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The Influence of WEDM Parameters on Surface Roughness and Cutting Speed for Ni-Based Superalloy and Multi-Parametric Optimization using Taguchi and Grey Relational Analysis

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***Abstract*—This research aims to examine the influence of Wire Electro-discharge Machining (WEDM) parameters on surface roughness (SR) and cutting speed to improve the productivity with a high surface finish of Ni-based super alloy namely Inconel 600 wrought superalloy. Non-conventional machining processes are the requirements of the fastest growing industries because of the precision, complex, intricate shape of the work material, higher tolerances and economically. WEDM is a variation and development of EDM and a spark erosion process in which the material removal takes place due to erosion caused by electric sparks. This process is utilized for machining of conductive and difficult-to machine material irrespective of hardness with the help of thin wire electrode. In this experimental work, the multi-parametric optimization has been done for the machining of Ni-based wrought Inconel-600 superalloy using standard brass wire having diameter 0.25 mm. The peak current (I_P), taper angle, pulse on Time (T_{on}), pulse of time (T_{off}) and die-electric fluid pressure had selected as operation constraints to conduct experimental trials. The cutting rate and surface roughness (SR) were considered as output responses. The experimental outcomes were optimized by Gray relational analysis coupled with a Taguchi method. The optimized parameters by multi-parametric optimization method showed the considerable improvement in the process and will facilitate the WEDM industries to improve the productivity with higher surface finish.**

***Index Terms*—WEDM, Ni-based superalloy, SR, Cutting rate, Multi-parametric optimization**

I. INTRODUCTION

WEDM is generally used to produce intricate, complex shapes which are impossible to produce by means of any other conventional and non-conventional machining methods. WEDM is practically versatile applicable in precision manufacturing industries to manufacture intricate, precise and close tolerance parts with higher accuracy. When a suitable voltage is supplied across the cathode (thin wire) and anode (workpiece), an electrostatic field of high strength is established which cause emission of an electron from the tool. In this process, the material is submerged in the dielectric medium. ‘Dielectric’ is the shield between the work electrode and material. The emitted electrons get accelerated towards workpiece and collide with the dielectric fields molecules, breaking them into electrons and ions. The produced electrons accelerate and dislodge. As a result, a spark is produced between anode and cathode and a very high temperature is developed on the electrode. The high temperature causes melting and vaporization of the material. A DC or AC servo mechanism maintains the gap between the wire and the material to prevent the short circuiting of wire. [1] The block diagram of WEDM is shown in figure 1.

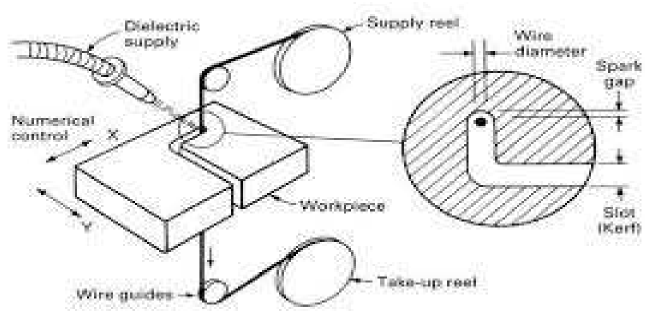

Figure 1: Schematic of Wire Electro-Discharge Machining (WEDM)

Nickel-based superalloys are extensively used in high precision components because of its excellent properties. However, based on the properties wrought Ni-based Inconel 600 superalloy is a well identified difficult-to-machine superalloy material. WEDM is revolutionizing machining and can cut all types of intricate and complex shapes up to 45 degrees. Any material which is electrically conductive can be cut by this process such as tungsten carbide, Inconel and all kinds of exotic metals. An attempt to use the WEDM process effectively and efficiently, researchers are trying continuously to improve and optimize the influential process parameters for the machining of highly precise metals. [2]

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Y. S. Liao et al (1997) reported the influence of WEDM process parameters such as T_{on} (pulse on time), T_{off} (Off time) and feed on the behavior of pulse trains. Experiments were conducted on SKD 11 tool steel. The authors concluded that pulse on time was a significant factor for pulse trains. [2] N. Tosun et al (2003) presented the impact of machining parameters of AISI 4140 steel material to measure the crater size of electrode. The researchers resulted that the crater size increases with pulse duration, servo voltage and wire speed whereas it decreases with dielectric pressure. [3] Ulas Caydas et al (2009) worked on the impact of parameters, i.e. pulse duration, open circuit voltage (SV), wire speed (WS) and dielectric pressure for the measurement of white layer thickness and SR. They developed the ANFIS model for the prediction of performance parameters. [4]

Vamsi Krishna Pasam et al (2010) investigated the effect of Ignition pulse current, short pulse duration, wire speed and wire tension on surface roughness by using Genetic Algorithm (GA). [5] Anish Kumar et al (2012) concluded that pulse on time (T_{on}), pulse of time (T_{off}), peak current (IP) and spark voltage (SV) had a higher impact on surface roughness. [6] S. V. Subrahmanyam et al. Concluded that the Grey relational method is the most appropriate for multi-parametric optimization. [7] A.V.S. Ram Prasad et al (2014) experimentally proved that the peak current (I_p) & pulse on time (T_{on}) were dominant parameters to maximize the Material Removal Rate and surface roughness after they studied the effect of parameters on Ti-6Al-4V alloy. [8] Somvir Singh et al (2016) concluded that the white layer increases with the increase in pulse on time and for SR and MRR, pulse on time, spark gap voltage and pulse off time are momentous parameters. [9]

Vladimir Simna (2016) reported that the greater height of work material increases the wire breakage probability. [10] Sameh Habib et al (2017) resulted that the WT (Wire tension), WS (Wire speed), flow rate & SV (Servo voltage) greatly affect the kerf width and MRR and kerf width decreases with the increase of wire tension and speed. [11] Tompe S.V. et al reported that the MRR increases with the increase in (T_{off}) pulse off time. From the literature survey, it is ascertained that no plausible works were reported for the prediction of SR and cutting speed by hybrid optimization on an Inconel-600 Ni-based superalloy using a standard brass wire in WEDM process. Therefore, this experimental analysis and optimization work is undertaken to optimize the parameters in WEDM by Grey relational method coupled with Taguchi method.

II. Experimental Plan

Design-of-experiments (DoE) needs cautions scheduling, practical layout of the trials, Taguchi has identical procedures for every DoE application steps and the DoE can dramatically decrease the amount of trials. [9] Thus, the five parameters such as Taper angle (U & V axis taper angle in degrees), pulse on time (T_{on}), peak current (I_p), dielectric pressure and pulse off time (T_{off}) had selected for the governing parameter, and each parametric quantity had three levels denoted by level-1, level-2 and level-3except taper angle. Taper angle had two levels, i.e. maximum (2) and minimum (1) angle, as designated in the Table I.

TABLE I. Allocated Values Of WEDM Constraints And Their Levels

Factor	Parameter	Units	Level-1	Level-2	Level-3
X_1	Taper	Degree	2	1	----
X_2	Peak current (I_p)	Amps	110	120	130
X_3	Pulse on time (T_{on})	µs	109	111	113
X_4	Pulse off time (T_{off})	µs	54	58	62
X_5	Dielectric pressure	Ltr/min	10	11	12

A. Experimental set-up

As per DoE, the experiments were performed on ELEKTRA Ultima-1F WEDM. Inconel 600 superalloy was used in the form of thick rectangular plate. The chemical composition of Inconel 600 superalloy consists of 72% min. Ni & Co, 14-17 % Cr, 6-10% Fe, 0.50% max. Si, 1% max. Mn, 0.015% max. S, 0.15% max. C and 0.50% max. Cu. It has excellent mechanical properties, high strength and resistance to corrosion, therefore, this superalloy is mostly demanded in aerospace, chemical, heat treatment, nuclear and gas turbine industries. The workpiece and the brass wire having DIA. ϕ 0.25 mm electrode was linked up with +ve and –ve polarity in the D.C. power source, respectively. De-ionized water having a conductivity level of 0.6 µs/cm was used as dielectric medium. The dielectric fluid was flushed from the top and bottom nozzles and material was submerged in dielectric. The WEDM set-up is shown in figure 2.

Figure 2: Experimental set-up of ELEKTRA Ultima-1F WEDM

The surface roughness of the machined material were measured with Mitutoyo surftest surface roughness testers. Each trial was evaluated thrice and the mean values were obtained.

The mathematical relation used to evaluate the Surface roughness (SR) is given below:

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$$SurfaceRoughness\ (Ra) = \frac{1}{L}\int_0^L |Zx|\langle dx\rangle \quad (\mu m) \qquad (1)$$

Where ; Ra is the surface roughness value measured in µm, L = evaluation length ; Z(x) = profile height function.

The ANOVA mathematical relation (Higher is the better) utilized to calculate the S/N ratio of Cutting speed is given below:

$$\eta_{HB} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n} y_i\right] \qquad (2)$$

The ANOVA mathematical relation (Lower is the better) used to calculate the S/N ratio of SR is given below:

$$\eta_{LB} = -10\log\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right] \qquad (3)$$

The S/N ratio n_{ij} for the i^{th} performance characteristics in the j^{th} experiment is evaluated by following relation :

$$\eta_{ij} = -10\ \log[\ L_{ij}\ ] \qquad (4)$$

Where; y=observed data and n= no. of trials

III. DOE AND MULTI-PARAMETRIC OPTIMIZATION

The aim of this experimental analysis is to increase the cutting rate and to minimize the value of surface roughness. In the present experimentation work, L_{18} (2^1 3^4) mixed Orthogonal Array (OA) was chosen.

TABLE II. DOE MATRIX OF L_{18} ORTHOGONAL ARRAY

Sl. No.	Taper (X1)	I_p (X2)	T_{on} (X3)	T_{off} (X4)	Dielectric pressure (X5)
1.	2	110	109	54	10
2.	2	110	113	58	11
3.	2	110	113	62	12
4.	2	120	109	54	11
5.	2	120	111	58	12
6.	2	120	113	62	10
7.	2	130	109	58	10
8.	2	130	111	62	11
9.	2	130	113	54	12
10.	1	110	109	62	12
11.	1	110	111	54	10
12.	1	110	113	58	11
13.	1	120	109	58	12
14.	1	120	111	62	10
15.	1	120	113	54	11
16.	1	130	109	62	11
17.	1	130	111	54	12
18.	1	130	113	58	10

This OA has 18 parametric combination therefore, the total number of 18 experiments were conducted to measure the interactions between the various factors. The parameter combinations using the L_{18} (2^1 3^4) mixed OA are shown in Table II. For accurate measurements minimum three values were taken for each specimen and the mean value was selected. The mean values of the Surface roughness and cutting rate are shown in the Table III.

TABLE III. MEASURED VALUES FOR OUTPUT RESPONSES, AS PER DOE

Sl. No.	Surface Roughness (Ra)	Cutting Speed (mm/min.)	S/N Ratio (Surface roughness)	S/N Ratio (Cutting Rate)
1.	1.56	0.876	-3.86249	-1.14992
2.	1.74	0.939	-4.81098	-0.54669
3.	2.05	0.987	-6.23508	-0.11366
4.	1.74	0.944	-4.81098	-0.50056
5.	1.95	0.989	-5.80069	-0.09607
6.	2.09	1.072	-6.40293	0.603896
7.	2.69	2.304	-8.59505	7.249649
8.	2.59	1.915	-8.266	5.643376
9.	2.75	3.070	-8.78665	9.742768
10.	1.29	0.590	-2.21179	-4.58296
11.	1.77	1.054	-4.95947	0.456812
12.	2.03	1.070	-6.14992	0.587676
13.	1.54	0.720	-3.75041	-2.85335
14.	1.74	0.780	-4.81098	-2.15811
15.	2.14	1.479	-6.60828	3.399363
16.	2.40	1.860	-7.60422	5.390259
17.	2.64	3.240	-8.43208	10.2109
18.	2.52	2.010	-8.02801	6.063921

A. Multi-parametric optimization using the Taguchi and Grey relational analysis method

The steps used for multi-parametric optimization using the Grey relational analysis is discussed below;

a) Normalization of the all experimental results of SR and cutting rate: Linear normalization of experimental values is performed in the range of 0 and 1. The normalized values for output responses were calculated by using the standard formula:

$$Normalized\ Results\ (X_{ij}) = \frac{(y_{ij}) - (min_j y_{ij}}{(max_j y_{ij}) - (min_{ij}\ y_{ij})} \qquad (5)$$

Where,

y_{ij} = i^{th} experiment results in j^{th} experiment.

(b) Calculation for the Grey relational coefficients: Grey relational coefficients are evaluated to express the relation between the ideal and factual experimental consequences. The standard formula used for the computation of Grey relational coefficients is given below:

$$\delta_{ij} = \frac{min_i\, min_j\, |x^o_i - x_{ij}| + \xi max_i\, max_j |x^o_i - x_{ij}|}{|x^o_i - x_{ij}| + \xi max_i\, max_i |x^o_i - x_j|},\ 0 < \xi \qquad (6)$$

Where,

x^o_i = ideal normalized result

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TABLE IV. CALCULATED VALUES FOR NORMALIZATION AND DEVIATION SEQUENCE

Sl. No.	S/N Ratio		Normalization		Deviation Sequence	
	Surface Roughness	*Cutting speed*	*Surface Roughness*	*Cutting speed*	*Surface Roughness*	*Cutting speed*
1.	-3.86249	-1.14992	0.748937948	0.130389	0.251062	0.869611
2.	-4.81098	-0.54669	0.604677379	0.176563	0.395323	0.823437
3.	-6.23508	-0.11366	0.388080778	0.209709	0.611919	0.790291
4.	-4.81098	-0.50056	0.604677379	0.180094	0.395323	0.819906
5.	-5.80069	-0.09607	0.454148347	0.211055	0.545852	0.788945
6.	-6.40293	0.60390	0.362551944	0.264634	0.637448	0.735366
7.	-8.59505	7.24965	0.029142565	0.773332	0.970857	0.226668
8.	-8.26600	5.64338	0.079189309	0.650380	0.920811	0.349620
9.	-8.78665	9.74277	0	0.964167	1.000000	0.035833
10.	-2.21179	-4.58296	1	-0.132393	0.000000	1.132393
11.	-4.95947	0.45681	0.582094332	0.253376	0.417906	0.746624
12.	-6.14992	0.58768	0.401032608	0.263393	0.598967	0.736607
13.	-3.75041	-2.85335	0.765984327	0.000000	0.234016	1.000000
14.	-4.81098	-2.15811	0.604677379	0.053217	0.395323	0.946783
15.	-6.60828	3.39936	0.331319377	0.478613	0.668681	0.521387
16.	-7.60422	5.39026	0.179840955	0.631005	0.820159	0.368995
17.	-8.43208	10.21090	0.053928959	1.000000	0.946071	0.000000
18.	-8.02801	6.06392	0.115385438	0.682570	0.884615	0.317430

TABLE V. CALCULATED VALUES FOR GREY RELATIONAL COEFFICIENTS AND GRADES

Sl. No.	Grey relational co-efficients		Grey relational Grade
	Surface Roughness	*Cutting speed*	
1.	0.400340	0.793161	0.596751
2.	0.452621	0.739030	0.595825
3.	0.563012	0.704514	0.633763
4.	0.452621	0.735193	0.593907
5.	0.524028	0.703180	0.613604
6.	0.579675	0.653908	0.616791
7.	0.944925	0.392671	0.668798
8.	0.863276	0.434639	0.648957
9.	1.000000	0.341491	0.670746
10.	0.333333	1.360147	**0.84674**
11.	0.462067	0.663680	0.562873
12.	0.554919	0.654971	0.604945
13.	0.394950	1.000000	0.697475
14.	0.452621	0.903804	0.678213
15.	0.601454	0.510927	0.556191
16.	0.735466	0.442085	0.588775
17.	0.902643	0.333333	0.617988
18.	0.812499	0.422808	0.617653

(c) Calculation for the Grey relational grade: Grey relational grades as shown in Table V are evaluated by the average of Grey relational coefficient using the formula given below:

$$\alpha_j = \frac{1}{m}\sum_{i=1}^{m}\delta_{ij} \tag{7}$$

Where,

α_j = Grey relational grade

m = No. of execution grade characteristics

(d) Calculation of the optimum levels: optimum levels are calculated to find the significant parameter.

TABLE VI. GREY RELATIONAL GRADE RESPONSE TABLE

Parameters	***Level-1***	***Level-2***	***Level-3***
X_1	0.626571294	0.641205873	-----------
X_2	0.640149501	0.626030003	0.635486248
X_3	0.665407575	0.61957673	0.616681446
X_4	0.599742484	0.633050017	0.668873251
X_5	0.623513172	0.598100031	0.680052549
Average Grey relational Grade= 0.63389			

(e) Selection of the optimum levels of process constraints by taking the highest values of levels for each parameter from the optimum level table as shown in Table VI. The Response table is clearly indicating the level values for process parameters. The highest value of process parameters for each parameter showed the best optimized value.

(f) Confirmation of experiment and verification of the optimized process parameters.

B. Confirmation of Experiment

After obtaining the optimized values of process parameters the last step is to confirm the experimentation.

TABLE VII. CONFIRMATION OF EXPERIMENT

	Predicted Values	**Experimental Values**
Level	$X_1 2 X_2 2 X_3 1 X_4 2 X_5 3$	$X_1 2 X_2 1 X_3 1 X_4 3 X_5 3$
Surface Roughness (µm)	1.54	1.29
Cutting rate (mm/min.)	0.720	0.590
Grade	0.69747	0.84674
Improvement in Grey relational grade: 0.14927		

The mathematical relation used to calculate the estimated Grey relational grade is given below:

$$\hat{\alpha} = \alpha_m + \sum_{i=1}^{q}(\bar{\alpha}_i - \alpha_m) \tag{8}$$

Where,

α_m = Total mean of the Grey relational grade at optimum level

q = No. of process parameters.

IV. TAGUCHI ANALYSIS

Taguchi analysis is used for the selection of best optimized parameter value for the individual process parameter and to measure the influence of each parameter at different levels.

A. Influence of Input parameters on Surface roughness

The main effect plot for data means is showing the effect of individual parameter at different level of SR (Ra). For the measurement of SR, smaller is better (S/N) was utilized because the minimum value of SR means the higher value of surface finish. Therefore, for the measurement of surface roughness, 'Smaller is better' ratio is used.

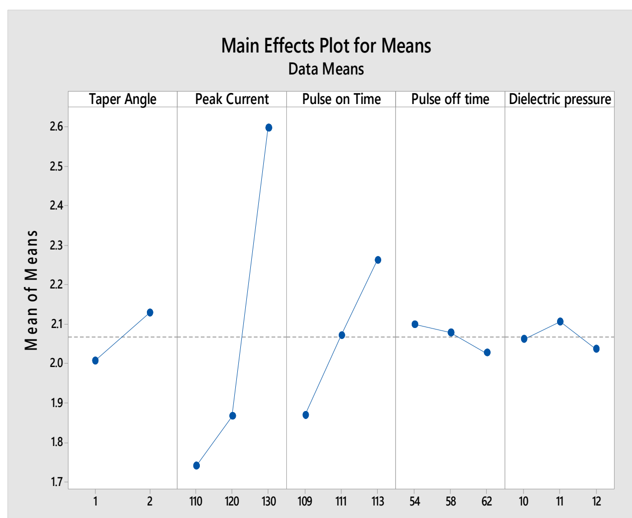

Figure 3: Main effect plot for data means (Smaller is better)

As per figure-3, main effect for data means the surface roughness is minimum at the level-1 of taper angle, level-1 of I_p, level-1 of T_{on}, level-3 of T_{off} and level-3 of the dielectric pressure. Therefore, these are the best optimized values of parameters for the minimum surface roughness. The rank given at 1,2,3,4 & 5 in table shows the most influencing parameters for surface roughness. For surface roughness, peak current and T_{on} is the most influencing parameter and dielectric pressure has the least significance, as shown in table VIII.

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TABLE VIII. RESPONSE TABLE FOR MEANS (SURFACE ROUGHNESS)

Level	Taper (X1)	I_p (X2)	T_{on} (X3)	T_{off} (X4)	Dielectric pressure (X5)
1	2.008	1.740	1.870	2.100	2.062
2	2.129	1.867	2.072	2.078	2.107
3	---	2.598	2.263	2.027	2.037
Delta	0.121	0.858	0.393	0.073	0.070
Rank	3	1	2	4	5

TABLE IX. LEVELS OF SELECTED INPUT PARAMETERS AT MINIMUM SURFACE ROUGHNES

Factor	Taper (X1)	I_p (X2)	T_{on} (X3)	T_{off} (X4)	Dielectric pressure (X5)
Level	1	1	1	3	3
Rank	3	1	2	4	5

B. Influence of Input parameters on Cutting speed

The main effect plot for data means as shown in figure 4 is showing the individual effect of each parameter at different levels of cutting speed. For the measurement of cutting speed, 'Higher is better' (S/N) ratio was utilized because the higher value of cutting speed means the higher performance and output of the machine. Therefore, higher is the better S/N ratio is used. As per figure no. 4, the most significant parameters for cutting speed are level-2 of taper angle, level-3 of I_p , level-3 of T_{on}, level-1 of T_{off} and level-3 of the dielectric pressure.

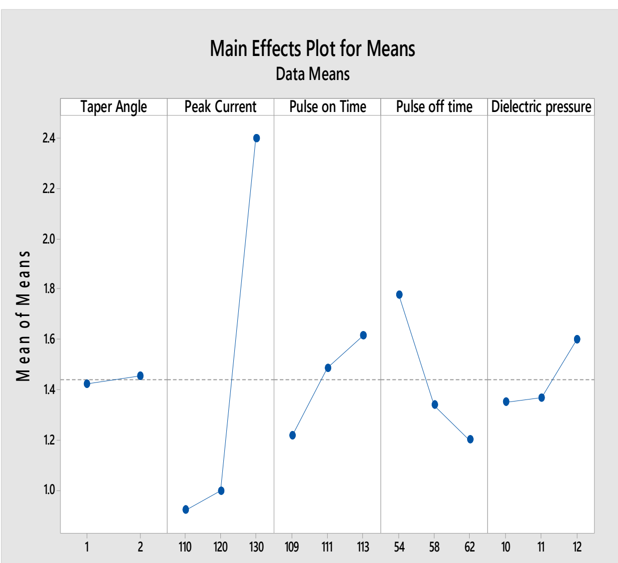

Figure 4: Main effect plot for data means (Higher is better)

The rank given in the table shows the most influencing parameters for cutting rate. For cutting rate, peak current and pulse off time is the most influencing parameter and taper angle is the least influencing parameter.

TABLE X. RESPONSE TABLE FOR MEANS (CUTTING SPEED)

Level	Taper (X1)	I_p (X2)	T_{on} (X3)	T_{off} (X4)	Dielectric pressure (X5)
1	1.4226	0.9193	1.2157	1.7772	1.3493
2	1.4551	0.9973	1.4862	1.3387	1.3678
3	---	2.3998	1.6147	1.2007	1.5993
Delta	0.0326	1.4805	0.3990	0.5765	0.2500
Rank	5	1	3	2	4

TABLE XI. LEVELS OF SELECTED INPUT PARAMETERS AT MAXIMUM CUTTING SPEED

Factor	Taper (X1)	I_p (X2)	T_{on} (X3)	T_{off} (X4)	Dielectric pressure (X5)
Level	2	3	3	1	3
Rank	5	1	3	2	4

V. RESULTS AND CONCLUSIONS

- The optimized parameters for the response of SR (Ra value) and cutting rate in WEDM are: 110 Amps of Peak current (I_p), 109 µs Pulse on time (T_{on}), 62 µs Pulse off time (T_{off}), 12 ltr/min. dielectric flow and minimum taper angle.
- The WEDM process parameters for super-alloy namely Inconel-600 has been optimized by Grey relational method coupled with Taguchi method.
- The optimal solution had calculated for surface roughness (SR) and cutting speed.
- An attempt had also been made to attain minimum and maximum evaluation of surface roughness (SR) and cutting speed respectively. The attained optimum outcomes had also been examined through a real experiment and established to be satisfactory.
- For surface roughness, the I_p and pulse on time (T_{on}) are the most significant parameter and the dielectric pressure is the least significant parameter.
- For cutting speed, peak current (I_p) and T_{off} are the most influencing parameter and taper angle is the least influencing parameter.
- The experimental results showed the considerable advancement in the process. The experimental results will facilitate the WEDM industries to improve the productivity, performances and cutting rate with higher surface finish.

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