iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 7 **Issue:** X **Month of publication:** October 2019

DOI: http://doi.org/10.22214/ijraset.2019.10065

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.177
Volume 7 Issue X, Oct 2019- Available at www.ijraset.com

Experimental Optimization of Process Parameters with Wire-EDM on Inconel 625

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Abstract: Inconel 625 Alloy was developed as a nickel-chromium alloy solid solution strengthened by its content of molybdenum and niobium. The alloy had two main areas of application like resistance to aqueous corrosion at ambient to slightly elevated temperatures and for high strength and resistance to creep, rupture, and corrosion at high temperatures, therefore had been widely used for more than five decades in the marine and petroleum industries for applications requiring high strength, fracture toughness, fabric-ability and resistance to corrosion. Inconel 625 is one such super alloy which has very good mechanical and thermal properties, and it is difficult to machine with traditional machining processes due to the high melting point and hardness. So, Wire EDM is a non - conventional machining process which is mainly used to machine hard and tough materials like Inconel 625. Design of experiment for three-level on six parameters i.e. peak current, pulse on time, pulse off time, wire feed rate, servo voltage and flushing pressure has obtained using MINITAB 18. Taguchi L27 orthogonal array along with ANOVA is used for optimizing the different parameters such to get maximum material removal rate and maximum hardness is obtained and confirmation test has been done for HV as Taguchi combination is not according to the design of experiments.
Keywords: Inconel 625, Taguchi L27, Material Removal Rate (MRR), Hardness(HV), Analysis Of Variance(ANOVA).

I. INTRODUCTION

Inconel 625 is superalloy of nickel and chromium which is mainly used in marine, petroleum, chemical industries due to its superiority mechanical, chemical and thermal properties [1]. These superalloys are very difficulties to machine with conventional machining methods such as turning, milling or grinding due to its very high hardness. To machining these superalloys non-convectional machining such as electrochemical machining, electric discharge machining, ultrasonic machining etc. are used because these are capable of machining with high accuracy and excellent finishing. Wire EDM is the advancement of EDM, electrothermal machining in which a series of spark is produced between the electrode (wire) and workpiece which is submerged in the dielectric fluid. During the pulse-on time or discharge period, work material is rapidly melted and vaporized to form a cut on the work-piece which is flashed by the dielectric fluid. Dielectric is used to cool the cutting zone and to remove the debris from the cutting zone to ready for the next cycle of discharge. Electrode wire is made of brass, copper or zinc-coated which have good electrical conductivity with a diameter of range 0.1, 0.15, 0.20, 0.25mm etc. depending on the type of application it is used for.

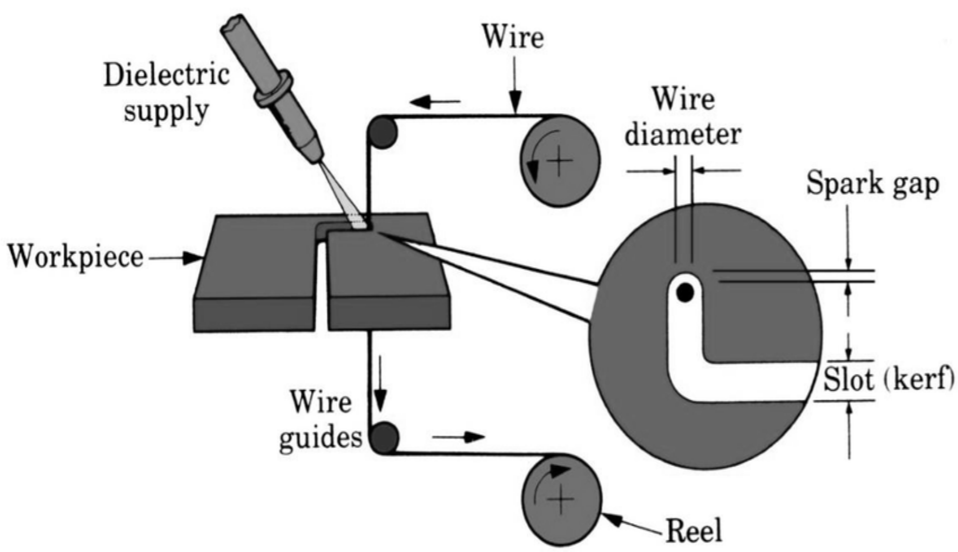

Fig.1. Schematic diagram of WEDM.

II. EXPERIMENT PROCEDURE

A. Abbreviations and Acronyms

Design of experiment (DOE), Material removal rate (MRR) and Micro-hardness (Hardness Vickers) HV

B. Experimental Material

Superalloy Inconel 625 can be manufactured these days in vacuum induction melted, controlled chemical composition, a fine-grain product that exhibits greatly improved toughness, hardness and thermal stability [1].

Table- I Chemical composition of Inconel 625.

S. No.	Chemical composition of Inconel 625	
	Element	Percentage %
1	Nickel (Ni)	61.56
2	Chromium (Cr)	21.47
3	Molybdenum (Mo)	8.10
4	Niobium (Nb)	2.53
5	Titanium (Ti)	0.15
6	Iron (Fe)	4.10
7	Aluminium (Al)	1.86
8	Silicon (Si)	2.26

Table- II Mechanical properties of Inconel 625

S. No.	Mechanical properties of Inconel 625	
	Properties	Value
1	Density (g/cm3)	8.44
2	Elastic modulus (GPa (at 21 °C))	207.5
3	Thermal conductivity (W/m °C (20–100 °C))	10.8
4	Electrical resistivity (μΩ-cm (20–100 °C))	132
5	Yield strength (MPa)	414–655
6	Tensile strength (MPa)	827–1034
7	Hardness (HB)	145–220
8	Melting point (°C)	1290–1350

The chemical composition and mechanical properties are as follows in table 1 and table 2[2].

C. Experimental Methodology

Inconel 625 plate of size 100*100*3 mm has been machined using Electronica Sprint wire-cut EDM machine and design of experiment for three-level on six parameters like peak current, pulse on time, pulse off time, wire feed rate, servo voltage and flushing pressure. Taguchi L27 orthogonal array along with ANOVA is used to optimize the different parameters such to get maximum material removal rate and maximum hardness is obtained. The wire of diameter 0.25 mm is tensioned between the lower and upper guide to obtained higher accuracy and Wire made of brass is used for the experiment. Dielectric fluid is deionized water with 12 to 16 TDS (total dissolved solids). Design of experiment for Taguchi orthogonal array, S/N and Mean table along their graphs to find the optimized combination of process parameters and ANOVA table for the contribution of parameters for MRR and HV has obtained using MINITAB 18.

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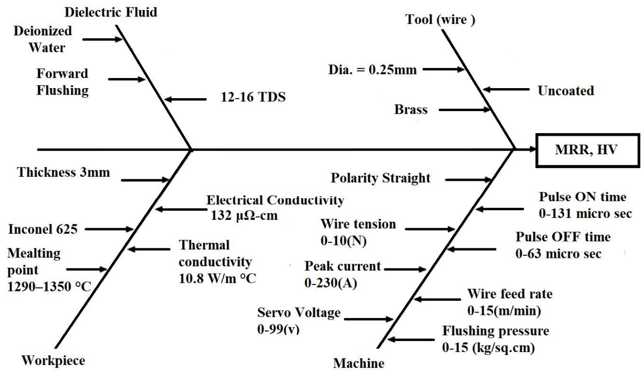

Fig.2.Electronica Sprint wire-cut EDM machine specification has been shown in the cause-effect diagram along with the tool, workpiece and Dielectric fluid to get outcomes as MRR and Micro-hardness HV [3].

Part design for cutting of plate has been done in solid works 2015, drawing sheet has been provided to the machining facility to cut small 27 pieces of size 10*10*3 mm from the plate using DOE.

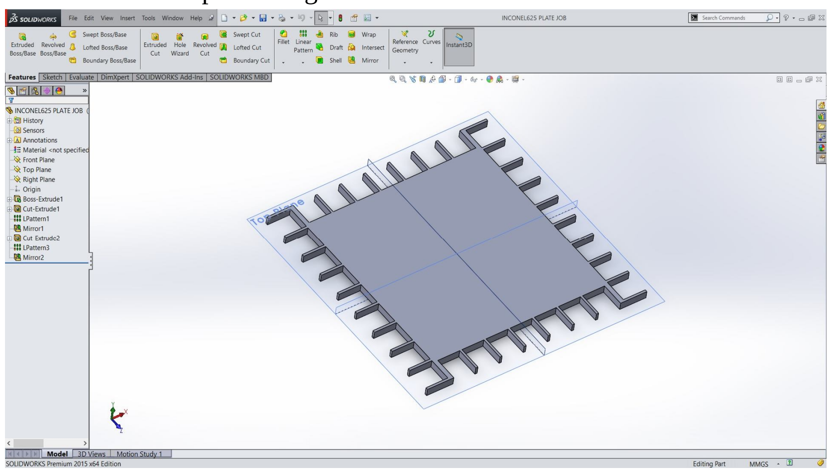

Fig. 3 Part modelling of Inconel 625 plate in solid works.

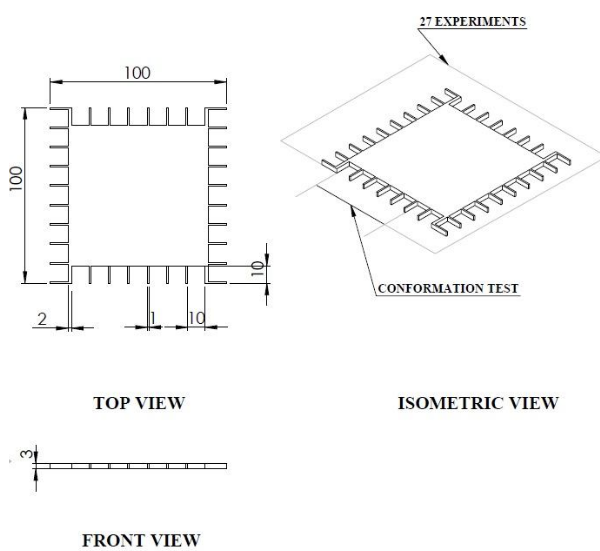

Fig. 4. Different views of part Inconel 625 plate from the drawing sheet.

D. Experimental Outcomes

1) *Material Removal Rate (MRR):* The material removal rate is the amount of the material removed per minute. The material removal rate is calculated by using the formula and its unit is g/min.

$$MRR = V_c \times T \times D \times KW$$

Vc= cutting speed (mm/min)
T = Thickness (mm)
D = Density
KW = Kerf (T_d + 2 x G_s)
T_d = Dia. of wire tool (0.25mm)
G_s = gap between workpiece and wire in mm

2) *Micro-hardness i.e. Hardness Vickers (HV):* Microhardness tester Fm-300e has been obtained precise Vickers (HV) and capability to get other values also like Knoop (HK) / Brinell (HB) /Fracture Toughness (Kc) measurements quick and easy.

Table- III
Shows the experimented values of Taguchi L-27 orthogonal array Matrix i.e Peak current, pulse-ON, pulse-OFF, wire feed rate, servo voltage, flushing pressure.

EXPT.NO	Peak Current	Pulse-ON	Pulse-OFF	Wire Feed Rate	Servo Voltage	Flushing Pressure
1	100	110	50	1	20	5
2	100	110	50	1	30	10
3	100	110	50	1	40	15
4	100	115	55	2	20	5
5	100	115	55	2	30	10
6	100	115	55	2	40	15
7	100	120	60	3	20	5
8	100	120	60	3	30	10
9	100	120	60	3	40	15
10	110	110	55	3	20	10
11	110	110	55	3	30	15
12	110	110	55	3	40	5
13	110	115	60	1	20	10
14	110	115	60	1	30	15
15	110	115	60	1	40	5
16	110	120	50	2	20	10
17	110	120	50	2	30	15
18	110	120	50	2	40	5
19	120	110	60	2	20	15
20	120	110	60	2	30	5
21	120	110	60	2	40	10
22	120	115	50	3	20	15
23	120	115	50	3	30	5
24	120	115	50	3	40	10
25	120	120	55	1	20	15
26	120	120	55	1	30	5
27	120	120	55	1	40	10

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III.RESULTS & DISCUSSIONS

Table- IV Experiment results of Inconel 625 by WEDM

S. No	Outcome Results	
	Material removal rate (MRR)	Hardness Vickers (HV)
1	0.025	175.0
2	0.041	183.0
3	0.040	185.0
4	0.033	176.0
5	0.045	172.0
6	0.044	175.0
7	0.039	171.0
8	0.069	174.0
9	0.054	177.0
10	0.035	180.0
11	0.034	182.0
12	0.033	182.0
13	0.046	184.0
14	0.044	188.0
15	0.040	185.0
16	0.040	169.0
17	0.033	170.0
18	0.045	174.0
19	0.031	192.0
20	0.030	185.0
21	0.025	187.0
22	0.032	184.0
23	0.037	188.0
24	0.046	189.0
25	0.036	194.0
26	0.047	174.0
27	0.049	184.0
Mean	0.040	180.7

A. Analysis of MRR

1) Signal to Noise Ratios for Material Removal Rate of Inconel 625 by wire EDM Process.

Table- V: Response Table for Signal to Noise Ratios for MRR for Larger is better.

Level	Peak Current	Pulse-ON	Pulse-OFF	Wire Feed Rate	Servo Voltage	Flushing Pressure
1	44.93	45.27	45.08	45.27	45.12	45.05
2	45.07	45.21	45.09	44.99	45.08	45.11
3	45.40	44.92	45.22	45.14	45.20	45.24
Delta	0.47	0.35	0.14	0.28	0.12	0.19
Rank	1	2	5	3	6	4

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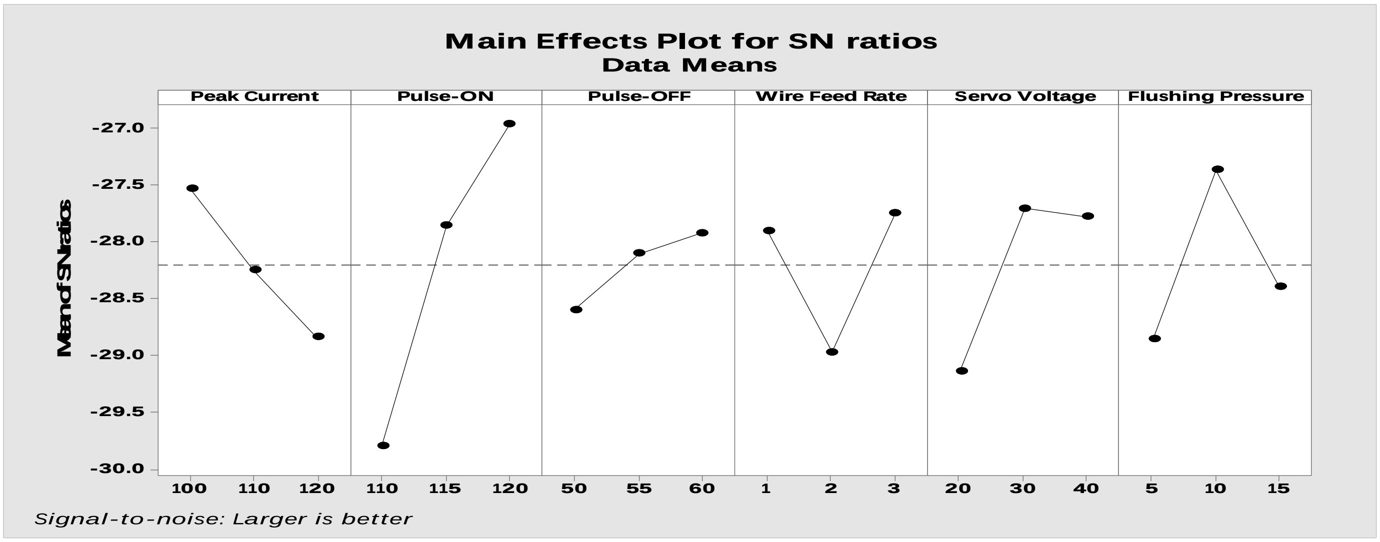

Fig.5. S/N Ratio of MRR graph and the combination levels **A1 B3 C3 D3 E2 F2**[4].

From figure 5, it has been observed that the combination for MRR is **A1 B3 C3 D3 E2 F2** i.e. peak current (100), pulse on time (120), pulse off time (60), wire feed rate (3), servo voltage (30) and flushing pressure (15) has been identified as the optimum value of process parameters.

2) ANOVA analysis of variance for MRR

Table- VI Response Table for Analysis of variance for MRR.

Source	*DF*	*Adj SS*	*Adj MS*	*F-Value*	*P-Value*	*% Contributions*
Peak Current (A)	2	0.000198	0.000099	2.99	0.083	8.80
Pulse-ON (µm)	2	0.000779	0.00039	11.73	0.001	34.62
Pulse-OFF (µm)	2	0.000082	0.000041	1.24	0.32	3.64
Wire Feed Rate (m/min)	2	0.000178	0.000089	2.67	0.104	7.91
Servo Voltage (V)	2	0.000269	0.000134	4.05	0.041	11.96
Flushing Pressure (kg/square cm)	2	0.000279	0.00014	4.2	0.037	12.40
Error	14	0.000465	0.000033			20.67
	26	0.00225				100.000

Pulse-ON is the most influential factor among the other input parameter and contribution is 34.62%.

B. Analysis of Hardness Vicker

1) Signal to Noise Ratios for Hardness Vickers of Inconel 625 by wire EDM Process

Table VII Response Table for Signal to Noise Ratios Hardness Vickers (HV) for Larger is better

Level	Peak Current (A)	Pulse-ON (µm)	Pulse-OFF (µm)	Wire Feed Rate (m/min)	Servo Voltage (V)	Flushing Pressure (kg/square cm)
1	44.93	45.27	45.08	45.27	45.12	45.05
2	45.07	45.21	45.09	44.99	45.08	45.11
3	45.40	44.92	45.22	45.14	45.20	45.24
Delta	0.47	0.35	0.14	0.28	0.12	0.19
Rank	1	2	5	3	6	4

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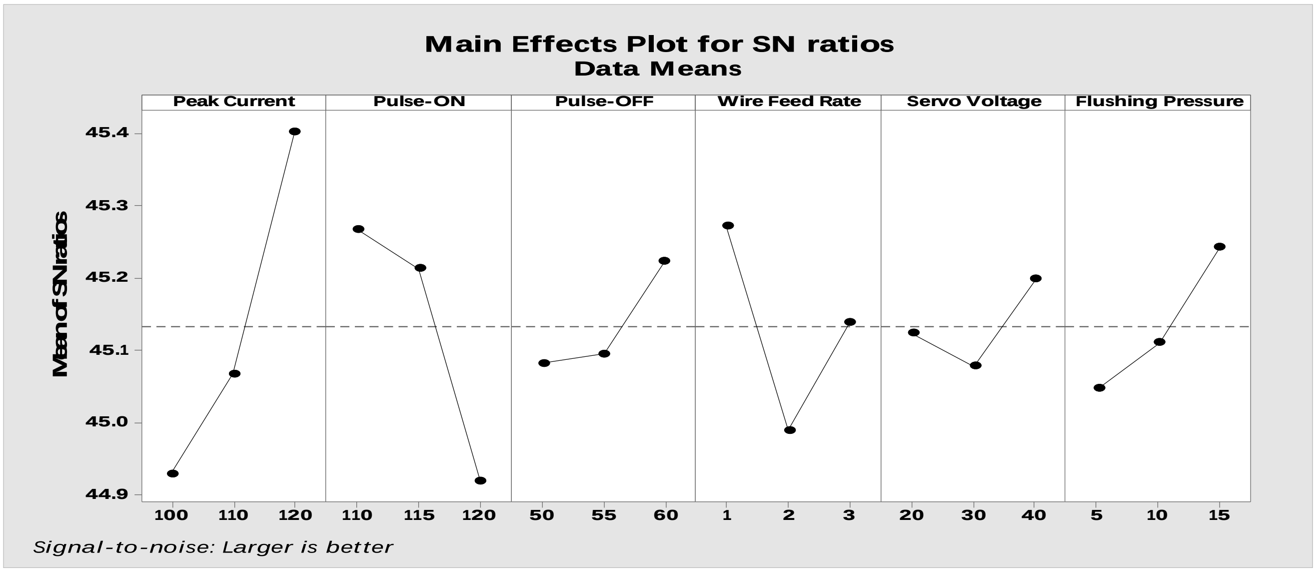

Fig.6. S/N Ratio of Hardness Vickers graph and the combination levels A3 B1 C3 D1 E3 F3

From figure 6, it has been observed that the combination for HV is A3 B1 C3 D1 E3 F3i.e. peak current (120), pulse on time (110), pulse off time (60), wire feed rate (1), servo voltage (40) and flushing pressure (15) has been identified as the optimum value of process parameters but this doesn't satisfy the L -27 orthogonal array such, we have to perform the confirmation test for the Hardness Vickers but we have seen a drastic decline in HV from average 396.9 HV of pre-machining condition to approximately average 180.7 HV of after machining condition.

2) *The confirmation test for Hardness Vickers:* As the confirmation test has been done for HV as Taguchi combination is not according to the design of experiments [5].

Table VIII Response Table for Mean of Hardness Vickers (HV)

Level	Peak Current (A)	Pulse-ON (µm)	Pulse-OFF (µm)	Wire Feed Rate (m/min)	Servo Voltage (V)	Flushing Pressure (kg/square cm)
1	176.4	183.4	179.7	183.6	180.6	178.9
2	179.3	182.3	179.9	177.8	179.6	180.2
3	186.3	176.3	182.6	180.8	182.0	183.0
Delta	9.9	7.1	2.9	5.8	2.4	4.1
Rank	1	2	5	3	6	4

Table IX Response Table for confirmation test of Hardness Vickers (HV)

Source	Parameters	Combination	Mean Value
Peak Current (A)	120	A3	186.3
Pulse-ON (µm)	110	B1	183.4
Pulse-OFF (µm)	60	C3	182.6
Wire Feed Rate (m/min)	1	D1	183.6
Servo Voltage (V)	40	E3	182.0
Flushing Pressure (kg/square cm)	15	F3	183.0

M(mean) = Total of all values/ No. of values and values should take from the table (Table IV).
Values for the combination taken from the mean table (Table IX).
Formula for conformation test = M + (A-M) + (B-M) + (C-M) + (D-M) + (E-M) + (F-M)
Conformation value = M + (A3-M) + (B1-M) + (C3-M) + (D1-M) + (E3-M) + (F3-M)
= 180.7 + (186.3-180.7) + (183.4-180.7) + (182.6-180.7) + (183.6-180.7) + (182.0-180.7) +(183.0-180.7)
=197.4

$$Error = \frac{197.4 - 180.7}{180.7} = 0.0924$$

3) ANOVA analysis of variance for Hardness Vickers.

Table X: Response Table for Analysis of variance for Hardness Vickers.

Source	DF	Adj SS	Adj MS	F-Value	P-Value	% CONTRIBUTIONS
Peak Current (A)	2	465.41	232.7	13.48	0.001	36.54
Pulse-ON (µm)	2	263.41	131.7	7.63	0.006	20.68
Pulse-OFF (µm)	2	46.52	23.26	1.35	0.292	3.65
Wire Feed Rate (m/min)	2	150.3	75.15	4.35	0.034	11.80
Servo Voltage (V)	2	27.19	13.59	0.79	0.474	2.13
Flushing Pressure (kg/square cm)	2	79.19	39.59	2.29	0.137	6.22
Error	14	241.63	17.26			18.97
Total	26	1273.63				100.00

Peak Current is the most influential factor among the other input parameter and contribution is 36.54%.

IV. CONCLUSION

The presents study deals with the optimization of the process parameters on Wire EDM machining for Inconel 625 alloy material by taking Material removable rate (MRR) and Microhardness (HV) as responses. After successful completion of all experimental analysis on Inconel, the following conclusions were drafted

1) For MRR, the optimization combination is A1 B3 C3 D3 E2 F2 0.69 g/min.
2) For MRR pulse-ON is the most influential factor among the other input parameter and contribution is 34.62%.
3) For Micro Hardness(HV) the optimization combination is A3 B1 C3 D1 E3 F3 with 197.4HV.
4) For Microhardness, the peak Current is the most influential factor among the other input parameter and contribution is 36.54%and confirmation test has been done for HV as Taguchi combination is not according to the design of experiments.
5) We could see the steep decline in Microhardness from average 396.9 HV of pre-machining condition to approximately average 180.7 HV of after machining condition.

V. ACKNOWLEDGEMENT

I owe a deep sense of gratitude to my Father Mr Omkar Singh, Mother Dr Rekha for their understanding, affection and financial support for this work. And I would like to thank Mr D. Sampath Kumar (Metallurgist), Mr Shamba Shiva, (Metallurgist), Virtue Meta-Sol. Material Solution, Balanagar, Hyderabad for Microhardness testing at their facility.

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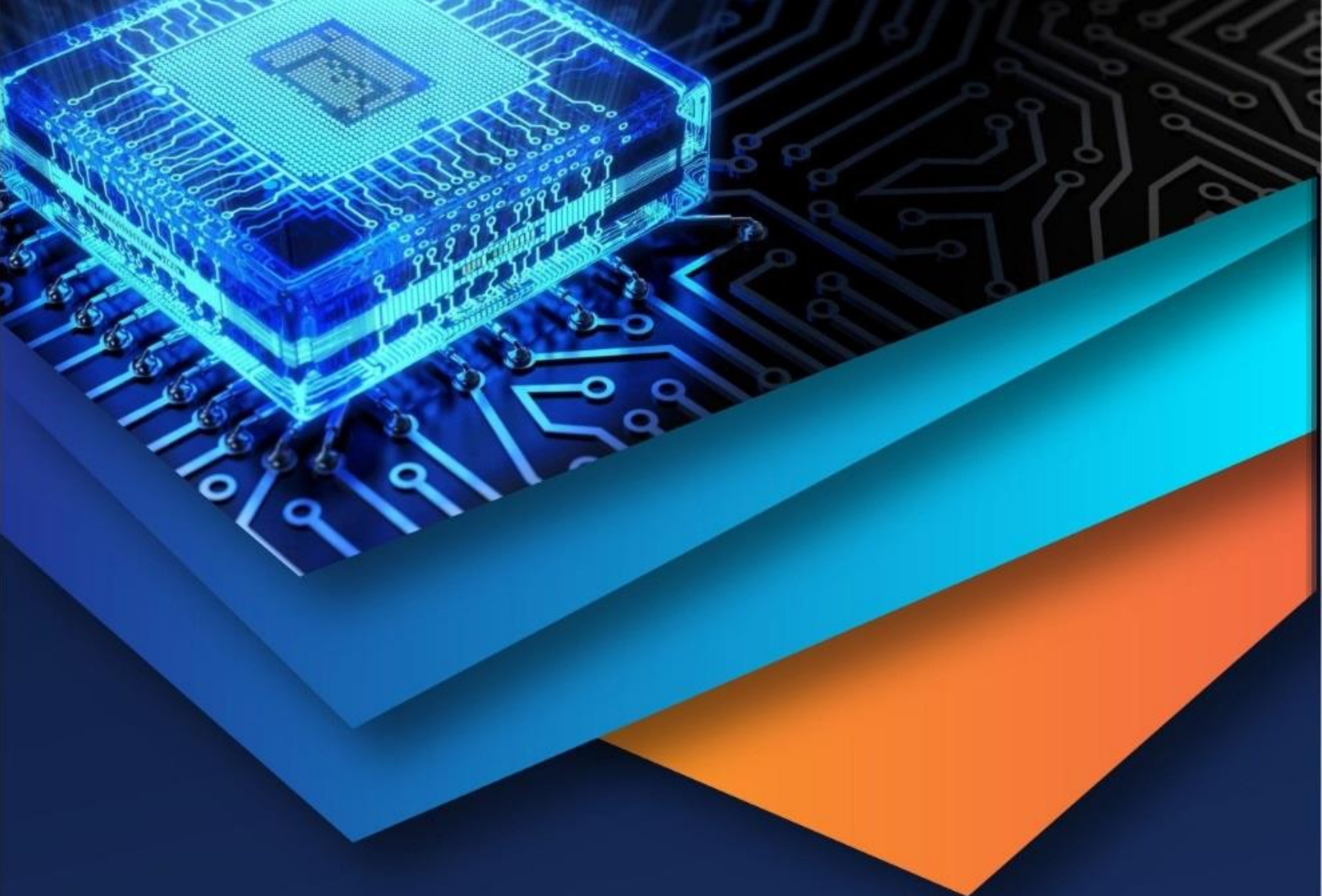

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