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Parametric Study of Machining on EN31 and EN19 Alloy Steels in WEDM to Analyze the Effect on Surface Roughness

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***Abstract* - Wire EDM can machine hard materials as well as alloys. Thus this study aims to analyze the effect of process parameters in WEDM on EN31 and EN19 alloy steels. The parameters selected for the optimization were Work material, Pulse on Time, Pulse off Time, Current, Voltage and Wire Feed for improvement in surface roughness. Taguchi L18 Orthogonal array was used for the best combination of experiment. The output responses were analyzed by ANOVA (Analysis of variance). The ANOVA result indicated that there is a significant effect on improvement in surface roughness when machining with all these six input parameter and coated wire. According to the present investigation, voltage was found to be the most significant factor followed by Ton and current, which affect the improvement in surface roughness.**
***Keywords:* Wire EDM, EN-31, EN-19, Surface Roughness, Zinc Coated Brass Wire, Work material, Pulse on Time, Pulse off Time, Current, Voltage, Wire Feed**

I. INTRODUCTION

New materials which are having high strength-to-weight ratio, heat resistance and hardness, such as nimonic alloys, alloys with alloying elements such as tungsten, molybdenum, and columbium cannot be machined by the conventional processes. If one use the traditional methods for the machining of these materials then the machining time will be quite high. Hence it was required to develop the non-conventional machining processes for the material removal [11].

Wire Electrical Discharge Machining (WEDM) is one of the non- conventional machining process used in industry today to machine hard materials. WEDM is a thermo electrical process in which the material from the work piece is detached by discrete sparks among the work piece and wire electrode. A thin film of dielectric fluid, mostly the distilled water, separates them [7,19]. The dielectric fluid is uninterruptedly fed to the machining region to flush away the eroded particles. The tool electrode and the work electrode are held at an accurately controlled distance from one another, and to maintain the required spark gap between work piece and wire electrode a servo control unit is used. The servo control unit correctly locates the tool in relation to the work piece surface, it also maintain the constant gap throughout the operation and when there is any changes between the gap condition the servo control system sense these changes that is used to again maintain the gap. This gap prevents the mechanical contact of the tool and work. To attain three dimensional shape and accuracy of the work piece, movement of wire is controlled numerically [1]. The schematic diagram of WEDM is shown in Fig. 1.

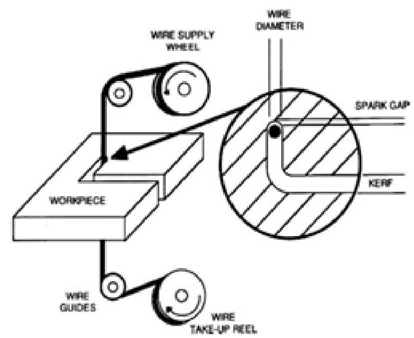

Fig. 1 Wire Electrical Discharge Machining [10]

II. REVIEW OF LITERATURE

Researchers' main focus is to improve the performance of the WEDM by increase the MRR, decreasing the roughness and kerf width. For this Sivakiran*et al.*, (2012) studied the influence of various machining parameters i.e. Pulse on, Pulse off, Bed speed and Current on metal removal rate in WEDM of EN-31 Steel [21] by linear regression. They found that parameters in order of current, pulse on, bed speed and pulse off influenced the MRR.

Jaganathan*et al.*,(2012) found that applied voltage and pulse width has great influence on MRR and surface roughness in machining EN-31 alloy steel using molybdenum wire in WEDM [4].

Reddy *et al.*, (2012) studied machining of EN-19 and SS420 Steel with Molybdenum wire of diameter 0.180 mm [16]. They found that major parameter influencing MRR for both the materials was Pulse-on followed by current. They also concluded EN-19 to be more suitable for better MRR whereas SS 420 for better surface finish.

Nourbakhsh*et al.*, (2013) concluded that effect of peak current and pulse width was more significant on cutting speed as well as on surface roughness while WEDM of titanium alloys [13]. They compared high-speed brass wire with zinc-coated brass wire and concluded that for smoother surface finish, zinc-coated brass wire is better.

Lodhi and Agarwal (2014) studied the effect of various machining parameter such as pulse-on time, pulse off time, peak current and wire feed for AISI D3 steel and found that the pulse on time and current had influenced more than the other parameters[9].

Gajjar and Desai (2015) studies WEDM using 0.25 mm diameter molybdenum wire and EN-31 tool Steel work piece [3]. They found that factor Pulse on time was most significant parameter in all response whereas Pulse off time has opposite effect. They also concluded that MRR decrease with increase of pulse off time, while surface roughness reduces. Servo voltage influences MMR whereas has little effect on surface roughness and KERF width. Patra and Rout (2015) studied WEDM with Zinc coated brass wire of 0.25 mm diameter on EN-31 steel and found the pulse on time and gap voltage have high influenced than the other parameters for surface roughness [14].

Kulkarni *et al.*, (2015) studied WEDM of EN-19 alloy steel through response surface methodology approach with copper and brass wires of 20 mm diameter [5]. They found that Work piece removal rate (WER) and Tool wear rate (TER) most affected by Discharge current followed by spark on time and spark off time. They also found that copper wire produce higher WER whereas brass wire produce higher TER.

Singh *et al.*, (2015) machined EN8 Steel with brass-copper (90:10) wire of 0.25mm diameter in WEDM [22]. They applied 'L_{18}' orthogonal array and found that servo voltage has the greatest effect on dimensional deviation followed by pulse off time, and wire feed. Dimensional deviation decrease as the wire feed rate and servo voltage increases.

Mohanty and Nayak (2016) concluded while machining EN-31 steel with brass wire that for high MRR, pulse on time and wire feed should increase whereas pulse off time and servo voltage should decrease [12].

Prajapati (2015) studied Kerf width for EN-19 material by varying material thickness, pulse on time, pulse off time, flushing pressure, wire tension and servo voltage using L_{27} orthogonal array in WEDM with Molybdenum coated brass wire of 0.25mm diameter [15]. Flushing pressure was found to be the most affective parameter followed by pulse on time and servo voltage. Interaction between flushing pressure and wire tension was also influenced Kerf width. Least affective parameters were Pulse off time and material thickness.

Dabadea*et al.*, (2016) studied WEDM of Inconel 718 using Taguchi methodology, L_8 Orthogonal Array [2] and confirmed that pulse-on-time was the most influential factor for MRR, SR, Kerf and servo voltage was the next significant parameter.

Manikandan *et al.*, (2016) studied WEDM using 0.25 mm diameter zinc coated copper wire and EN-31 steel work piece and found that pulse on time at 131μs, pulse off time at 36 μs, and wire tension at 6kgf are the best process parameters for surface roughness [10].

Kumar and Naik (2016) optimized the performance of non-electrical input parameters in machining on EN-31 alloy steel [8]. They found that the MRR and improvement in Surface roughness was affected in order of wire feed-rate, wire tension and dielectric pressure.

Rizvi *et al.*, (2016) concluded that peak current influenced the surface roughness to highest extent followed by voltage whereas pulse on duration was least influencing parameter in Wire EDM with EN-40 as work material and brass wire as tool [17].

Thomas and Sushant (2017) studies WEDM on EN-31 steel work piece and found that pulse on time and wire tension influences surface roughness the most [24].

Shinge*et al.*, (2017) found that peak current has greatest effect on surface roughness and 115μs pulse-on time, 47μs pulse-off time, 70A peak current, and 4kgf wire tension were optimal parametric combinations for surface roughness of WEDM process of EN-31 steel [18].

III. EXPERIMENTAL SETUP

In this present work two different material, EN-31 and EN-19 steels, were chosen for the experimentation as both are commonly used in industries for many automobile applications. The experiments were conducted on Ultracut 843 WEDM machine with zinc coated brass wire of 0.25mm diameter. The work piece used during the experimentation were rectangular in shape having dimensions of 45mm×45mm×20mm. A pool of work piece for both the materials was created to conduct the experiments as per the design of experiments. The composition of the materials are shown in the Table I and Table II.

TABLE I COMPOSITION OF EN-31

Element	C	Si	Mn	P	S	Cr	Mo	Ni	V
Percentage (%)	1.4	0.233	0.544	0.035	0.057	1.12	0.023	0.073	0.005

TABLE II COMPOSITION OF EN-19

Element	Si	C	Mn	S	P	Cr	Mo
Percentage (%)	0.25	0.41	0.85	0.039	0.031	1.11	0.29

IV. PROCESS PARAMETER AND THEIR RANGE

For the experimentation six process parameter were selected and are shown in the Table III whereas fixed parameter in Table IV.

TABLE III PROCESS PARAMETER AND THEIR RANGE

Sr. No.	Parameter	Symbol	Unit	Range
1	Work Material	WP	Nil	EN31, EN19
2	Pulse On Time	T_{ON}	µs	105-115
3	Pulse Off Time	T_{OFF}	µs	10-30
4	Current	C	A	10-12
5	Voltage	V	V	20-40
6	Wire Feed	WF	m/min	4-8

TABLE IV FIXED PARAMETER DURING EXPERIMENTS

Sr. No.	Parameters	Unit	Set Value
1	Wire Tension	Kgf	7
2	Wire Material	Nil	Zinc Coated Brass(0.25mm)
3	Dielectric Fluid Pressure	kg/cm^2	6

V. SELECTION OF ORTHOGONAL AARAY AND PARAMETER ASSIGHNMENT

In the present study the mixed level design L_{18} orthogonal array had been selected for the experiments design in "Design Expert 10.0.3" to study the effect on improvement in surface roughness (ΔR_a). According to this design for the six parameters, the work material was of two levels and the other remaining five parameters were of three level. Each parameter was analyzed in every level. The machining parameters with their levels are shown in Table 5. A standard L_{18} with the parameters assigned and experimental data is as shown in Table VI.

TABLE V MACHINING PARAMETER AND THEIR LEVELS

Sr. No.	Parameters	Units	Level 1	Level 2	Level 3
1	Work Material	NIL	EN31	EN19	---
2	Pulse On Time	µs	105	110	115
3	Pulse Off Time	µs	10	20	30
4	Current	A	10	11	12
5	Voltage	V	20	30	40
6	Wire Feed	m/min	4	6	8

TABLE VI:L_{18} OA PARAMETERS TRIAL CONDITIONS AND EXPERIMENTAL RESULTS FOR ΔR_A

Expt. No.	Work Material	T_{ON}	T_{OFF}	Current	Voltage	Wire Feed	ΔR_a R1	R2	R3	SN Ratio
1	EN19	105	10	10	20	4	30.42	24.4	27.41	28.65
2	EN19	105	20	11	30	6	20.34	17.36	18.85	25.45
3	EN19	105	30	12	40	8	12.67	17.21	14.94	23.28
4	EN19	110	10	10	30	6	43.57	36.17	39.87	31.94
5	EN19	110	20	11	40	8	6.92	4.23	5.58	14.4
6	EN19	110	30	12	20	4	21.15	29.09	25.12	27.78
7	EN19	115	10	11	20	8	11.56	17.03	14.3	22.78
8	EN19	115	20	12	30	4	43.25	48.37	45.81	33.19
9	EN19	115	30	10	40	6	38.06	40.35	39.21	31.86
10	EN31	105	10	12	40	6	36.62	32.55	34.59	30.75
11	EN31	105	20	10	20	8	10.27	12.72	11.5	21.11
12	EN31	105	30	11	30	4	34.94	23.28	29.11	28.92
13	EN31	110	10	11	40	4	21.64	22.36	22	26.85
14	EN31	110	20	12	20	6	18.13	14.5	16.32	24.14
15	EN31	110	30	10	30	8	48.8	37.9	43.35	32.6
16	EN31	115	10	12	30	8	71.66	68.6	70.13	36.91
17	EN31	115	20	10	40	4	66.8	61.75	64.28	36.15
18	EN31	115	30	11	20	6	23.89	28.69	26.29	28.32

VI. EFFECT OF MACHINING PARAMETERS ON IMPROVEMENT IN SURFACE ROUGHNESS (R_a)

The average value of raw data and S/N ratio for each parameters at levels 1, 2 and 3 are calculated and values are given in the Table 7 and Table 8. The level L_1, L_2 and L_3 represent levels 1,2 and 3 respectively of parameters $L_2 – L_1$ the average main effects when the corresponding parameters changes from level 1 to level 2. $L_3 – L_2$ is the main effect when the corresponding parameter changes from 2 to 3.

Fig. 2 shows the effect of work material on the improvement in surface roughness. In this study the improvement in surface roughness of EN31 was higher. It was due to the reason that the improvement in surface roughness of the material is inversely proportional to the hardness of the material. The EN19 material was harder than EN31. So the sparks does not properly remove the material from EN19. The improvement in surface roughness of EN19 was less compared to EN31.

TABLE VII AVERAGE VALUE AND MAIN EFFECT OF RAW DATA: IMPROVEMENT IN SURFACE ROUGHNESS

Process Parameter	**Level**	**Material**	**T_{on}**	**T_{off}**	**Current**	**Voltage**	**Wire Feed**
Type of Data		**Raw data**	**Raw data**	**Raw data**	**Raw data**	**Raw data**	**Raw data**
Average Values (MR)	L_1	25.68	22.73	34.72	37.6	20.15	35.62
	L_2	35.28	25.37	27.05	19.35	41.19	29.19
	L_3	*	43.33	29.67	34.48	30.1	26.63
Main Effects (MR)	$L_2 - L_1$	9.61	2.64	-7.66	-18.25	21.03	-6.44
	$L_3 - L_2$		17.96	2.62	15.13	-11.09	-2.55
Difference $\{(L_3 - L_2) - (L_2 - L_1)\}$		9.61	15.32	10.28	33.38	-32.12	3.88

TABLE VIII AVERAGE VALUE AND MAIN EFFECT ON IMPROVEMENT IN SURFACE ROUGHNESS

Process Parameter	**Level**	**Material**	**T_{on}**	**T_{off}**	**Current**	**Voltage**	**Wire Feed**
Type of Data		**S/N ratio(dB)**	**S/N ratio(dB)**	**S/N Ratio(dB)**	**S/N ratio(dB)**	**S/N ratio(dB)**	**S/N ratio(dB)**
Average Values (MR)	L_1	26.59	26.36	29.64	30.38	25.46	30.26
	L_2	29.53	26.29	25.74	24.45	31.5	28.74
	L_3	*	31.54	28.79	29.34	27.21	25.18
Main Effects(MR)	$L_2 - L_1$	2.94	-0.08	-3.9	-5.93	6.04	-1.51
	$L_3 - L_2$		5.25	3.05	4.89	-4.29	-3.56
Difference $\{(L_3 - L_2)-(L_2 - L_1)\}$		2.94	5.33	6.96	10.82	-10.33	-2.05

Fig. 3 shows the variation of improvement in surface roughness with respect to the change in pulse on time. When T_{on} increase from 105 to 110µs then there was minor improvement in surface roughness, because the discharge energy was less. With higher values of T_{on}, improvement in Surface Roughness tends to be increase. During the experiment when T_{on} was increased from 110µs to 115µs it was seen that the surface roughness improves at higher rate. It was due to the reason that with increased value of pulse on time larger discharge energy produces a fine surface on the work surface. The higher value of discharge energy may also cause wire breakage.

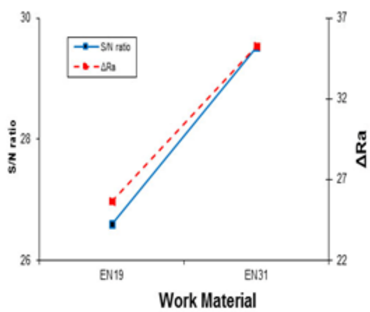

Fig. 2 Effect of work piece material on Improvement in Surface Roughness

The variation from the different level of pulse off time is shown inFig. 4. The improvement in surface roughness was minimum at second level of pulse-off time. This is due to the reason that with a too short pulse-off time the continuously spark was produced and the fine surface of work piece was obtained. When the Pulse off time was increase from 10µs to 20µs, then there was a sharp decrease in improvement in surface roughness, because there was increase in spark gap and hence the rough surface was produced. But when the pulse off time increased from the second level to third level again the roughness improves. It was due to the reason that as pulse off time increases, the energy in spark also increases, help to remove required material from the work piece. There by producing fine surface.

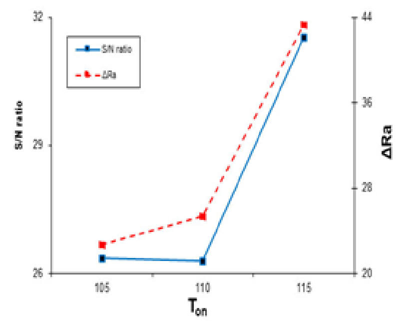

Fig. 3Effect of Ton on the Improvement in Surface Roughness

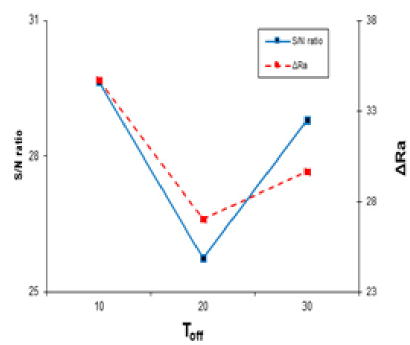

Fig. 4 Effect of T_{off} on the Improvement in Surface Roughness

The effect of peak current on the surface roughness of materialis shown in Fig. 5. Peak current was found to be the major factor affecting the Surface Roughness. During the experimentation process the fine surface of material was observed at first level where the value of peak current was 10A. In the next level when the current was increases from 10Amp to 11Amp the quality of the surface decreases. This was because, higher the peak current, larger the discharge energy, which results in increase of cutting rate and decrease in surface accuracy. Due to this, craters with higher depth are formed on the surface leading to surface roughness. Again when the current increases from 11A to 12A, the improvement in surface roughness again increases.

Servo voltage has the greatest effect on surface finish. The effect of voltage on the surface roughness of materialis shown in Fig. 6. The minimum improvement in surface roughness was observed at 20 Volt. After that when the voltage was increased from 20V to 30V, the improvement in surface roughness was increased at high rate. From the first and second it was clear that the surface roughness is directly proportional to the value of voltage. The reason for improvement in the surface roughness by increasing the voltage is that as the servo voltage increases, the delay time of ignition was also increases. So the discharge cycle for a given period decreases which leads to decrease in the spark energy. As a result small craters are produced on the work piece surface which leads to decrease in the cutting rate and improvement in the surface finish. When again voltage was increased from 30V to 40V, there was decrease in surface finish because of too long delay time in ignition.

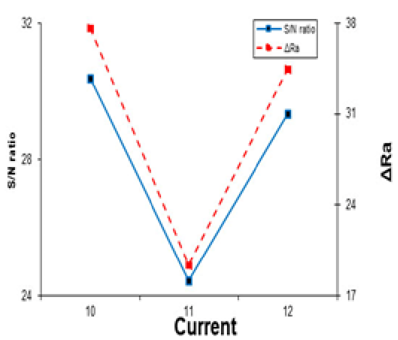

Fig. 5 Effect of current on the Improvement in Surface Roughness

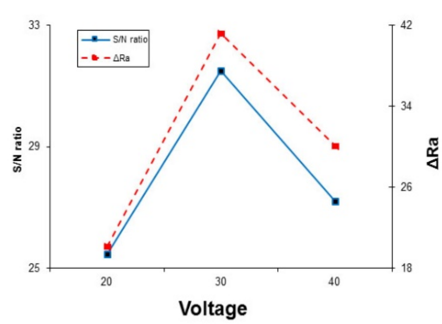

Fig.6 Effect of Voltage on the Improvement in Surface Roughness

The effect of wire feed rate on the surface roughness of materialis shown in Fig. 7. It was clear from the graph that, with lower value of wire feed rate the improvement in surface roughness tends to be increase. When the wire feed rate was increased from 4mm/min to 6mm/min, then the improvement in Surface roughness was less. Upon further increased from 6mm/min to 8mm/min, the improvement in surface roughness reaches to the minimum.

It was due to the reason that improvement in surface roughness decreases with increase in wire feed rate, because new wire comes in contact rapidly when wire feed rate increases and the spark does not affect the work piece properly. So less energy is available to remove material from work surface leading to surface degradation.

In order to study the significance of the process parameter towards the ΔR_a, The analysis of variance was (ANOVA) performed. The pooled version of ANOVA of the raw data and the S/N data for the material removal are given in Table 9 and Table 10.

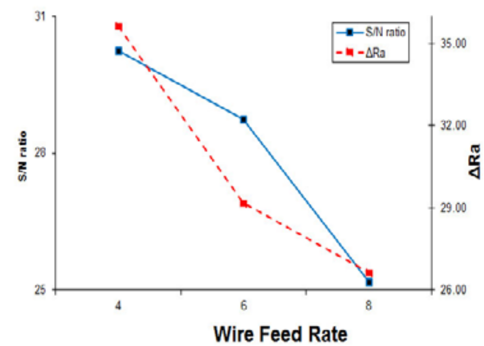

Fig. 7 Effect of Wire feed rate on the Improvement in Surface Roughness

VII. OPTIMUM RESPONSE CHARACTERISTICS ESTIMATION

The optimal value of response characteristics is predicted considering the effect of the significant parameter only. The average value of response characteristics obtained through the confirmation experimentation must be within the 95% confidence level, CI_{CE}. However the average value of quality characteristics obtained from the confirmation experiments may or may not lie within 95% confidence interval, CI_{POP} (calculated for the mean of population).

TABLE IX POOLED ANOVA (RAW DATA, ΔRA).

SOURCE	SS	DOF	V	F-Ratio	P
Work Material	1246.28	1	1246.28	114.16	7.77
T_{on}	4524.46	2	2262.23	207.22	28.21
T_{off}	545.99	2	272	114.16	3.4
Current	3429.54	2	1714.77	157.07	21.39
Voltage	5059.69	2	2529.84	231.74	31.55
Wire Feed	772.51	2	386.25	35.38	4.82
Error	458.51	42	10.92		2.86
T	16036.98	53			100
Significant at 95% confidence level, Critical= 3.22 SS-Sum of squares, DOF-Degree of freedom, V-Variance					

TABLE X POOLED ANOVA (S/N RATIO, ΔRA)

SOURCE	SS	DOF	V	F-Ratio	P%
Work Material	38.76	1	38.78	10.51	7.21
T_{on}	108.69	2	54.34	14.72	20.21
T_{off}	50.59	2	25.3	6.85	9.41
Current	120.33	2	60.16	16.3	22.37
Voltage	115.84	2	57.92	15.69	21.54
Wire Feed	81.47	2	40.74	11.04	15.15
Error	22.15	6	3.69		4.12
Total	537.84	17			100
Significant at 95% confidence level, Critical= 5.14 SS-Sum of squares, DOF-Degree of freedom, V-Variance					

The mean at the optimal ΔR_a is calculated as:-

$$\Delta R_a = \overline{W}_2 + \overline{T_{on}}_3 + \overline{T_{off}}_1 + \overline{C}_1 + \overline{V}_2 + \overline{WF}_1 - 5\overline{T} \quad \text{-- (1)}$$

$\overline{T}$ = Overall mean of responses = 30.48

$\overline{W}_2$ = Average value of ΔR_a at the first level of work piece is 35.28 (Table VII)

$\overline{T_{on}}_3$ = Average value of ΔR_a at the second level of pulse on time is 43.33 (TableVII)

$\overline{T_{off}}_1$ = Average value of ΔR_a at the second level of pulse off time is 34.72 (Table VII)

$\overline{C}_1$ = Average value of ΔR_a at the second level of current is 37.6 (Table 7)

$\overline{V}_2$ = Average value of ΔR_a at the first level of voltage is 41.19 (Table VII)

$\overline{WF}_1$ = Average value of ΔR_a at the third level of wire feed is 35.62 (Table VII)

Substituting all these values in equation 1, ΔR_a= 75.34

The confidence interval of confirmation experimentation(CI_{CE}) and of population(CI_{POP}) is calculated by the following equation:-

$$CI_{CE} = \sqrt{F_\alpha(1, f_e) V_e \left[\frac{1}{n_{eff}} + \frac{1}{R}\right]} \quad \text{--(2)}$$

$$CI_{POP} = \sqrt{\frac{F_a(1, f_e) V_e}{n_{eff}}} \quad \text{--(3)}$$

Where,

$F_\alpha(1, f_e)$ =The F-Ratio at the confidence level of (1-α) against DOF 1 and error degree of freedom $f_e = 4.35$ (Tabulated F value)

F_e = eror DOF= 42

N = Totalnumber of results = 54 (Treatment =18)

R= Sample size for the confirmation experiments = 3

V_e = Error variance = 10.92

$$n_{eff} = \frac{1}{1 + [DOF\ associated\ response\ ]} = 5.4$$

So, $CI_{CE} = \pm 4.96$

And $CI_{POP} = \pm 2.97$

The 95% confirmation interval of predicted optimal range (for confirmation run of three experiments) is:-

Mean $\Delta R_a - CI_{CE} < \Delta R_a >$ Mean $\Delta R_a + CI_{CE}$

$70.78 < \Delta R_a > 80.30$

The 95% confirmation interval of predicted mean is:-

Mean $\Delta R_a - CI_{POP} < \Delta R_a >$ Mean $\Delta R_a + CI_{POP}$

$72.37 < \Delta R_a > 78.31$

VIII. CONFIRMATION EXPERIMENTS

In order to validate the obtained results, three confirmation experiments have been conducted for improvement in Surface Roughness at the optimal values i.e. work piece: W_2 i.e. EN31, Pulse on time: $T_{on\,3}$ i.e. 115µs, Pulse off time: $T_{off\,1}$ i.e. 10µs, Current: C_1 i.e. 10Amp, Voltage: V_2 i.e. 30V and Wire feed:WF_1 i.e.4 mm/min for both the raw data and S/N data. The results are given in the Table 11.

TABLE XI PREDICTED OPTIMAL VALUES, CONFIDENCE INTERVALS AND RESULTS OF CONFIRMATION EXPERIMENTS

Response characteristics	Optimal process parameters	Predicted Optimal value	Confidence interval 95%	Actual value
Improvement in R_a	$W_2 T_{on\,3} T_{off\,1} C_1 V_2 WF_1$	75.34	CI_{CE} : $70.78 < \Delta R_a > 80.30$ CI_{POP} : $72.37 < \Delta R_a > 78.31$	76.18
CI_{CE} − Confidemce interval for the mean of confirmation experiments CI_{POP} − Confidemce interval for the mean of population				

IX. CONCLUSION

The important conclusions drawn from the present study are summarized below:-

1. Voltage was found to be the most significant factor affecting the improvement in surface roughness followed by T_{on} and current.
2. EN31 material obtain better surface finish compared to EN19.
3. There was continuous improvement in surface with increase in Pulse on Time.
4. As the wire feed rate increases the improvement in surface roughness decreases. The maximum improvement was observed at 4mm/min of wire feed rate.

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