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Improvement of Surface Quality of INCONEL-625 Using Utility Method in EDM Machining By Varying Current Densities

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Abstract: *Electro discharge machining (EDM) process is an advanced machining process because of burrs free, less metallurgical damage, stress free and very precise machining. It produces mould cavity, deep holes, complex shapes and sizes by spark erosion process in all types of electroconductive materials. This process is used to make dies of different shapes and sizes and also used in various industries like automobiles, aerospace, nuclear reactor and surgical instruments. The operating temperature of the super alloys varies from 1200F to 1300F. Nickel based super alloys widely used for aerospace engine components, power-generation turbines, rocket engines, chemical processing plants, petrochemical, food processing, nuclear reactor, pollution control equipment and other tough environments applications. INCONEL 625 used in this process due to their high hardness and high wear resistant properties. In the present study, INCONEL 625 workpiece material is machined by EDM using two different diameters of copper tool such as 10mm and 15mm. The experiment are carried out economically by varying the input current, pulse on time, pulse off time and flushing pressure according to Taguchi's* L_9 *orthogonal array. Four output parameters such as: surface roughness, crackwidth, surface crack density and hardness are optimized simultaneously using the Utility optimization method to obtain the best level of input parameters. When the diameter are varied, a better result is found out based on the value of signal to noise ratio. Then ANOVA method is used to find out the most effective input parameter. Finally, a confirmation test is carried out to obtain the best diameter of copper tool. This technique can also be extended for other process optimization and helpful for industry personnel to select appropriate process parameters for making a die of long life.*

Index Terms: *ANOVA, EDM, Taguchi's* L_9 *orthogonal array, Utility method.*

I. INTRODUCTION

Electro-discharge machining is a non-conventional machining process used in various industries such as aerospace, automobiles, nuclear industry, surgical instrument, sports, optical, dental, jewellery etc. The various harder and difficult to machine materials such as stainless steel, nimonics, nickel based alloy, metal matrix, conductive ceramics are machined by this process. The thermal energy of the EDM process is used to machine electrically conductive materials regardless of hardness is a distinctive advantage in the manufacturing of mold and die making. EDM is a process for eroding and removing material by transient action of electric sparks on electrically conductive materials, one being the workpiece electrode and the other being the tool electrode, immersed in a dielectric fluid and separated by a small gap. The main mode of erosion is caused due to local thermal effect of an electric discharge [1]. Bighnesh Kumar Sahu et.al [2] studied the influence of peak discharge current, pulse on duration and gap voltage on the material removal rate, surface crack density and white layer thickness while INCONEL-718 was machined in EDM. D Sudhakara et.al [3] reported that, the effective parameter was the input current. According to them, the change of current, affected severely on MRR, surface roughness, crack length and crack widths. Gangadharudu Talla et.al [4] investigated EDM, utilizing the graphite powder and its various combination of concentration. They had also varied different machining parameters to study the output parameters such as: surface roughness, surface crack density, white layer thickness (WLT), microhardness, depth profile, possible phase changes and residual stress during powder mixed EDM of INCONEL 625. Hwa-teng Lee and T.Y.Tai [5] reported that, surface cracks were formed while machining D2 and H13 tool steels in EDM. They maintained the pulse voltage of 120 V and pulse current in the range of 12-16A together with a pulse on duration of 6-9 µs and could able to avoid the formation of cracks. Munmun Bhaumik and Kalipada Maity [6] studied the machining of AISI 304 stainless steel by using tungsten carbide electrode with silicon carbide powder mixed EDM considering kerosene as dielectric. According to them, an increase in peak current and powder concentration decreased the surface crack density. Rahul et.al [7] reported the presence of different types of cracks formed in INCONEL 718 during EDM. Effects of significant process parameters on surface topography in terms of roughness average, surface crack density, white layer thickness, etc. had been graphically represented by them. Finally, utility theory in conjugation with Taguchi's optimization philosophy had been attempted to select the most favorable process environment (parameters setting) to satisfy optimal surface roughness, surface crack density and white layer thickness; thereby, ensuring high product quality along with its specified functional requirements in appropriate application domain. S. Rajendran, et.al [8] analyzed the crack formation and spherical form of resolidified layer on T90Mn2W50Cr45 tool steel surface while machined in EDM.

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They found that the pulse current was directly proportional with resolidified layer thickness and crack density. Soni Kumari et.al [9] analysed the surface roughness, surface crack density, white layer thickness and microhardness of INCONEL-825 super alloy. Various metallurgical characteristics of EDMed surface were studied by them. Dileep kumar Mishra et.al [10] studied the influence of the process parameters on various process performance characteristics like material removal rate, surface roughness, surface crack density, white layer thickness, circularity, radial overcut and hole taper. An optimal parameter setting had been identified for sound hole making and thereby to improve the electro-discharge machining performance. Rahul et.al [11] repoted that the experimental investigation on assessing machining performance during Electro-Discharge Machining (EDM) of INCONEL 625 by varying gap voltage, peak current, pulse-on time, duty factor and flushing pressure (each varied at four discrete levels) to examine machining performance characteristics like electrode wear ratio, radial overcut, roughness average, and surface crack density of EDMed end product obtained by utilizing different parameters settings as per design of experiment. Gangadharudu Talla [12] established the criteria for powder material selection by investigating the influence of various powder-suspended dielectrics and machining parameters on various EDM characteristics of INCONEL 625 (a nickel-based super alloy). They used different powders such as aluminum (Al), graphite, and silicon (Si) those were having significant variation in their thermo-physical characteristics. Results showed that powder properties like electrical conductivity, thermal conductivity, density, and hardness played a significant role in changing the machining performance and the quality of the machined surface. Among the three powders, highest material removal rate was observed for graphite powder due to its high electrical and thermal conductivities. Best surface finish and least radial overcut (ROC) were attained using Si powder. Maximum microhardness was found for Si due to its low thermal conductivity and high hardness

It is observed from the stated past research works that a few works have been reported on the improvement of surface quality of INCONEL 625. In the present work, extensive experimental work has been carried out on INCONEL 625 to achieve minimum possible surface crack density, minimum crack width, higher surface finish and highest achievable hardness, using utility method the most popular multi-response optimization technique. It will be highly helpful for the industry personnel to decide judiciously the input parameters for best surface quality with long life assurance for popularly used die material INCONEL 625.

II. EXPERIMENTAL WORK

The experiment was conducted on an Electro-Discharge Machine with Model ECOWIN MIC-432CS CNC EDM as shown in Fig.1. The workpiece INCONEL 625 with compositions as shown in Tab.I was machined with two different diameters (10mm and 15mm) of copper tool separately. Four input parameters were varied such as: input current, pulse on time, pulse off time and flushing pressure with their ranges presented in Tab.II. All the input parameters were arranged as per L_9 orthogonal array [13] in Tab.III. According to the L_9 orthogonal array, experiments have been carried out and the output parameters such as surface roughness (SR), crackwidth (CW), surface crack density (SCD) and hardness were determined. The values of output parameters for 10mm and 15mm diameter are shown in Tab.IV and Tab.V respectively. It may be noted that the hardness of the unmachined surface of INCONEL 625 was measured as 325Hv by a micro-hardness testing machine.

Fig.1 ECOWIN MIC-432CS CNC EDM

Table-I: The composition of workpiece (INCONEL 625)

Element	Weight%
C	1.01
Al	0.20
Si	0.28
P	0.02
Ti	0.20
Cr	16.62
Fe	22.42
Co	0.07
Ni	52.66
Nb	1.91
Mo	4.61

Table-II: Input parameters and their ranges

Input parameters	Value at Low level (1)	Value at Medium level (2)	Value at High level (3)
Input current (A)-amp	10	20	30
Pulse on time(B)-μs	200	500	1000
Pulse off time(C)-μs	100	175	250
Flushing pressure(D)-$\frac{kgf}{cm^2}$	0.15	0.25	0.5

Table-III: Arrangement of input parameters in L_9 orthogonal array

Expt.No.	Input current (A)-amp	Pulse on time(B)-μs	Pulse off time(C)-μs	Flushing pressure (D)-$\frac{kgf}{cm^2}$
1	10	200	100	0.15

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2	10	500	175	0.25
3	10	1000	250	0.5
4	20	200	175	0.5
5	20	500	250	0.15
6	20	1000	100	0.25
7	30	200	250	0.25
8	30	500	100	0.5
9	30	1000	175	0.15

Table-IV: Experimental values of output parameters (for 10mm diameter of copper tool)

Expt.No.	SR in µm	C.W in µm	SCD in µm	Hardness in Hv
1	1.98	1.58	0.007618	375
2	2.38	1.99	0.006815	587
3	2.51	1.8	0.009773	872
4	2.25	2.37	0.004458	497
5	2.65	2.19	0.00622	516
6	2.87	1.82	0.006625	908
7	2.96	1.97	0.008005	676
8	3.09	1.58	0.009324	802
9	3.2	1.69	0.010212	742

Table-V: Experimental values of output parameters (for 15mm diameter of copper tool)

Expt.No.	SR in µm	C.W in µm	SCD in µm	Hardness in Hv
1	1.85	1.7	0.01035	445
2	2.9	1.55	0.01255	602
3	2.63	1.84	0.014259	511
4	2.15	1.87	0.006325	3786
5	2.78	1.99	0.004856	700
6	3.18	2.65	0.010687	402
7	2.45	1.42	0.004228	441
8	3.3	2.3	0.007423	378
9	3.58	2.4	0.006971	8023

III. OPTIMIZATION OF EXPERIMENTAL RESULTS USING UTILITY TECHNIQUE

Here Utility method is used as an optimization technique. In order to achieve the minimum loss to the society, the output parameters are simultaneously optimized and get the best level of input parameters.

Utility method:

Utility can be determined by the level of satisfaction of the customers irrespective of the level of expectations or input parameters. So that the summation of utilizes of each objective function indicates the overall utility of a product. It is used for multi-response optimization [14].

The steps followed in this optimization technique are stated in the following.

Step-1: Calculation of constant A:

The value of constant A can be calculated using Eq.1 as follows:

$$A=\frac{9}{\log_{10}\left(\frac{Y^*}{Y^-}\right)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (1)$$

Where, Y^*=maximum value of the each output parameter

Y^-=minimum value of each output parameter

Step-2: Calculation of individual utility:

The individual utility(u_{pq}) is represented as:

$$u_{pq}=A\times\log_{10}\frac{y_{pq}}{Y^-} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Where, u_{pq}=individual utility at pth rows and at qth column.

y_{pq}=response variable at pth rows and at qth column. First of all, the constant (A) for all the output can be calculated using Eq.1

and after that, the individual utility value can be calculated by using Eq.2. The calculated values are shown in Tab.VI and Tab.VII.

Table-VI: The individual utility of output parameters (for 10mm diameter of copper tool)

Expt.No.	u_{pq-SR}	u_{pq-CW}	u_{pq-SCD}	u_{pq-HV}
1	9	9	3.182005	0
2	5.55032	3.878997	4.391481	4.560449
3	4.553264	6.106394	0.477111	8.588277
4	6.603394	0	9	2.866588
5	3.535687	1.753285	5.383448	3.248408
6	2.040498	5.861124	4.698505	9
7	1.461615	4.103208	2.643952	5.997165
8	0.655796	9	0.987794	7.736629
9	0	7.506078	0	6.945247

Table-VII: The individual utility of output parameters (for 15mm diameter of copper tool)

Expt.No.	u_{pq-SR}	u_{pq-CW}	u_{pq-SCD}	u_{pq-HV}
1	9	6.403854	2.372059	0.4807
2	2.871757	7.73637	0.945173	1.370878
3	4.204039	5.262273	0	0.888093
4	6.951247	5.028974	6.018055	6.78768
5	3.447873	4.131774	7.974734	1.815175
6	1.615225	0	2.134843	0.181339
7	5.170541	9	9	0.454101
8	1.110252	2.043355	4.83297	0
9	0	1.429418	5.298085	9

Step-3: Calculation of overall utility:

The overall utility can be calculated by using Eq.3 as follows:

$$u_p=\sum_{q=1}^{n} w_q \times u_{pq} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

Where, w_q=weightage of each output parameter.

The weightage of each output parameter can be calculated by the analytical hierarchy process (AHP) [15] in which w_1 =0.56, w_2 =0.26, w_3 =0.12 and w_4 =0.06 are the weightage of surface roughness, crack width, surface crack density and hardness respectively. The calculated overall utility values are shown in Tab.VIII and Tab.IX.

Step-4: Calculation of signal-to-noise ratio of overall utility:

Signal-to-noise ratio of overall utility can be calculated using following formula (Eq.4) and these values are shown in Tab.VIII and Tab.IX.

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$$\text{S/N-}u_p = -10\text{x}\log_{10}\frac{1}{u_p^{\,2}} \quad \text{..............................(4)}$$

Table-VIII: Overall utility and signal-to-noise ratio (for 10mm diameter of copper tool)

Expt.No.	Overall utility-u_p	S/N-u_p	Rank
1	7.761841	17.79929	1
2	4.917323	13.83457	3
3	4.71004	13.46049	4
4	4.949896	13.89192	2
5	3.276757	10.30888	7
6	3.770391	11.52773	5
7	2.562442	8.173082	8
8	3.289979	10.34386	6
9	2.368295	7.488716	9
	Avg.= 4.178552		

Table-IX: Overall utility and signal-to-noise ratio (for 15mm diameter of copper tool)

Expt.No.	Overall utility-u_p	S/N-u_p	Rank
1	7.018491	16.92488	1
2	3.815314	11.6306	5
3	3.775738	11.54004	6
4	6.329659	16.02761	3
5	4.070949	12.19391	4
6	1.171587	1.375493	9
7	6.342749	16.04555	2
8	1.73297	4.77582	7
9	1.547419	3.792159	8
	AVG= 3.97832		

From the Tab.VIII, for the 10mm diameter of copper tool, the Expt. No.1 shows the highest value of signal-to-noise ratio of overall utility. The corresponding level combination of input parameter is $A_1B_1C_1D_1$. i.e 10amp of input current, 200 µs of pulse on time, 100 µs of pulse off time and 0.15 $\frac{kgf}{cm^2}$ of flushing pressure. Then a graph is plotted between experiment number with overall utility and is presented in Fig.2.

Similarly from the Tab.IX, for the 15mm diameter of copper tool, the Expt. No.1 shows the highest value of signal-to-noise ratio of overall utility. The corresponding level combination of input parameter is $A_1B_1C_1D_1$. i.e 10amp of input current, 200 µs of pulse on time, 100 µs of pulse off time and 0.15 $\frac{kgf}{cm^2}$ of flushing pressure. Then a graph is plotted in between experiment number with overall utility and is presented in Fig.3.

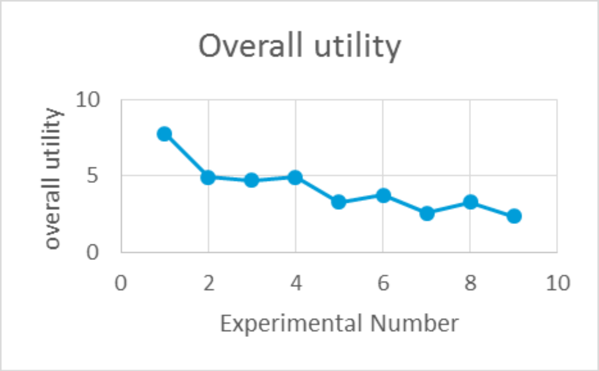

Fig-2: Experiment number with overall utility (for 10mm diameter)

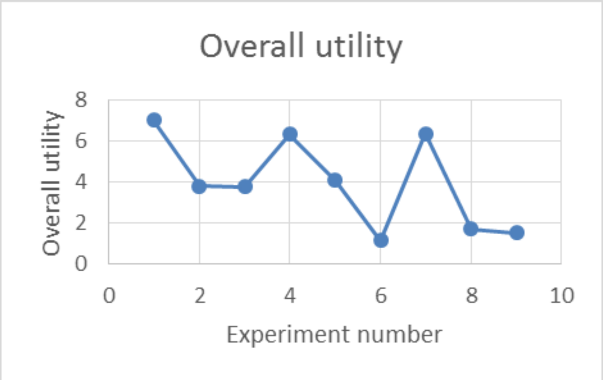

Fig-3: Experiment number with overall utility (for 15mm diameter)

Step-5 Average response of the Overall Utility:

The experimental design is a orthogonal array design in which the effect of each machining parameter on the overall utility at different levels can be determined. The mean of the overall utility for the input current at levels 1, 2 and 3 can be calculated by averaging the overall utility for the experiments 1 to 3, 4 to 6 and 7 to 9 respectively. The mean of the Overall utility for each level of the other machining parameters can be calculated in similar manner. The average responses of overall utility are presented in Tab.X. for 10mm diameter and Tab.XI for 15mm diameter.

Table-X: Average responses of overall utility (for 10mm diameter)

Machining parameters	LEVEL-1	LEVEL-2	LEVEL-3
Input current-A	5.796401	3.999015	2.740239
Pulse on time-B	5.091393	3.828019	3.616242
Pulse off time-C	4.940737	4.078505	3.516413
Flushing pressure-D	4.468964	3.750052	4.316638

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Table-XI: Average responses of overall utility (for 15mm diameter)

Machining parameters	LEVEL-1	LEVEL-2	LEVEL-3
Input current-A	4.869848	3.857398	3.207713
Pulse on time-B	6.563633	3.206411	2.164915
Pulse off time-C	3.307683	3.897466	4.729812
Flushing pressure-D	4.212286	3.77655	3.946122

From the average responses of overall utility (Tab.X) the optimum level is $A_1B_1C_1D_1$ which implies 10 amp of input current, 200 µs of pulse on time, 100 µs of pulse off time and 0.15 $\frac{kgf}{cm^2}$ of flushing pressure. Then a graph is plotted between the average responses of overall utility and the level of input parameters as shown in Fig.4.

Similarly the average response of overall utility (Tab.XI) the optimum level is $A_1B_1C_3D_1$ which implies 10 amp of input current, 200 µs of pulse on time, 250 µs of pulse off time and 0.15 $\frac{kgf}{cm^2}$ of flushing pressure. Then a graph is plotted between the average response of overall utility and the level of input parameters as shown in Fig.5.

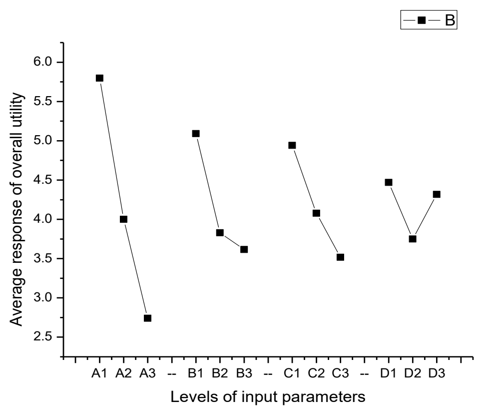

Fig 4. Average response of overall utility with different levels of input parameters

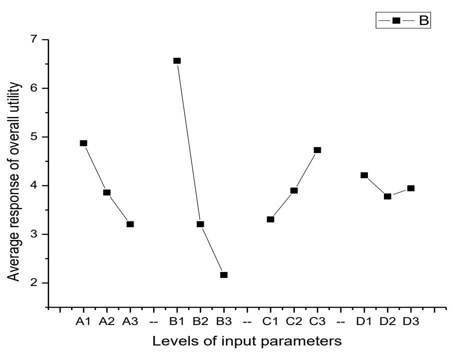

Fig 5. Average response of overall utility with different levels of input parameters

IV. ANALYSIS OF VARIANCE (ANOVA) OF UTILITY TECHNIQUE

The main aim of the analysis of variance is to find out the importance of the input parameters. The machining parameter which significantly affects the performance characteristics that can be determined. This is accomplished by separating the total variability of the optimization technique which is measured by the sum of the squared deviations from the total mean of the overall utility, into contributions by each machining parameter and the error.

For Utility technique,

First, the total sum of the squared deviations SS_T is determined.

Sum of squared deviation of total

SST=$\sum_{p=1}^{m}(u_p - u_g)^2$……………………………….(5)

Sum of squared deviation of first input parameter of A

SSA=$\sum_{k}^{l}(u_k - u_g)^2$………………………………….(6)

Where, u_g=total mean of the overall utility value.

u_k=the mean value of the overall utility in the corresponding input parameter at different level.

m= number of experiments.

k= (1, 2, 3,…………..l), l= number of levels

Similarly, sum of squared deviation for other input parameters are calculated using Eq.6.

Sum of squared deviation of error,

SSE=SST-(SSA+SSB+SSC+SSD+…..) ……….........(7)

Once the sums of squared deviation of all are calculated, the mean square can be calculated as follows:

Mean square of the input current (A)

$MS_A=\frac{SS_A}{DOF}$ ………………………………………. …..(8)

Where, DOF =Degrees of freedom of the input parameters. It is calculated as: levels of input parameter-1

Fo is the fisher's test and the value can be calculated as

$Fo=\frac{MS_A}{MS_{Error}}$ ……..................(9)

Percentage contribution of input current (A) = $\frac{SS_A}{SS_T}\times 100$ ………………………………………………. (10)

Similarly the percentage contribution of other parameters can be determined.

The different parameters for ANOVA for utility method of both 10mm and 15mm diameter of copper tool can be calculated using Eq.5 to Eq.10 and are presented in Tab.XII and Tab.XIII respectively.

Table-XII: Analysis of variance (ANOVA) for Utility (for 10mm diameter)

Machining parameter	Error Parameter	DOF	SS	MS	FO	% contribution
Input current -A		2	14.15	7.08	16.44	64.57
Pulse on time-B		2	3.82	1.91	4.43	17.41

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Pulse off time-C		2	3.09	1.54	3.59	14.09
Flushing pressure-D	**ERROR**	2	0.86	0.43	1	3.93
ERROR		0	0	0		
TOTAL		8	21.92	2.74		100

Table-XIII: Analysis of variance (ANOVA) for Utility Method (for 15mm diameter)

Machining parameter	**Error parameter**	**DOF**	**SS**	**MS**	**FO**	**% Contribution**
Input current-A		2	4.21	2.10	14.54	10.72
Pulse on time-B		2	31.70	15.85	109.53	80.74
Pulse off time-C		2	3.06	1.53	10.58	7.80
Flushing pressure-D	ERROR	2	0.29	0.1	1	0.74
ERROR		0	0	0		
TOTAL		8	39.27	4.91		100

V. CONFIRMATION TEST:

Once the optimal level of each machining parameters is determined, the final step is to predict and verify the improvement of the performance characteristics using this optimal level of the machining parameters.

The estimated value for Utility technique using the optimal level of the machining parameters can be calculated as:

$$u = u_g + \sum_h^q (u_h - u_g) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 11$$

Where, u_h = the highest mean of Overall utility at levels of each input parameter.

h= (1, 2, 3,…………..q), q= no of input parameters

For the 10mm diameter of copper tool, the estimated value of overall utility is 7.761841. It matches with overall utility value from Tab.VIII is 7.761841.Then one experiment was conducted on the optimum level combination in EDM machine and the values of SR, CW, SCD and hardness are evaluated. These values are shown in Tab.XIV.

For the 15mm diameter of copper tool, the estimated value of overall utility is 7.359004. It matches with overall utility value from Tab.IX is 7.018491.Then one experiment was conducted on the optimum level combination in EDM machine and the values of SR, CW, SCD and hardness are evaluated. These values are shown in Tab.XV.

Table-XIV: Experimental values of optimum level combination and initial level combination (for 10mm diameter)

Optimum level (Experiment.)	**Initial machining**
Level=$A_1B_1C_1D_1$	**Level=$A_1B_1C_1D_1$**
Overall utility=7.761841	Overall utility =7.761841
S/N- Overall utility=17.79929	S/N- Overall utility=17.79929
SR=1.98	SR=1.98
CW=1.58	CW=1.58
SCD=0.006259	SCD=0.006259
Hardness=375	Hardness=375

Table-XV: Experimental values of optimum level combination and initial level combination (for 15mm diameter)

Optimum level (Experiment.)	**Initial machining**
Level=$A_1B_1C_3D_1$	**Level=$A_1B_1C_1D_1$**
Overall utility=7.051058	Overall utility =7.018491
S/N- Overall utility=16.96509	S/N- Overall utility=16.92488
SR=2	SR=1.85
CW=1.68	CW=1.7
SCD=0.006235	SCD=0.01035
Hardness=945	Hardness=445

It is clearly obvious from this table (Tab.XIV) and (Tab.XV) that, the overall utility value corresponding to the optimum level combination of input parameter is higher compared to the maximum possible overall utility value of initial machining i.e optimum level combination is justified.

VI. SUMMARY OF THE OPTIMIZATION RESULTS:

A. Utility optimization technique (For 10mm diameter of copper tool)

a. From the overall utility (Tab.VIII), the experiment no.1 i.e (Level combination= $A_1B_1C_1D_1$ i.e, $I_p = 10$ amp, T_{on} =200μs, T_{off} =100μs, F_p =0.15 $\frac{kgf}{cm^2}$) has highest overall utility. The value of overall utility is **7.761841.**

b. The signal-to-noise ratio for overall utility is **17.79929.**

c. From Tab.X, the optimum Level combination is **$A_1B_1C_1D_1$ (I_p =10 amp, T_{on}=200μs, T_{off}=100μs, F_p=0.15$\frac{kgf}{cm^2}$)** and the corresponding S/N ratio is **17.79929.**

d. From the ANOVA (Tab.XII), the most effective input parameter is **input current** which has **64.57%** contribution.

B. Utility optimization technique (For 15mm diameter of copper tool)

a. From the overall utility (Tab.IX), the experiment no.1 (Level combination= $A_1B_1C_1D_1$ i.e, $I_p = 10$ amp, T_{on} =200μs, T_{off} =100μs, F_p =0.15 $\frac{kgf}{cm^2}$) has highest overall utility. The value of overall utility is **7.018491.**

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b. The signal-to-noise ratio for overall utility is **16.92488.**

c. From Tab.XI, the optimum Level combination is $\mathbf{A_1B_1C_3D_1}$ ($\mathbf{I_p}$ =10 amp, $\mathbf{T_{on}}$=200μs, $\mathbf{T_{off}}$=250μs, $\mathbf{F_p}$=0.15$\frac{\mathbf{kgf}}{\mathbf{cm^2}}$) and the corresponding S/N ratio is **16.96509**.

d. From the ANOVA (Tab.XIII), the most effective input parameter is **pulse on time** which has **80.74%** contribution.

VII. CONCLUSION

- From the summary of results, 10mm diameter is better than the 15mm diameter because of higher overall utility and higher signal-to-noise ratio values.
- The optimum level combination of 10mm diameter of copper tool is $\mathbf{A_1B_1C_1D_1}$ i.e 10 amp of input current, 200μs of pulse on time, 100μs of pulse of time and 0.15 $\frac{\mathbf{kgf}}{\mathbf{cm^2}}$ of flushing pressure are the appropriate input parameters for obtaining better quality surface for INCONEL 625.
- From the ANOVA (Tab.XII) the most effective input parameter is input current. It has 64.57% contribution.
- The hardness of unmachined surface of workpiece INCONEL 625 is measured as 325Hv. The hardness of the machined surface is 375. That means there is 1.5% improvement of hardness of machined surface.
- The surface roughness and crackwidth of 10mm diameter of copper tool is better than the 15mm diameter of copper tool.

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