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Optimization of Process Parameters in Wire Electrical Discharge Machining of D3 Steel

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ABSTRACT
D3 steel, known for its hardness and tenacity, is difficult to machine. This research uses Wire Electrical Discharge Machining (WEDM)'s non-contact nature to better understand how machining factors affect surface quality. WEDM is used to optimise D3 steel machining characteristics such surface roughness, taper angle, and machining time.
The study uses Taguchi Optimization Method and Multi-objective Grey Relational Analysis to examine the effects of Pulse On Time, Pulse Off Time, Dielectric Pressure, Fine Pulse Current, Wire Feed Rate, Wire Tension, Servo Voltage, and Servo Feed Rate. The research uses these methods to find the best parameter values for D3 steel machining that improve surface quality, taper angle, and machining time. Results show that altering Pulse on Time greatly affects surface smoothness and cutting speed. However, Pulse Off Time and Dielectric Pressure greatly affect cut width. This method revealed how WEDM parameters effect outcomes, helping improve the procedure. This research may affect precision machining businesses, improving production efficiency and quality.

Keywords *- surface roughness, taper angle, machining time, d3 steel, wire electrical discharge machining (WEDM), Taguchi optimization method, grey relational analysis.*

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I. INTRODUCTION

Many industries need alloy materials with outstanding hardness, strength, toughness, and impact resistance. The blank and cutting tool are fixed in fixtures and machined using suitable equipment to gradually remove material layers from the work surface. The product then has the right proportions and finish. Machining also uses a cutting fluid, a lubricant and cooling medium. Conventional machining has problems including unachievable complicated forms, no micromachining, and frequent tool wear that shortens tool life. Non-conventional machining technologies cut ultra-hard materials to the right dimensions with little waste and tool-to-workpiece contact. These technologies reduce contact and frictional stresses compared to traditional machining in excess. Water jet and laser beam machining are non-conventional machining technologies with high equipment costs, low workpiece height, and poor surface smoothness. Electrical discharge machining (EDM) may resolve these issues by shaping metal or other conductive materials using electric sparks.

Wire electrical discharge machining (WEDM) is a popular, economical, and innovative machining method that cuts difficult-to-machine materials of any hardness into complex, precise, and accurate shapes in low volume and highly changeable complex parts. It can be used to machine high-strength and temperature-resistant metals too. Also known as spark machining or electro-erosion machining, WEDM precisely removes metal using electric sparks, allowing the creation of intricate designs from tough materials that are hard to cut conventionally.

WEDM works by current flowing between two electrodes, where the workpiece is positive and the tool (thin wire) is negative, both traveling through a liquid or gas. When DC or AC is applied, an electric field forms. Electrons leave from the negative side and flow toward the positive side, interacting with molecules in the liquid or gas to charge or ionize them and create a plasma channel between the wire and the object being worked on. The sparking gap must be kept minimal. This route allows a quick current spike between electrodes. The spark melts metal and the surrounding liquid or gas, creating a tiny imprint on the workpiece at 8,000 to 12,000 degrees Celsius. This melting and evaporation process shapes the workpiece by removing small fragments of material. A thin coating of dielectric fluid, usually deionized water, protects the wire and substance. This fluid cools and ensures precision cutting. The fluid is filtered to remove molten metal pieces. While cutting, the wire moves ahead and around the workpiece to avoid touching it. Cutting is stress-free when the wire never contacts the workpiece.

II. Literature Survey

In WEDM Surface roughness, taper angle and machining time mostly influenced by Pulse On Time (Ton), Peak Current (Ip), Pulse Off Time (Toff), Wire Feed Rate, Dielectric Pressure.Optimum level of these process parameters can be found out by using Taguchi Method for each response.Multi-objective optimization and the optimal solution can be determined by using Grey Relational Analysis technique.These are some of the findings from below literature survey

Table 1: Details of literature

MATERIAL	Input parameter	Output parameter	Methodology	Significant parameters
AISI H11 tool steel	TON , TOFF , Wf	SR, KW	DOE, TA, ANOVA	Al - TON for longitudinal SR, TOFF for transverse SR, WF for KW, MS - IP for longitudinal and transverse SR, TON for KW
Inconel-825	TON, TOFF, CS, WF, WP, WT, SV, SF	SR, MRR , SGW	DOE, TA, fuzzy- GRA, ANOVA	TON, followed by CS
Maraging steel 300	TON, TOFF, IP, WT, SV	SR, WC	DOE, ANOVA	TON, SV, TOFF are the significant parameters. SR can be further reduced by using silver coated brass wire than normal brass wire
Stainless steel (SS 304 grade)	TON, TOFF, IP	SR, KW	DOE, ANOVA, GRA	TON, followed by IP, TOFF
Aluminum 6082 T6 alloy	TON, TOFF, IP	MT	DOE, TA	Significant factor is TOFF followed by TON
Al 6063/ ZrSiO4(p)	TON, TOFF, IP, SV	CR	DOE, ANOVA, RSM	CR increases with increase in TON, IP and decrease in TOFF, SV
Nickel Titanium (NiTi) shape memory or superelastic alloy is also termed as Nitinol, TiNi (Ti50Ni50)	TON, TOFF, WF, SV	SR, MRR	DOE, TA, ANOVA	WF is the most significant factor followed by TON & TOFF
Al-Cu-TiC-Si P/M composite	WP, WT, DF, IP, V	SR, MRR	DOE, TA, ANOVA	DF is the significant factor
Inconel 718	TON, TOFF, IP, WF, WT, SV	SR, CR	DOE, ANOVA, RSM	TON & SV for SR, TON, TOFF, SV for CR
TITANIUM	TON, TOFF, WF, WT	MRR, SR	TA, ANNOVA	TON is the significant factor, increase in TON increases both MRR & SR
Skd 61 alloy steel	TON, TOFF, WF, WT, SV, OV, WP	SR, MRR	TA, ANNOVA	FOR MRR - TOFF followed by TON, For SR OV followed by WT
SS304	TON, TOFF, SV, IP	SR, MRR	DOE, TA	IP is the significant paramener
AL6061 HYBRID COMPOSITE	TON, TOFF, IP, Gapset Voltage, WT	CT	TA	Lower TON & TOFF gives better Cutting Time
HSS M42 Grade	TON, WT, SV	MRR	DOE, TA, ANOVA	Increase in TON, MRR inceases, Increase in SV decreases MRR
TITANIUM	TON, TOFF , IP, WT , SV	MRR, Kerf Width, SR	ANNOVA	Increase in TON, TOFF, IP, SV, WT increases Kerf Width, Increase in TON, TOFF increases MRR, Increase in TON, IP increases SR

III. Material and Method

The project began by extensively reviewing existing knowledge to identify gaps and areas that lack comprehensive understanding. Subsequently, crucial process parameters and their varying levels to be evaluated were identified. Employing an efficient experimental design, specifically an orthogonal array, streamlined the experimental tests, ensuring comprehensive coverage of necessary variations without unnecessary redundancy. Following a meticulously planned approach, experiments were conducted, adhering to predetermined parameters, and output response data was collected systematically. Thorough analysis of this data, relationships between different factors were unveiled, offering insights into their impact on experimental outcomes. To validate the findings, a confirmatory experiment was conducted, further strengthening the reliability of the conclusions. Figure 3.1 shows the flow in which the project was carried out. The subsequent sections of the chapter describe the selection of orthogonal array and the conduct of experiments in detail.

Table 2: Process parameters and their levels

Sr. No.	**Parameter Name**	**Symbol**	**Range**	**Levels**		
				1	**2**	**3**
1	Fine pulse (current)	IP	0-2	1	2	-
2	Pulse on time	TON	0-31	12	16	20
3	Pulse off time	TOFF	0-63	50	57	63
4	Dielectric pressure	WP	0-15	10	12	14
5	Wire feed rate	WF	0-15	2	3	4
6	Wire tension	WT	0-15	8	10	12
7	Servo voltage	SV	0-99	18	19	20
8	Servo feed rate	SF	0-999	75	100	125

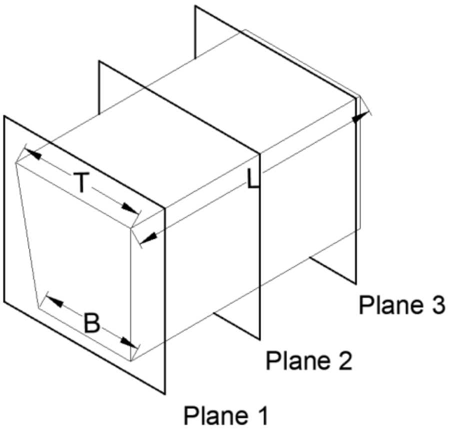
The block of D3 Steel was purchased from ESUFALI DAWOODBHOY & CO was machined through milling and surface grinding to the size 48mm x 49mm x 64mm. The material specification according to other standards are – ASTM A681 TYPE D3. Chemical composition analysis of the material, performed at Deep Metallurgical Services, Thane – 400604, Maharashtra, confirmed that the composition of the various elements in the blocks were as per standards (table 3).

Table 3 : Chemical composition of D3 Steel

Element	**Actual content (%)**
Carbon (C)	2.029
Manganese (Mn)	0.405
Silicon (Si)	0.476
Chromium (Cr)	12.14
Nickel (Ni)	0.114
Molybdenum (Mo)	0.0348
Vanadium (V)	0.0446

Figure 1: Setup of work piece on WEDM machine.

Surface roughness (Ra) was measured using Mitutoyo SJ 210 tester reflects average microscopic irregularities' height.Standardized parameters: measuring speed - 0.25mm/s, sampling length - 5, cut-off wavelength - 0.25µm, short wavelength - 2.5µm. Ra measured at three locations per workpiece for comprehensive evaluation of surface quality, ensuring precision and consistency assessment. Taper angle indicates the variance between the upper and lower surfaces of a machined feature. Minimizing taper is crucial for ensuring accurate dimensions and straight sidewalls in produced parts. It is computed using the difference in width between the top and bottom locations of the block and the block's height The kerf taper angle was determined at three distinct planes of the workpiece using a micrometer. The average value was consideredto measure the variance in width along the cut material. Machining time is the duration for a cutting operation on a workpiece, it was measured with a help of calibrated stopwatch in minutes. It considers factors like feed rate, speed, depth of cut, and material properties, impacting the operation duration. Accurate observation from tool engagement to completion ensures precise recording. Analysis helps optimize processes, identify bottlenecks, enhance efficiency, reduce costs, and improve overall productivity.



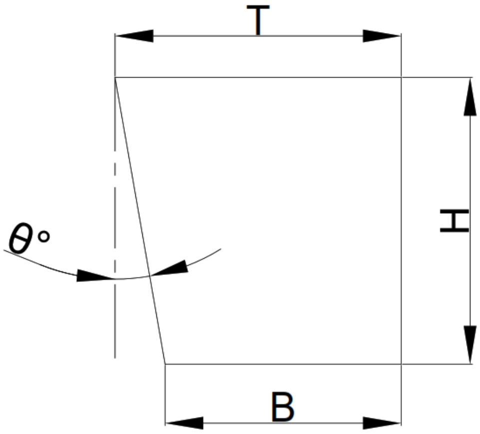


Figure 2(a): Planes for taper angle measurement **Figure 2(b): Parameters for taper angle calculation**

Table 4:Design of Experimentation with L18 orthogonal array and experimental results
L18 Orthogonal Array with Input Parameters and Output Parameters

Exp. No.	Fine Pulse (Current)	Pulse On Time	Pulse Off Time	Dielectric Pressure	Wire Feed Rate	Wire Tension	Servo Voltage	Servo Feed Rate	Average surface roughness (Ra)	Average taper angle (°)	Machining time (mins)
1	1	12	50	10	2	8	18	75	1.885	0.06	70
2	1	12	57	12	3	10	19	100	1.27	0.016	178
3	1	12	63	14	4	12	20	125	1.444	0.024	220
4	1	16	50	10	3	10	20	125	1.687	0.08	80
5	1	16	57	12	4	12	18	75	1.867	0.02	89
6	1	16	63	14	2	8	19	100	1.898	0.08	97
7	1	20	50	12	2	12	19	125	2.345	0.088	54
8	1	20	57	14	3	8	20	75	1.909	0.032	77
9	1	20	63	10	4	10	18	100	2.114	0.036	77
10	2	12	50	14	4	10	19	75	1.887	0.385	79
11	2	12	57	10	2	12	20	100	1.503	0.2	117
12	2	12	63	12	3	8	18	125	1.856	0.008	142
13	2	16	50	12	4	8	20	100	2.046	0.028	60
14	2	16	57	14	2	10	18	125	1.932	0.004	103
15	2	16	63	10	3	12	19	75	1.748	0.012	163

16	2	20	50	14	3	12	18	100	2.004	0.144	48
17	2	20	57	10	4	8	19	125	2.199	0.733	60
18	2	20	63	12	2	10	20	75	2.236	0.024	70

IV. Impact on Surface Roughness

The main effect plot (Figure 3) shows the influence of each parameter on surface roughness. Itindicates that surface roughness decreases with increase in wire tension and servo voltage, but it increases with increase in fine pulse and pulse on time. Initial increase in pulse off time, wire feed rate and servo feed rate decrease surface roughness but further increase in their value leads to anincrease in surface roughness.On the other hand, increase in dielectric pressure initially increases surface roughness, but further increase in its value leads to an improvement in surface roughness.

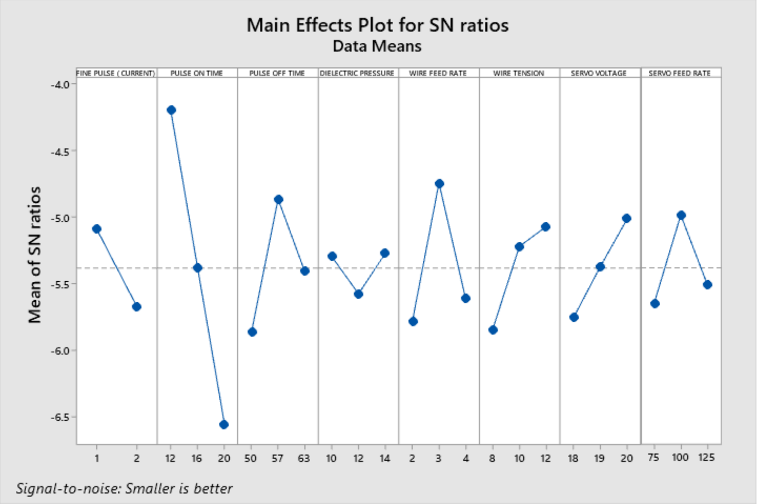


Figure 3 : Mean S/N ratio graph for surface roughness

Table 5 : ANOVA for S/N ratio – surface roughness

Source	DF	Seq SS	Adj SS	Adj MS	F	P	%Contribution
Fine pulse (current)	1	1.5442	1.5442	1.5442	3.18	0.217	5%
Pulse on time	2	16.7755	16.7755	8.3877	17.25	0.055	53%
Pulse off time	2	3.0102	3.0102	1.5051	3.09	0.244	10%
Dielectric pressure	2	0.3473	0.3473	0.1737	0.36	0.737	1%
Wire feed rate	2	3.7196	3.7196	1.8598	3.82	0.207	12%
Wire tension	2	2.051	2.051	1.0255	2.11	0.322	7%
Servo voltage	2	1.6652	1.6652	0.8326	1.71	0.369	5%
Servo feed rate	2	1.4604	1.4604	0.7302	1.5	0.4	5%
Residual Error	2	0.9727	0.9727	0.4864			3%
Total	17	31.5461					

V. Impact on Taper Angle

The main effect plot (Figure 4) shows the influence of each parameter on taper angle. It demonstrates that taper angle increases with increase in fine pulse and servo feed rate while it decreases with increase in pulse off time and wire tension. Increase in pulse on time, dielectric pressure and wire feed rate initially decreases taper angle but further increase in their values increase the taper angle too. Increase in servo voltage, increases taper angle initially, but it decreases with further increase in the levels. Analysis of variance indicates that pulse off time (18.93%), dielectric pressure (15.89%), servo voltage (15.53%), pulse on time (14.72%) have major influence on taper angle values while the effect of wire tension (2.21%) is not significant considering the selected levels.

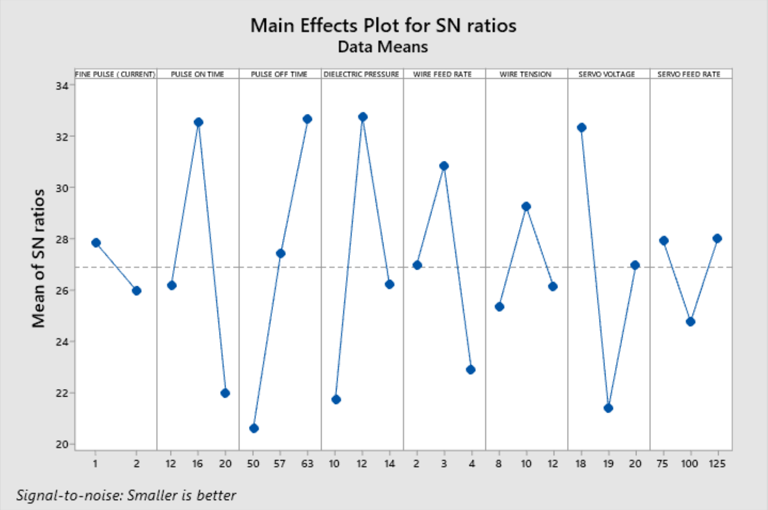


Figure 4 . : Mean S/N ratio graph for taper angle

Table 6 : ANOVA for S/N ratio – Taper Angle

Source	DF	Seq SS	Adj SS	Adj MS	F	P	**% Contribution**
FINE PULSE (CURRENT)	1	15.91	15.91	15.91	0.06	0.826	0.69%
PULSE ON TIME	2	340.63	340.63	170.32	0.67	0.6	14.72%
PULSE OFF TIME	2	437.89	437.89	218.94	0.86	0.539	18.93%
DIELECTRIC PRESSURE	2	367.69	367.69	183.84	0.72	0.582	15.89%
WIRE FEED RATE	2	189.23	189.23	94.61	0.37	0.73	8.18%
WIRE TENSION	2	51.05	51.05	25.52	0.1	0.909	2.21%
SERVO VOLTAGE	2	359.17	359.17	179.59	0.7	0.587	15.53%
SERVO FEED RATE	2	40.69	40.69	20.35	0.08	0.926	1.76%
Residual Error	2	511.16	511.16	255.58			
Total	17	2313.41					

VI. Impact on Machining Time

The main effect plot (Figure 5) shows the influence of each parameter on machining time. It demonstrates that machining time decreases with increase in fine pulse, pulse on time. Increase in pulse off time, dielectric pressure, servo feed rate, and wire tensionhowever increases the machining time. Increase in wire feed rate and servo voltage initially increases the machining time but further increase, decreases the machining time. The analysis of variance indicates that pulse on time(44%) andpulse off time (38%) have major influence on machining time values. The effect of Dielectric pressure on machining time (0.2%) may be neglected.

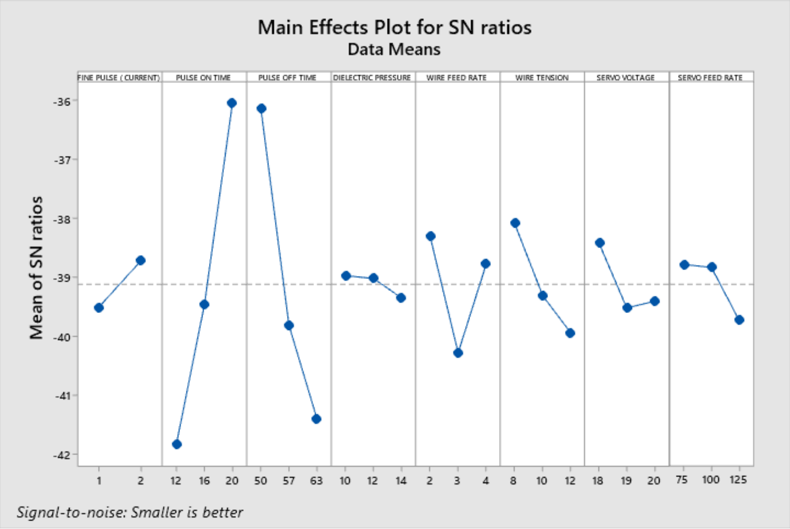


Figure 5 : Mean S/N ratio graph for machining time

Table 7 : ANOVA for S/N ratio – Machining Time

Source	DF	Seq SS	Adj SS	Adj MS	F	P	% Contribution
Fine pulse (current)	1	2.829	2.829	2.829	0.67	0.5	1%
Pulse on time	2	102.768	102.768	51.384	12.13	0.076	44%
Pulse off time	2	88.405	88.405	44.2026	10.43	0.087	38%
Dielectric pressure	2	0.515	0.515	0.2576	0.06	0.943	0.22%
Wire feed rate	2	12.893	12.893	6.4466	1.52	0.397	5%
Wire tension	2	10.765	10.765	5.3823	1.27	0.44	5%
Servo voltage	2	4.397	4.397	2.1986	0.52	0.658	2%
Servo feed rate	2	3.433	3.433	1.7165	0.41	0.712	1%
Residual Error	2	8.473	8.473	4.2363			4%
Total	17	234.478					

Table 8: Summary of optimum parameters levels

PARAMETER	IP	TON	TOFF	WP	WF	WT	SV	SF
Optimal Paramer for Surface Roughness	1	12	57	14	3	12	20	100
Optimal Paramer for Taper Angle	1	16	63	12	3	10	18	75
Optimal Paramer for Machining Time	2	20	50	10	2	8	18	75

VII. Grey Relational Grade Analysis (GRA)

Grey Relational Analysis (GRA) is a method used to analyze relationships between various factors when information is limited or incomplete. It simplifies the problem by focusing on a single response and transforming multiple responses into a comparable format. This involves normalizing experimental data to a scale of 0 to 1 and calculating the grey relational coefficient. By assigning equal weight to each output response, GRA computes a grey relational grade, enabling us to understand the connections between factors despite uncertainties, ultimately aiding in decision-making and problem-solving processes. Figure 6 indicates that to achieve an optimal combination, a decrease in fine pulse and pulse off time is required. Increase in pulse on time, dielectric pressure, wire feed rate, wire tension and servo feed rate initially increase GRA values however further increase in their levels can decrease the GRA value. Initial increase in servo voltage decreases the GRA value while further increase leads to an improvement in GRA value. The analysis of variance helps to determine the individual contribution of the parameters to the GRA value. The parameters arranged sequentially in the descending order of their significance are fine pulse (18%), dielectric pressure (18%), servo voltage (18%), wire feed rate (14%), servo feed rate (9%), wire tension (3%), pulse on time (2%) and pulse off time (2%).

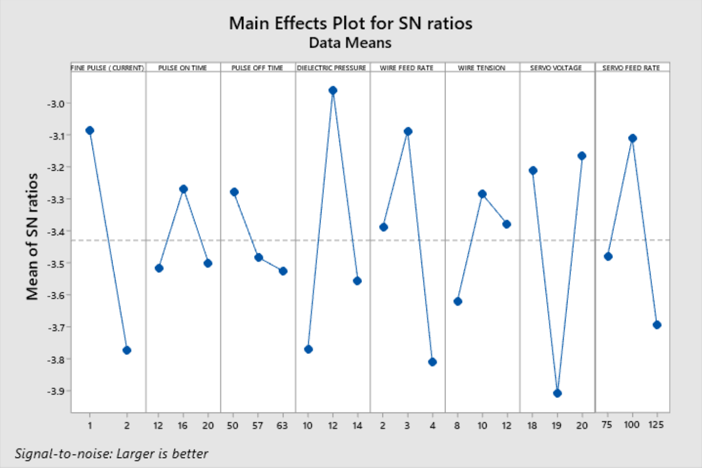


Figure 6 : S/N ratio graph of GRA grades

Table 9 :Grey relational co-efficients and grades

Sr No.	SR	KERF TAPER	M T	SMALLER THE BETTER			DEVITATION SEQUENCE			GR COEFFICIENT			GR GRADE
				Normalised SR	Normalised KT	Normalised CT	RA	KT	CT	SR	KT	CT	
1	1.885	0.06	70	0.427	0.918	0.872	0.573	0.082	0.128	0.466	0.859	0.796	0.707
2	1.27	0.016	178	1	0.978	0.244	0	0.022	0.756	1	0.958	0.398	0.785
3	1.444	0.024	220	0.838	0.967	0	0.162	0.033	1	0.755	0.939	0.333	0.676
4	1.687	0.08	80	0.612	0.891	0.814	0.388	0.109	0.186	0.563	0.821	0.729	0.704
5	1.867	0.02	89	0.444	0.973	0.762	0.556	0.027	0.238	0.474	0.948	0.677	0.7
6	1.898	0.08	97	0.416	0.891	0.715	0.584	0.109	0.285	0.461	0.821	0.637	0.64
7	2.345	0.088	54	0	0.88	0.965	1	0.12	0.035	0.333	0.806	0.935	0.691
8	1.909	0.032	77	0.406	0.956	0.831	0.594	0.044	0.169	0.457	0.92	0.748	0.708
9	2.114	0.036	77	0.215	0.951	0.831	0.785	0.049	0.169	0.389	0.911	0.748	0.682
10	1.887	0.385	79	0.426	0.475	0.82	0.574	0.525	0.18	0.465	0.488	0.735	0.563
11	1.503	0.2	117	0.783	0.727	0.599	0.217	0.273	0.401	0.697	0.647	0.555	0.633
12	1.856	0.008	142	0.454	0.989	0.453	0.546	0.011	0.547	0.478	0.979	0.478	0.645
13	2.046	0.028	60	0.278	0.962	0.93	0.722	0.038	0.07	0.409	0.929	0.878	0.739
14	1.932	0	103	0.384	1	0.68	0.616	0.004	0.32	0.448	1	0.61	0.686
15	1.748	0.012	163	0.555	0.984	0.331	0.445	0.016	0.669	0.529	0.968	0.428	0.642
16	2.004	0.144	48	0.317	0.804	1	0.683	0.196	0	0.423	0.718	1	0.714
17	2.199	0.733	60	0.136	0	0.93	0.864	1	0.07	0.367	0.333	0.878	0.526
18	2.236	0.024	70	0.101	0.967	0.872	0.899	0.033	0.128	0.357	0.939	0.796	0.697

Table 10: Optimal combination – GRA

PARAMETER	**IP**	**TON**	**TOFF**	**WP**	**WF**	**WT**	**SV**	**SF**
Input Values	1	16	50	12	3	10	20	100

Table 11:ANOVA for S/N ratio – GRA

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**	**% Contribution**
FINE PULSE (CURRENT)	1	2.1492	2.1492	2.1492	2.48	0.256	19%
PULSE ON TIME	2	0.2348	0.2348	0.1174	0.14	0.881	2%
PULSE OFF TIME	2	0.2104	0.2104	0.1052	0.12	0.892	2%
DIELECTRIC PRESSURE	2	2.1305	2.1305	1.0652	1.23	0.449	18%
WIRE FEED RATE	2	1.5913	1.5913	0.7957	0.92	0.522	14%
WIRE TENSION	2	0.3612	0.3612	0.1806	0.21	0.828	3%
SERVO VOLTAGE	2	2.0973	2.0973	1.0486	1.21	0.453	18%
SERVO FEED RATE	2	1.058	1.058	0.529	0.61	0.621	9%
Residual Error	2	1.7353	1.7353	0.8676			15%
Total	17	11.5679					

VIII. Conclusions

Taguchi optimization and ANOVA analysis reveal that pulse on time significantly impacts surface roughness, while wire feed rate, pulse off time, and wire tension have less influence. Dielectric pressure's effect on roughness is insignificant. Machining time is mainly influenced by pulse on and off times, with servo feed rate, fine pulse, and dielectric pressure having negligible impact. Dielectric pressure and pulse off time affect taper angle, along with wire and servo feed rates, while wire tension has minimal effect on taper angle. Grey relational analysis (GRA) highlights the need to reduce fine pulse and pulse off time for optimal response parameters. Initially, increasing pulse on time, dielectric pressure, wire feed rate, wire tension, and servo feed rate levels enhances GRA values, but further increments can lead to a decline. The descending order of process parameter contributions to GRA values is: fine pulse (18%), dielectric pressure (18%), servo voltage (18%), wire feed rate (14%), servo feed rate (9%), wire tension (3%), pulse on time (2%), and pulse off time (2%).The confirmatory run validates the GRA analysis. Potential future work may center on limiting the investigation to solely the critical parameters and conducting an elaborative analysis across their various levels to optimize material removal rates, surface quality, and overall process effectiveness.

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