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Multi response optimization of Wire electrical discharge machining process parameters using Taguchi based Grey Relational Analysis

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Abstract

This paper presents a study that investigates the effect of the WEDM process parameters on the surface roughness average and the kerf width of the stainless steel (SS 304). Nine experimental runs based on an orthogonal array of Taguchi method are performed and grey relational analysis method is subsequently applied to determine an optimal WEDM parameter setting. Surface roughness and kerf width are selected as the quality targets. An optimal parameter combination of the WEDM process is obtained using Grey relational analysis. By analyzing the Grey relational grade matrix, the degree of influence for each controllable process factor onto individual quality targets can be found. The pulse ON time is found to be the most influential factor for both the surface roughness and the kerf width. Further, the results of the analysis of variance (ANOVA) reveals that the pulse ON time is the most significant controlled factor for affecting the multiple responses in the WEDM according to the weighted sum grade of the surface roughness and the kerf width..

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Keywords: WEDM; surface roughness; kerf width; Grey relational analysis; optimization

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1. Introduction

Stainless steel (SS) is one of the widely used materials for various products which are often made by several cutting and finishing operations. Owing to the inherent characteristics of SS such as high strength, hardness and good corrosion resistance, its machinability is poor and it often requires high speed for machining. Further, the quality of the machined surface is also relatively not up to the mark. Non-conventional machining processes such as WEDM have the potential to machine SS accurately. However, it is important to select optimum combination of WEDM parameters for achieving optimal machining performance (Lin et al., 2000).

The electrical discharge machining (EDM) process is one of the best alternatives for machining an ever increasing number of high-strength, non-corrosion, and wear resistant materials (Abu Zeid, 1997). The technology of monitoring and control of the machining processes has been accelerated because of the need for improvement in machining efficiency and part quality. The degree of accuracy of workpiece dimensions obtainable and the fine surface finishes make WEDM particularly valuable for applications involving manufacture of stamping dies, extrusion dies and prototype parts. WEDM process has been a key process for the tooling and manufacturing industry. WEDM was introduced in the late 1960s', and has revolutionized the tool and die, mold, and metal working industries. It can machine anything that is electrically conductive regardless of the hardness, from relatively common materials such as tool steel, aluminum, copper, and graphite, to exotic space-age alloys including titanium, carbide, polycrystalline diamond compacts and conductive ceramics. In WEDM, material is removed by means of rapid and repetitive spark discharges across the gap between the tool and the workpiece. The WEDM process plays a predominant role in some manufacturing sectors, because this process has the capability to cut complex and intricate shapes of components in all electrically conductive materials with better precision and accuracy. (Mahapatra and Patnaik, 2006).

The most important performance measures in WEDM are material removal rate (MRR), surface roughness and kerf width. Discharge current, pulse duration, pulse frequency, wire speed, wire tension, average working voltage and dielectric flushing conditions are the machining parameters which affect the performance measures. Among the other performance measures, the kerf width, which determines the dimensional accuracy of the finished part, is of utmost importance. The wire–workpiece gap usually ranges from 0.025 to 0.075mm and is constantly maintained by a computer controlled positioning system (Tosun et al., 2004). The kerf width is calculated by summing up the wire diameter (ranges 0.05–0.4 mm) to 2 × "wire-workpiece gap distance". In WEDM operations, surface roughness is one of the components that determine the surface integrity. In setting the machining parameters, the main goal is the minimum surface roughness with the minimum kerf width.

In past a lot of work has been carried out to investigate the effect of WEDM parameters on various performance parameters. Scott et al. (1991) formulated a multi-objective optimization problem and presented a solution for the selection of the best parameter settings to achieve the desired MRR and surface quality on a WEDM machine. Lajis et al. (2009) optimized the process parameters in the cutting of Tungsten Carbide ceramic using EDM with a graphite electrode by using Taguchi methodology. In their paper, EDM parameter such as peak current, voltage, pulse duration and interval time were found to have a significant influence on machining characteristic such as MRR, electrode wear rate (EWR) and surface roughness. The results of their paper revealed that, in general the peak current significantly affects the EWR and surface roughness, while the pulse duration mainly affects the MRR. Singh and Maheshwari (2007) presented an investigation on the optimization of process parameters for the EDM of 6061Al/Al2O3p/20p work specimens by employing the Taguchi Design of Experiment (DOE) methodology. They selected one noise factor i.e. aspect ratio (with two levels), and five control factors, viz. pulse current, pulse ON time, duty cycle, gap voltage and tool electrode lift time (three levels each), for the experiment to obtain the optimal settings of factors and the effect of these factors on multiple performance characteristics, namely, MRR, Tool Wear Rate (TWR) and surface roughness. Tzeng and Chen (2007) performed an experimental study to optimize the precision and accuracy of the high-speed EDM process. Their paper describes the application of the fuzzy logic analysis coupled with Taguchi method to optimize the precision and accuracy of the high-speed EDM process. Kumar et al. (2012) made an attempt to model the response variable i.e. surface roughness in WEDM process using response surface methodology. They varied six parameters i.e. pulse ON time, pulse OFF time, peak current, spark gap voltage, wire feed and wire tension to investigate their effect on surface roughness and subsequently, they optimized the surface roughness using multi-response optimization through desirability. Rao and Sarcar (2009) evaluated the optimal parameters for machining brass with wire and studied the influence of these parameters on MRR and Surface roughness.

Liao et al. (1997) performed an experimental study to determine the variation of the machining parameters on the MRR, gap width and surface roughness. Huang et al. (1999) investigated experimentally the effect of machining parameters on the gap width, the surface roughness and the depth of white layer on the machined workpiece surface. Tosun et al. (2004) presented an investigation on the optimization and the effect of machining parameters on the kerf and the MRR in WEDM operations. They recommended equal importance for both the response variables (kerf and MRR).

In order to maintain a high production rate with an acceptable quality level, it is important to select the optimum combination of WEDM parameters such as current, pulse ON time, pulse OFF time and feed rate as these parameters have impact on multi performance characteristics like surface roughness, kerf width, micro-hardness and microstructure. Surface roughness and kerf width plays an important role in many areas and is a factor of great importance in the evaluation of machining accuracy.

Taguchi method can be applied for optimization of process parameters to obtain optimum condition with lowest cost and minimum number of experiments which leads to production of high quality products. Owing to the advantages offered by the Taguchi method, researchers have extensively used this method to plan experiments for the purpose of optimization of process and design parameters (Kamaruddin et al., 2004; Verma et al., 2012). Rao et al. (2010) applied Taguchi method to find the optimal cutting parameters for surface roughness in WEDM machining of Aluminum BIS-24345. Saini et al. (2013) used Taguchi method with analysis of variance (ANOVA) to optimize the WEDM parameters while cutting composite material Al6061/SICP. Another Taguchi method based study was conducted by Kaladhar et al. (2012) to investigate the effect of cutting parameters on surface finish to obtain optimal setting of the cutting parameters.

The Grey relational analysis is a method for measuring the degree of approximation among the sequences using a Grey relational grade (Siddiquee et al., 2010). It is a new technique for performing prediction, relational analysis, and decision making in many areas. Theories of the Grey relational analysis have attracted considerable interest among researchers (Khan et al., 2012). Some other researchers have also performed the optimization of process parameters. For example, Ramanujam et al., (2011) presented the detailed experimental investigation on turning Aluminium Silicon Carbide particulate Metal Matrix Composite (Al-SiC –MMC) using polycrystalline diamond (PCD) 1600 grade insert. The objective was to establish a correlation between cutting speed, feed and depth of cut to the specific power and surface finish on the work piece. The optimum machining parameters were obtained by Grey relational analysis. Tzeng et al. (2009) investigated the optimization of CNC turning operation parameters for SKD11 alloy tool steel using Grey relational analysis method. Taguchi method based Grey relational was applied by Sharma and Bhambri (2012) to investigate the optimization of two response parameters (surface roughness and MRR) by three cutting parameters (cutting speed, feed rate and depth of cut) during high speed turning of AISI H13 under dry conditions.

It appears from the literature presented above that not much work has been done to investigate the effect of WEDM parameters on kerf with surface roughness of the machined surface. Keeping this in view, the present work is aimed to investigate the effect of three WEDM parameters (current, pulse ON time and pulse OFF time) on surface roughness and kerf width during WEDM of SS. The Taguchi L_9 (3^3) design is utilized for experimental planning for this purpose. The Grey relational analysis is then applied to examine how the input factors influence the quality targets of surface roughness and kerf width. An optimal parameter combination was then obtained. Through analyzing the Grey relational grade matrix, the most influential factors for individual quality targets of cutting operations can be identified.

2. Grey relational analysis

The following sections present the procedure for grey relational analysis that has been used in this study to obtain the optimum WEDM parameters and also to identify the most influential parameters that affect surface roughness and kerf width.

2.1. Data preprocessing

Data preprocessing is used to transform the given data sequence into dimensionless data sequence and it involves the transfer of the original sequence to a comparable sequence. Let the original reference sequence and comparability sequence be represented as $x_0^{(O)}(k)$ and $x_i^{(O)}(k)$, i = 1,2,...., m; k = 1,2,...., n, respectively, where m is the total number of experiment to be considered, and n is the total number of observation data . Data preprocessing converts the original sequence to a comparable sequence. Several methodologies of preprocessing data can be used in Grey relation analysis, depending on the characteristics of the original sequence (Tzeng et al., 2009; Deng, 1989; Yang et al., 2007). For the original sequence "the-larger-the-better", the original sequence is normalized as follows (Tzeng et al., 2009):

$$x_i^*(k) = \frac{x_i^{(O)}(k) - \min(x_i^{(O)}(k))}{\max(x_i^{(O)}(k)) - \min(x_i^{(O)}(k))} \quad (1)$$

For "the-smaller-the-better" characteristic of the original sequence, the original sequence is normalized as follows (Tzeng et al., 2009):

$$x_i^*(k) = \frac{\max(x_i^{(O)}(k)) - x_i^{(O)}(k)}{\max(x_i^{(O)}(k)) - \min(x_i^{(O)}(k))} \quad (2)$$

In case, if a defined target value, OB, exists, then the original sequence is normalized as follows (Tzeng et al., 2009):

$$x_i^*(k) = 1 - \frac{\left|x_i^{(O)}(k) - OB\right|}{\max\left\{\max(x_i^{(O)}(k)) - OB, OB - \min(x_i^{(O)}(k))\right\}} \quad (3)$$

There is an alternate simple method for normalizing the original sequence where the original sequence is divided by the first value of the sequence i.e. $x_i^{(O)}(1)$ as follows:

$$x_i^*(k) = \frac{x_i^{(O)}(k)}{x_i^{(O)}(1)} \quad (4)$$

where, $x_i^{(O)}(k)$: the original sequence, $x_i^*(k)$: the sequence after the data preprocessing, $\max x_i^{(O)}(k)$: the largest value of $x_i^{(O)}(k)$, and $\min x_i^{(O)}(k)$: the smallest value of $x_i^{(O)}(k)$.

2.2. Grey relational coefficients and Grey relational grades

After the data preprocessing, a grey relational coefficient is calculated using the preprocessed sequences. The grey relational coefficient can be calculated as (Tzeng et al., 2009):

$$\gamma(x_0^*(k), x_i^*(k)) = \frac{\Delta_{\min} + \zeta\,\Delta_{\max}}{\Delta_{0i}(k) + \zeta\,\Delta_{\max}} \text{ and } 0 < \gamma(x_0^*(k), x_i^*(k)) \le 1 \quad (5)$$

where $\Delta_{0i}(k)$ is the deviation sequence of the reference sequence $x_0^*(k)$ and comparability sequence $x_i^*(k)$; namely

$$\Delta_{0i}(k) = \left|x_0^*(k) - x_i^*(k)\right|,$$

$$\Delta_{\max} = \max_{\forall j \in i} \max_{\forall k} \left|x_0^*(k) - x_j^*(k)\right|,$$

$$\Delta_{\min} = \min_{\forall j \in i} \min_{\forall k} \left|x_0^*(k) - x_j^*(k)\right|$$

with ζ : distinguishing coefficient, $\zeta \in [0,1]$.

After calculation of the grey relational coefficients, grey relational grade is calculated using the following relationship (Tzeng et al., 2009):

$$\gamma(x_0^*, x_i^*) = \sum_{k=1}^{n} \beta_k \gamma(x_0^*(k), x_i^*(k)) \text{ , where } \sum_{k=1}^{n} \beta_k = 1 \quad (6)$$

The grey relational grade $\gamma(x_0^*, x_i^*)$ represents the degree of correlation between the reference and comparability sequences. In case of two identical sequences, the grey relational grade is equal to 1. The grey relational grade also indicates the degree of influence exerted by the comparability sequence on the reference sequence. Consequently, if a particular comparability sequence is more important to the reference sequence than other comparability sequences, the grey relational grade for that comparability sequence and the reference sequence will exceed as compared to other grey relational grades. The grey relational analysis is actually a measurement of the absolute value of data difference between the sequences, and can be used to approximate the correlation between the sequences.

3. Experimental procedures and test results

3.1. Materials

Stainless steel (SS 304 grade) with 200 mm × 40 mm × 10 mm size was used as work-piece material. The composition of the work-piece material is shown in Table 1.

Table1: Material composition of stainless steel

Element	Concentration (% by weight)	Element	Concentration (% by weight)
Iron	70.32	Molybdenum	0.174
Carbon	0.062	Aluminum	0.0005
Silicon	0.18	Copper	0.247
Manganese	1.28	Chromium	18.30
Sulphur	0.0052	Niobium	0.045
Phosphorous	0.034	Vanadium	0.044
Nickel	8.02	Titanium	0.007

3.2. Schematic of machining

The experimental studies were performed on a Steer Corporation DK7712 NC WEDM machine. This machine can be used to cut work piece in accordance with the predetermined locus (The schematic is shown in Fig. 1). Different settings of current, pulse ON time and pulse OFF time are used in the experiments. Frequency setting is kept constant throughout the experiments.

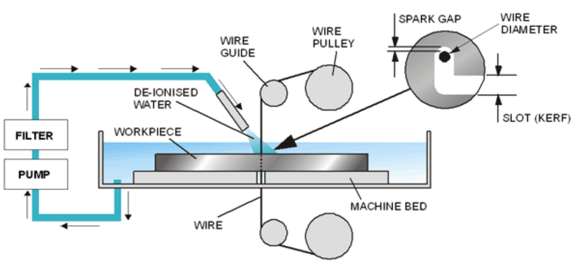

Fig. 1: Schematic of WEDM process

3.3. Experimental parameters and design

The experiments were conducted with three controllable 3-level factors and two response variables. Nine experimental runs based on the orthogonal array L_9 (3^3) were carried. Table 2 shows three controlled factors, i.e., current (i.e., A (Ampere)), pulse ON time (i.e., B (μs)) and pulse OFF time (i.e., C (μs)) with three levels for each factor. Table 3 shows the nine cutting experimental runs according to the selected orthogonal table. After cutting, two quality objectives of the workpieces were chosen, including the surface roughness (i.e., R_a (μm)) and kerf width (i.e., μm).

Table 2: Experimental factors and their levels

Factor	Symbol	Unit	Level-1	Level-2	Level-3
Current	A	A	2	3	4
Pulse on time	B	μs	15	20	25
Pulse off time	C	μs	3	4	5

Table 3: Orthogonal array L_9 (3^3) of the experimental runs

Exp. No.	A	B	C
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	3
5	2	2	1
6	2	3	2
7	3	1	2
8	3	2	3
9	3	3	1

3.4. Measuring apparatus

The surface roughness values were measured by the surface roughness tester (model: SURFTEST, SV-2100; make: Mitutoyo, Japan). The stereozoom microscope (make: Focus, Japan) was used to get kerf width values.

4. Results and discussion

The following sections describe the results of the present study and also present a discussion on the results in light of the available literature.

4.1. Best experimental run

The experimental results for the surface roughness and kerf width are listed in Table 4. Typically, small values of both surface roughness and kerf width are desirable for good quality and accuracy in the machining operation. Thus, the data sequences have a "the-smaller-the-better characteristic" for both surface roughness and kerf width therefore, Eq. (2) was employed for data preprocessing. The values of the surface roughness and the kerf width are set to be the reference sequence $x_0^{(O)}(k)$, k = 1, 2. Moreover, the results of nine experiments were the comparability sequences

$x_i^{(O)}(k)$, i = 1, 2, ...,9, k = 1, 2. Table 5 listed all of the sequences after implementing the data preprocessing using Eq. (2). The reference and the comparability sequences were denoted as $x_0^*(k)$ and $x_i^*(k)$, respectively. Also, the deviation sequences Δ_{0i}, $\Delta_{\max}(k)$ and $\Delta_{\min}(k)$ for i = 1, 2, ..., 9, k = 1, 2 can be calculated.

Table 4: Orthogonal array L_9 (3^3) of the experimental runs and results

Run no.	A	B	C	R_a (µm)	*Kerf width* (µm)
1	1	1	1	2.881	236.84
2	1	2	2	3.707	263.16
3	1	3	3	4.029	266.5
4	2	1	3	4.113	210.53
5	2	2	1	5.313	236.84
6	2	3	2	5.176	210.53
7	3	1	2	3.937	219.3
8	3	2	3	5.505	263.16
9	3	3	1	5.105	271.93

The distinguishing coefficient ζ can be substituted for the grey relational coefficient in Eq. (5). If all the process parameters have equal weighting, ζ is set to be 0.5. Table 6 shows the grey relational coefficients and the grade for all nine comparability sequences. This investigation employs the response table of the Taguchi method to calculate the average Grey relational grades for each factor level, as illustrated in Table 7.

Table 5: The sequence after data preprocessing

Reference/Comparability sequence		R_a	*Kerf width*
Reference sequence		1.0000	1.0000
Comparability sequences	No. 1	0.0000	0.4285
	No. 2	0.3148	0.8572
	No. 3	0.4375	0.9116
	No. 4	0.4695	0.0000
	No. 5	0.9268	0.4285
	No. 6	0.8746	0.0000
	No. 7	0.4024	0.1428
	No. 8	1.0000	0.8572
	No. 9	0.8476	1.0000

Since the Grey relational grades represents the level of correlation between the reference and the comparability sequences, the larger Grey relational grade means the comparability sequence exhibiting a stronger correlation with the reference sequence. Based on this study, one can select a combination of the levels that provide the largest average response. Fig. 2 shows the mean value of Grey relational grade at different levels of each WEDM process parameters. The dashed line in this figure is the value of the total mean of the Grey relational grade. In Table 7 and Fig. 2, the combination of A_2, B_1, and C_2 shows the largest value of the Grey relational grade for the factors A, B, and C, respectively. Therefore, $A_2B_1C_2$ i.e. a current of 3 A, pulse ON time of 15 µs, a pulse OFF time of 4 µs, and is the optimal parameter combination of the cutting operations.

Table 6: The calculated grey relational coefficient and grey relational grade for nine comparability sequences.

Experimental run (Comparability sequences)	Orthogonal array L_9 (3^3)			Grey relational Coefficient		Grey relational grade
	A	B	C	R_a	*Kerf width*	
1	1	1	1	1.0000	0.5385	0.7693
2	1	2	2	0.6137	0.3684	0.4910
3	1	3	3	0.5333	0.3542	0.4438
4	2	1	3	0.5157	1.0000	0.7579
5	2	2	1	0.3504	0.5385	0.4445
6	2	3	2	0.3637	1.0000	0.6819
7	3	1	2	0.5541	0.7778	0.6659
8	3	2	3	0.3333	0.3684	0.3509
9	3	3	1	0.3710	0.3333	0.3522

Table 7: The response table for grey relational

Levels	Factors		
	A	B	C
1	0.5680	0.7310	0.5220
2	0.6281	0.4288	0.6129
3	0.4563	0.4926	0.5175

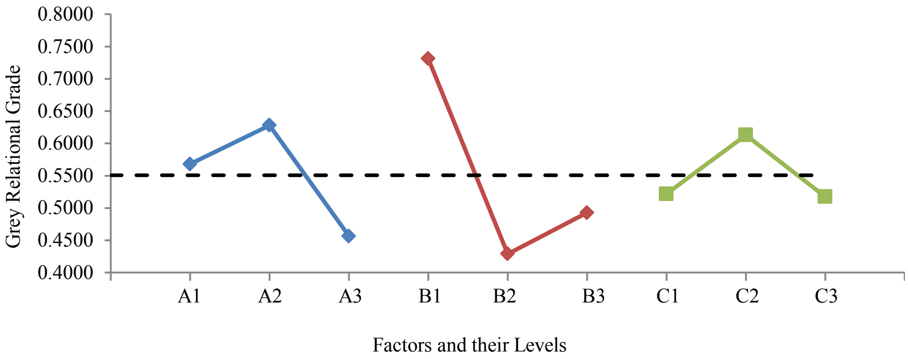

Fig. 2: Grey relational grade graph

4.2. Most influential factor

Grey relational analysis is applied to examine how the process parameters influence the quality targets of workpieces. The values of the factor level in nine experimental runs are set to the comparability sequences for three controllable factors. Table 8 lists all of the sequences.

Table 8: The sequence after data preprocessing for the reference sequences and comparability sequences

Experimental run	Comparability sequences			Reference sequences	
	A	B	C	R_a	*kerf*
1	1	1	1	1.00	1.00
2	1	1.33	1.33	1.29	1.11
3	1	1.67	1.67	1.40	1.13
4	1.5	1	1.33	1.43	0.89
5	1.5	1.33	1.67	1.84	1.00
6	1.5	1.67	1	1.80	0.89
7	2	1	1.67	1.37	0.93
8	2	1.33	1	1.91	1.11
9	2	1.67	1.33	1.77	1.15

Data preprocessing was performed based on Eq. (4), and Table 8 shows the normalized results. Subsequently, the deviation sequences were calculated using the method mentioned above. The deviation sequences and the distinguishing coefficient then were substituted into Eq. (5) to obtain the Grey relational coefficients. Additionally, the Grey relational coefficients are averaged using an equal weighting to obtain the Grey relational grade. Table 9 listed the Grey relational coefficients and the grade of the surface roughness of the reference sequence and comparability sequences. Table 10 gives the Grey relational coefficients and the grade of the kerf width for the reference sequence and the comparability sequences.

Table 9: The calculated grey relational coefficient and grey relational grade for experimental factors to experimental result of the R_a

	A	B	C
Grey relational coefficient	1.0000	1.0000	1.0000
	0.6137	0.9132	0.9132
	0.5333	0.6265	0.6265
	0.8629	0.5157	0.8235
	0.5696	0.4697	0.7234
	0.6056	0.7825	0.3637
	0.4182	0.5541	0.6001
	0.8362	0.4395	0.3333
	0.6663	0.8171	0.5075
Grey relational grade	0.6784	0.6798	0.6546

The Grey relational grades in Tables 9 and 10 can be further arranged in a matrix form shown as follows:

$$\gamma = \begin{bmatrix} \gamma(R_a, \mathrm{A}) & \gamma(R_a, \mathrm{B}) & \gamma(R_a, \mathrm{C}) \\ \gamma(k\mathrm{erf}, \mathrm{A}) & \gamma(k\mathrm{erf}, \mathrm{B}) & \gamma(k\mathrm{erf}, \mathrm{C}) \end{bmatrix} \tag{7}$$

$$= \begin{bmatrix} 0.6784 & 0.6798 & 0.6546 \\ 0.5766 & 0.6843 & 0.6694 \end{bmatrix}$$

By comparing Row 1 and Row 2, some conclusion can be drawn from this matrix. In the first row $\gamma(R_a, \mathrm{B}) > \gamma(R_a, \mathrm{A}) > \gamma(R_a, \mathrm{C})$, it means that the order of importance for the controllable factors to the surface roughness, in sequence, is the factor B, A, and C. Similarly, from the second row $\gamma(k\mathrm{erf}, \mathrm{B}) > \gamma(k\mathrm{erf}, \mathrm{C}) > \gamma(k\mathrm{erf}, \mathrm{A})$, the order of importance for the controllable factors to the kerf width, in sequence, is the factor B, C, and A.

Table 10: The calculated grey relational coefficient and grey relational grade for experimental factors to experimental result of the *kerf width*

	A	B	C
Grey relational coefficient	1.0000	1.0000	1.0000
	0.8285	0.7105	0.7105
	0.8109	0.4964	0.4964
	0.4677	0.8286	0.5490
	0.5179	0.6194	0.4449
	0.4677	0.4074	0.8286
	0.3333	0.8788	0.4192
	0.3766	0.7105	0.8285
	0.3867	0.5072	0.7470
Grey relational grade	0.5766	0.6843	0.6694

The most influential factors that affect the output variables are determined by identifying the maximum values in each row. Hence, based on the maximum values in the matrix of the Grey relational $(\gamma(R_a, \mathrm{B}), (k\mathrm{erf}, \mathrm{B})) = (0.6798, 0.6843)$, it can be found that the factor B, the pulse ON time, has the most influence on both the surface roughness and the kerf width with γ value of 0.6798 and 0.6843 respectively. Additionally, Table 11 gives the results of the analysis of variance (ANOVA) for the surface roughness, and the kerf width using the calculated values from the Grey relational grade of Table 6 and the response table of Table 7. According to Table 11, factor B, the pulse ON time with 67.13% of contribution, is the most significant controlled parameters for the cutting operation in WEDM followed by factor A, the current with 20.10% of contribution and factor C, the pulse OFF time with 7.68% of contribution if the minimization of both the surface roughness and the kerf width is simultaneously considered. Clear view of contribution of factors from Table 11 is shown in Fig. 3.

Table 11: ANOVA results for R_a and *kerf width*

Factor	Level 1	Level 2	Level 3	Degree of freedom	Sum of squares	Mean square	F value	Contribution (%)
A	0.5680	0.6281	0.4563	2	0.0456	0.0228	3.9445	20.10
B	0.7310	0.4288	0.4926	2	0.1522	0.0761	13.1776	67.13
C	0.5220	0.6129	0.5175	2	0.0174	0.0087	1.5065	7.68
Error				2	0.0116	0.0058	1.0000	5.09
Total				8	0.2268	0.0283		100.00

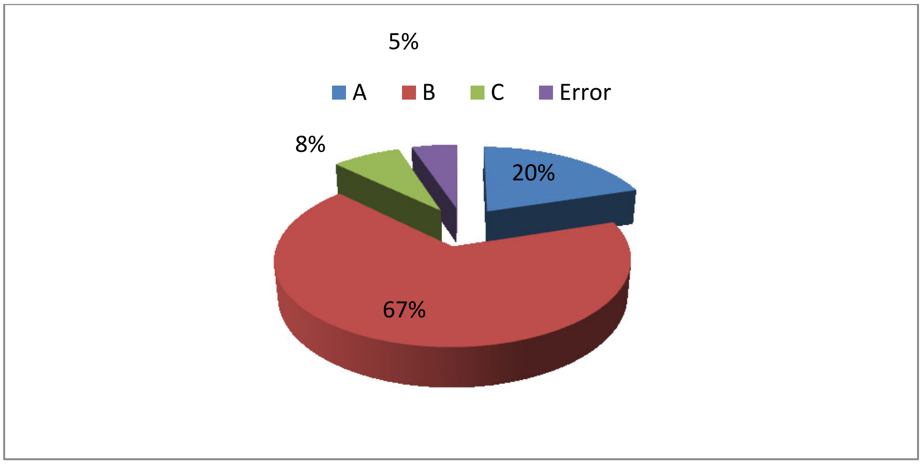

Fig. 3 Contribution of factors.

An increase in the discharge energy due to increase in the pulse ON time has been reported in the literature (Rao et al., 2010). Conversely, a decrease in the pulse ON time reduces the discharge energy to which the workpiece is exposed and therefore, smaller craters are formed on the workpiece. Decrease in the pulse ON time leads to reduction in both the surface roughness and the separation of the two freshly machined surfaces. The closer separation of machined surfaces results in a decrease in the kerf width. Thus, decrease in pulse ON time decreases both surface roughness and kerf width and vice-versa.

Further, the current affects the roughness and kerf width in a similar manner. The current is the driving force for the formation of crater due to which the machining takes place. An increased amount of current increases the energy input which increases the MRR but at the same time it may adversely affect the surface roughness and kerf width. Hence, an appropriate amount of current is essential for achieving minimum surface roughness as well as kerf width.

Thus, the combination of the parameters and their levels i.e. $A_2B_1C_2$ with minimum contribution of the pulse OFF time (7.68%) and maximum contribution of the pulse ON time (67.13%) would set out just right parameter combination to cause minimum surface roughness along with the minimum kerf width.

4.3. Confirmation test

After identifying the most influential parameters, the final phase is to verify the surface roughness and the kerf width by conducting the confirmation experiments**.** The $A_2B_1C_2$ is an optimal parameter combination during WEDM process via the grey relational analysis. Therefore, the condition $A_2B_1C_2$ of the optimal parameter combination was treated as a confirmation test. The result of the confirmation test gives the surface roughness average and the kerf width similar to those given in Table 4.

5. Conclusions

The effects of current, pulse ON time and pulse OFF time are experimentally investigated in machining of SS 304 using NC Wire-cut EDM process. The grey relational analysis based on the Taguchi method's response table was used to optimize the WEDM process parameters for SS. Based on the results of the present study, the following conclusions are drawn:

- Increase in the pulse ON time leads to the increase in both the surface roughness and the kerf width and vice versa.
- Increase in the pulse current leads to the increase in the surface roughness.

- From the response table of the average grey relational grade, it is found that the largest value of the grey relational grade is for the current of 3 A, the pulse ON time of 15 μs, the pulse OFF time of 4 μs. It is the recommended levels of the controllable parameters of the WEDM machining process as the minimization of the both surface roughness average and kerf width are simultaneously considered.
- The order of the importance for the controllable factors to the surface roughness average, in sequence, is the pulse ON time, the current and the pulse OFF time. However, for kerf width the sequence is the pulse ON time, pulse OFF time, and the current.
- Through ANOVA, the percentage of contribution to the WEDM process, in sequence, is the pulse ON time, the current and the pulse OFF time. Hence, the pulse ON time is the most significant controlled factor for the WEDM operation when the minimization of the both the surface roughness average and the kerf width are simultaneously considered.

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