Research Article

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Microstructural analysis and multi response optimization of WEDM of Inconel 825 using RSM based desirability approach

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Abstract: Increasing demand of aerospace industry for more heat resistant and tough material have open up the possibility of the use of Inconel 825 for making of combustor casing and turbine blades. Because of its robust nature, Inconel 825 is a difficult-to-cut material with conventional methods. Wire-cut electrical discharge machining (WEDM), a non traditional method uses thermoelectric erosion principle to produce intricate shape and profiles of such difficult-to-cut material. In this study, various operating parameters of WEDM are optimized using desirability approach and microstructural behavior at optimum combinations was studied. Input parameters *viz.* pulse-on time, pulse-off time, peak current, spark gap voltage, wire tension, wire feed and performance has been measured in term of material removal rate, surface roughness and wire wear ratio. It has been observed that at 110 machine unit pulse-on time (T_{on}), 35 machine unit pulse-off time (T_{off}), 46 volt gap voltage (SV), 120 ampere peak current (IP), 11 machine unit wire tension (WT) and 5 m/min wire feed (WF), the values obtained for material removal rate (MRR), surface roughness (SR) and wire wear ratio (WWR) were 27.691 mm³/min, 2.721 μ m and 0.117 respectively. Scanning electron microscopy, energy dispersive spectrograph and X-ray diffraction analysis has also been carried out to study the surface characterization. Comparatively less numbers of cracks, pockmarks, craters, and pulled out material were found on work specimen surface and wire electrode surface under standardized conditions, thus maintaining the surface integrity of the machined surface.

Keywords: Wire-cut electrical discharge machining; Inconel 825; Response surface methodology; Material removal rate; Surface roughness; Wire wear ratio

1 Introduction

In the field of manufacturing technologies to achieve better design configuration, use of new and difficult-to-machine materials demands the development of economically more feasible processes. Superalloys, due to their high-temperature mechanical strength and high corrosion resistance properties, are currently being used in technologically advanced industries such as marine, space, automobiles and other applications [1, 2]. Such properties are mainly significant to the aerospace industry for manufacturing of turbine disks, blades, combustors and casing [3]. Nickel-based superalloys are the most multifaceted widely used alloy for the hottest parts and constitute over 50% of the weight of advanced aircraft engines. Among Nickel based superalloys, Inconel series possesses high temperature corrosion resistance, oxidation resistance and creep resistance properties which are important for aerospace industry for manufacturing of turbine disks, blades, combustors and casing [4]. Among the various Inconel series, Inconel 825 possesses superior mechanical properties, provides resistance to chloride pitting as well as resistance to a variety of oxidizing atmospheres than other Inconel alloys [5].

Inconel 825 has an austenitic structure that imparts high ductility and work hardening properties to this superalloy resulting in a gummy machining behavior similar to that of steels. In addition, because of high temperature resistant and less thermal conductivity, Inconel 825 remains strong at the temperature of chip formation during machining. Inconel 825 also contains abrasive titanium and aluminium particles. All these factors make Inconel 825, a difficult to machine material even in comparison to steels resulting in increased cost to the manufacturer [6]. During machining, Inconel 825 has a propensity

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to weld the cutting tool that causes tool failure [7, 8]. Because of high toughness and hardness, the machining of this hard material with conventional method is very difficult [9]. Moreover, high abrasive particles in its microstructure, tendency forming chip to weld the tool and built up edges (BUE) make it more difficult to machine [10]. Generation of high temperature is also a problem due to abrasion between tool and material [11].

WEDM is non-traditional machining technique works on spark erosion principal in which a discrete form of spark is generated in between the gap of wire and work-piece ranges from 0.025 mm to 0.5 mm. By the use of non-conventional technique in machining of superalloys a revolutionary change has been found in tools. WEDM is best alternative of making intricate shape and profile with better surface finish and accurate dimensions of hard and tough material like Inconel 825 [12].

The performance characteristics of WEDM is material removal rate (MRR), surface roughness (SR) which are influenced by numerous machining characteristics such as pulse-on time (T_{on}), pulse-off time (T_{off}), peak current (IP), gap voltage (SV), wire tension (WT) and wire feed (WF) [13]. Optimum machining parameters selection of WEDM, avoid the wire breakage problem and surface roughness because improperly selected parameters reduce productivity and quality requirements. To establish the relationship between output and input parameters a suitable modeling and optimization technique is necessary.

Generally, the values of input parameters are selected on the basis of machine manuals but it does not ensure optimal machining performances. Conventional experimental design methods require a large amount of experimental data for determining the best combination of parameters, which is expensive and prolonged. To overcome these problems, researchers applied factorial design named Design of Experiment. Taguchi's methodology has been used in various studies to obtain best combination of parameters for desired machining performances [14–18]. Response surface methodology is a better approach than taguchi method as it can help to find the nearest range of machining parameters beyond or within the range of level of factors. Also, RSM is a more mathematical approach as it identifies the interaction between the variables rather than investigating the effect of individual parameters [19].

Goyal [20] investigated the effect of process parameters of WEDM on Inconel 625 and found that pulse-on time, tool electrode and current intensity are the significant parameters that affect the MRR and SR. Kumar *et al.* [21] optimized the machining parameters *i.e.* current 1 A, pulse-on-time 0.98 μ s, pulse-off-time 0.03 μ s, tool material 0.31 and the powder (suspended particles) 0.64

on machining of Inconel 800 using Powder mixed EDM by employing desirability based RSM approach. Amongst the nickel based superalloy, many reports have been published on the WEDM cutting of Inconel 718 [10, 18, 22–24]. A thorough scrutiny of the previous investigations suggests that despite of having superior properties over other nickel based alloys, much less work has been done on Inconel 825. While there are some reports on ECM/EDM of Inconel 825 [25, 26], only one author had focused on standardization of machining characteristics of WEDM using Inconel 825 [5]. Rajyalakshmi and Venkata Ramaiah [5] had optimized the multiple response measures of WEDM on Inconel 825 by consideration of Taguchi grey relational analysis to obtain improved material removal rate, surface roughness and spark gap. The substantial improvement in the output responses were observed under optimal set of conditions.

Moreover, surface integrity investigation is required to determine the final performance of the machined product. Since WEDM process occurs at very high temperature (8000-12000°C), it is having significant impact on the surface integrity of the work piece. Surface parameters including surface morphology, residual stress surface roughness, microstructure, and micro-hardness are crucial in determining the final performance of the machined specimen. The formation of heat affected zone, micro-cracks, porosity etc. remains a big problem in material microstructure processed by WEDM [10, 27]. Therefore, analysis of surface integrity is required to determine the final performance of the machined product. Thus, after critically analyzing the literature, it was revealed that most of the work reported in the literature has been focused on machining of work materials such as ceramics, titanium and its alloys etc. using WEDM or EDM. There is limited work done on the machining of Inconel 825 by using WEDM. Moreover, mostly two machining characteristics such as MRR and surface roughness (SR) have been investigated in literature. No investigation work is available involving wire wear ratio as output response in WEDM of Inconel 825. So, wire wear ratio can be considered as an output response of the WEDM process. Therefore, in this study, to find the optimal performance of WEDM a suitable modeling and optimization technique, RSM, is used to establish the relationship between performance characteristics and controllable input parameters. Multi-objective optimization was carried out using RSM based desirability approach. In addition, surface integrity studies of the finally machined sample was also performed.

Table 1: Chemical, physical and mechanical properties of Inconel 825

Chemical composition of Inconel 825										
Element	Ni	Fe	Cr	Mo	Cu	Ti	C	P	S	Mg
Content (%)	38-46	22	19.5-23.5	2.5-3.5	1.5-3.0	0.6-1.2	0.05 max	0.002 max	0.003 max	1.0 max
Physical properties of Inconel 825										
Property	Density	Melting Point		Coefficient of expansion			Modulus of rigidity		Modulus of elasticity	
Metric	8.14 g/cm³	1370-1400 °C		14.0 m/m/°C (20–100 °C)			75.9 N/mm2		196 MPa	
Mechanical properties of Inconel 825										
Property	Alloy state	Tensile strength MPa		Yield strength MPa		Elongation A 5 %			Brinell hardness HB	
Metric	825	662		338		30			≤ 200

Figure 1: Mechanism of material removal

2 Materials and methods

2.1 Work material

Inconel 825 (150 mm × 150 mm × 10 mm) was used as work material for the present study. Table 1 shows the chemical, physical and mechanical properties of work material. All experiments were performed using CNC WEDM machine tool (ELECTRA SPRINT CUT 734) in advanced manufacturing laboratory of Mechanical Engineering Depart-

ment, N.I.T., Kurukshetra, Haryana, India. The workpiece was mounted with the help of a fixture on the machine table. The electrode material used was a single-strand plain brass wire of diameter 0.25 mm. Wire was continuously fed through the workpiece by a microprocessor. The upper head supplied the fresh wire under tension through the workpiece and lower head received the used wire after machining. A suitable gap of 0.025 - 0.5 mm was maintained between wire and the workpiece (Figure 1).

Table 2: Experimental factors and their levels for machining process

S. No.	Symbol	Parameter	Units	Level (−2)	Level 2 (−1)	Level 3 (0)	Level 4 (1)	Level 5 (2)
1	A	Pulse-on time (T_{on})	MU*	107	109	111	113	115
2	B	Pulse-off time (T_{off})	MU*	32	35	38	41	44
3	C	Gap Voltage (SV)	V*	42	46	50	54	58
4	D	Peak Current (IP)	A*	110	120	130	140	150
5	E	Wire Tension (WT)	MU*	8	9	10	11	12
6	F	Wire feed rate (WF)	m/min	4	5	6	7	8

*MU – machine Unit; V-Voltage; A-Ampere

2.2 Selection of input and output parameters

Six parameters *i.e.* pulse-on time (T_{on}), pulse-off time (T_{off}), peak current (IP), gap voltage (SV), wire tension (WT) and wire feed (WF) were chosen as input parameters as suggested from literature search. The machining performance was measured in terms of material removal rate (MRR), surface roughness (SR) and wire wear ratio (WWR). During experimentation, it was reported that due to constant wire diameter the kerf width varies negligibly. Consequently, the MRR was calculated by taking equation 1 into consideration:

$$MRR (\text{mm}^3/\text{min}) = \text{cutting speed}(\text{mm}/\text{min}) \quad (1) \\ \times \text{thickness of material (mm)}$$

The surface roughness (Ra) of machined specimen is measured in μm using Accretech's surfcomflex instrument SJ-301. Least count of the instrument is 0.8 μm .

A sampling length of 5 mm was selected for measurement. Wire wear ratio is measured by using initial wire weight and used wire weight. It is the ratio of difference between initial wire weight and used wire weight to the initial wire weight. Used wire weight for one specimen is directly measured by using weighing machine. The least count the weighing machine is 0.02g. Fresh wire weight used for one specimen is measured by calculating the length of used wire. One meter length of fresh wire was of 0.400 mg. The fresh wire weight is calculated by multiplying the length of used wire to the weight of the one meter fresh wire.

Some factors which are likely to affect the performance measures *viz.* extent and profile of the product (rectangular), conductivity of the dielectric (20 mho), temperature of the dielectric (28°C), pulse peak voltage setting (110 V), work piece thickness (15 mm), wire feed setting (6 m/min), servo feed setting, wire type (0.25mm diameter brass) and angle of cut (vertical) are kept constant.

2.3 Design of experiments

Central composite design (CCD) at α value of ± 2 was employed using Design expert software (version 9.0.7, Statease) to optimize the levels of significant variables. Table 2 shows the coded and actual values of the variables. MRR, SR and WWR were taken as response parameters. Response data were fed and analyzed by ANOVA to generate 3D plots indicating the optimum conditions and interaction among these factors. Regression equation 2 was used to fill the data by multiple regression procedure. The developed empirical statistical model showed the relation between measured characteristics and input parameters of the experiment

$$y = \beta_0 + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^k \sum_{j=1, i < j}^k \beta_{ij} X_i X_j + \sum_{i=1}^k \beta_{ii} X_i^2 + \epsilon \quad (2)$$

where, y is the predicted response [MRR, SR and WWR], x_i, x_j are the independent variables, β_0 is intercept coefficient, β_i are the regression coefficients of zero order, β_{ij} is the squared coefficients. The quality of fitting by the polynomial model equation was expressed using coefficient of determination R^2 .

The individual desirability index (d) for each response is calculated. Desirability function approach is extensively used for single and multiple quality characteristics problems. The optimization process searches the optimum value of MRR, SR and WWR by maximization of MRR while minimizing the SR and WWR. If the output response is required to be maximized then desirability index (d) is calculated by using the equation 3.

$$d = \begin{cases} 0 & y < L \\ \left(\frac{y-L}{T-L} \right)^r & L \leq y \leq T \\ 1 & y > T \end{cases} \quad (3)$$

If the output response (y) is required to be minimized then desirability index (d) is calculated by using the equa-

tion 4.

$$d = \begin{cases} 1 & y < T \\ \left(\frac{U-y}{U-T}\right)^r & L \leq y \leq T \\ 0 & y > U \end{cases} \quad (4)$$

If the output response (y) is required to achieve a particular target T then desirability index (d) is calculated by using the equation 5.

$$d = \begin{cases} 0 & y < L \\ \left(\frac{y-L}{T-L}\right)^{r1} & L \leq y \leq T \\ \left(\frac{U-y}{U-T}\right)^{r2} & T \leq y \leq U \\ 0 & y > U \end{cases} \quad (5)$$

Where d is the desirability index, L is the lower value, U is the upper value, and T is the target value. Desirability function (d) assigns number between 0 and 1. For $d = 0$ representing the completely undesirable value and $d = 1$ representing the completely desirable value.

Global desirability (D) is the combination of individual desirability for each response and can be calculated by using the equation 6.

$$D = (d_1 \times d_2 \cdot d_m)^{1/m} \quad (6)$$

Where, m is the number of responses.

2.4 Prediction of optimum values for maximum MRR, minimum SR and WWR

After getting the model equation that explains the process, it was used for optimization of the process parameters using the numerical optimization option of the software. Criteria were set for each independent variable and the response (dependent variable). The independent variables were kept in the range used by the experimental set up. The response for MRR was set to maximum and for SR and WWR, set to minimum. Response data was generated both for single response and multiple response optimizations. A solution was generated with predicted levels of the independent variables and predicted maximum MRR, minimum SR and minimum WWR.

2.5 Validation experiments

To ensure the validity of the chosen quadratic model, experiments were designed using the predicted optimum values of the parameters from equation 1. The responses

were measured and compared with the predicted value. Experiments were conducted in triplicates and the data presented as mean $\pm$ SD.

2.6 Scanning electron micrographs of Inconel 825 specimens

All measurement related to surface micrograph were performed on JEOL scanning electron Microscope (Model 6100, JEOL, USA); a profile measuring microscope that determine the surface microstructures, formation of recast layer and heat-affected zone of the work material machined with WEDM. Etching process of machined sample was carried out with krolls reagent (2% (v/v) hydrofluoric acid, 10% (v/v) nitric acid). Then, the samples were cleaned using acetone (CH_3)₂CO.

2.7 Elemental and phase analysis of machined Inconel 825

The very high temperatures used in WEDM process immediately liquefy and vaporize the work material from the surface during the discharge process. The reactions between work specimen, wire electrode and dielectric resulted in the formation of different compounds. Energy Dispersive spectrograph (EDS) analysis was used to measure the element composition of machined surface. X-ray diffraction studies was carried out to analyze the phases of WEDM machined Inconel 825

3 Results and discussion

A variety of materials can be machined by using WEDM for instance titanium alloys, steels, and superalloys but steel is the material which has been studied in majority. Inconel 825 is a nickel based super alloy that has found wide range of applications owing to its high temperature stability. For optimal machining performance, standardization of important machining parameters viz. pulse-on time, pulse-off time, spark gap, peak current, voltage, wire tension, wire feed is required [9]. Many workers had used various strategies to optimize WEDM parameters for materials like steel, aluminum, Inconel 718 etc. [10, 15–17] but there are very few reports on the use of WEDM for the machining of Inconel 825 [4]. Therefore, this study was focused on the standardization of WEDM parameters for the machining of Inconel 825. Response surface methodology

Table 3: Central composite design with actual responses

Run	T _{ON}	T _{OFF}	SV	IP	WT	WF	MRR	SR	WWR
1	0.000	0.000	0.000	0.000	0.000	-2.378	21.27	2.618	0.21966
2	0.000	0.000	0.000	0.000	0.000	0.000	20.44	2.306	0.01531
3	-1.000	-1.000	1.000	1.000	1.000	1.000	18.59	2.453	0.01347
4	1.000	-1.000	1.000	-1.000	1.000	1.000	27.79	2.967	0.0041
5	1.000	1.000	1.000	-1.000	-1.000	1.000	20.63	2.766	0.01908
6	1.000	-1.000	1.000	-1.000	-1.000	-1.000	27.69	2.867	0.01425
7	1.000	1.000	-1.000	1.000	-1.000	1.000	20.06	2.711	0.00337
8	0.000	0.000	0.000	0.000	0.000	0.000	21.97	2.673	0.13256
9	-1.000	1.000	-1.000	-1.000	-1.000	1.000	17.01	2.783	0.01848
10	-1.000	-1.000	1.000	1.000	-1.000	-1.000	21.34	2.844	0.15013
11	1.000	1.000	-1.000	1.000	1.000	-1.000	31.81	2.793	0.00976
12	-1.000	1.000	1.000	1.000	-1.000	1.000	16.17	2.716	0.05423
13	-1.000	1.000	-1.000	1.000	-1.000	-1.000	20.23	2.732	0.02236
14	1.000	-1.000	-1.000	-1.000	-1.000	1.000	27.63	2.678	0.00032
15	0.000	0.000	0.000	0.000	0.000	0.000	21.89	2.911	0.03677
16	0.000	0.000	0.000	0.000	0.000	0.000	20.41	2.875	0.03255
17	-1.000	-1.000	-1.000	1.000	-1.000	1.000	28.94	2.442	0.07354
18	2.378	0.000	0.000	0.000	0.000	0.000	31.25	3.32	0.01093
19	1.000	-1.000	-1.000	1.000	1.000	1.000	34.72	2.84	0.04773
20	0.000	-2.378	0.000	0.000	0.000	0.000	30.87	2.613	0.01845
21	0.000	2.378	0.000	0.000	0.000	0.000	17.19	2.667	0.01298
22	1.000	-1.000	1.000	1.000	1.000	-1.000	31.42	3.271	0.02028
23	-1.000	1.000	1.000	1.000	1.000	-1.000	18.55	2.514	0.00291
24	0.000	0.000	0.000	0.000	0.000	0.000	35.93	2.963	0.01573
25	1.000	1.000	-1.000	-1.000	1.000	1.000	28.95	3.299	0.15061
26	-1.000	-1.000	-1.000	-1.000	-1.000	-1.000	25.79	2.721	0.20167
27	-1.000	-1.000	1.000	-1.000	1.000	-1.000	19.92	2.489	0.14103
28	0.000	0.000	0.000	0.000	-2.378	0.000	24.09	2.767	0.00394
29	0.000	0.000	0.000	2.378	0.000	0.000	27.08	2.684	0.01292
30	-1.000	-1.000	1.000	-1.000	-1.000	1.000	20.21	2.681	0.02832
31	1.000	1.000	1.000	1.000	1.000	1.000	27.68	2.742	0.04154
32	0.000	0.000	0.000	0.000	2.378	0.000	26.05	2.792	0.00823
33	0.000	0.000	0.000	0.000	0.000	0.000	24.59	3.074	0.00545
34	-1.000	-1.000	-1.000	1.000	1.000	-1.000	25.47	2.622	0.01644
35	0.000	0.000	0.000	0.000	0.000	0.000	23.94	2.461	0.01049
36	0.000	0.000	-2.378	0.000	0.000	0.000	25.57	2.594	0.00661
37	1.000	1.000	1.000	1.000	-1.000	-1.000	33.28	2.892	0.12435
38	-1.000	1.000	-1.000	1.000	1.000	1.000	20.52	2.415	0.00404
39	-1.000	1.000	1.000	-1.000	-1.000	-1.000	16.7	2.521	0.04631
40	1.000	1.000	1.000	-1.000	1.000	-1.000	24.46	2.263	0.03279
41	-1.000	1.000	1.000	-1.000	1.000	1.000	16.71	2.318	0.01062
42	-1.000	-1.000	-1.000	-1.000	1.000	1.000	23.14	2.485	0.08701
43	0.000	0.000	2.378	0.000	0.000	0.000	19.61	2.734	0.01789
44	1.000	1.000	-1.000	-1.000	-1.000	-1.000	28.39	2.805	0.00616
45	1.000	-1.000	-1.000	-1.000	1.000	-1.000	34.56	2.827	0.00815
46	-2.378	0.000	0.000	0.000	0.000	0.000	14.7	2.844	0.03203
47	0.000	0.000	0.000	0.000	0.000	2.378	25.77	2.94	0.01582
48	1.000	-1.000	-1.000	1.000	-1.000	-1.000	36.14	2.833	0.02691
49	1.000	-1.000	1.000	1.000	-1.000	1.000	36.13	2.842	0.01832
50	0.000	0.000	0.000	0.000	0.000	0.000	29.48	2.853	0.00853
51	-1.000	1.000	-1.000	-1.000	1.000	-1.000	23.67	2.64	0.1215
52	0.000	0.000	0.000	-2.378	0.000	0.000	28.08	2.748	0.08998

is a statistical method for analyzing the outcome of multiple input parameters on responses. In this study RSM has been employed to study and optimize the individual and interactive effect of operating parameters on the cutting of Inconel 825. Three significant parameters *i.e.* material removal rate (MRR), surface roughness (SR) and wire wear ratio (WWR) was taken as output parameters as these responses have crucial effect on surface integrity of Inconel 825. A total of 52 experiments were conducted as suggested by the software and results were fed and analyzed by ANOVA as shown in Table 3. In all the studies done so far, machining performance is optimized in such a way so that maximum material removal rate can be achieved with little damage to material surface.

3.1 Analysis of variance for MRR

By applying multiple regression analysis on the experimental data, a predictive two factor polynomial equation was constructed to describe the correlation between MRR and the six process parameters as follows:

Final Equation in Terms of Coded Factors: (7)

$$\begin{aligned} \text{MRR} = & 25.30 + 3.73 * A - 2.80 * B - 1.59 * C + 0.40 * D \\ & + 0.75 * E - 0.29 * F - 1.14 * A * B + 0.93 * A * C \\ & + 0.68 * A * D + 0.16 * A * E - 0.23 * A * F + 0.093 * B * C \\ & + 0.10 * B * D + 1.74 * B * E - 0.24 * B * F + 0.13 * C * D \\ & - 1.26 * C * E + 0.39 * C * F + 0.084 * D * E + 0.41 * D * F \\ & + 0.024 * E * F \end{aligned}$$

Figure 2: Perturbation plot showing the effect of individual parameters on MRR

Where, R is the response ($\text{MRR}, \text{mm}^3 \text{min}^{-1}$), A, B, C, D, E and F were the coded values of pulse-on time, pulse-off time, gap voltage, peak current, wire tension and wire feed rate respectively. The analysis of variance for the response surface model is summarized in Table 4. The Model F-value of 33.67 implies that the model is significant. The p-values < 0.05 indicated that the linear (A, B, C, E) and interactive (AB, AC, AD, BE, CE) terms had quite significant influence on material removal rate.

The percentage contribution of $A, B, C, E, AB, AC, AD, BE, CE$ for MRR is 45.19, 25.38, 8.18, 1.84, 3.12, 2.07, 1.09, 7.26 and 3.81% respectively which are calculated from Table 4 by dividing the each variable sum of square term by “model” sum of square. The lack of fit was found to be not significant. The p-value for lack of fit was 0.9298, indicating that this model adequately fit into the data. The determination coefficient R^2 (0.9593) indicated that the predicted and experimental values had perfect coherence with each other. The value of adjusted R^2 (0.9308) suggested that the variation of 93.08% in the MRR was attributed to the independent variables and 6.92% of the total variation could not be explained by the model.

3.1.1 Individual effect of Process parameters on MRR

Effect of individual process parameters on MRR is determined by perturbation graph (Figure 2). It was observed that pulse-on time (A), peak current (D) and wire tension (E) has significant effects on MRR during machining of Inconel 825 by WEDM. The steep curve of T_{on} , WT, IP showed that MRR is highly sensitive to pulse-on time (A), followed by Wire tension (E) and peak current (D) when compared with other controllable factors such as wire feed (F), gap voltage (C) and pulse-of time (B).

3.1.2 Interactive effect of process parameters on MRR

The interaction between two variables is presented in Figure 3 which was generated by the pair-wise combination of the two factors while keeping the other one at its optimum level. The three dimensional plot between pulse-on time and pulse-off time (AB), pulse-on time and gap voltage (AC), pulse-on time and peak current (AD), pulse-on time and wire tension (AE), pulse-off time and wire tension (BE) and peak current and wire tension (DE), peak current and wire feed (DF), wire tension and wire feed (EF) with MRR are shown in Figure 3 (a-h) respectively.

From the figure it was observed that pulse-on time had significant positive effect on MRR, as MRR increased

Figure 3: Three dimensional plot of combined effects of (a) pulse-on time and pulse-off time (b) pulse-on time and gap voltage (c) pulse-on time and peak current (d) pulse-on time and wire tension (e) pulse-off time and wire tension (f) and gap voltage and wire tension (g), peak current and wire tension (h), peak current and wire feed (i), wire tension and wire feed on MRR when other factors were kept constant

from $19 \text{ mm}^2/\text{min}$ to $33 \text{ mm}^2/\text{min}$ approximately with an increase in value of pulse-on time from 109 MU to 113 MU (Figure 3a) while pulse-off time had negative effect on MRR, as MRR decreased with increases in value of pulse-off time from 35 MU to 41 MU (Figure 3a). However, when

applied in combination, the MRR value decreases. At high value of T_{on} , high discharge energy is produced leading to melting of more work material from the surface. High intense heat produced in plasma zone accelerates the ero-

Table 4: Analysis of variance (ANOVA) for response MRR

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	1334.74	21	63.56	33.67	< 0.0001	significant
A-Pulse-on Time	603.23	1	603.23	319.54	< 0.0001	
B-Pulse-off Time	338.79	1	338.79	179.46	< 0.0001	
C-Gap Voltage	109.23	1	109.23	57.86	< 0.0001	
D-Peak Current	7.04	1	7.04	3.73	0.0630	
E-Wire Tension	24.66	1	24.66	13.06	0.0011	
F-Wire Feed	3.69	1	3.69	1.95	0.1725	
AB	41.72	1	41.72	22.10	< 0.0001	
AC	27.71	1	27.71	14.68	0.0006	
AD	14.58	1	14.58	7.72	0.0093	
AE	0.79	1	0.79	0.42	0.5216	
AF	1.66	1	1.66	0.88	0.3564	
BC	0.27	1	0.27	0.15	0.7060	
BD	0.33	1	0.33	0.18	0.6779	
BE	96.95	1	96.95	51.36	< 0.0001	
BF	1.89	1	1.89	1.00	0.3248	
CD	0.54	1	0.54	0.28	0.5982	
CE	50.95	1	50.95	26.99	< 0.0001	
CF	4.98	1	4.98	2.64	0.1149	
DE	0.22	1	0.22	0.12	0.7326	
DF	5.48	1	5.48	2.90	0.0988	
EF	0.018	1	0.018	9.561E-003	0.9228	
Residual	56.63	30	1.89			
Lack of Fit	33.79	23	1.47	0.45	0.9298	not significant
Pure Error	22.85	7	3.26			
Cor Total	1391.37	51				
Std. Dev.		1.37			R-Squared	0.9593
Mean		25.30			Adj R-Squared	0.9308
C.V. %		5.43			Pred R-Squared	0.9137
PRESS		120.04			Adeq Precision	21.727

sion process which results in increase in the material removal rate [28, 29].

Similarly, gap voltage was shown to have negative effect on MRR (Figure 3b). The spark gap voltage is theoretical voltage difference between wire electrode and workpiece during erosion [30]. In combination pulse-on time and gap voltage reduced the MRR. MRR will be maximum at 113 MU pulse-on time and low gap voltage *i.e.* 46 V to 48 V (Figure 3b). The reason can be attributed due to the fact that high value of gap voltage increases the gap between two successive sparks and less discharge energy is pro-

duced between the gaps resulted in decreased MRR [31, 32]. Similar results have been reported during the WEDM machining of Ti50Ni50-xCu_x alloy using both brass wire and zinc coated brass wires [33].

It is evident from Figure 3c that MRR increased with increase in the value of pulse-on time and peak current as discharge energy is the product of pulse-on time and peak current which in turn improve MRR [34]. MRR is maximum (30 mm²/min) at 113 MU pulse-on time and 140 amp peak current (Figure 3c). At higher value of IP the gap condition become unstable and to stable the gap condition it is nec-

essary to reduce the value of peak current. Similarly, MRR is maximum ($29 \text{ mm}^3/\text{min}$) at interactive effect of pulse-on time (113 MU) and wire tension (11 kg-f) (Figure 3d) while wire tension in combination with pulse-off time and peak current decreases MRR (Figure 3e-3f). Wire tension is the gram equivalent load with which the continuously fed wire is kept under tension so that it remains straight between the wire and workpiece. Saini *et al.* [34] also analyzed the effect of wire tension on MRR in the machining of Ti-6Al-4V Alloy. They observed that MRR decreases with increase in wire tension. Wire feed have little positive effect on MRR thus, resulting in little increase in MRR in combination with peak current and wire tension (Figure 3g-3h). Similar results had been observed by Patel *et al.* [35].

3.2 Analysis of variance for surface roughness (SR)

By applying multiple regression analysis on the experimental data, a predictive two factor polynomial equation was constructed to describe the correlation between SR and the six process parameters as follows: Final Equation in Terms of Coded Factors:

Final Equation in Terms of Coded Factors : (8)

$$\begin{aligned} SR = & 2.68 + 0.12 * A - 7.032E - 003 * B + 0.019 * C \\ & + 0.012 * D - 0.022 * E - 8.676E - 003 * F \\ & - 0.041 * A * B - 1.219E - 003 * A * C + 0.022 * A * D \\ & + 0.053 * A * E + 0.039 * A * F - 0.078 * B * C \\ & + 6.781E - 003 * B * D - 0.066 * B * E + 0.049 * B * F \\ & + 0.067 * C * D - 0.053 * C * E + 0.011 * C * F \\ & + 0.028 * D * E - 0.078 * D * F + 0.014 * E * F \end{aligned}$$

The Model F-value of 37.20 implies the model is significant. In this case A, C, E, AB, AD, AE, AF, BC, BE, BF, CD, CE, DE, DF are significant model terms for SR with their contribution percentage of 36.87, 0.837, 0.346, 3.016, 0.893, 5.083, 2.681, 11.173, 7.821, 4.357, 7.821, 0.212, 1.396 and 10.614% respectively which are calculated from Table 4 by dividing the each variable sum of square term by “model” sum of square. Lack-of fit value of 0.1642 implies that it is not significant relative to pure error. The determination coefficient for SR is found to be 0.9630 which shows that the factorial model can explain the variation in the surface roughness up to the extent of 96.30%. On the basis of the high values of the determination coefficient, it can be said that the proposed model is adequate in representing the process. The other R^2 statistics, the Pred R^2 (0.8491), is in good agreement with the Adj R^2 (0.9371).

Figure 4: Perturbation plot showing the effect of individual parameters on SR

3.2.1 Individual effect of Process parameters on surface roughness (SR)

Surface roughness is the variation or irregularity of a machined surface from its ideal atomic value. Roughness of surface must be minimum for high quality material [11]. Therefore, the effect of each parameter on surface roughness of Inconel 825 was determined by perturbation plot (Figure 4). The steep slope curves and relatively flat line was observed which shows that surface roughness is highly sensitive to pulse-on time (A) and peak current (C) and less sensitive to wire tension (E), wire feed (F).

3.2.2 Interactive effect of process parameters on SR

The two variables interaction when the others were kept at its optimum value is for SR is presented in Figure 5 were generated on the basis of two factors combination while keeping the other one at its optimum level. The interaction plot between pulse-on time and pulse-off time (AB), pulse-on time and peak current (AD), pulse-on time and wire tension (AE), pulse-on time and wire feed (AF), pulse-off time and gap voltage (BC), pulse-off time and wire tension (BE), pulse-off time and wire feed (BF), gap voltage and peak current (CD), gap voltage and wire tension (CE), peak current and wire tension (DE) peak current and wire feed (DF), wire tension and wire feed (EF) are shown in Figure (5a-5k) respectively.

From the Figure 5a-5b, it was observed that surface roughness increases upto $2.756 \mu\text{m}$ at combination of

Figure 5: Three dimensional plot of combined effects of (A) pulse-on time and pulse-off time (B) pulse-on time and peak current (C) pulse-on time and wire tension (D) pulse-on time and wire feed (E) pulse-off time and gap voltage (F) pulse-off time and wire tension (G) pulse-off time and wire feed (H) gap voltage and peak current (I) gap voltage and wire tension (J) peak current and wire tension (K) peak current and wire feed (L) wire tension and wire feed on SR when other factors were kept constant

pulse-on time and pulse-off time. The reason can be attributed to the fact that pulse-on time is the prominent factor to increase the discharge energy. At high value of pulse-on time duration of current flowing increases and high discharge energy produced between two electrodes which in turn increase the surface roughness [29]. At low value of pulse-on time, the time duration of current flowing decreases and at high value of pulse-off time, the time interval between two sparks increases so that discharge energy produced was less and less temperature generated between two electrodes which in turn improve the surface roughness [36].

At high value of pulse-on time 113 machine unit, surface roughness increases upto 2.838 μm with increase in the value of peak current from 120 A to 140 A. as shown in fig 5b. Minimum surface roughness occurred (2.569 μm) at low value of pulse-on time *i.e.* 111 to 109 machine unit and low value of peak current 125 to 120 A (Figure 5b). At high value of peak current, the pulse discharge energy increases which in turn increase the cutting rate as well as increase the surface roughness and WWR [37, 38].

Wire tension is significant process parameter for surface roughness and affects the geometry of specimen cut from the workpiece. Surface roughness decrease with increase of wire tension from 9 to 11 machine unit and when applied in combination with pulse-on time the surface roughness increases upto 2.834 μm as shown in Figure 5c. It has been observed that increase in wire tension will reduce the vibrations of wire and cause reduction in surface roughness resulting in improved quality of the machined surface [32]. Wire feed has little effect on surface roughness. Increase in wire feed resulted in less increase (Figure 5d). At high value of wire feed with pulse-on time, the surface roughness increases upto 2.835 μm because at high value of wire feed, more wire moves on wire guides through the geometry of the workpiece resulting in large area of the wire get exposed to sparking zone forming large craters and pockmarks on the work surface which in turn increase the surface roughness [39].

Figure 5e-5f shows the interactive effect of pulse-off time with gap voltage and wire tension. The surface roughness decreases upto 2.618 μm and 2.590 μm respectively as shown in Figure 5e-5f. At high value of gap voltage spark gap becomes wider which leads to less numbers of sparks per unit time and slow down the cutting rate as a result less numbers of craters form on work surface [40]. High value of pulse-off time increases the gap between two successive sparks which in turn decrease the surface roughness [41]. Wire feed has negative significant effect on surface roughness (2.746 to 2.714 μm) with pulse-off time whereas peak current has positive influence on surface roughness (2.717

to 2.777 μm) when applied in combination with gap voltage (Figure 5g-5h). At high value of peak current the pulse discharge energy increases which leads to increase in the cutting rate as well as increase in the surface roughness.

3.3 Analysis of variance for wire wear ratio (WWR)

By applying multiple regression analysis on the experimental data, a predictive two factor polynomial equation was constructed to describe the correlation between WWR and the six process parameters as follows:

Final Equation in Terms of Coded Factors : (9)

$$\begin{aligned} \text{WWR} = & 0.028 - 7.211\text{E} - 003 * A - 2.300\text{E} - 003 * B \\ & + 1.777\text{E} - 003 * C - 6.534\text{E} - 003 * D - 1.851\text{E} \\ & - 004 * E - 6.258\text{E} - 003 * F + 0.017 * A * B + 5.031\text{E} \\ & - 004 * A * C + 3.858\text{E} - 003 * A * D + 6.473\text{E} \\ & - 003 * A * E + 0.011 * A * F - 2.647\text{E} - 003 * B * C \\ & - 3.798\text{E} - 003 * B * D + 6.251\text{E} - 003 * B * E + 6.696\text{E} \\ & - 003 * B * F + 0.014 * C * D - 0.011 * C * E - 9.720\text{E} \\ & - 003 * C * F - 0.011 * D * E - 5.424\text{E} - 003 * D * F, ./ \\ & + 0.013 * E * F \end{aligned}$$

The F-value of model is 23.07 indicates that model is significant (Table 5). In this case A, D, F, AB, AD, AE, AF, BD, BE, BF, CD, CE, CF, DE, DF, EF are significant model terms for WWR with their contribution percentage of 4.69, 3.85, 3.53, 19.51, 0.99, 2.79, 7.47, 0.96, 2.60, 2.98, 13.59, 8.38, 6.29, 7.97, 1.96 and 11.26% respectively, which are calculated from Table 4 by dividing the each variable sum of square term by “model” sum of square. Lack-of fit value of 0.4856 implies that it is not significant relative to pure error. The determination coefficient for WWR is found to be 0.9417 which shows that the quadratic model can explain the variation in the wire wear ratio up to the extent of 94.17%. On the basis of the high values of the determination coefficient, it can be said that the proposed model is adequate in representing the process. The other R^2 statistics, the Pred R^2 (0.8340), is in good agreement with the Adj R^2 (0.9009).

3.3.1 Individual effect of Process parameters on WWR

Figure 6 shows the Perturbation plot of WWR. From the figure it was clear that wire wear ratio is highly sensitive to pulse-on time (A), peak current (D) and wire feed (F), as increase in these factors results in decrease in WWR while

Table 5: Analysis of variance (ANOVA) for response SR

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	1727.36	21	0.085	37.20	< 0.0001	Significant
A-Pulse-on Time	637.26	1	637.26	288.17	< 0.0001	
B-Pulse-off Time	2.06	1	2.06	0.93	0.3417	
C-Gap Voltage	14.74	1	14.74	6.67	0.0149	
D-Peak Current	5.99	1	5.99	2.71	0.1104	
E-Wire Tension	20.14	1	20.14	9.11	0.0052	
F-Wire Feed	3.14	1	3.14	1.42	0.2426	
AB	51.93	1	51.93	23.48	< 0.0001	
AC	0.046	1	0.046	0.021	0.8865	
AD	15.14	1	15.14	6.85	0.0138	
AE	87.77	1	87.77	39.69	< 0.0001	
AF	46.24	1	46.24	20.91	< 0.0001	
BC	188.11	1	188.11	85.06	< 0.0001	
BD	1.42	1	1.42	0.64	0.4295	
BE	134.48	1	134.48	60.81	< 0.0001	
BF	75.10	1	75.10	33.96	< 0.0001	
CD	137.81	1	137.81	62.32	< 0.0001	
CE	85.32	1	85.32	38.58	< 0.0001	
CF	3.67	1	3.67	1.66	0.2076	
DE	24.24	1	24.24	10.96	0.0024	
DF	186.30	1	186.30	84.25	< 0.0001	
EF	6.46	1	6.46	2.92	0.0978	
Residual	66.34	30	2.21			
Lack of Fit	57.81	23	2.51	2.06	0.1642	not significant
Pure Error	8.53	7	1.22			
Cor Total	1793.71	51				
Std. Dev.	1.49		R-Squared		0.9630	
Mean	16.72		Adj R-Squared		0.9371	
C.V. %	8.89		Pred R-Squared		0.8491	
PRESS	270.62		Adeq Precision		35.840	

increase in pulse-off time (B), gap voltage (C) and wire tension (E) increase WWR.

3.3.2 Interactive effect of process parameters on WWR

Based on analysis of variance, the interactions between peak current and pulse-on time (AD), pulse-on time and wire tension (AE), pulse-on time and wire feed (AF), pulse-off time and peak current (BD), gap voltage and wire tension (CE), gap voltage and wire feed (CF), peak current and

wire tension (DE) peak current and wire feed (DF) which contribute significantly for WWR are shown in Figure 7 (a-g) respectively.

From the interaction plot, it was observed that wire wear ratio set at its minimum value *i.e.* 0.0217 at low value of pulse-on time and peak current. The highest increment of WWR *i.e.* 0.0443 was observed at high value of pulse-on time (113 machine unit) and peak current (140 A) (Figure 7a). It was observed experimentally that high value of pulse-on time increases the discharge energy which leads to formation of large craters on the tool surface and wear

Figure 6: Perturbation plot showing the effect of individual parameters on WWR

out the wire electrode rapidly. Similar report has been found from the interaction plot (Figure 7b) of pulse-on time and wire tension. When pulse-on time and wire tension is set at highest value the wire wear ratio is recorded as 0.0354. The higher wire wear ratio *i.e.* 0.0332 is also accompanied at highest value of pulse-on time and wire feed as shown in Figure 7c. In contrast, at high value of pulse-off time, rate of spark generated get decreased and decreased value of WWR was observed *i.e.* 0.0219 (Figure 7d). It was observed from the Figure 7e that increase value of peak current results in a corresponding increase of wire wear ratio from 0.0235 to 0.0310 due to intense thermal effect on the surface of wire electrode and more material eroded from the wire electrode in the form of craters [37]. In contrast, at high value of pulse-off time, rate of spark generated get decreased and WWR of 0.019 was observed as minimum. Similarly, when gap voltage is set up at high level 54 V and wire tension is set up 11 MU, the wire wear ratio of 0.02 was recorded as minimum. At high value of wire tension fewer craters were observed on wire electrode surface so less wire wear ratio was recorded [32].

3.4 Multi response optimization using desirability approach

After optimizing the each output responses individually, multi-response optimization was carried out for the response variables MRR, SR and WWR. Desirability function approach is extensively used for single and multiple quality characteristics problems [42]. It is based on the idea that the "quality" of a product or process which is outside the

desired limit is completely undesirable for multiple quality characteristics. The method results in operating conditions which provides the "most desirable" output response characteristics. Numerical optimization option of design expert software was used to carry out this. The values of six input variables were kept in range and the response factor MRR was set to maximum while SR was set to minimum. The value of WWR is target to minimum value. The lower and upper limit of each variable was taken individually and the weight of each variable and response was set to their default value of 1. Because the target of the present study is to increase the cutting rate while maintaining the minimum surface damage, the importance of MRR, SR and WWR were taken as 3.

Experiments were performed under predicted conditions as given by the software. It was observed that at 110 MU T_{on} , 35 MU T_{off} , 46 V SV, 120A IP, 11 MU WT and 5 m/min WF, the values obtained for MRR, SR and WWR were 27.691, 2.721 and 0.117 respectively which are near to the predicted values (Table 6) with an error of less than 5%. Thus, the model was successfully validated.

3.5 Microstructure analysis of worked specimen surface and wire electrode surface

To study the effect of machining on work surface, scanning electron micrograph was performed for Inconel 825 machined with WEDM and wire electrode used. The surface topography includes micro-cracks, craters, debris, spherical debris, pockmarks, heat affected zone and recast layer. The experiments which were showing maximum MRR (run 48) (Figure 8), minimum SR (run 40) (Figure 9) and minimum WWR (run 14) (Figure 10) were chosen for SEM analysis. Material cut with finally optimized values was also scanned using surface analysis (Figure 11).

3.5.1 Effect of operating parameters on machined surface for maximum MRR

It was observed that at maximum value of MRR *i.e.* 36.14 mm²/min (Exp. 48), deep and large craters were formed due to high value of pulse-on time (113 MU) and high value of peak current (140 A) (Figure 8a). The reason can be attributed to the fact that at high value of pulse-on time and discharge energy, intense heat transfers towards the work surface which causes melting and evaporation of more work material from the surface resulting in larger numbers of pockmarks, craters and spherical debris [10, 27]. Dur-

Figure 7: Three dimensional plot of combined effects of (A) pulse-on time and peak current (B) pulse-on time and wire tension (C) pulse-on time and wire feed (D) pulse-off time and peak current (E) gap voltage and wire tension (F), gap voltage and wire feed (G) peak current and wire tension (H) peak current and wire feed on WWR when other factors were kept constant

Figure 8: Scanning electron micrographs of work material for MRR

ing machining some amount of the melted material was carried away by deionized water and material extruded in pulled-out shape formed on work surface. Rest of the material re-solidified in the form of spherical or irregular shapes of debris on work surface and because of the dramatic temperature changes in the workpiece a multi layered surface is created named as recast layer, heat affected zone and the transformed layer as shown in Figure 8(d). From the Figure 8(d) it was observed that due to rapid heating and quenching heat affected zone is formed below the recast layer and due to thermal residual stresses some cracks produced near the zone. These spherical nodules were formed due to high value of pulse-on time and high value of peak current which also resulted in the martensite structure.

3.5.2 Effect of operating parameters on machined surface of minimum SR

On the other hand, fewer craters and less micro-crack and fewer pockmarks were observed on the machined specimen surface when run 40 showing minimum surface roughness was analyzed through SEM (Figure 9). The reason can be because peak current at its low value and high value of pulse-off time increase the time interval between two sparks resulting in less material removal from the surface and improved smoothness. Low value of peak current transfers less intense heat towards the surface of the sample [37, 38]. Moreover, high value of pulse-off time increase the time interval between the spark thus leads to improve the surface roughness [43]. It was observed from the Figure 9(d) that the recast layer and heat affected zone tends to decrease with parallel decrease of peak current

Figure 9: Scanning electron micrographs of work material for SR

and increase of pulse-off time. The change in grain structure from the base structure is less apparent as compared to Figure 8(d).

3.5.3 Effect of operating parameters on machined surface of minimum WWR

Similarly, minimum WWR was achieved from exp 14 which is identified as, pulse-on time 113 MU, pulse-off time 35 MU, spark gap voltage 46 V, peak current 120 amp, wire tension 9 MU, wire feed 7 m/min. SEM micrographs of the specimen showed less numbers of craters, cracks and debris on wire electrode surface (Figure 10). The reason can be because when peak current and spark gap voltage are set at lowest level (120amp and 46 V) the wire wear ratio reaches its minimum value so fewer craters and fewer microcracks were created on the surface of wire electrode [44].

3.5.4 Effect of operating parameters on machined surface under optimized condition

Under optimized conditions of process parameters, multiple quality characteristics *i.e.* MRR, SR and WWR get slightly improved. It was observed from the SEM Micrograph, that at optimal combination of input parameters *i.e.* 111 MU T_{on} , 35 MU T_{off} , 46V SV, 140A IP, 9 MU WT and 6 m/min WF comparatively less numbers of cracks, pockmarks, craters, and pulled out material were found on work specimen surface and wire electrode surface (Figure 11) as compared to under unoptimized conditions. The reason can be because at low value of pulse-on time and gap voltage less heat transfer toward the workpiece surface which causes melting and evaporation of less work material from the surface in comparison to single quality characteristics.

Table 6: Analysis of variance (ANOVA) for response surface WWR

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	21328.33	21	1015.63	23.07	< 0.0001	Significant
A-Pulse-on Time	999.31	1	999.31	22.70	< 0.0001	
B-Pulse-off Time	101.69	1	101.69	2.31	0.1390	
C-Gap Voltage	60.71	1	60.71	1.38	0.2495	
D-Peak Current	820.39	1	820.39	18.64	0.0002	
E-Wire Tension	0.66	1	0.66	0.015	0.9035	
F-Wire Feed	752.51	1	752.51	17.09	0.0003	
AB	4156.68	1	4156.68	94.43	< 0.0001	
AC	3.59	1	3.59	0.082	0.7770	
AD	211.26	1	211.26	4.80	0.0364	
AE	594.90	1	594.90	13.51	0.0009	
AF	1592.61	1	1592.61	36.18	< 0.0001	
BC	99.47	1	99.47	2.26	0.1432	
BD	204.74	1	204.74	4.65	0.0392	
BE	554.70	1	554.70	12.60	0.0013	
BF	636.62	1	636.62	14.46	0.0007	
CD	2895.66	1	2895.66	65.78	< 0.0001	
CE	1786.32	1	1786.32	40.58	< 0.0001	
CF	1341.37	1	1341.37	30.47	< 0.0001	
DE	1698.44	1	1698.44	38.58	< 0.0001	
DF	417.75	1	417.75	9.49	0.0044	
EF	2398.93	1	2398.93	54.50	< 0.0001	
Residual	1320.62	30	44.02			
Lack of Fit	1033.56	23	44.94	1.10	0.4856	not significant
Pure Error	287.07	7	41.01			
Cor Total	22648.95	51				
Std. Dev.	6.63		R-Squared		0.9417	
Mean	81.13		Adj R-Squared		0.9009	
C.V. %	8.18		Pred R-Squared		0.8340	
PRESS	3759.52		Adeq Precision		24.877	

3.6 Elemental and phase analysis of machined sample

From the EDX analysis of work specimen, it was observed that some metal particles are present on the work surface other than base material because during WEDM process some of the debris cannot be flushed from the sparking gap so that rest part of debris get deposited on the surface as compounded form (Figure 12). EDX analysis showed that significant amount of elements migrated from wire electrode to workpiece. Fe (Ferrous), Cr (Chromium), Cu (Copper), Ni (Nickel) was observed at highest peak in the spectrum of EDX which shows that an appreciable amount of these elements are migrated to the surface of the workpiece. Migration of the elements depends upon the value of pulse-on time and gap voltage. At high value of pulse-on time and gap voltage, spark energy increases which causes more melting and evaporation of material [45].

Some residual of the C (Carbon), Cu (Copper) and O (Oxygen) elements were also observed on the machined sample because of decomposition of dielectric, re-

per), Ni (Nickel) was observed at highest peak in the spectrum of EDX which shows that an appreciable amount of these elements are migrated to the surface of the workpiece. Migration of the elements depends upon the value of pulse-on time and gap voltage. At high value of pulse-on time and gap voltage, spark energy increases which causes more melting and evaporation of material [45].

Figure 10: Scanning electron micrographs of work material for WWR

Table 7: Validation of predicted model

Type of optimization	Objective	Optimization parameters						Response (Predicted)	Response (Experimental)	Desirability
		T _{on}	T _{off}	SV	IP	WT	WF			
Single response	Maximize MRR	113	35	54	140	9	7	35.841	34.012	0.986
Single response	Minimize SR	109	35	46	140	9	7	2.072	2.152	1.000
Single response	Minimize WWR	109	35	51	132	9	5	0.110	0.116	1.000
Multi response & Maximize MRR	Minimize SR, WWR	110	35	46	120	11	5	28.166, 2.700, 0.111	27.691 2.721 0.117	0.715

solidification of the wire electrode and mixing of the debris at elevated temperature.

The debris that gets deposited in compounded form on the work surface was examined by X-ray diffraction analysis. Different compounds were formed due to migration of workpiece elements, tool electrode elements and decomposition of deionized water. Different phases were

analyzed by transfer of the tool and dielectric elements on the work surface by using X' Pert High score plus (Figure 13). It was observed from the Figure 13 that copper dioxides (CuO_2), Molybdenum dioxides (MoO_2) and ferric oxide (FeO) were found as compounded form on the surface of the specimen.

Figure 11: Scanning electron micrographs of work material under optimized conditions

Figure 12: EDX analysis of work material

Figure 13: XRD analysis of work material

4 Conclusions

In this study, multi objective optimization was carried out to study the effect of WEDM machining parameters on machine performance using RSM based desirability approach and microstructure analysis at optimum combinations of process parameters was performed.

- It was concluded that pulse-on time, gap voltage and peak current have significant positive effect on increasing MRR while increase in pulse-off time resulted in decreased SR.

- Comparatively less numbers of cracks, pockmarks, craters, and pulled out material were found on work specimen surface and wire electrode surface as compared to under unoptimized conditions.
- EDX analysis showed that significant amount of elements migrated from wire electrode to workpiece.
- Copper dioxides (CuO_2), Molybdenum dioxides (MoO_2) and ferric oxide (FeO) were found as compounded form on the surface of the specimen.
- The optimum parametric combination obtained from the present study will be advantageous for working on high strength, high thermal conductivity and low melting point materials like nickel alloys even at higher temperatures.

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References

- [1] Akca E., Gursel A., A review on Superalloys and IN718 Nickel-Based INCONEL Superalloy, *Period. Eng. Nat. Sci.*, 2013, 3(1), 15-27.
- [2] Palakudtewar R.K., Gaikwad S.V., Dry Machining of Superalloys: Difficulties and Remedies, *Int. J. Sci. Res.*, 2014, 3(7), 277-282.
- [3] Payal H., Maheshwari S., Bharti P.S., Process Modeling of Electric Discharge Machining of Inconel 825 Using Artificial Neural Network, *World Acad. Sci. Eng. Technol.*, 2017, 11(3), 562-566.
- [4] Kumar P. Meenu, Kumar V., Optimization of Process Parameters for WEDM of Inconel 825 Using Grey Relational Analysis, *Decis., Sci. Lett.*, 2018, 7(4), 405-416
- [5] Rajyalakshmi G., Venkata Ramaiah P., Multiple process parameter optimization of wire electrical discharge machining on Inconel 825 using Taguchi grey relational analysis, *Int. J. Adv. Manuf. Tech.* 2013, 69, 1249-1262.
- [6] Pleta A., Mears L., Cutting Force Investigation of Trochoidal Milling in Nickel-Based Superalloy, *Procedia Manuf.*, 2016, 5, 1348-1356.
- [7] Liao Y.S., Lin H.M., Wang J.H., Behaviors of end milling Inconel 718 superalloy by cemented carbide tools, *J. Mater. Proc. Technol.*, 2008, 201(1-3), 460-465.
- [8] Ulutan D., Ozel T., Machining induced surface integrity in titanium and nickel alloys: A review, *Int. J. Mach. Tool Manu.*, 2011, 51, 250-280.
- [9] Goswami A., Kumar J., Investigation of surface integrity, material removal rate and wire wear ratio for WEDM of Nimonic 80A alloy using GRA and Taguchi method, *J. Eng. Sci. Technol.*, 2014, 1, 173-184.
- [10] Singh A., Anandita S., Gangopadhyay S., Microstructural analysis and multi response optimization during ECM of Inconel 825 using hybrid approach, *Mater. Manuf. Proc.*, 2015, 30(7), 842-851.
- [11] Rahul Datta S., Biswal B.B., Mahapatra S.S., A Novel Satisfaction Function and Distance-Based Approach for Machining Performance Optimization during Electro-Discharge Machining on Super Alloy Inconel 718, *Arabian J. Sci. Eng.* 2017, 42, 1999-2020.
- [12] Rajyalakshmi G., Venkata P.A., A parametric optimization using Taguchi method: effect of WEDM parameters on surface roughness machining on Inconel 825, *Elixir Int. J.*, 2012, 43, 6669-6674.
- [13] Aggarwal V., Singh S., Garg R.K., Parametric modeling and optimization for wire electrical discharge machining of Inconel 718 using response surface methodology, *Int. J. Adv. Manuf. Tech.*, 2015, 79, 31-47.
- [14] Mahapatra S.S., Patnaik A., Optimization of wire electrical discharge machining (WEDM) process parameters using Taguchi method, *Int. J. Adv. Manuf. Tech.*, 2007, 34, 911-925.
- [15] Chhabra S., Gupta D., Yadav P., Optimizing the Process Parameters of WEDM using Taguchi Technique on P-21 die steel, *Int. J. Innov. Res. Sci. Eng. Technol.*, 2014, 3(7), 14815-14821.
- [16] Patra D.R., Rout I.S., Sahoo M., Optimization of WEDM parameters using Taguchi method for higher material removal rate on EN31 steel, *Int. J. Eng. Res. Appl.*, 2015, 5(6), 57-62.
- [17] Singh V.K., Singh S., Multi-objective optimization using Taguchi Based Grey Relational Analysis for Wire EDM of Inconel 625, *J. Mater. Sci. Mech. Eng.*, 2015, 2, 38-42.
- [18] Dabade U.A., Karidkar S.S., Analysis of response variables in WEDM of Inconel 718 using Taguchi technique, *Procedia CIRP*, 2016, 41, 886-891.
- [19] Raykundaliya D.P., Shanubhogue A., Comparison Study: Taguchi Methodology vis.-a-vis. Response Surface Methodology through a case study of accelerated failure in Spin-on-Filter, *Int. Adv. Res. J. Sci. Eng. Technol.*, 2015, 2, 1-5.
- [20] Goyal A.J., Investigation of material removal rate and surface roughness during wire electrical discharge machining (WEDM) of Inconel 625 super alloy by cryogenic treated tool electrode, *King Saud Univ.- Sci.*, 2017, 29(4), 528-535.
- [21] Kumar S., Dhingra A.K., Kumar S., Parametric optimization of powder mixed electrical discharge machining for nickel based superalloy inconel-800 using response surface methodology, *Mech. Adv. Mater. Modern Pro.*, 2017, 3(7), 1-17.
- [22] Bijeta Nayak B., Sankar Mahapatra S., Optimization of WEDM process parameters using deep cryo-treated Inconel 718 as work material, *Int. J. Eng. Sci. Technol.*, 2015, 19, 161-170.
- [23] Li L., Li Z.Y., Wei X.T., Cheng X., Machining Characteristics of Inconel 718 by Sinking-EDM and Wire-EDM, *Mater. Manuf. Proc.*, 2015, 30(8), 968-973.
- [24] Yusoff Y., Mohd Zain A., Sharif S. et al., Potential ANN prediction model for multi-performances WEDM on Inconel 718, *Neural Comp. Appl.*, 2018, 30(7), 2113-2127.
- [25] Mohanty A., Gangadharudu T., Gangopadhyay S., Experimental Investigation and Analysis of EDM Characteristics of Inconel 825, *Mater. Manuf. Proc.*, 2014, 29(5), 540-549.
- [26] Shen Y., Liu Y., Dong H., Zhang K., Lv L., Zhang X., Wu X., Zheng C., Ji R., Surface integrity of Inconel 718 in high-speed electrical discharge machining milling using air dielectric, *Int. J. Adv. Manuf. Technol.*, 2017, 90, 691-698.
- [27] Kumar P., Gupta M., Kumar V., Surface integrity analysis of WEDMed specimen of Inconel 825 superalloy, *Int. J. Data Net. Sci.*, 2018, 2
- [28] Ramakrishnan R., Karunamoorthy L., Multi response optimization of wire EDM operations using robust design of experiments, *Int. J. Adv. Manuf. Tech.*, 2006, 29(1-2), 105-112.
- [29] Manjaiah M., Narendranath S., Basavarajappa S., Gaitonde V.N., Wire electric discharge machining characteristics of titanium nickel shape memory alloy, *Trans. Nonferr. Met. Soc. China*, 2014, 24, 3201-3209.
- [30] Singh B., Misra J.P., A critical review of wire electric discharge machining, In: DAAAM International Scientific Book, Chapter 23, 249-266, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-09-9, ISSN 1726-9687, Vienna, Austria, DOI: 10.2507/daaam.scibook.2016.23, 2016.
- [31] Habib S.S., Study of the parameters in electrical discharge machining through response surface methodology approach, *App. Math. Model.* 2009, 33, 4397-4407.
- [32] Arikatla S.P., Mannan K.T., Krishnaiah A., Parametric Optimization in Wire Electrical Discharge Machining of Titanium Alloy Using Response Surface Methodology, *Mat. Today: Proc.* 2017, 4(2A), 1434-1441.
- [33] Saini P.K., Verma M., Experimental Investigation of Wire-EDM Process Parameters on MRR of Ti-6Al-4V Alloy, *Int. J. Innov. Technol. Explor. Eng.* 2014, 4, 2278-3075.
- [34] Somashekhar K.P., Ramachandran N. Mathew J., Optimization of Material Removal Rate in Micro-EDM Using Artificial Neural Network and Genetic Algorithms, *J. Mater. Manuf., Proc.* 2010, 25(6), 467-475.
- [35] Patel P.R., Patel B.B., Patel V.A., Effect of Machining Parameters on Surface Roughness for 6063 Al-TiC (5 & 10 %) Metal Matrix Composite Using RSM, *Int. J. Res. Eng. Technol.*, 2013, 2, 65-71.

- [36] Nahak B., Yusufzai M.Z.K., Vashista M., Correlation between surface integrity of EDMed high carbon high chromium die steel with Barkhausen Noise parameters, *Int. J. Appl. Eng. Res.*, 2017, 12, 5709-5714.
- [37] Bobbili R., Madhu V., Gogia A.K., Multi response optimization of wire-EDM process parameters of ballistic grade aluminium alloy, *Int. J. Eng. Sci. Technol.*, 2015, 18, 720-726.
- [38] Singh J., Singh R., Kumar R., Optimization of Micro WEDM process parameters formachining on Ti-6Al-4V Alloy, *Int. J. Innov. Res. Sci. Technol.*, 2016, 2(11), 701-706.
- [39] Goswami A., Kumar J., Investigation of surface integrity, material removal rate and wire wear ratio for WEDM of Nimonic 80A alloy using GRA and Taguchi method, *Int. J. Eng. Sci. Technol.*, 2014, 17(4), 173-184.
- [40] Guo Y., Wang L., Zhang G., Hou P., Multi-response optimization of the electrical discharge machining of insulating Zirconia, *Mater. Manuf. Proc.*, 2016, 32(3), 294-301.
- [41] Holmberg J., Wretland A., Berglund J., Beno T., Surface integrity after post processing of EDM processed Inconel 718 shaft, *Int. J. Adv. Manuf. Technol.*, 2017, 96, 1429-1443.
- [42] Myers R.H., Montgomery D.C., Anderson-Cook C.M., 2009, *Response Surface Methodology: Process and Product Optimization Using Designed Experiments*, John Wiley and Sons, Hoboken.
- [43] Pradhan M.K., Biswas C.K., Modeling and Analysis of process parameters on Surface Roughness in EDM of AISI D2 tool Steel by RSM Approach, *Int. J. Mech. Mechatron. Eng.* 2009, 3, 1132-1137.
- [44] Chalisgaonkar R., Kumar J., Multi-response optimization and modeling of trim cut WEDM operation of commercially pure titanium (CPTi) considering multiple user's preferences, *Int. J. Eng. Sci. Technol.*, 2015, 18(2), 125-134.
- [45] Khosrozadeh B., Shabgard M., Effects of hybrid electrical discharge machining processes on surface integrity and residual stresses of Ti-6Al-4V titanium alloy, *Int. J. Adv. Manuf. Technol.*, 2017, 93, 1999-2011.