International Journal of Industrial Engineering Computations 6 (2015) 351–364

Contents lists available at GrowingScience

International Journal of Industrial Engineering Computations

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An experimental investigation and statistical modelling for trim cutting operation in WEDM of Nimonic-90

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C H R O N I C L E

Article history:
Received October 14 2014
Received in Revised Format February 10 2015
Accepted February 24 2015
Available online February 25 2015

Keywords:
Nimonic-90
Wire electrical discharge machining
Trim cutting
Response surface methodology (RSM)
Desirability function

A B S T R A C T

Trim cutting operation in wire electrical discharge machining (WEDM) is considered as a probable solution to improve surface characteristics and geometrical accuracy by removing very small amount of work materials from the surface obtained after a rough cutting operation. In this study, an attempt has been made to model the surface roughness and dimensional shift in trim cutting operations in WEDM process through response surface methodology (RSM). Four process parameters; namely pulse-on time (Ton), servo voltage (SV), wire depth (W_d) and Dielectric flow rate (FR) have been considered as input parameters in trim cutting operations for modelling. Desirability function has been employed to optimize multi performance characteristics. Increasing the value of Ton, W_d and FR increases the surface roughness and dimensional shift but increasing SV decreases both surface roughness and dimensional shift. Quadratic models have been proposed for both the performance characteristics. In present experimentation, thickness of recast layer was observed in the range of 6μm to 12μm for low to high value of discharge parameters.

1. Introduction

Machining of high strength-heat resisting alloys and metal matrix composites with high precision is the main challenge for manufacturing industries. While machining of different materials with various machine tools, it is essential to satisfy the surface integrity of the machined surface. Nickel alloys are specially used for combustion chamber in aero-engines and other components for commercial and military aircrafts (Choudhury & Baradie, 1998; Ezugwu, 2005). These alloys possess excellent mechanical and chemical properties at elevated temperature and high corrosion resistance (Guo et al., 2009). Machinability of these materials with conventional machining processes is a great challenging task due to complex nature of material properties. Due to low thermal conductivity, Ni alloys leads to work hardening during machining and increasing temperature of tool tip results in quick wear of tool tip/ rack face and adhesion of work piece material to the cutting edge due to high thermal affinity (Choudhury & Baradie, 1998; Ulutan & Ozel, 2011). Surface drag, material pull out, cracking and tearing of work surface occur during machining of Ni based alloys with conventional machining processes (Wei, 2002;

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doi: 10.5267/j.ijiec.2015.2.006

Arunachalam et al., 2004; Sharman et al., 2004; Krain et al., 2007; Hood et al., 2011; Kortabarria et al., 2011; Soo et al., 2011).

Wire electrical discharge machining (shown in Fig. 1) is an electro thermal process, which removes electrical conductive materials by mean of repetitive electric sparks across a spark gap between a continuous moving conductive wire and work piece. Each discharge melts or vaporizes a small amount of materials from the machined surface, which is flushed away by the dielectric fluid flowing between wire electrode and work surfaced. WEDM provides the best alternatives for machining the exotic, conductive and hard materials with the scope of generating intricate shape and profile (Cheng et al., 2014).

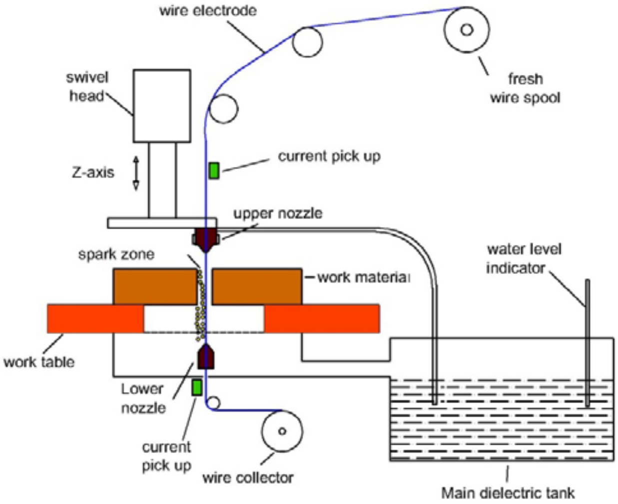


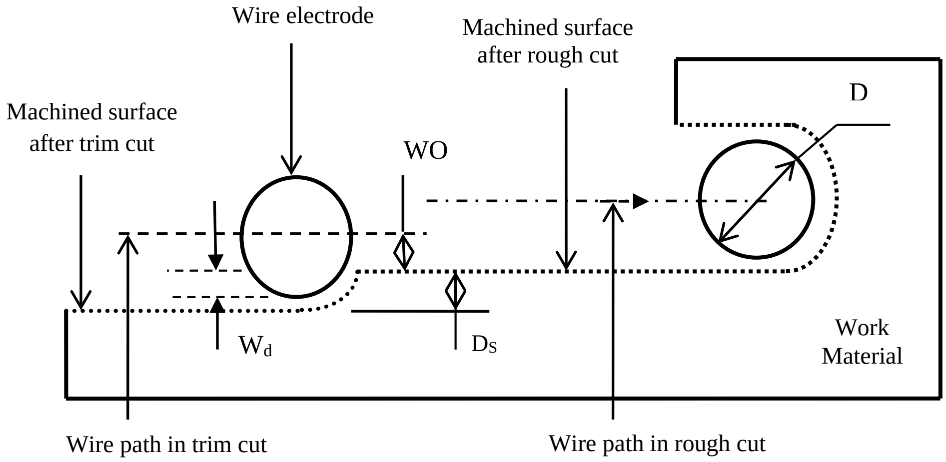
Fig. 1. Schematic representation of WEDM process

Jangra et al. (2011) utilized the grey based Taguchi method to optimize the MRR and SR for WEDM of WC-Co composite. Results revealed that taper angle, pulse on time (Ton) and pulse off time (Toff) are the most significant process parameters. Yang et al. (2012) proposed a hybrid method including RSM and back – propagation neural network (BPNN) integrated simulated annealing algorithm (SAA) to determine an optimal setting for machining of pure Tungsten in WEDM. RSM and BPNN/SAA methods were effective tools for the optimization of parameters in WEDM process. Jangra et al. (2011) developed a mathematical model using digraph and matrix method to evaluate the machinability of tungsten carbide composite on WEDM. Factors affecting the machinability of tungsten carbide composite were grouped in five broad categories namely work material, machine tool, tool electrode, cutting conditions, and geometry to be machined. Kumar et al. (2012) presented the influence of WEDM parameters on machinability of Nimonic-90. Influence of WEDM parameters namely discharge current (Ip), pulse-on time (Ton), pulse-off time (Toff), servo voltage (SV) and wire feed rate (W_F) were investigated on cutting speed. The experiments were conducted by varying a single variable at a time while keeping other parameters at constant level on 5 axis sprint cut (ELPUSE-40) wire EDM manufactured by Electronic M/C Tool LTD India. Experimental results showed that the Ip, Ton and Toff produces noticeable influence on Cutting speed.

Khanna and Singh (2013) developed a mathematical model for cryogenic treated D-3 material by means of RSM and then solved the optimization problem by desirability function. Bobbili et al. (2014) carried out a study for optimising the WEDM process parameters like pulse on time (Ton), pulse off time (Toff), wire feed rate (W_F), flushing pressure and servo voltage (SV) during the machining of high strength Armor steel. Results show that Ton, Toff and SV are significant variables to both material removal rate (MRR) and SR. Bhuyan and Yadava (2014) investigated the effect of input process variable on MRR and Kerf width during machining of Borosilicate Glass using a hybrid machining process "Travelling wire electrochemical spark machining" (TWECSM). MRR and Kerf width increase with increase in applied voltage, pulse on time and electrolyte concentration. Gupta and Jain (2014) investigated the behaviour of the micro geometry parameters of miniature spur gears produced by WEDM process and optimized the process parameters for minimizing the total profile and accumulated pitch deviation using response surface methodology. The various experimental and theoretical studies show that process capability of WEDM could be improved significantly by correct selection of machining parameters for a given material. Sharma et al. (2013) optimized the process parameters of WEDM using response surface methodology. Desirability approach has been adopted for multi response (i.e. CS and dimensional deviation) optimization. Ton is the most significant factor for multi response optimization, while two way interactions also played significant role in the process.

1.1 Trim Cutting Operation

The majority of past research works focus on rough cutting operation in WEDM. Damaged surface layer with poor surface integrity, micro cracks, heat affected zone are the major shortcoming in rough cutting operation (Lee & Li, 2003; Wang et al., 2009; Jangra, 2012). The defects are due to high heat energy generated across the electrodes and re-solidification of melted debris's that do not flushed out quickly out of a narrow spark gap (Puri & Bhattacharyya, 2003; Rebelo et al., 1998; Sarkar et al., 2011). Trim cutting is considered as a probable solution to improve the surface integrity, geometrical accuracy and fatigue life by removing the degraded materials on the machined surface. In trim cutting operation, wire electrode trace back the same wire path of first cut with low discharge energy and certain values of wire offset (Huang et al., 1999) as shown in Fig. 2. Wire offset (WO) is the distance between the center of electrode and work surface after rough cut. Wire depth (W_d) is the distance travelled perpendicular and inside the work piece during trim cutting operation. The wire depth (W_d) is related to wire offset value. Increasing wire offset value decreases the W_d.



D: wire diameter; WO: wire offset; W_d: wire depth; D_S: dimensional shift

Fig. 2. Terminology used in trim cutting operation

Han et al. (2007) explained the influence of machining parameters namely Ton, Ip, sustained pulse time, pulse-interval time, polarity effect, work material and dielectric, on surface roughness after a single trim cut of WEDM. Sarkar et al. (2008) developed a second order mathematical model in term of machining parameters for surface finish, dimensional shift and cutting speed in trim cutting of γ-titanium aluminide using response surface methodology (RSM) on WEDM. Machining parameters namely pulse-on time, peak current, dielectric flow rate and effective wire offset were considered for a single trim cutting operation in WEDM. The minimum value of surface roughness obtained was 1.28μm. Klink et al. (2011) presented the comparison of the surface finish, microstructure, micro hardness and residual stresses after rough and trim cuts in WEDM.

Jangra et al. (2014) conducted an experimental study on rough and trim cutting operation in WEDM of four hard to machine materials namely WC-Co composite, HCHCr steel alloy, Nimonic-90 and Monel-400. Result shows that using single trim cutting operation with correct machining parameters and appropriate wire offset, surface characteristics could be improved irrespective of the rough cutting operation. Jangra KK (2015) investigated the multi-pass cutting operation in WEDM of WC-Co composite. Trim cuts were performed using Taguchi method to investigate the influence of rough cut history, discharge current, pulse-on time, wire offset and number of trim cuts for two performance characteristics namely surface roughness and depth of material removed. A technological data has provided for rough and trim cut on WEDM for efficient machining of WC-5.3%Co composite.

Despite many research works on WEDM, investigation on WEDM of Nimonic 90 is still missing. Nimonic-90 is a nickel-chromium-cobalt based alloy, most widely used in the aerospace and air craft industries in the manufacturing of turbine blades and combustion chamber, valve in turbo motors and disc in gas turbine. This material possesses excellent strength at extreme pressure and temperature. In present work, investigation on trim cutting operation in WEDM of Nimonic-90 has been presented. Machining parameters namely pulse on time, servo voltage, dielectric flow rate and wire depth have been investigated on surface characteristics and dimensional shift in trim cutting operation. A standard second order experimental design called face centered Central Composite Design (CCD) in term of machining parameter has been adopted using response surface methodology (RSM). Desirability function has been employed to optimize two performance characteristics simultaneously.

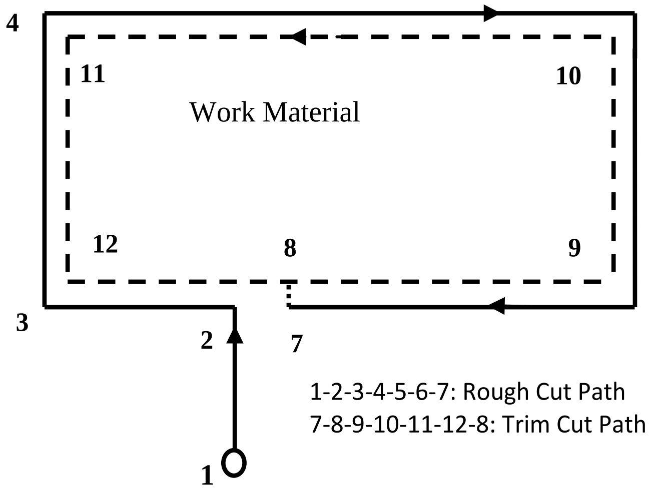


Fig. 3. Cutting operations in WEDM process

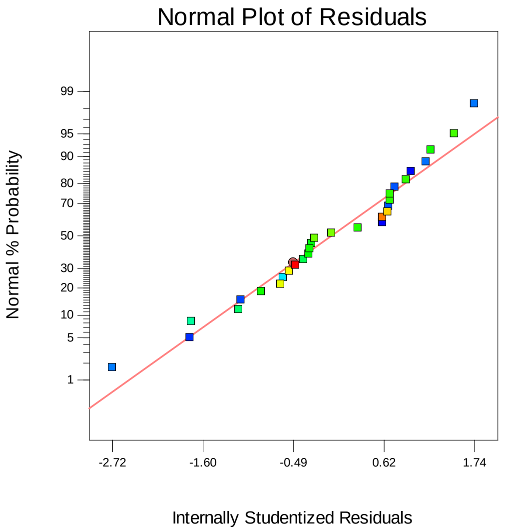


Fig. 4. Residuals plot for SR

2. Experimentation procedure

In present work, Nimonic-90 has been selected for conducting experiments on 5 axis sprint cut (ELPUSE-40) Wire EDM manufactured by Electronic M/C Tool LTD India. Nimonic-90, a nickel based super alloy containing 60% Ni, 19.3% Cr, 15% Co, 3.1% Ti, and 1.4% Al, hot forged in rectangular plate of 12.5 mm thickness; has been selected as work piece material. It has density; 8.18 g/cm^3, melting point; 1370 ^{0}C, hardness; 365 HV, thermal conductivity; 11.47 W/mĊ and modulus of elasticity; 220MPa. The major characteristic of Nimonic-90 is its high rupture strength and creep resistance at high temperature (upto 900^{0}C).

In present experimentation, trim cutting operations were performed at different combination of process parameters after a rough cut performed at constant parameters. Using WEDM, work material was machined and samples were obtained in the form of rectangular punches of dimension 6 mm × 10 mm × 12.5 mm. Fig. 3 shows the schematic diagram of the cutting operation performed in present work. According to path programme (Fig. 3), firstly, a rough cut (1-2-3-4-5-6-7) was performed at constant value of discharge parameters and zero wire offset value. The machine was halted at point 7 to change the input machining parameters and then subsequently trim cut (7-8-9-10-11-12-8) was performed according to the experimental plan mentioned in Table 3. Dimensional shift (Ds) was calculated after measuring the dimensions of punch with the help of an optical microscope. To measure the punch width (PW) after rough cut, a rough cut path; 1-2-3-4-5-6-7-2 was followed to remove the punch out of work material. Rough cut were repeated at same parameter setting to obtain an average value of PW after rough cut. Ds can be obtained as

Ds : (Punch width after rough cut – Punch width after trim cut)/2.

In case of trim cutting, the prime objective is to improve surface roughness and to reduce dimensional inaccuracy. Therefore, high discharge energy parameters combination providing maximum cutting rate has been selected in rough cutting operation, while in trim cutting operation low discharge energy parameters resulting, low surface roughness, has been selected. Fixed Machining parameters setting for rough cutting and trim cutting operation are shown in Table 1. A zinc coated brass wire having a fixed diameter of 0.25mm has been selected as wire electrode. Distilled water having conductivity 20 mho has been used as a dielectric fluid.

Table 1

Fixed machining parameters in rough & trim cutting operation

Rough cut parameters	
Pulse on Time, Ton = 118 μs	Wire Tension W_T = 10 N
Pulse off Time, Toff = 35 μs	Discharge Current, Ip = 150 machine unit
Dielectric Flow Rate, FR=12L/min	Servo Voltage, SV = 30 V
Wire Feed rate, W_F = 5 mm/min	Servo Feed, SF=150mm/min
Trim cut parameters	
Pulse off time, Toff = 30 μs	Work material thickness =12.5 mm
Discharge current, Ip =110 machine unit	Wire feed rate, W_F = 2mm/min
Wire tension, W_T = 8N	Servo feed, SF = 150

The pulse on time (Ton), servo voltage (SV), wire depth (W_d) and dielectric flow rate (FR) have been considered as main process parameters in trim cutting operation for investigation. Dimensional shift (Ds) and surface roughness (SR) are two response parameters. Table 2 shows the process parameters and their levels for trim cutting operation. Value of wire depth (Wd) was varied by varying the wire offset in trim cut. Experiments were performed according to the layout of experimental design for Face CCD of second order shown in Table 3.

Table 2

Variable process parameters and their levels for Trim cutting conditions

Parameter	Units	Levels	
Pulse on Time (Ton)	μs	104	112
Servo Voltage (SV)	V	20	40
Wire depth (W_d)	μm	10	30
Dielectric Flow Rate (FR)	L/min	2	6

3. Response Surface Methodology and Experimental Design

Response surface methodology (RSM) is a collection of mathematical and experimental techniques that requires sufficient number of experimental data to analyse the engineering problem and to develop mathematical models for several input variables and output performance characteristics (Myers & Montgomery, 1995; Jangra & Grover, 2012). By using the design of experiments and applying regression analysis, the modelling of the desired response (Y) to several independent input variables (x_i) can be gained. In RSM, the quantitative form of relationship between desired response and independent input variables could be represented as:

$$Y = \Phi(x_1, x_2, \dots \dots \dots .., x_k) \pm e_r \qquad (1)$$

The function Φ is called response surface or response function. The residual e_r measures the experimental errors (Cochran & Cox, 1962). In applying the RSM, the dependent variable is viewed as a surface to which a mathematical model is fitted. For the development of regression equations related to various performance characteristics of WEDM process, the second order response surface has been assumed as:

$$Y = b_0 + \sum_{i=1}^{k} b_i X_i + \sum_{i=1}^{k} b_{ii} X_i^2 + \sum_{i<j=2}^{2} b_{ij} X_i X_j \pm e_r \qquad (2)$$

where Y is the corresponding response variables i.e. surface roughness and dimensional shift produced by various process variables of WEDM. b_0 is constant and $b_i, b_{ii,} b_{ij}$ are the coefficient of linear, quadratic and cross product terms. The model parameters can be estimated most effectively if proper experimental designs are used to collect the data. The objective of this study was to identify an optimal setting for process parameters that can be minimizing the surface roughness and dimensional shift of a WEDM process in trim cutting operation.

Table 3

The layout of experimental design for Face CCD of second order and experimental results

Exp. No.	Ton	SV	W_d	FR	SR (µm)	D_S (µm)
1	104	20	10	2	1.31	14
2	112	20	10	2	2.03	17
3	104	40	10	2	1.1	16
4	112	40	10	2	1.51	14
5	104	20	30	2	1.25	38
6	112	20	30	2	2.45	38
7	104	40	30	2	1.22	43
8	112	40	30	2	2.22	45
9	104	20	10	6	1.18	22
10	112	20	10	6	2.41	29
11	104	40	10	6	1.11	17
12	112	40	10	6	1.97	28
13	104	20	30	6	1.25	40
14	112	20	30	6	2.9	48
15	104	40	30	6	1.3	46
16	112	40	30	6	2.69	54
17	104	30	20	4	1.32	23
18	112	30	20	4	2.53	27
19	108	20	20	4	2.03	23
20	108	40	20	4	1.81	27
21	108	30	10	4	1.86	20
22	108	30	30	4	2.2	47
23	108	30	20	2	1.72	27
24	108	30	20	6	2	36
25	108	30	20	4	2.03	28
26	108	30	20	4	2.08	27
27	108	30	20	4	2.09	27
28	108	30	20	4	2.06	29
29	108	30	20	4	2.08	30
30	108	30	20	4	2.12	27

4. Results and Discussions

In present study, on the basis of inputs process parameters and their level as listed in Table 2, a standard second order experimental design called face centred Central Composite Design (CCD) has been adopted for analysing and modelling the WEDM parameters for average value of surface roughness and dimensional shift is illustrated in Table 3. Surface roughness value (SR) was measured in terms of mean absolute deviation (Ra) using the digital surface tester Mitutoyo 201P. Regression equations have been developed for correlating the input process parameters with response parameters using RSM. To analyze the experimental data, Design expert (DX7), a statistical tool, has been utilized. Analysis of Variance (ANOVA) has been performed on the experimental data to test the goodness of fit of the model. This includes the test for significance of the regression model, test for significance on model coefficients and test for lack of fit model adequacy.

4.1 Analysis of Surface roughness (SR)

Table 4 shows the fit summary for SR, after backward elimination process. The Model F-value of 232.85 implies the model is significant. There is only a 0.01% chance that a large “Model F-Value” could occur due to noise. In this case A, B, C, D, AB, AC, AD, BC, A^2, B^2, D^2 are significant model terms.Values greater than 0.05 indicate the model terms are not significant. Selected model would be statistically significant, if *p*-value for the model terms are less than 0.05 (i.e. $\alpha = 0.05$, or 95% confidence level) (Myers & Montgomery, 1995). Using backward elimination process, insignificant terms (*p*-value > 0.05) have been eliminated from the reduced quadratic model. Table 4 shows that the *p*-value for quadratic model is significant, which shows that the terms in the model have significant effect on output response. In present case, the value of R^2 and R^2 (adj.), called coefficient of determination, is over 99%. When R^2 approaches unity, the better the response model fits the actual data. Also, test of ‘lack of fit’ shows insignificant effect, which is desirable for selecting the models. Fig. 4 shows that the residuals are normally distributed about a straight line, which means that the errors are normally distributed. Consequently, the proposed model for SR can be considered as significant for fitting and predicting the experimental results. The final response equation after eliminating the non-significant terms for surface roughness is given below:

Final Equation in Terms of actual factors:

$$\text{Surface roughness} = -63.92711 + 1.12996 \times Ton + 0.22186 \times SV - 0.33958 \times Wd - 1.17592 \times FR - 1.78125E\text{–}003 \times Ton \times SV + 3.15625E\text{-}003 \times Ton \times Wd + 0.014063 \times Ton \times FR + 5.12500E\text{-}004 \times SV \times Wd - 4.91477E\text{-}003 \times Ton^2 - 8.36364E\text{-}004 \times SV^2 - 0.035909 \times FR^2 \quad (3)$$

In order to analyse the influence of WEDM parameters on SR, response surface graphs have been plotted as shown in Fig. 5a-5d. Fig. 5a-5d shows the noticeable influence of process parameters on surface roughness. Surface roughness increases with increasing the value of Ton, W_d and FR while it decreases with increasing value of SV. The influence of FR is non-symmetric. The curved plots show the interaction among the input parameters. The parameter namely Ton, SV, W_d, FR and their interactions are highly significant for SR as shown by ANOVA Table 4.

Table 4
ANOVA table for fitted model for SR

Source	Sum of Square	Degree of Freedom	Mean Square	F-Value	Prob > F	
Model	7.25	11	0.66	232.85	< 0.0001	**significant**
A-Ton	5.19	1	5.19	1835.66	< 0.0001	
B-SV	0.2	1	0.2	69.38	< 0.0001	
C-Wd	0.5	1	0.5	176.68	< 0.0001	
D-FR	0.22	1	0.22	78.52	< 0.0001	
AB	0.081	1	0.081	28.7	< 0.0001	
AC	0.26	1	0.26	90.11	< 0.0001	
AD	0.2	1	0.2	71.55	< 0.0001	
BC	0.042	1	0.042	14.85	0.0012	
A^2	0.018	1	0.018	6.2	0.0228	
B2	0.02	1	0.02	7.02	0.0163	
D2	0.059	1	0.059	20.69	0.0002	
Residual	0.051	18	2.83E-03			
Lack of Fit	0.046	13	3.57E-03	3.94	0.0697	**not significant**
Pure Error	4.53E-03	5	9.07E-04			
Cor Total	7.3	29				
	R-Squared		0.9930	**Pred R-Squared**		0.9773
	Adj R-Squared		0.9887	**Adeq Precision**		54.7377

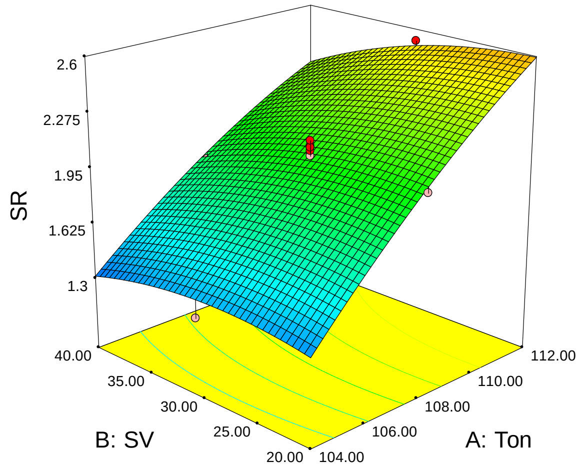


Fig. 5a. Combined effect of SV and Ton on SR

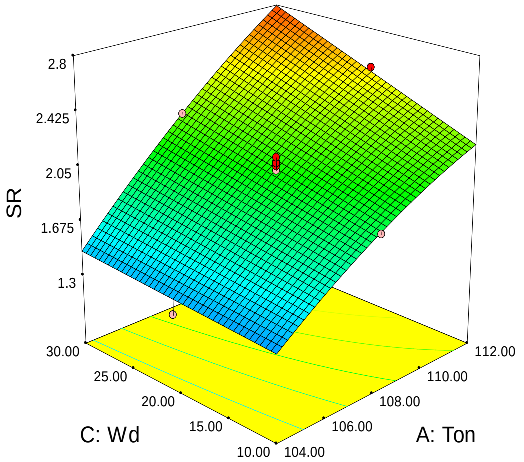


Fig. 5b. Combined effect of W_d and Ton on SR

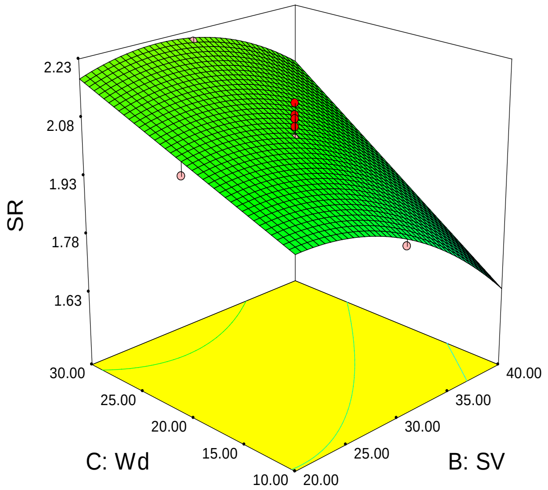


Fig. 5c. Combined effect of W_d and SV on SR

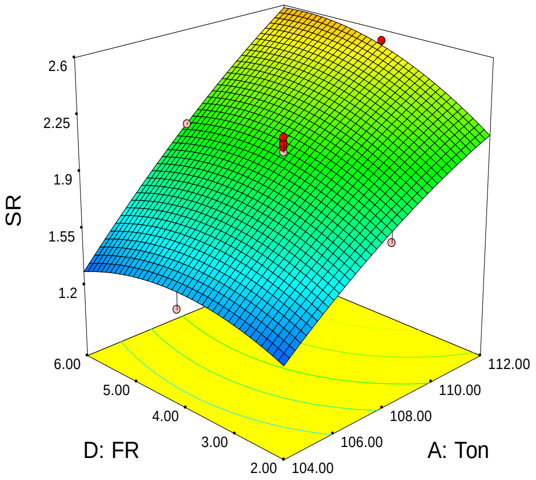
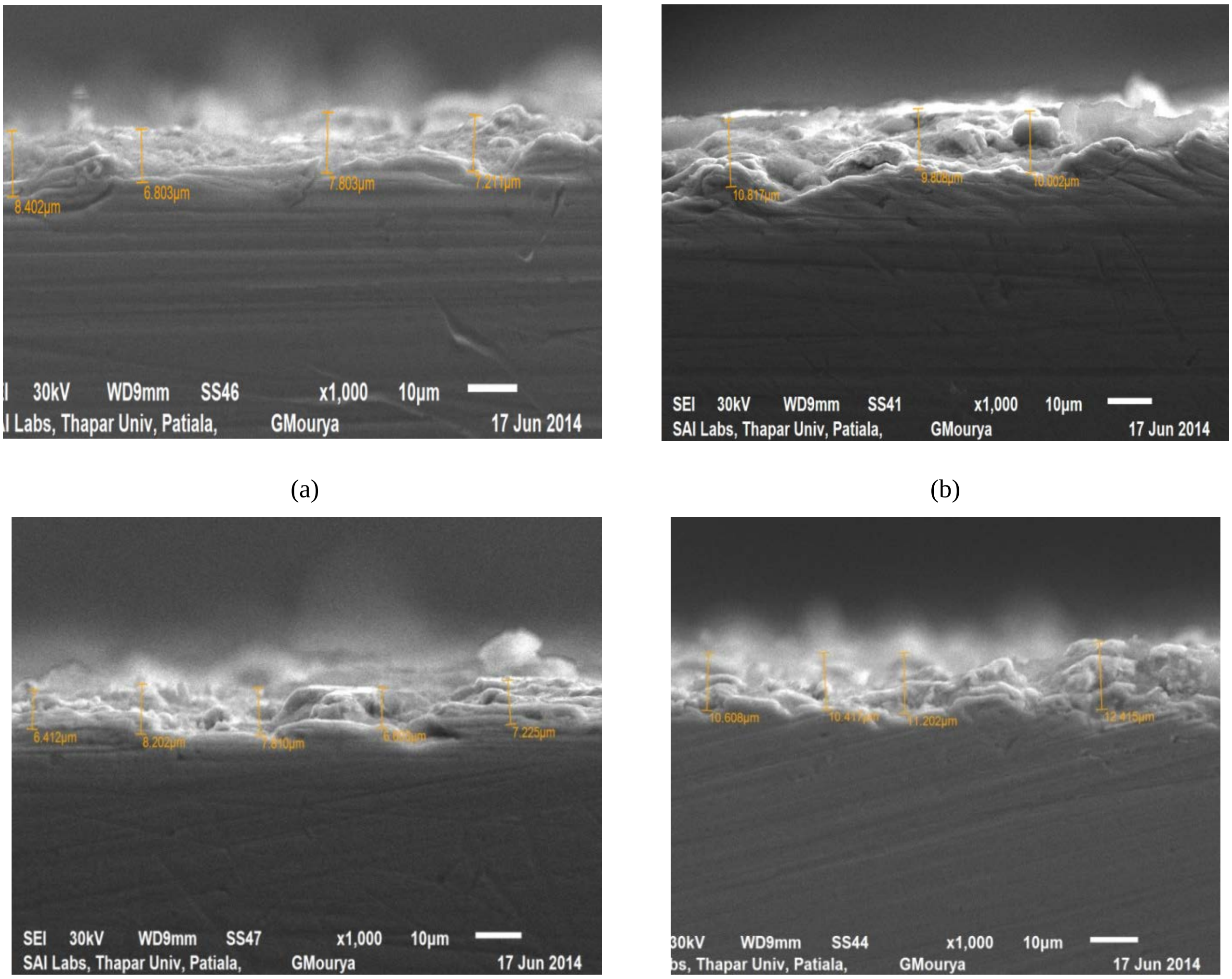


Fig. 5d. Combined effect of FR and Ton on SR

High discharge energy due to high value of Ton results into overheating and evaporation of molten metal resulting into high pressure energy that creates large size craters on work surface. The diameter and depth of crater increases with increasing of pulse-on time and hence increases the surface roughness. Increasing the value of wire depth (W_d) decreases the gap between wire electrode and work surface which increases the effective sparking on work surface and hence melting and erosion of the surface material increases. This causes increases in SR.

Surface roughness decreases with increasing the value of servo voltage as shown in Fig. 5c. Increasing SV increases the gap between work material and wire electrode that result into low ionization of dielectric medium and hence low discharge energy get generated. At low dielectric flow rate (FR), laminar dielectric flow is maintained that results into effective spark generation in trim cutting operation which removes the surface irregularities completely after the rough cutting operation. Therefore, low FR results into lower surface roughness. In order to examine the extent of surface damage (Recast layer) on machined surface, specimen were polished to have mirror finish on the transverse section and observation through scanning electron microscope (SEM) was made. Recast layer (RCL) is a hard skin on the work surface formed due to the re-solidification of melted residual material which was not completely expelled during the process (Puri & Bhattacharyya, 2005). The morphology of recast layer is much different from bulk material and it adversely affects the working life of machined component (Liao et al., 2004; Soo et al., 2013) Fig. 6a-6d shows the SEM micrographs of transverse section of sample correspond to sample no 3, 4, 15 and 26 respectively.



(a) (b)

(c) (d)

Fig. 6. SEM images showing recast layer on machined surface correspond to (a) exp. trial 3; (b) exp. trial 4; (c) exp. trial 15; (d) exp. trial 26

Recast layer (RCL) was observed which was discontinuous and non-uniform and the average thickness of damaged surface varies from 6μm to 12μm. This thickness of RCL is low as compared to rough cutting operation. In trim cutting operation, RCL is mostly influenced by pulse on time and wire depth. At high discharge energy, melting and evaporation of material causes high pressure energy in plasma channel (Li et al., 2013) which plough out the material from the work surface and create large size irregularities on work surface. Therefore, low value of Ip and Ton is suggested for trim cutting operation.

4.2 Analysis of Dimensional Shift (Ds)

Table 5 shows the fit summary for Ds, after backward elimination process. The Model F-value of 193.29 implies the model is significant. There is only a 0.01% chance that a large "Model F-Value" could occur due to noise. Values of "Prob > F" less than 0.050 indicate model terms are significant. In this case A, B, C, D, AD, BC, CD, A^2, B^2, C^2, D^2 are significant model terms. The "Lack of Fit F-value" of 1.02 implies there is a 953.58 % chance that a large "Lack of Fit F-value" could occur due to noise. The "Pred R-Squared" of 0.9916 is in reasonable agreement with the "Adj R-Squared" of 0.9865. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Fig. 7 shows that the residuals are normally distributed about a straight line which means that the errors are normally distributed. The final response equation after eliminating the non – significant terms for surface roughness is given below:

Final Equation in Terms of actual factors:

$$\text{Dimensional Shift} = -1963.695 + 37.021 \times \text{Ton} + 1.392 \times \text{SV} - 1.501 \times W_d - 31.036 \times \text{FR} - 0.173\times\text{Ton}^2 - 8.0454\text{ E} - 0.0277\times\text{SV}^2 + 0.0572 \times W_d^2 + 0.932 \times \text{FR}^2 + 0.242 \times \text{Ton} \times W_d + 0.0193 \times \text{SV} \times W_d - 0.0343\times W_d \times \text{FR} \quad (4)$$

Table 5

ANOVA table for Ds (after backward elimination)

Source	Sum of Squares	Degree of Freedom	Mean Square	F Value	Prob > F	
Model	3444.21	11	313.11	193.29	< 0.0001	**significant**
A-Ton	93.38	1	93.39	57.65	< 0.0001	
B-SV	24.5	1	24.5	15.12	< 0.0011	
C-Wd	2738	1	2738	1690.27	< 0.0001	
D-FR	256.88	1	256.88	158.58	< 0.0001	
AD	60.06	1	60.06	37.07	< 0.0001	
BC	60.06	1	60.06	37.07	< 0.0001	
CD	7.56	1	7.56	4.66	0.0444	
A^2	19.90	1	19.91	12.28	0.0025	
B^2	19.90	1	19.91	12.28	0.0025	
C^2	85.01	1	85.01	52.47	< 0.0001	
D^2	36.01	1	36.01	22.23	0.0002	
Residual	29.16	18	1.62			
Lack of Fit	21.16	13	1.63	1.017189	0.5358	**not significant**
Pure Error	8.00	5	1.60			
Cor Total	3473.37	29				

R-Squared	0.9916	**Pred R-Squared**	0.9751
Adj R-Squared	0.9865	**Adeq Precision**	50.503

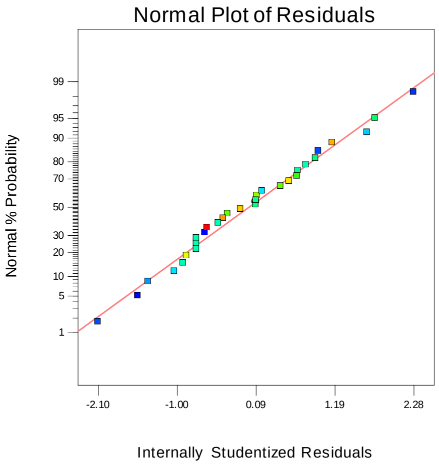


Fig. 7. Residuals plot for SR

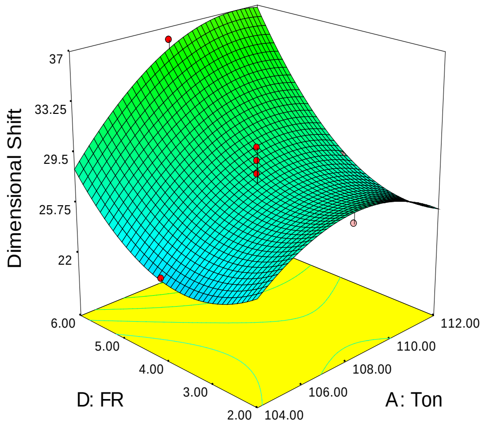


Fig. 8a. Combined effect of FR and Ton on D_S

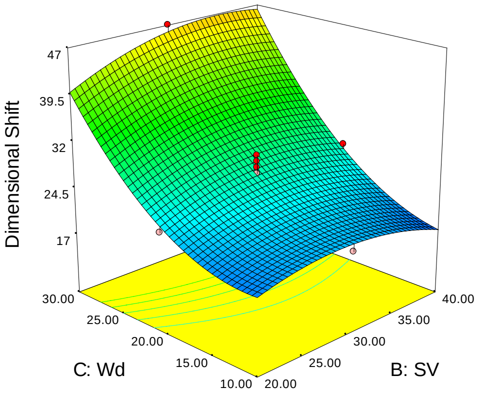


Fig. 8b. Combined effect of W_d and SV on D_S

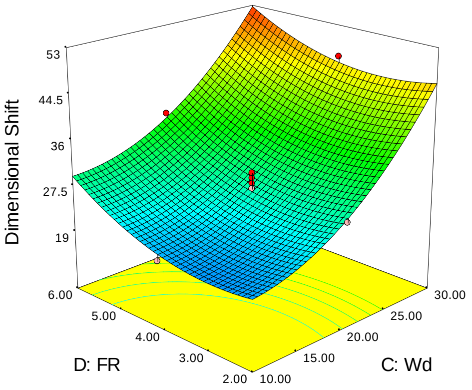


Fig. 8c. Combined effect of FR and W_d on D_S

Dimensional shift (D_S) is the thickness of material removed perpendicular to the cutting direction of wire electrode in trim cutting operation only. It depends on the melting, evaporation and flushing out of the surface material. Increase in the value of Ton results into high heat generation that increases the melting and evaporation of work material and hence the value of D_s increases as shown by response surface plot in Fig. 8a. D_s increases with decrease in the value of servo voltage as shown in Fig. 8b. Increasing the value of wire depth (W_d) increases the effective sparking on work surface and hence melting and erosion of the surface material increases as a result, D_s increases as shown in Fig. 8c. Increase in FR increases the flushing rate of eroded particles and hence D_s increases with increasing FR and Ton as shown in Fig. 8a. The interaction among the parameters can be noticed by the contour plot on 3D surface plot.

5. Multi performance optimization through Desirability function approach

In order to obtain an optimum parametric setting for two performance characteristics, desirability function has been utilised. Derringer and Suich (1980) proposed a multiple response optimization techniques approach called Desirability function. The general approach is to first convert each response *$y_i(x)$* into an individual desirability function (*d_i*) and varied over the range $0 \leq d_i \leq 1$. The simultaneous objective function is a geometric mean of all converted responses. In the present study, Design Expert 7 has been used to optimize the response variables. Derringer and Suich (1980) defined the three types of desirability function depending on the type of response characteristics as:

(I) For the "larger- the-better" type:

$$d_i = \begin{cases} 0 & y_i \leq y_i^* \\ \left[\dfrac{y_i - y_i^*}{y_i^{'} - y_i^*} \right] & y_i^* \leq y_i \leq y_i^{'} \\ 1 & y_i \geq y_i^{'} \end{cases} \tag{5}$$

where y_{i^*} is the minimum acceptable value of y_i, y_i' is the highest value of y_i; *t* is the shape function for desirability.

(II) For the smaller-the-better type:

$$d_i = \begin{cases} 0 & y_i \leq y_i^{''} \\ \left[\dfrac{y_i^* - y_i}{y_i^* - y_i^{''}} \right]^r & y_i^{''} \leq y_i \leq y_i^{'} \\ 1 & y_i \geq y_i^* \end{cases} \tag{6}$$

where $y_i^{''}$ is the lowest value of y_i, y_i^* is the maximum acceptable value of y_i; *r* is the shape function for desirability.

(III) For the nominal-the-best type:

$$d_i = \begin{cases} \left[\dfrac{y_i - y_i^*}{C_i - y_i^{''}} \right]^s & y_i^* \leq y_i \leq c_i \\ \left[\dfrac{y_i - y_i^*}{c_i - y_i^{'*}} \right]^t & c_i^{'} \leq y_i \leq y_i^* \\ 1 & y_i > y_i^* \text{ or } y_i^* > y_i \end{cases} \tag{7}$$

where *C_i* is the most acceptable or target value and *s* and *t* are the exponential parameters that determine the shape of desirability function. Overall desirability function of the multi-response system can be measured by combining the individual desirability functions. It can be represented as $D = (d_1^{w1}.d_2^{w2} \ldots\ldots d_n^{wn})$; where w_j ($0 < w_j < 1$) is the weight value given for the importance of jth response variable and $\sum_{j=1}^{n} w_j = 1$. The parameters settings with maximum overall desirability value are considered to be the optimal parameter combination. In this study, the objective is to find optimal parameters setting that maximize the overall desirability function for minimum surface roughness value and dimensional shift. The ranges and targets of inputs parameters namely Ton, SV, W_d and FR and the response characteristics surface roughness and dimensional shift are given in Table 6.

Table 6

Range of Input Parameters; SR and D_S for Desirability

Constraint	Goal	Lower Limit	Upper Limit	Important
Pulse-on Time (Ton)	in range	104	112	3
Servo voltage (SV)	in range	20	40	3
Wire depth (W_d)	In range	10	30	3
Dielectric flow rate (FR)	In range	2	6	3
SR (µm)	Minimize	1.12	3.52	3
D_S (µm)	Minimize	14	54	3

Table 7 shows the possible combination of WEDM process parameters that give the high value of desirability. Corresponding to highest desirability, optimal combination of WEDM parameters for multi performance characteristics are Ton 104µs; SV 40V; W_d 10µm and FR 2 L/min. Experimental value obtained corresponding to optimal setting for SR and D_S were 1.1 µm and 16 µm that are closer to the predicted values in Table 7.

Table 7

Process parameters combination for high value of desirability

Number	**Process Parameters**				**Predicted Response**		**Desirability**
	Ton	**SV**	**Wd**	**FR**	**SR**	**DS**	
1	104.05	39.96	10.02	2.03	1.08917	13.9156	1.000
2	104.01	39.97	10.27	2.09	1.09519	13.8076	1.000
3	104	40	11.08	2.09	1.09999	14.1202	0.998
4	104	39.97	11.4	2.06	1.09999	14.3722	0.995
5	104	40	11.97	2.37	1.14347	14	0.988
6	104	39.99	10	2.72	1.16272	12.6019	0.982
7	104	40	10	2.88	1.17614	12.4514	0.979
8	104	40	10	4.64	1.2051	13.8867	0.970

6. Conclusions

In this study, trim cutting operation in WEDM has been performed on Nimonic 90: a nickel based super alloy. Two performance characteristics namely surface roughness (SR) and dimensional shift (D_S) for WEDM of Nimonic-90 have been modelled and analyzed using Response Surface Methodology (RSM) for trim cutting operation. Trim cutting operation has been performed to improve the machined surface characteristics and dimensional accuracy after a rough cutting operation. Four process parameters namely Ton, SV, W_d and FR have been selected as variable parameters; while other parameters were kept fixed for trim cutting operation. Face centered central composite design has been adopted to carry out experimental study.

Quadratic model has been proposed to determine the optimal combination of surface roughness and dimensional shift. Using response surface graphs, the developed mathematical models are able to explain the effect of process variables on performance characteristics efficiently. Increasing the value of Ton, W_d and FR increases the surface roughness and dimensional shift but increases of SV decreases the both surface roughness and dimensional shift. Using desirability function, a scale free quantity called desirability has been obtained for two performance characteristics to optimize multi-performance characteristics. Correspond to highest desirability, the optimal combination of discharge parameters was Ton: 110 µs; SV 40V; W_d10 µm and FR 2 L/min. Confirmation experiments have proven the goodness of the proposed models and desirability function approach.

Using SEM micrographs, effect of discharge energy on surface morphology has been examined. Average thickness of recast layer varies from 6 µm to 12 µm was found on the machines surfaced after trim cutting operation Present research approach is useful for achieving high productivity while maintain surface roughness and geometrical accuracy within desire limits for machining complex and intricate shapes in hard and exotic materials. Machining of Nimonic-90 with WEDM at optimized setting yields better performance and more economic as compared to conventional processes that proves the potential of WEDM in aerospace industries.

References

Arunachalam, R.M., Mannan, M.A., & Spowage, A.C. (2004). Surface integrity when machining age hardened Inconel 718 with coated carbide cutting tools. *International Journal of Machine Tools & Manufacture*, 44(14), 1481-1491.

Bhuyan, B.K., &Yadava, V. (2014). Experimental Study of Travelling Wire Electrochemical Spark Machining of Borosilicate Glass. *Materials and Manufacturing Processes*, 29(3), 298-304.

Bobbili, R., Madhu, V., & Gogia, A.K. (2013).Effect of Wire-EDM Machining Parameters on Surface Roughness and Material Removal Rate of High Strength Armor Steel. *Materials and Manufacturing Processes*, 28(4), 364–368.

Cheng, X., Yang, X.H., Huang, Y.M., Zheng, G.M., & Li, L. (2014).Helical surface creation by wire electrical discharge machining for micro tools. *Robotics and Computer-Integrated Manufacturing*, 30(3), 287–294.

Choudhury, I.A., & El-Baradie, M.A. (1998). Machinability of nickel-base super alloys- a general review. *Journal of Materials Processing Technology*, 77(1-3), 278-284.

Cochran, G., & Cox, G.M. (1962). Experimental Design. *Asia Publishing House*, New Delhi.

Deringer, G.,& Suich, R. (1980). Simultaneous optimization of several response variables. *Journal of Quality Technology*, 12(4), 214-219.

Ezugwu, E.O. (2005). Key improvements in the machining of difficult-to-cut aerospace alloys. *International Journal of Machine Tools & Manufacture*, 45(12-13), 1353-1367.

Guo, Y.B., Li, W., & Jawahir, I.S. (2009). Surface integrity characterization and prediction in machining of hardened and difficult-to-machine alloys-a state-of-art research review and analysis. *Journal of Machine Science & Technology*, 13(4), 437- 470.

Gupta, K., & Jain, N.K. (2014). Analysis and optimization of micro-geometry of miniature spur gears manufactured by wire electric discharge machining. *Precision Engineering*, 38(4), 728-737.

Han, F., Jiang, J., & Yu, D. (2007). Influence of machining parameters on surface roughness in finish cut of WEDM. *International Journal of Advance Manufacturing Technology*, 34(5-6), 538-546.

Hewidy, M.S., El-Taweel, T.A., & El-Safty, M.F. (2005). Modeling the machining parameters of wire electrical discharge machining of Inconel 601 using RSM. *Journal of Materials Processing Technology*, 169(2), 328–336.

Hood, R., Soo, S.L., Aspinwall, D.K., Andrews, P., & Sage, C. (2011). Twist drilling of Haynes 282 Superalloy, *Procedia Engineering*, 19, 150-155.

Huang, J.T., Liao, Y.S., & Hsue, W.J. (1999). Determination of finish- cutting operation and machining –parameters setting in wire electrical discharge machining. *Journal of Materials Processing Technology*, 87(1-3), 69-81.

Jangra, K., Grover, Chan FTS, &Aggarwal, A. (2011). A Digraph and matrix method to evaluate the machinability of tungsten carbide composite with wire EDM. *International Journal of Advance Manufacturing Technology*, 2(3), 959-974.

Jangra, K., Grover, S., & Aggarwal, A. (2011). Simultaneous optimization of material removal rate and surface roughness for WEDM of WC-Co composite using grey relational analysis along with Taguchi method. *International Journal of Industrial Engineering Computations*, 2(3), 479–490.

Jangra, K. (2012). Study of unmachined area in intricate machining after rough cut in WEDM. *International Journal of Industrial Engineering Computations*, 3(5), 887-892.

Jangra, K., & Grover, S. (2012). Modeling and experimental investigation of process parameters in WEDM of WC- 5.3% Co using response surface methodology. *Mechanical Science*, 3, 63-72.

Jangra, K.K., Kumar, V., Kumar, V. (2014). An experimental and comparative study on rough and trim cutting operation in WEDM of hard to machine materials. *Procedia Materials Science*, 5, 1603 – 1612.

Jangra, K.K. (2015). An experimental study for multi-pass cutting operation in wire electrical discharge machining of WC- 5.3% Co composite. *International Journal of Advance Manufacturing Technology*, 76, 971-982.

Khanna, R., & Singh, H. (2013) Performance analysis for D-3 material using response surface methodology on WEDM. *International Journal of Machining and Machinability of Materials*, 14, 45 – 65.

Klink, A., Guoa, Y.B., & Klocke, F. (2011).Surface integrity evolution of powder metallurgical tool steel by main cut and finishing trim cuts in wire-EDM. *Procedia Engineering*, 19, 178-183.

Kortabarria, A., Madariaga, A., Fernandez, E., Esnaola, J.A., & Arrazola, P.J. (2011).A comparative study of residual stress profiles on Inconel 718 induced by dry face turning, *Procedia Engineering*, 19, 228 – 234.

Krain, H.R., Sharman, A.R.C., & Ridgway, K. (2007). Optimisation of tool life and productivity when end milling Inconel 718 TM. *Journal of Material Processing Technology*, 189(1-3), 153-161.

Kumar, V., Jangra, K., & Kumar, V. (2012). Effect of WEDM parameters on machinability of Nimonic-90.*Proceedings of the National Conference on Trends and Advances in Mechanical Engineering (TAME), YMCA University of Science and Technology*, 511-516.

Lee, S.H., & Li, X.P. (2003).Study of the surface integrity of the machined workpiece in the EDM of tungsten carbide. *Journal of Materials Processing Technology*, 139(1-3), 315-321.

Li, L., Guo, Y.B., Wei, X. T., & Li, W. (2013). Surface integrity characteristics in wire-EDM of Inconel 718 at different discharge energy. *Procedia CIRP*, 6, 221 – 226.

Liao, Y.S., & Yu, Y.P. (2004). The energy aspect of material property in WEDM and its application. *Journal of Materials Processing Technology*, 149(1-3), 77–82.

Myers, R.H., & Montgomery, D.H. (1995). Response surface methodology. Wiley, New York.

Puri, A.B., & Bhattacharyya, B. (2003). An analysis and optimisation of the geometrical inaccuracy due to wire lag phenomenon in WEDM. *International Journal Machine Tools & Manufacturing*, 43(2), 151-159.

Puri, A.B., & Bhattacharyya, B. (2005). Modelling and analysis of white layer depth in a wire cut EDM process through response surface methodology. *International Journal of Advance Manufacturing Technology*, 25(3-4), 301-307.

Rebelo, J.C., Morao Dias, A., Kremer, D., & Lebrun, J.L. (1998). Influence of EDM pulse energy of on the surface integrity of martensitic steel. *Journal of Materials Processing Technology*, 84(1-3) , 90-96.

Sarkar, S., Sekh, M., Mitra, S., & Bhattacharyya, B. (2008). Modeling and optimization of wire electrical discharge machining of γ- TiAl in trim cutting operation. *Journal of Materials Processing Technology*, 205(1-3), 376-387.

Sarkar, S., Mitra, M., & Bhattacharyya, B. (2011). A novel method of determination of wire lag for enhanced profile accuracy in WEDM. *Precision Engineering*, 35(2), 339-347.

Sharman, A.R.C., Hughes, J.I., & Ridgway, K. (2004). Workpiece Surface Integrity and Tool Life Issues When Turning Inconel 718 TM Nickel Based Superalloy. *Journal of Machine Science & Technology*, 8(3), 399-414.

Sharma, N., Khanna, R., Gupta, R. D., & Sharma, R. (2013). Modeling and Multiresponse optimization on WEDM for HSLA by RSM. *International Journal of Advance Manufacturing Technology*, 67(9-12), 2269-2281.

Soo, S.L., Hood, R., Aspinwall, D.K., Voice, W.E., & Sage, C. (2011). Machinability and surface integrity of RR1000 nickel based super alloy. *CIRP Annals- Manufacturing Technology*, 60(1), 89–92.

Soo, S.L., Antar, M.T., Aspinwall, D.K., Sage, C., Cuttell, M., Perez, R., & Winn, A.J. (2013).The effect of wire electrical discharge machining on the fatigue life of Ti-6Al-2Sn-4Zr-6Mo aerospace alloy. *Procedia CIRP*, 6, 216-220.

Ulutan, D., &Ozel, T. (2011). Machining induced surface integrity in Titanium and Nickel Alloys-A review. *International Journal of Machine Tools & Manufacture*, 51(3), 250-280.

Wang, C.C., Chow, H.M., Yang, L.D., & Lu, C.T. (2009). Recast layer removal after electrical discharge machining via Taguchi analysis: a feasibility study. *Journal of Materials Processing Technology*, 209(8), 4134-4140.

Wei, X. (2002). Experimental study on the machining of a shaped hole Ni based super heat resistant alloy. *Journal of Material Processing Technology*, 129(1), 143-147.

Yang, R.T., Tzeng, C.J., Yang, Y.K., & Hsieh, M.H. (2012).Optimization of wire electrical discharge machining process parameters for cutting tungsten. *International Journal of Advance Manufacturing Technology*, 60(1-4), 135-147.