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EXPERIMENTAL INVESTIGATIONS ON WIRE ELECTRICAL DISCHARGE MACHINE TO MODEL CUTTING RATE AND SURFACE ROUGHNESS OF INCONEL 601

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Abstract-Conventional and Non-conventional machining methods can be employed to give the desired shape to hard, tough and difficult-to-cut materials, but the non-conventional machining processes are more suitable because they result in better accuracy and surface finish in work materials. Wire electrical discharge machining is a non-conventional process for machining the hard-to-cut materials like Inconel 601. In this paper, an experimental investigation has been carried out on wire electrical discharge machine to model cutting rate and surface roughness of Inconel 601 using response surface methodology. The process parameters considered in the study are pulse on time, peak current, servo voltage and wire tension, whereas, the performance parameters are cutting speed and surface roughness. At the end of investigation, the results show that the process parameters such as pulse on time and peak current have significantly affected the cutting speed and surface roughness. The cutting speed increases with the increase of pulse on time and peak current and deceases with increase of servo voltage. The surface roughness increases with the increase of pulse on time and peak current and decreases with the decrease of pulse on time and peak current.

Keywords: Wire Electrical Discharge Machining, Pulse on time, Peak current, Servo voltage, Wire tension, Cutting speed, Surface roughness, Response surface methodology

1. INTRODUCTION

The machining processes are mainly used to remove the excess material from the workpiece. Depending on the contact between the tool and workpiece, these can be classified into conventional and non-conventional machining processes. The conventional methods involve significant tool wear as there is a physical contact between the tool and the workpiece. Moreover, they cannot be used to machine complex geometries in high strength materials like superalloys [1-3]. On the other hand, the non-conventional machining methods do not involve direct physical contact between the tool and workpiece. They use modern technology employing chemical, electro-chemical, thermal, thermoelectric and mechanical energy to machine the workpiece [4]. These methods are generally preferred over conventional methods because they result in precise geometry, better accuracy and surface finish and longer tool life. Wire electric discharge machining (WEDM) is a thermoelectric energy based non-conventional process which can be used to machine complex geometries and profiles in hard-to-cut materials like superalloys [5-6].

Superalloys, also known as heat-resistant or high-temperature alloys, are in huge demand owing to their several key characteristics such as resistance to corrosion, oxidation and thermal creep resistance, excellent mechanical strength and good surface stability. They are widely employed in gas turbine, aircraft, nuclear reactors, submarine and petrochemical equipment. Inconel 601 is a hard-to-cut nickel-chromium-iron superalloy that exhibits good resistance to oxidation and aqeous solution and possesses high toughness and mechanical strength [7-8]. However, it is difficult to be cut by conventional methods. Therefore, non-conventional techniques such as WEDM are generally used for machining Inconel 601. In this work, an experimental investigation has been carried out for machining Inconel 601 using wire electrical discharge machine to model cutting rate and surface roughness through response surface methodology. The schematic of WEDM process is shown in Fig. 1. The WEDM set up consists of wire electrode, workpiece and dielectric fluid.

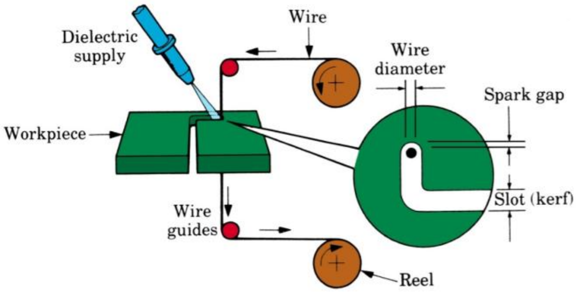

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Fig. 1: Schematic of WEDM Process

The rest of the paper is organized as follows: Section 2 describes the related work. Section 3 discusses the experimental work including input and output parameters and experimental design procedure. It is followed by results and discussion in Section 4. Finally, the conclusions drawn from the proposed work and future scope are discussed in Section 5.

2. RELATED WORK

Significant work has been done in the past for determining the impact of process parameters on performance measures during wire electrical discharge machining of a variety of work materials. Hewidy et al. [7] used response surface methodology to correlate the various machining parameters with volumetric metal removal rate, wear ratio and surface roughness during WEDM of Inconel 601 using copper wire. Ramakrishnan and Karunamoorthy [9-10] developed artificial neural network models to determine the effect of input parameters on material removal rate and surface roughness during wire electrical discharge machining of Inconel 718 using Taguchi technique. Antar et al. [11] examined the impact of process parameters on various surface integrity aspects such as surface roughness, recast layer, tensile residual stresses and microhardness during WEDM of Udimet 720 and Ti-6Al-2Sn-4Zr-6Mo. Patil and Brahmankar [12] optimized surface finish, cutting speed, and kerf width using Taguchi technique in WEDM of alumina particulate-reinforced aluminum matrix composites (Al/Al_2O_{3p}). Kondayya and Krishna [13] used two evolutionary approaches, namely, genetic programming and non-dominated sorting genetic algorithm-II in WEDM process for modeling and optimization of metal removal rate and surface roughness while machining AISI D3 steel. Yu et al. [14] investigated the effect of process parameters on cutting speed, machining groove width and surface roughness during WEDM of polycrystalline silicon. Shandilya et al. [15] investigated the effect of significant process parameters on frequency of wire breakage, average cutting speed, material removal rate, surface roughness and surface morphology of the machined surface during wire electric discharge cutting of SiCp/6061 aluminum metal matrix composites.

Kumar et al. [16] modeled the relationship between process parameters and responses such as material removal rate, surface roughness and wire wear ratio for pure titanium work material using Box-Behnken design of response surface methodology. Selvakumar et al. [17] experimentally analyzed the effect of the optimal machining parameter combination on cutting speed and surface roughness for wire electrical discharge machining of 5083 aluminum alloy using Taguchi experimental design L9 orthogonal array. Manjaiah et al. [18] analyzed the impact of input parameters on material removal rate and surface roughness while WEDM of $Ti_{50}Ni_{40}Cu_{10}$ using Taguchi technique. Subsequently, Prasad et al. [19] also used Taguchi technique to experimentally investigate the effect of input parameters on material removal rate and surface roughness during WEDM of titanium alloy (Ti-6Al-4V). Sharma et al. [20] used genetic algorithm and response surface methodology to optimize WEDM process parameters for high-strength low-alloy steel for overcut performance measure. Bobbili et al. [21] investigated the use of multi response technique on Taguchi method coupled with grey relational analysis for ballistic grade aluminum alloy. The machining performance was evaluated by material removal, surface roughness and gap current. Aggarwal et al. [22] modeled and optimized process parameters and performance measures such as material removal rate and surface roughness during wire electrical discharge machining of Inconel 718 using response surface methodology. Sharma et.al [23] evaluated the effect of wire diameter parameter on WEDM performance characteristics such as cutting speed, surface roughness, surface topography, recast layer formation, micro hardness, micro structural and metallurgical changes. Nayak et al. [24] experimentally investigated and optimized the impact of various WEDM process parameters on angular error, surface roughness and cutting speed for deep cryo-treated Inconel 718. Unune and Mali [25] attempted to improve machining rate of micro-wire EDM with low-frequency workpiece vibration assistance to optimize the material removal rate and kerf width performance measures, while fabricating micro channels in Inconel 718. Rao and Venkaiah [26] employed a modified Cuckoo search algorithm involving two-stage initialization to determine the global optimal values of parameters during wire electrical discharge machining process of Inconel 690. Saha and Mondal [27] determined the effect of WEDM parameters on material removal rate, surface roughness and machining time for welded nano-structured hardfacing material using Taguchi’s (L25) orthogonal array. Singh et al. [28] studied the effect of process parameters on material removal rate, gap current, surface roughness, gap voltage and cutting rate using Taguchi’s orthogonal array L27 (3^5). Authors used response surface methodology to develop mathematical models for finding the relationships between WEDM process parameters and performance measures while machining AISI D2 steel material.

Literature reveals that the materials used by most investigators during wire electrical discharge process are steel, tungsten or some superalloys. Very less work has been reported on the machining of Inconel 601 superalloy using WEDM process. So, in this investigation the WEDM of Inconel 601 has been carried out. Moreover, most of the researchers have investigated the influence of limited number of process parameters on the performance of WEDM process. The effect of many machining parameters on Inconel 601 has not been fully explored using WEDM. Therefore, this study proposes single and multi-objective parameteric optimization for modeling cutting rate and surface roughness with the help of response surface methodology.

3. EXPERIMENTATION

To carry out the experimental work, the wire electric discharge machine (SPRINTCUT-734) manufactured by ELCTRONICA has been used. The set up of machine is shown in Fig. 2.

Fig. 2: Sprintcut-734 WEDM machine

The machine consists of wire electrode, power supply system, dielectric system, wire frame and wire feed system. In the present work, brass wire having diameter of 0.025 mm is used to perform the experiments. The wire travels through wire guides and the material is cut in vertical plane. It is controlled by CNC. The selected workpiece is Inconel 601 which is a rectangular bar of size 20 mm × 20 mm × 300 mm. Table 1 gives the chemical composition of workpiece.

Table 1: Chemical composition of Inconel 601

Ni	**Cr**	**Al**	**C**	**Mn**	**Si**	**Fe**
61.5	22.5	1.4	.05	.3	.2	14

In the present study, four input parameters namely, pulse on time, peak current, servo voltage and wire tension have been selected on the basis of their effectiveness as presented by previous researchers. The units of these four independent process parameters, their ranges and various levels are given in Table 2. Apart from these parameters, there are five more input process parameters which are kept fixed during experimentation. The units and range of these constant parameters are listed in Table 3. The cutting speed and surface roughness have been selected as output parameters. Cutting speed affect the rate of production and hence, economics of the machining while surface roughness is the most important surface integrity aspect. The cutting speed (CS) is displayed directly on the WEDM machine tool. The unit of cutting speed is mm/min and it is measured as follows:

CS = Length cut in mm/time consumed in min

Surface roughness is one of the most important performance measure. The surface roughness is measured by Mitutoyo’s surftest instrument after machining work material.

Table 2: Input parameters, their units, range and levels through preliminary experiments

Sr. No	Parameters	Units	Range	Level 1	Level 2	Level 3	Level 4	Level 5
1	Pulse on time	μs	106-126	106	111	116	121	126
2	Peak current	A	80-200	80	110	140	170	200
3	Servo voltage	V	15-75	15	30	45	60	75
4	Wire tension	Kg	3-11	3	5	7	9	11

Table 3: Constant input parameters, their units and ranges

S.No.	Parameters	Units	Range
1	Pulse off time	µs	52
2	Wire feed	m/min	8
3	Servo feed	mm/min	2100
4	Peak voltage	Volts	1
5	Flushing pressure	kg/cm^2	1

The design of experiment approach has been used to design the experiments and identify the important input parameters which control and improve process performance. The coded and real values of input variables at different levels are suggested by response surface methodology and shown in Table 4.

A total of thirty trial runs are performed as per response surface methodology's central composite design and cutting rate has been noted and surface roughness has been calculated for each trial (Table 5). The run order is randomized to eliminate biasing. The work specimen is cleaned to make sure that it is free from foreign particles. For each specified combination, same wire material is used to keep experimental conditions same. After assigning the values of independent parameters to CNC machine like pulse on time, peak current, servo voltage and wire tension, the other constant parameter values are also entered on machine like pulse off time, wire feed, servo feed, fluid pressure and voltage. Then, the machine is used to cut the material and the value of cutting speed is noted down. In this work, the 30 pieces are cut from the workpiece for different combinations of input process parameters. Following this, the surface finish of the workpiece is checked using Mitutoyo tester.

Table 4: Coded values and real values of input variables at different levels

Parameters	Symbol	Designation	Levels				
Coded values			-2	-1	0	1	2
Pulse on time (µs)	T_{on}	A	106	111	116	121	126
Peak current (A)	IP	B	80	110	140	170	200
Servo voltage (V)	SV	C	15	30	45	60	75
Wire tension (Kg)	WT	D	3	5	7	9	11

Table 5: Experimental observations (Four Variable-Five Level Experimental Design Matrix)

Std run	Run order	Pulse on time	Peak current	Servo voltage	Wire tension	Cutting speed	Surface roughness
1	21	111.00	110.00	30.00	5.00	0.72	1.3
2	2	121.00	110.00	30.00	5.00	0.84	1.75
3	28	111.00	170.00	30.00	5.00	0.74	1.35
4	1	121.00	170.00	30.00	5.00	0.85	1.65
5	24	111.00	110.00	60.00	5.00	0.23	0.98
6	8	121.00	110.00	60.00	5.00	0.66	1.7
7	29	111.00	170.00	60.00	5.00	0.47	1.56
8	12	121.00	170.00	60.00	5.00	0.87	1.77
9	15	111.00	110.00	30.00	9.00	0.68	1.57
10	7	121.00	110.00	30.00	9.00	0.88	1.95
11	11	111.00	170.00	30.00	9.00	0.37	1.00
12	19	121.00	170.00	30.00	9.00	0.83	1.84
13	22	111.00	110.00	60.00	9.00	0.35	0.95
14	30	121.00	110.00	60.00	9.00	0.82	1.88
15	16	111.00	170.00	60.00	9.00	0.58	0.54
16	13	121.00	170.00	60.00	9.00	0.82	1.7
17	10	106.00	140.00	45.00	7.00	0.58	1.15
18	9	126.00	140.00	45.00	7.00	1.17	1.25
19	5	116.00	80.00	45.00	7.00	0.76	1.72

20	17	116.00	200.00	45.00	7.00	0.87	1.8
21	25	116.00	140.00	15.00	7.00	1.05	2.1
22	18	116.00	140.00	75.00	7.00	0.73	1.5
23	4	116.00	140.00	45.00	3.00	0.07	0.4
24	26	116.00	140.00	45.00	11.00	0.09	0.5
25	23	116.00	140.00	45.00	7.00	1.02	2.02
26	14	116.00	140.00	45.00	7.00	1.06	2.06
27	27	116.00	140.00	45.00	7.00	0.95	1.95
28	6	116.00	140.00	45.00	7.00	0.96	1.96
29	20	116.00	140.00	45.00	7.00	1.00	2.00
30	3	116.00	140.00	45.00	7.00	1.01	1.01

4. RESULTS AND DISCUSSION

Based on experimental data, statistical analysis has been performed using Design Expert Dx-8 software. Analysis of variance (ANOVA) for experimental data has been performed to establish the significance of input variables and the confidence level of their effect. Statistical inferences have been drawn in respect of model adequecy, precision, lack of fit etc.

4.1. Statistical observations for cutting rate

The results of ANOVA for cutting rate are summarized in Table 6.

Table 6: Analysis of variance (ANOVA) for cutting rate

Source	Sum of square	DF	Mean Square	F- value	p-value	Remarks
Model	2.28	11	0.21	55.98	< 0.0001	Significant
A-pulse on time	0.54	1	0.54	146.70	< 0.0001	Significant
B-peak current	0.014	1	0.014	3.66	0.0719	Significant
-servo voltage	0.13	1	0.13	34.47	< 0.0001	Significant
AC	0.026	1	0.026	7.13	0.0156	Significant
BC	0.064	1	0.064	17.22	0.0006	Significant
BD	0.023	1	0.023	6.28	0.0220	Significant
CD	0.033	1	0.033	9.00	0.0077	Significant
A^2	0.026	1	0.026	6.90	0.0171	Significant
B^2	0.057	1	0.057	15.36	0.0010	Significant
C^2	0.020	1	0.020	5.31	0.0333	Significant
D^2	1.44	1	1.44	389.53	<0.0001	Significant
Residual	0.067	18	3.701E-003			
Lack of Fit	0.058	13	4.494E-003	2.74	0.1364	Not Significant
Pure Error	8.200E-003	5	1.640E-003			
Cor Total	2.35	29				
Standard Deviation	0.061		R-Squared			0.9716
Mean	0.73		AdjR-Squared			0.6542
C.V. %	8.28		PredR-Squared			0.9210
PRESS	0.19		Adeq Precision			28.79

The following inferences can be drawn from Table 6:

i. The Model F-value of 55.98 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.

ii. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, C, AC, BC, BD, CD, A^2, B^2, C^2, D^2 are significant model terms.

iii. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms, model reduction may improve the model.

iv. The "Lack of Fit F-value" of 2.74 implies the Lack of Fit is not significant relative to the pure error. There is a 13.64% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good if we want the model to fit.

v. The "Pred R-Squared" of 0.9210 is in reasonable agreement with the "Adj R-Squared" of 0.9542.

vi. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 28.479 indicates an adequate signal. This model can be used to navigate the design space.

4.2. Effect of process parameters on cutting rate

Regression equation for cutting rate has been obtained in terms of input parameters.
It can be expressed by following second-order polynomial:
Cutting speed = -5.92187+0.14055 × T_{on}-6.81044E-003 × IP-0.11286 ×SV+5.41667E-00 4× T_{on} × SV +1.40278E-00 4× IP × SV+1.49668E-00 3 ×IP ×WT+4.26210E-00 3 ×SV × WT-5.81205E-004 × $T_{on}{}^{2}$-3.28112E-005 × IP^{2}-4.79116E-005 × SV^{2}-0.029334 × WT
The normal probability plot of residuals has been drawn and shown in Fig. 3.
All the data points are falling on a straight line. Thus, the data is normally distributed. The plot of predicted vs actual values is shown in Fig. 4. It could be seen that all the actual values are following predicted values. So, there exists a good correlation between the actual and predicted values.

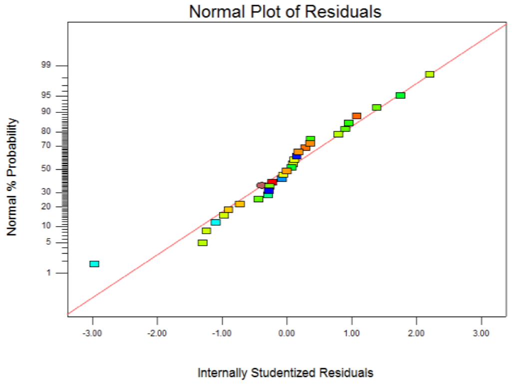

Fig. 3: Normal probability plot of residuals for cutting speed

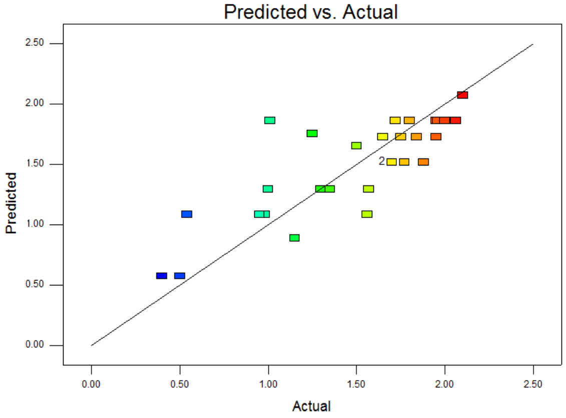

Fig. 4: Predicted vs. Actual plot for cutting speed

4.3. Interaction effect of process parameters on cutting rate

The interaction effect of pulse on time and servo voltage on cutting speed is shown in Fig. 5. It shows that the cutting speed reaches at a maximum value of 1.12 mm/min when pulse reaches at value of 121 µm and the value of servo voltage is 30 V. This graph shows that if the value of pulse on time increases, the cutting speed also increases, on the other hand, it is seen that with the decrease in the servo voltage, the cutting speed increases. Whenever the value of pulse on time increases, the more energy is applied between the workpiece and wire electrode due to which the cutting speed becomes high. Servo voltage controls the discharge gap between wire and workpiece.
Decreasing the servo voltage results in narrower spark gap which results in large ionization of spark gap and hence, more melting of work material.

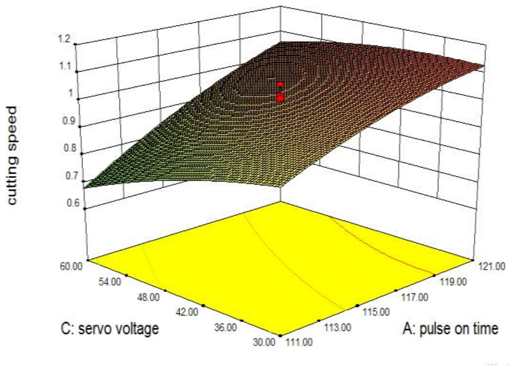

Fig. 5: Interaction effect of pulse on time and servo voltage on cutting speed

The interaction effect of peak current and servo voltage on cutting rate is shown in Fig. 6. It shows that cutting speed goes to a maximum value of 0.96 mm/min corresponding to the values of peak current of 170 A and servo voltage of 30 V. This is due to the fact that high value of peak current means an increase in the discharge energy across the electrode. This results in an increase in cutting speed with the increase in peak current.

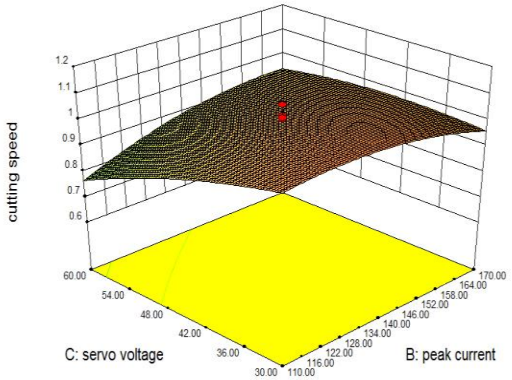

Fig. 6: Interaction effect of peak current and servo voltage on cutting speed

The interaction between the peak current and wire tension for cutting rate is shown in Fig. 7. The higher value of peak current, higher is the cutting speed because that high value of peak current means an increase in the discharge energy across the electrode. This results in an increase in cutting speed with the increase in peak current. The wire tension has not any significant effect on the cutting speed.

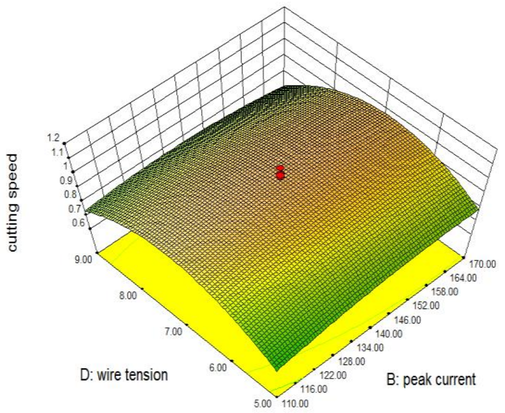

Fig. 7: Interaction effect of peak current and wire tension on cutting speed

The interaction between servo voltage and wire tension for cutting rate is shown in Fig. 8. With increase in servo voltage, the cutting speed decreases because decreasing the servo voltage results in narrower spark gap which results in large ionization of spark gap and hence, more melting of work material.

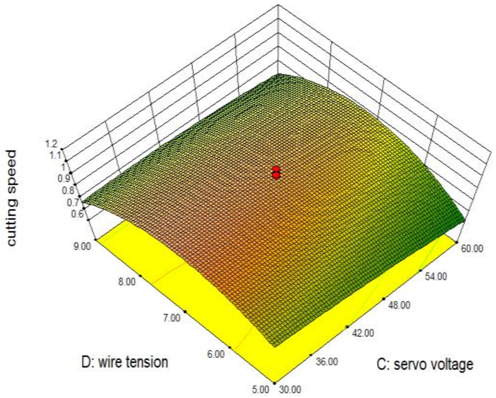

Fig. 8: Interaction effect of wire tension and servo voltage on cutting speed

The wire tension has not noticeable effect on the cutting speed. Therefore, in brief, one can say that the pulse on time, peak current and servo voltage has significant effect on the cutting speed.

4.4. Statistical observations for surface roughness

The results of ANOVA for surface roughness are summarized in Table 7. The following inferences can be drawn:

i. The Model F-value of 12.63 implies the model is significant. There is only a 0.01% chance that a "Model F-Value" this large could occur due to noise.
ii. Values of "Prob > F" less than 0.0500 indicate model terms are significant. In this case A, A^2, D^2 are significant model terms.
iii. Values greater than 0.1000 indicate the model terms are not significant.
iv. If there are many insignificant model terms model reduction may improve the model.
v. The "Lack of Fit F-value" of 0.44 implies the Lack of Fit is not significant relative to the pure error. There is a 91.09% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good if we want the model to fit.
vi. The "Pred R-Squared" of 0.3913 is not as close to the "Adj R-Squared" of 0.6160 as one might normally expect. This may indicate a large block effect or a possible problem with model and/or data.
vii. "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. A ratio of 12.143 indicates an adequate signal. This model can be used to navigate the design space.

Table 7: Analysis of variance (ANOVA) for surface roughness

Source	**Sum of mean Squares**	**DF**	**Mean Square**	**F-Value**	**p-value Prob > f**	**Remarks**
Model	4.61	4	1.15	12.63	< 0.0001	Significant
A-pulse on time	1.12	1	1.12	12.29	0.0017	Significant
C-servo voltage	0.27	1	0.27	2.92	0.0998	Significant
A^2	0.51	1	0.51	5.62	0.0258	Significant
D^2	2.95	1	2.95	32.25	< 0.0001	Significant
Residual	2.28	25	0.091			
Lack of Fit	1.46	20	0.073	0.44	0.9109	not Significant
Standard Deviation		0.30	R-Squared			0.6690
Mean		1.50	Adj R-Squared			0.6160
C.V. %		20.19	Pred R-Squared			0.3913
PRESS		4.20	Adeq Precision			12.143

4.5. Effect of process parameters on surface roughness

Regression equation for surface roughness obtained in terms of input parameters can be expressed by following equation:

Surface roughness =

$$-56.63525+0.96813 \times T_{on}-7.02778E\text{-}003 \times SV-3.98655E\text{-}003 \times T_{on}^{2}-2.52468E\text{-}003 \times WT^{2}$$

The normal probability plot of residuals has been drawn and shown in Fig. 9. All the data points are following the straight line. Thus, the data is normally distributed. Fig. 10 shows the plot of actual vs predicted values. It can be seen from the Fig. 10 that all the actual values are following the predicted values.

4.6. Interaction effect of process parameters on surface roughness

The interaction effect of pulse on time and wire tension on surface roughness is shown in Fig. 11. It shows that surface roughness goes to a maximum value when the value of pulse on time is maximum i.e. 121 µm. As pulse on time increases, the time for which current passes increases which lead to more erosion on the work surface and hence increase in surface roughness. Wire tension has not any significant effect on surface roughness.

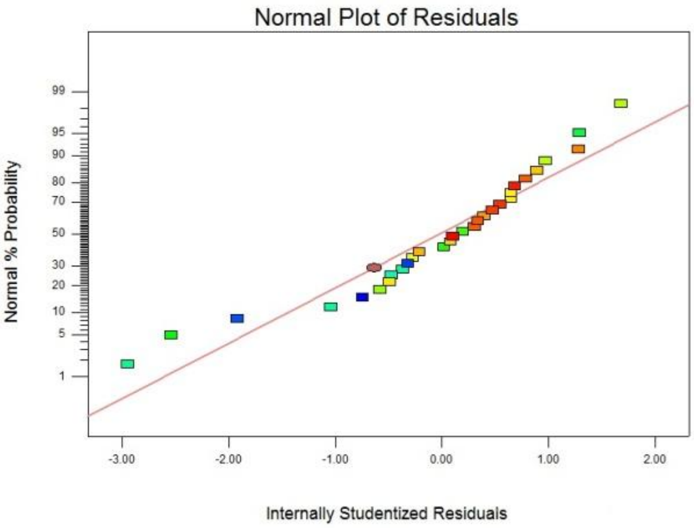

Fig. 9: Normal probability plot of residuals for surface roughness

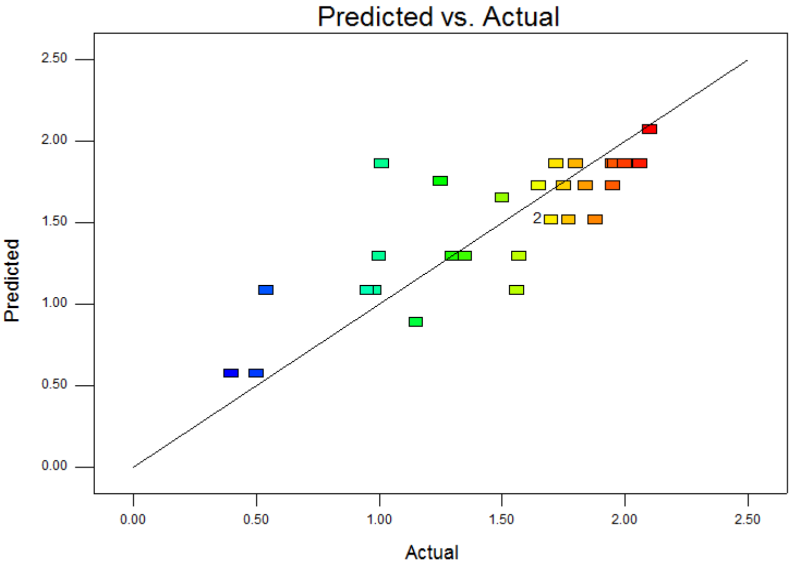

Fig. 10: Predicted vs. Actual plot for surface roughness

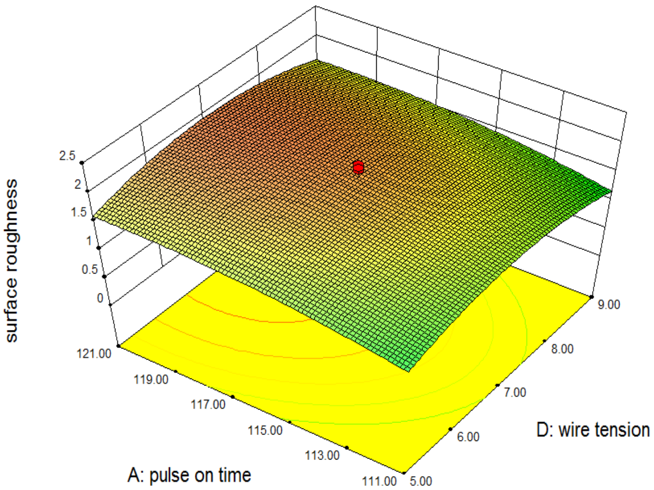

Fig. 11: Interaction effect of pulse on time and wire tension on surface roughness

The interaction effect of pulse on time and servo voltage on surface roughness is shown in Fig. 12. It shows that the surface roughness goes to a maximum value of 2.2 μm at the high value of pulse on time of 121 μs and low value of servo voltage of 30 V. Increasing the value of servo voltage leads to increased spark gap and hence reduces the discharge energy. This plot shows that if the value of pulse on time increases, the value of surface roughness increases. Further, when the value of servo voltage increases keeping pulse on time at low values, the surface roughness decreases. Increasing the servo voltage increases the gap between the work material and tool results in low discharge medium and hence, low energy is generated, thus decrease in surface roughness.

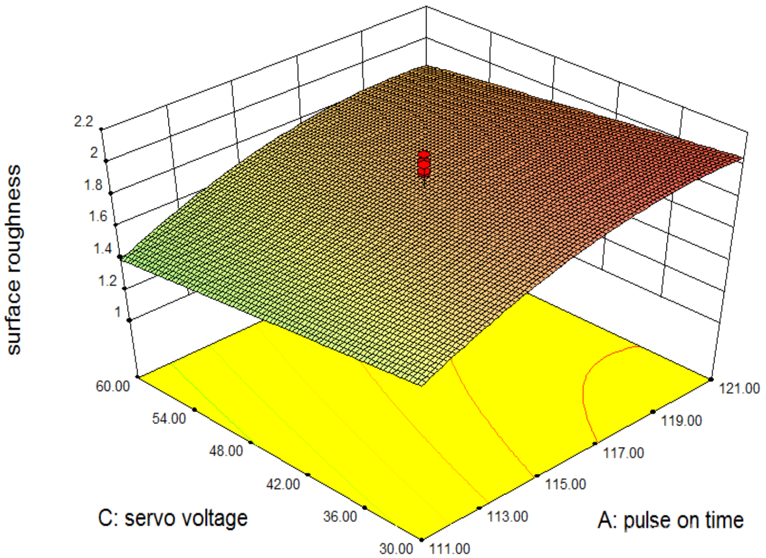

Fig. 12: Interaction effect servo voltage and pulse on time on surface roughness

5. MULTI-RESPONSE OPTIMIZATION USING DESIRABILITY FUNCTION

To overcome the problem of conflicting response of single-response optimization, multi-response optimization has been carried out using desirability function. Desirability function has been used to determine the optimum WEDM parameters for optimizing the cutting speed and surface roughness in this investigation. The maximum and minimum levels are provided for all response characteristics which are to be optimized. The goal is to find optimal parameter setting that maximizes the overall desirability function for higher cutting rate and minimum surface roughness. Table 8 shows the constraints for input parameters as well as for cutting speed and surface roughness. Table 9 shows the optimal combination of WEDM process parameters that gives the high value of desirability and predicted value of various response characteristics. The WEDM parameters for multi-response characteristics are pulse on time of 126 μs, peak current of 172 A, servo voltage of 75 V and wire tension of 9 g.

6. CONCLUSIONS AND SCOPE FOR FUTURE WORK

Based upon experimental results obtained in the present work, the following conclusions have been drawn:

i. The input parameters such as pulse on time and peak current are found to be significant for both cutting speed and surface roughness during wire electrical discharge machining of Inconel 601 material.
ii. The empirical relations have been suggested for cutting rate and surface roughness response characteristics.
iii. The process parameters such as pulse on time and peak current have significantly affected the cutting speed. The cutting speed increases with the increase of pulse on time and peak current.
iv. The surface roughness increases with increase of pulse on time and peak current and decreases with the decrease of pulse on time and peak current.
v. Wire tension parameter is negligible factor affecting the cutting speed and surface roughness.
vi. The surface roughness is maximized at high value of pulse on time and peak current and minimized at high values of servo voltage.
vii. The pulse on time is more significant for both cutting speed as well as surface roughness as compared to other input process parameters. Hence, to achieve better surface finish, low value of pulse on time is needed.
viii. The maximum value of cutting speed is 1.17 mm/min and the minimum value of surface roughness is 0.40 µm.

In the present work, effect on cutting rate and surface roughness is studied during the machining of Inconel 601 using WEDM. Research can further be extended to study the effect of various input process parameters on other machining characteristics such as hardness, micro-structure and residual stresses of generated surfaces.

Table 8: The constraints for input parameters and performance measures

Constraints	Goal	Lower limit	Upper Limit	Lower Weight	Upper weight	Importance
Pulse on time	In range	106	126	1	1	3
Peak current	In range	80	200	1	1	3
Servo voltage	In range	15	75	1	1	3
Wire tension	In range	3	11	1	1	3
Cutting speed	Maximize	0.07	1.17	1	1	3
Surface roughness	Minimize	0.4	2.1	1	1	3

Table 9: Process parameters combination for high value of desirability

Response	Process parameters				Predicted response		Desirability
	Pulse on time	Peak current	Servo voltage	Wire tension	Cutting speed	Surface roughness	
Single response optimization to maximize cutting speed	126	153	42	7	1.17	_	1.00
Single response optimization to minimize surface roughness	116	140	45	3	_	0.4	1.00
Multi- response optimization to maximize cutting speed and minimize surface roughness	126	172	75	9	0.83	0.93	0.688

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