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Analysis of Process Parameters in Wire EDM with Stainless Steel using Single Objective Taguchi Method and Multi Objective Grey Relational Grade

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Abstract

With the increasing demands of high surface finish and machining of complex shape geometries, conventional machining process are now being replaced by non-traditional machining processes. Wire EDM is one of the non-traditional machining processes. Surface roughness and kerf width are of crucial importance in the field of machining processes. This paper summarizes the Grey relational theory and Taguchi optimization technique, in order to optimize the cutting parameters in Wire EDM for SS304. The objective of optimization is to attain the minimum kerf width and the best surface quality simultaneously and separately. In this present study stainless steel 304 is used as a work piece, brass wire of 0.25mm diameter used as a tool and distilled water is used as a dielectric fluid. For experimentation Taguchi's $L_{16,}$ orthogonal array has been used. The input parameters selected for optimization are gap voltage, wire feed, pulse on time, and pulse off time. Dielectric fluid pressure, wire speed, wire tension, resistance and cutting length are taken as fixed parameters. For each experiment surface roughness and kerf width was determined by using contact type surf coder and video measuring system respectively. By using multi – objective optimization technique grey relational theory, the optimal value is obtained for surface roughness and kerf width and by using Taguchi optimization technique, optimized value is obtained separately. Additionally, the analysis of variance (ANOVA) is too useful to identify the most important factor.

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Keywords: WEDM; Taguchi's L-16 orthogonal array; Surface Roughness; Kerf Width; Taguchi Optimization Method; Grey Relation Analysis.

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1. Introduction

WEDM is based on Electrical Discharge Machining Process, which is also called electro-erosion machining process. When the gap voltage is sufficiently large (i.e. reaches the breakdown voltage of dielectric fluid), high power spark is produced, which increase the temperature about 10,000 degrees Celsius. By this way the metal is removed from the work piece. Stainless Steel (S304) is used as a work piece. Stainless Steel 304 is a nickel and chromium based alloy, which is widely used in valves, refrigeration equipment, evaporators, cryogenic vessels due to their exceptional corrosion resistant, high ductility, non-magnetic and it retains solid phase up to 1400 degree Celsius. The chemical composition of the work material is shown in table 1.

Table 1. Chemical Composition of Stainless Steel

Chemical Composition Wt%	Carbon (C)	Manganese (Mn)	Silicon (Si)	Sulphur (S)	phosphorous (P)	Nickel (Ni)	Chromium (Cr)
Work Material	0.08	1.86	0.41	0.016	0.026	8.42	18.26
Range	Up to 0.08	Up to 2.00	Up to 0.75	Up to 0.030	Up to 0.045	8.00 - 10.50	18.00 - 20.00

Brass wires are alloys of copper and zinc possesses reasonable conductivity with high tensile strength when compared to the copper wires. In this experiment, brass wire having 65% of copper and 35% of zinc is selected as a tool due to its properties, availability and low cost. The gap between the wire and work piece usually ranges from 0.025 to 0.075 mm and is constantly maintained by a computer controlled positioning system [1].

The selection of optimum machining parameters in WEDM is an important step [2, 3]. Taguchi Optimization technique is single parameter optimization based on the signal to noise ratio. Grey relational analysis is applied to optimize the parameters having multi-responses through grey relational grade. Furthermore, a statistical analysis of variance (ANOVA) is performed to see which process parameters are statistically significant [4].

Nomenclature

GV	gap voltage (V)
WF	wire feed (mm/min)
T_{ON}	pulse on time (μs)
T_{OFF}	pulse off time (μs)
R_a	Surface Roughness
K_f	Kerf Width
%P	Percentage Contribution
Units	
V	Volts
mm	Millimetre
min	Minute
μs	Micro Seconds
μm	Micro meter
Abbreviation	
WEDM	wire cut electrical discharge machining
DOF	degrees of freedom
LB	lower the better
SS	stainless steel

2. Design of experiments

Taguchi Technique is applied to plan the experiments [5]. Orthogonal arrays were introduced in the 1940s and have been widely used in designing experiments [6]. It is used to reduce the number of experiments needed to be performed than the full factorial experiment. Based on the machine tool, cutting tool and work piece capability, the process parameters and the level for the process parameters were selected and listed in Table 2.

Table 2. Machining parameters and their levels

S. No	Process Parameter	Unit	Level 1	Level 2	Level 3	Level 4
1	Gap Voltage	V	40	45	50	55
2	Wire Feed	mm/min	2	4	6	8
3	Pulse ON time (T_{on})	µs	4	6	8	10
4	Pulse OFF time (T_{off})	µs	4	6	8	10

Taguchi proposed to acquire the characteristic data by using orthogonal arrays, and to analyze the performance measure from the data to decide the optimal process parameters. The designed combination of input parameters and its corresponding surface roughness and kerf width is shown in table 3 respectively.

Table 3. Experimental Results

Exp. No.	Process Parameters				Surface Roughness [µm]	Kerf Width [mm]
	Gap Voltage [V]	Wire Feed [mm/min]	Pulse on Time [µs]	Pulse off Time [µs]		
1	40	2	0.315	4	2.36	0.315
2	45	4	0.308	6	2.28	0.308
3	50	6	0.308	8	2.17	0.308
4	55	8	0.297	10	2.51	0.297
5	50	4	0.299	4	2.56	0.299
6	55	2	0.300	6	2.85	0.300
7	40	8	0.296	8	2.48	0.296
8	45	6	0.289	10	2.34	0.289
9	55	6	0.293	4	2.02	0.293
10	50	8	0.301	6	2.22	0.301
11	45	2	0.294	8	2.05	0.294
12	40	4	0.298	10	2.39	0.298
13	45	8	0.305	4	2.32	0.305
14	40	6	0.308	6	2.32	0.308
15	55	4	0.297	8	2.21	0.297
16	50	2	0.311	10	2.49	0.311

3. Taguchi's Optimization Method

Optimization of process parameters is the key step in the Taguchi method to achieve high quality without increasing cost [7]. However, originally Taguchi method was designed to optimize single performance characteristics [8]. According to Taguchi method, the S/N ratio is the ratio of Signal to Noise where signal represents the desirable value and noise represents the undesirable value. The response R_a and K_f reported in Table 3, which is used to calculate the Signal to Noise Ratio (S/N) using the equation (1). The experimental results are now transformed into a signal-to-noise (S/N) ratio [9]. Since surface roughness and kerf width is desired to be at minimum, so Lower the Better characteristic is used for S/N ratio calculation. The optimal setting would be the one which could achieve lowest S/N ratio [10]. The S/N Ratio for the experiments conducted is shown in Table 4.

$$S/N_{LB} = -10 \times \log\left(\frac{1}{r}\sum_{i=1}^{r} y_i^2\right) \quad (1)$$

where S/N_{LB} is the Signal to noise ratio (Lower the better), y_i - output characteristic(R_a) and r – no of trials .

Table 4. Corresponding S/N ratios for Surface Roughness and Kerf Width

Exp No.	S/N Ratio for surface roughness	S/N Ratio for kerf width
1	-7.4582	10.0338
2	-7.1587	10.2290
3	-6.7292	10.2290
4	-7.9935	10.5449
5	-8.1648	10.4866
6	-9.0969	10.4576
7	-7.8890	10.5742
8	-7.3843	10.7820
9	-6.1070	10.6626
10	-6.9271	10.4287
11	-6.2351	10.6331
12	-7.5680	10.5157
13	-7.3098	10.3140
14	-7.3098	10.2290
15	-6.8878	10.5449
16	-7.9240	10.1448

The mean value of S/N ratio for surface roughness and kerf width is tabulated for four levels are tabulated as shown in Table 5 and Table 6 respectively.

Table 5. S/N Ratio Mean for Surface Roughness

S. No.	Process Parameters	S/N Ratio Mean			
		Level 1	Level 2	Level 3	Level 4
1	Gap Voltage	-7.5563	-7.0220	-7.4363	-7.5213
2	Wire Feed	-7.6786	-7.4448	-6.8826	-7.5299
3	Ton	-7.3349	-8.1338	-6.7093	-7.3579
4	Toff	-7.2600	-7.6231	-6.9353	-7.7175

From Fig.1, it can be seen that S/N Ratio decreases up to a short period then increases correspondingly to gap voltage. The S/N Ratio decreases up to a certain limit then increases correspondingly to the wire feed. When pulse on time and pulse off time increases, the S/N ratio will be deflected with increasing and decreasing.

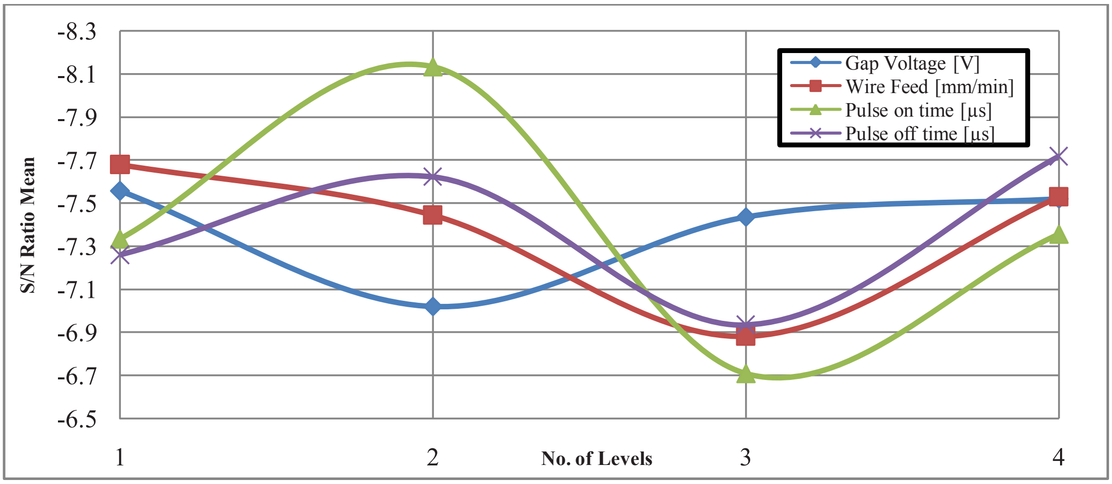

Fig.1. Effects of Process Parameters on Mean S/N Ratio for Surface Roughness

Table 6. S/N Ratio Mean for Kerf Width

S. No.	Process Parameters	S/N Ratio Mean			
		Level 1	Level 2	Level 3	Level 4
1	Gap Voltage	10.3382	10.4895	10.3223	10.5525
2	Wire Feed	10.3173	10.4441	10.4757	10.4655
3	Ton	10.2592	10.5751	10.5600	10.3082
4	Toff	10.3743	10.3361	10.4953	10.4969

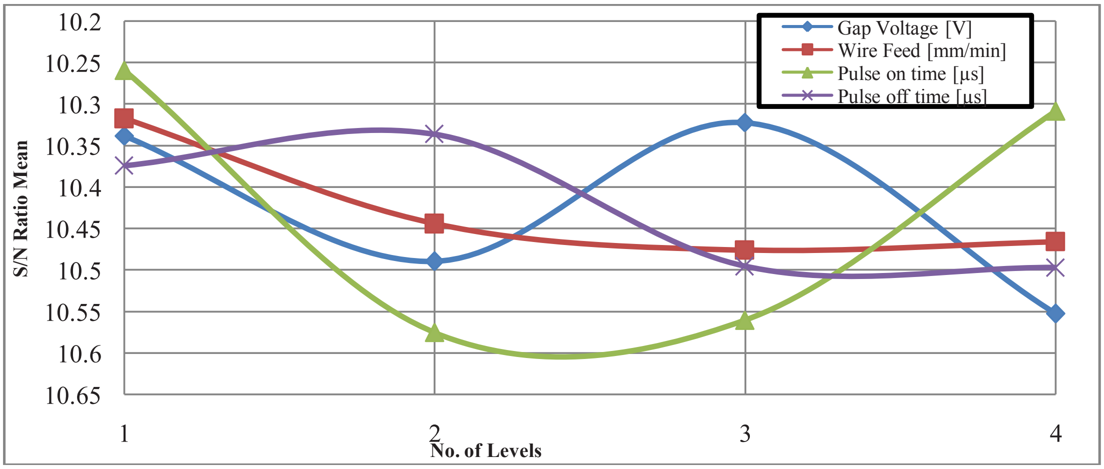

Fig.2. Effects of Process Parameters on Mean S/N Ratio for Kerf Width

From Fig.2, it can be seen that S/N Ratio increases up to a short period then decreases gradually when the pulse off time and wire feed increases. With respect to the increase in pulse on time, the S/N Ratio decreases up to a short period and then increases gradually. The S/N ratio will be deflected with increasing and decreasing when the Gap Voltage increases.

4. Grey Relational Analysis

Grey theory has been widely used in engineering analysis, and it reveals the potential to solve the setting of optimal machining parameters associated with a process with multiple output parameters [11]. The steps to be carried out are

1. Grey Relational Normalization
2. Grey Relational Gathering
3. Grey Relational Coefficient
4. Grey Relational Grade

Step 1: Normalize the measured values of surface roughness and kerf width ranging from zero to one. This process is known as Grey relational normalization.

Step 2: From the Grey relational normalization values, the grey relational gathering value can be determined using the required characteristics. Since both surface roughness and kerf width cannot be optimized for minimum value, lower the better and nominal the better characteristics are used to get the minimum surface roughness and nominal Kerf width respectively.

Step 3: The Grey relational co-efficient is calculated to represent the relationship between the desired and actual data.

Step 4: The average value of the grey relational co-efficient value of surface roughness and kerf width is known as overall Grey relational grade.

Now, the multiple objective optimization problems have been transformed into a single equivalent objective function optimization problem using this approach. The four above mentioned values are shown in the table 4. From the grey relational grade values obtained, the means of the grey relational grades at different levels of process parameters were calculated [12].

Table 7. Grey Relational Gathering, Co-efficient and Grades Values

Exp. No	Grey Relational Normalized Values		Grey Relational Gathering values		Grey Relational Coefficient values		Grey Relation Grade Values
	Surface Roughness	Kerf Width	Surface Roughness	Kerf Width	Surface Roughness	Kerf Width	
1	0.8281	1.0000	0.5903	1.0000	0.5496	1.0000	0.7748
2	0.8000	0.9778	0.6868	0.7309	0.6149	0.6501	0.6325
3	0.7614	0.9778	0.8194	0.7309	0.7346	0.6501	0.6924
4	0.8807	0.9429	0.4097	0.3079	0.4586	0.4194	0.4390
5	0.8982	0.9492	0.3496	0.3842	0.4346	0.4481	0.4414
6	1.0000	0.9524	0.0000	0.4230	0.3333	0.4643	0.3988
7	0.8702	0.9397	0.4457	0.2691	0.4742	0.4062	0.4402
8	0.8211	0.9175	0.6144	0.0000	0.5646	0.3333	0.4490
9	0.7088	0.9302	1.0000	0.1539	1.0000	0.3714	0.6857
10	0.7789	0.9556	0.7593	0.4618	0.6750	0.4816	0.5783
11	0.7193	0.9333	0.9639	0.1915	0.9327	0.3821	0.6574
12	0.8386	0.9460	0.5543	0.3455	0.5287	0.4331	0.4809

13	0.8140	0.9683	0.6387	0.6158	0.5805	0.5655	0.5730
14	0.8140	0.9778	0.6387	0.7309	0.5805	0.6501	0.6153
15	0.7754	0.9429	0.7713	0.3079	0.6862	0.4194	0.5528
16	0.8773	0.9873	0.4337	0.8461	0.4920	0.7646	0.6283

Since the experiment is done by Taguchi's L-16 orthogonal array, the separation of the effect of each machining parameter on the grey relational grade at different levels is tabulated as shown in table 8.

Table 8. Grey Relational Grade value for corresponding levels

S. No	Process Parameter	Grey Relational Grade Mean			
		Level 1	Level 2	Level 3	Level 4
1	Gap Voltage	0.5778	0.5780	0.5851	0.5191
2	Wire Feed	0.6148	0.5269	0.6106	0.5076
3	Pulse-on Time	0.6347	0.4324	0.6006	0.5924
4	Pulse-off Time	0.6187	0.5562	0.5857	0.4993

From Fig.3, it can be seen that S/N Ratio slightly increases up to a certain limit then decreases when gap voltage increases. The S/N ratio will be deflected with increasing and decreasing when the wire feed, the Pulse on time and the Pulse off time increases.

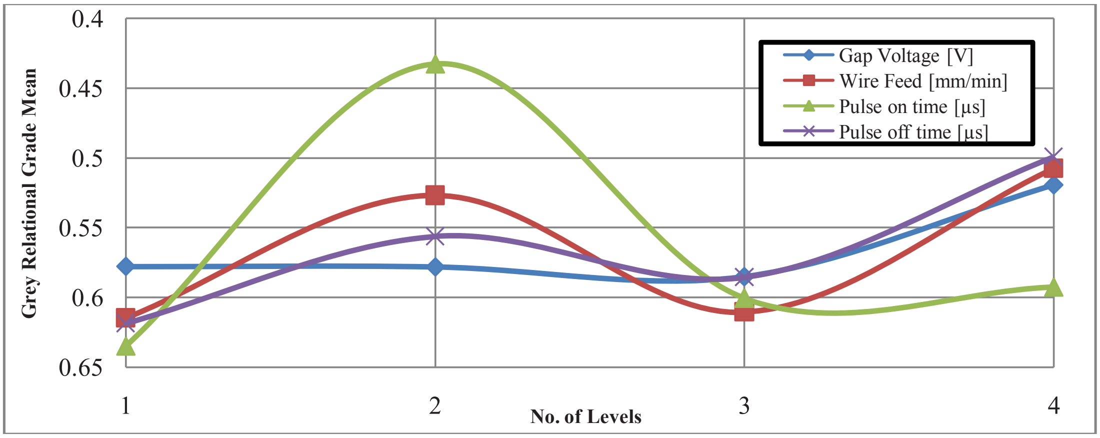

Fig.3. Effects of Process Parameters on Mean Grey Relational Grade

5. Analysis of Variance

ANOVA is a statistically based, objective decision-making tool for detecting any differences in the average performance of groups of items tested [13]. The purpose of the Analysis of Variance (ANOVA) is to investigate which machining parameter significantly affects the performance characteristic [14].

5.1. S/N Ratio for Surface roughness

The results obtained by using analysis of variance to find out the percentage contribution of each input factor on the surface roughness are shown in table 5. It is seen that the pulse on time [µs] has the major influence on the surface roughness [15].

Table 9. ANOVA table for Surface roughness

Factors	Sum of Square	DOF	Mean Squares	%P (Percentage Contribution)
Gap Voltage	0.7293	3	0.2431	9.3451
Wire Feed	1.4527	3	0.4842	18.6146
Pulse ON time	4.0817	3	1.3606	52.3020
Pulse OFF time	1.5404	3	0.5135	19.7383

5.2. S/N Ratio for Kerf width

The results obtained by using analysis of variance to find out the percentage contribution of each input factor on the kerf width are shown in Table 5. It is seen that the pulse on time [µs] has the major influence on the kerf width.

Table 10. ANOVA table for Kerf width

Factors	Sum of Square	DOF	Mean Squares	%P (Percentage Contribution)
Gap Voltage	0.1539	3	0.0513	24.4791
Wire Feed	0.0647	3	0.0216	10.2911
Pulse ON time	0.3277	3	0.1092	52.1234
Pulse OFF time	0.0824	3	0.0275	13.1064

5.3. Grey Relation Grade

The results obtained by using analysis of variance to find out the percentage contribution of each input factor on both surface roughness and kerf width are shown in Table 5. It is seen that the Pulse ON Time has the major influence on the Surface Roughness and Kerf Width.

Table 11. ANOVA table for Surface roughness and Kerf width

Factors	Sum of Square	DOF	Mean Squares	%P (Percentage Contribution)
Gap Voltage	0.0114	3	0.0038	6.4334
Wire Feed	0.0371	3	0.0124	20.9368
Pulse ON time	0.0978	3	0.0326	55.1919
Pulse OFF time	0.0309	3	0.0103	17.4379

6. Results & Discussions

The results obtained from the Taguchi Optimization technique to get the minimum Surface Roughness and minimum Kerf Width are shown in table 12. The grey relational analysis result is also shown in the table 13 to get the minimum surface roughness and nominal Kerf Width.

Table 12. Optimum conditions using Taguchi Optimization method

S. No.	Process Parameter	Units	Surface Roughness		Kerf Width	
			Best Level	Value	Best Level	Value
1	Gap Voltage	V	1	40	3	50
2	Wire Feed	mm/min	1	2	1	2
3	Pulse on time	µs	2	6	1	4
4	Pulse off time	µs	4	10	2	6

Table 13. Optimum Conditions using Grey Relational Analysis

S. No.	Process Parameter	Units	Best Level	Value
1	Gap Voltage	V	3	50
2	Wire Feed	mm/min	1	2
3	Pulse on time	µs	1	4
4	Pulse off time	µs	1	4

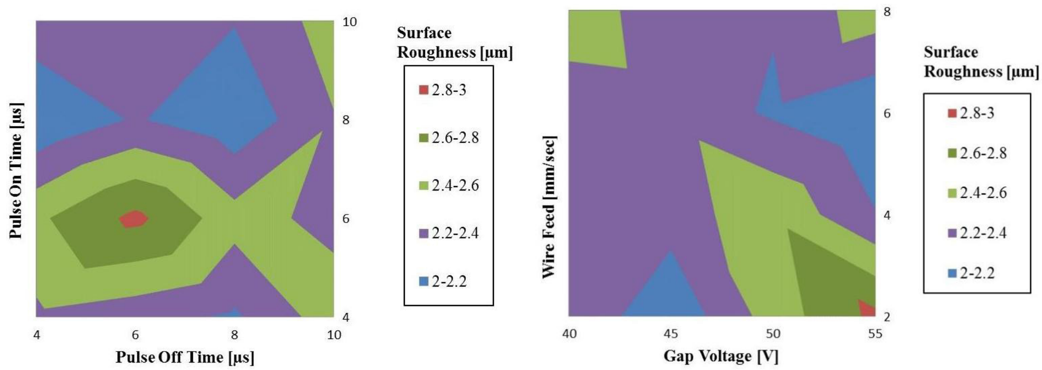

Fig.4. Range of occurrence of surface roughness

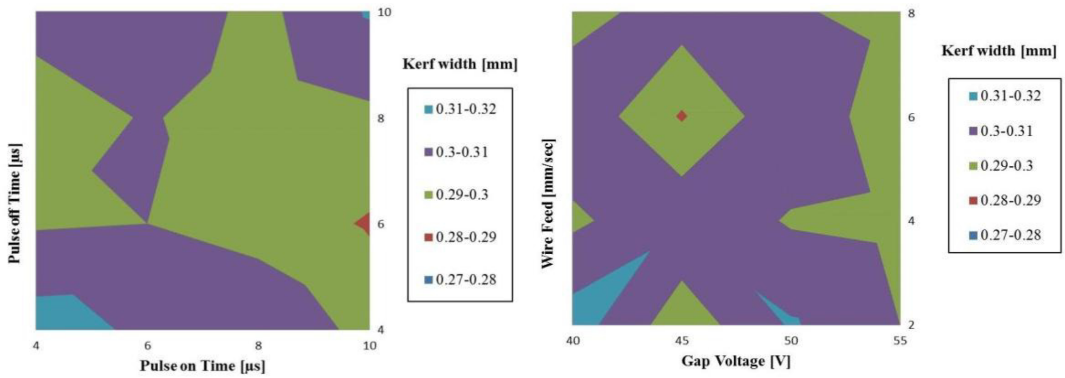

Fig.5. Range of occurrence of kerf width

From Fig. 4, it can seen that for a particular value of input parameter the corresponding range of occurrence of surface roughness can be determined and vice versa. From Fig. 5, it can be seen that for a particular value of input parameter the corresponding range of occurrence of kerf width can be determined and vice versa.

7. Conclusion

Experimental investigation on wire electrical discharge machining of Stainless Steel (SS304) has been done using brass wire of 0.25mm. The following conclusions are made.

- Based on the Taguchi's Optimization method, the optimized input parameter combinations to get the minimum surface roughness are 40V gap voltage, 2mm/min wire feed, 6 µs pulse on time, 10 µs pulse off time and similarly optimized conditions to get the minimum kerf width are 50V gap voltage, 2mm/min Wire Feed, 4 µs pulse on time, 6 µs pulse off time.
- Based on the Grey relational analysis, the optimized input parameter combinations to get both the minimum surface roughness and the nominal kerf width are 50V gap voltage, 2mm/min wire feed, 4 µs pulse on time and 4 µs pulse off time.
- The Analysis of Variance resulted that the pulse on time has major influence on the surface roughness (µm) and kerf width (mm) in both the Taguchi optimization method and Grey relational analysis.
- The objectives such as surface roughness and kerf width are optimized using a single objective taguchi method and multi objective grey relational analysis and the same has been validated with the experimental results.

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