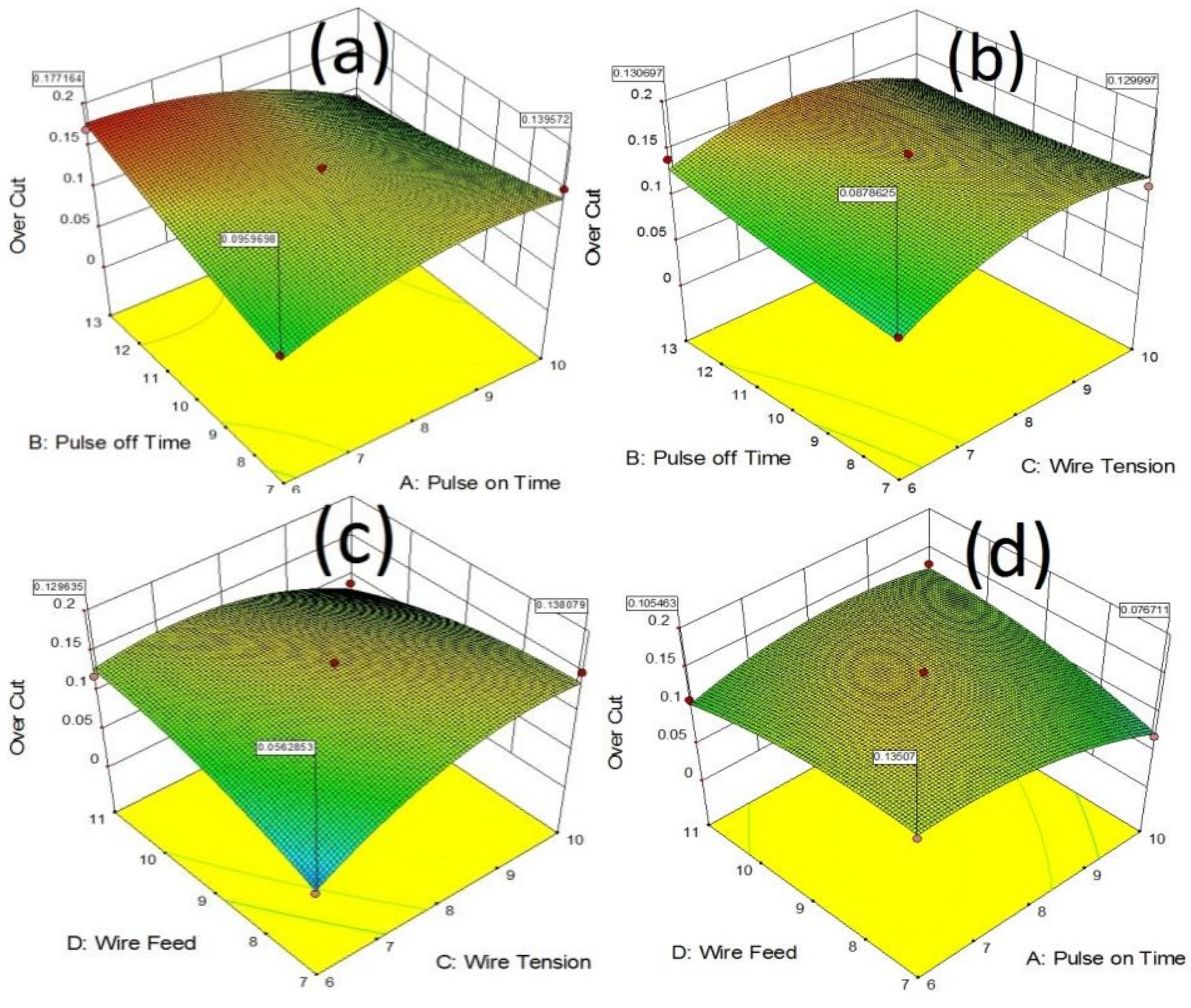


Fig. 10 Actual vs. Predicted graph for Over Cut



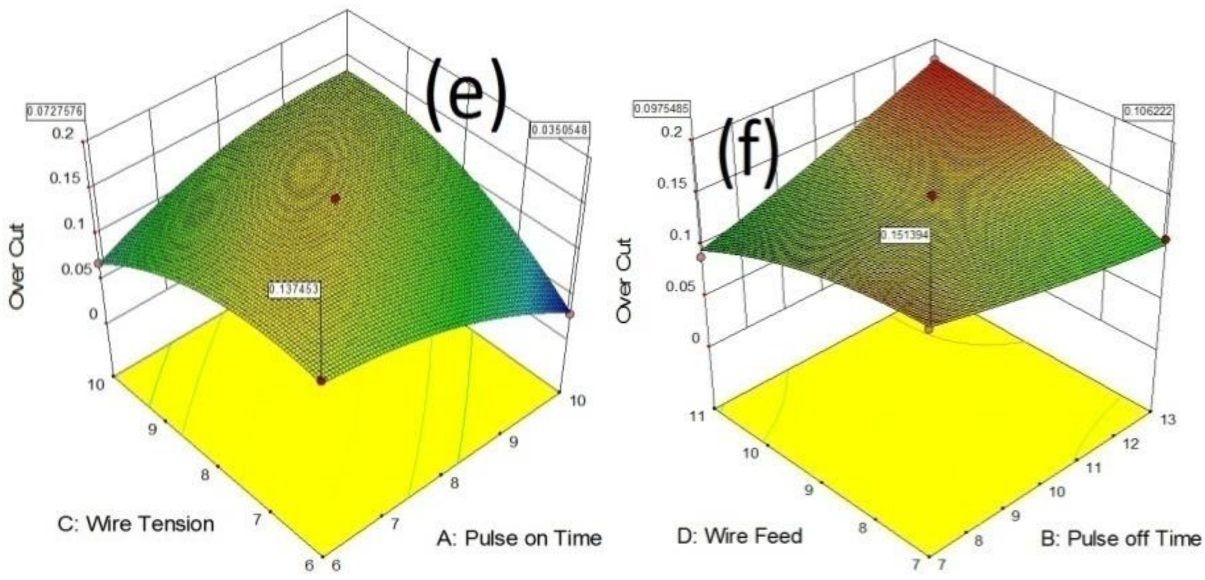


Fig. 11 Response surface and contour plots showing the interaction effects of (a) T_{ON} and T_{OFF} (b) WT and T_{OFF} (c) WT and WF (d) T_{ON} and WF (e) T_{ON} and WT (f)T_{OFF} and WF on the Over Cut of sintered pure Titanium, while the other two parameters are at their respective center value

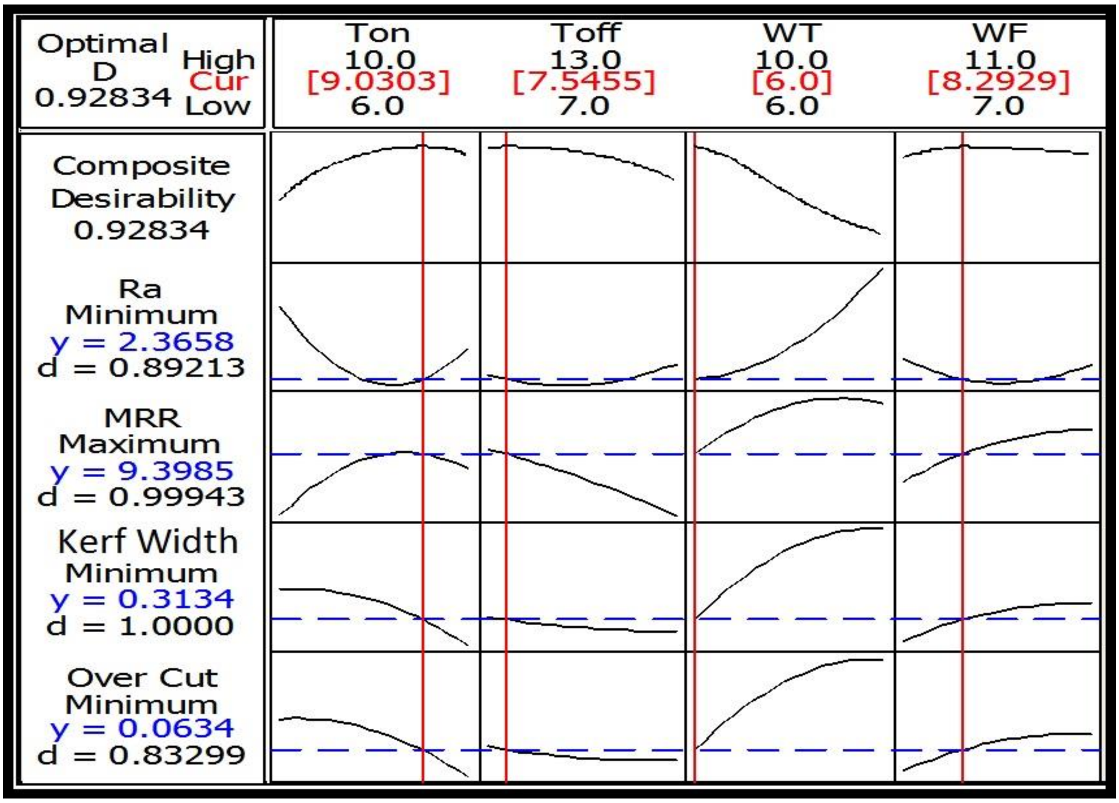
4 Multi-Objective Optimization Analysis

Multi objective optimization analysis for WEDM on sintered pure Titanium has been carried out and optimized results of Surface Roughness (Ra), Material Removal Rate (MRR), Kerf Width and Over Cut are shown in Fig 12. In multi objective optimization target is set to minimize Surface Roughness, Kerf Width and Over cut and to maximize the MRR. The target values for different output responses are set as shown in Table 7.

Table 7. Output Responses vs. its target value

Output Responses	Target Values
Surface Roughness (Ra)	2.30 μm
Material Removal Rate (MRR)	9.40 mm^3/min
Kerf Width	0.35 mm
Over Cut	0.04 mm

In order to achieve the desired output, equal importance has been given to the lower, the target and the upper bound of the linear desirability function. For linear desirability function (d), the value of the weight is considered as 1. In Fig.12 each row of the graph corresponds to a response variable (Eq.1, Eq.2, Eq. 3 and Eq. 4) with the process parameters along the column. Each cell of the graph shows the variation of responses as a function of process parameters while the other parameters are kept constant. The vertical line inside the graph indicates the optimum parameter setting and horizontal dotted line represents the optimized response values. The displayed numbers at the top of the column show the upper and lower limit of the process parameters setting and the optimum parameter level setting respectively. At the left side of each row, goal of responses, predicted response (y) at the optimum parametric setting, and individual desirability value (> 0.80) are given. MINITAB 16 statistical software has been used for optimization of Wire cut EDM process on fabricated sintered pure Titanium, the optimum Material Removal Rate (9.3985 mm^3/min), Surface Roughness (2.3658 μm), Kerf Width (0.3134 mm) and Over Cut (0.0634 mm) have been obtained at Pulse on Time of 9.0303 µs, Pulse off Time of 7.5455 µs, Wire Tension of 6.0kgf and Wire Feed of 8.2929 m/min. The value of composite desirability factor (D) is 0.92834



5 Confirmatory Test

The results of response optimization obtained by desirability function analysis, have been validated by conducting confirmatory test. Confirmatory experiment has been conducted at optimum parametric setting. The tested results of experiments at optimum conditions are presented in Table 8. It is obtained from Table.8 that there is a very small error percentage between predicted and the experimental values, which validate the applied optimization technique.

Table 8. Optimization validation test results

Optimum condition					**Responses**			
Pulse on Time (Ton) µs	Pulse off Time (Toff) µs	Wire Tension (WT) kgf	Wire Feed (WF) m/min		Surface Roughness (Ra) µm	Material Removal Rate (MRR) mm^3/min	Kerf Width mm	Over Cut mm
9.03	7.56	6.0	8.30	Experimental Predicted IError %I	2.40 2.36 1.67	9.58 9.40 1.88	0.34 0.32 5.88	0.07 0.064 8.57

CONCLUSION

Based on the experimental results and analysis, the following conclusions can be drawn:

- The multi-objective optimized process parameters for responses have been validated using final confirmation experiments and the results are found to be satisfactory. The error percentage between the optimization model prediction and the final confirmation experiments are found to be approx ~ 1.67% for Surface Roughness, approx ~ 1.88% for Material Removal Rate, approx ~ 5.88% for Kerf Width and approx ~ 8.57 % for Over cut.

- The 3-D response surface and contour plots show that Pulse on Time (T_{ON}) plays a vital role as input parameters and influences the output responses. With the increase in T_{ON} both MRR and Ra value increases simultaneously. Pulse on Time (T_{ON}) shows this behaviour irrespective of other parameters position in center line value.
- For Kerf Width and Over Cut it has been observed in 3-D response surface and contour plots that Pulse On Time, Pulse off Time, Wire Feed and Wire Tension shows different results in different cases because these factors depends on other parameters position in centre line value.
- The actual vs. predicted graph in case of both the responses (Ra and MRR) shows good agreement with each other and satisfies the present work to be on the right track.

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