

## Analysis of WEDM Process Parameters on Surface Roughness and Kerf using Taguchi Method

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### ABSTRACT

In obtaining the best quality of engineering parts, the quality of machined surface plays an essential role. The fatigue strength, wear resistance, and corrosion of workpiece are some of the aspects of the qualities that can be improved. This paper investigates the effect of wire electrical discharge machining (WEDM) process parameters on surface roughness and kerf on stainless steel using distilled water as dielectric fluid and brass wire as tool electrode. The selected process parameters are voltage open, wire speed, wire tension, voltage gap, and off time. Empirical models using Taguchi method were developed for the estimation of surface roughness and kerf. The analysis revealed that off time has major influence on surface roughness and kerf. The optimum machining parameters for minimum surface roughness and kerf were found to be 10 V open voltage, 2.84  $\mu$ s off time, 12 m/min wire speed, 6.3 N wire tension, and 54.91 V voltage gap.

*Keywords:* WEDM, Surface roughness, Kerf, Process parameters, Taguchi method, ANOVA, S/N ratio

### 1 INTRODUCTION

Wire electrical discharge machining (WEDM) is a specialized thermal machining process used to machine complex shape components with high accuracy using a thin single-strand metal wire (0.1 or 0.25mm diameter) as an electrode. It is a technique used in industry for high-precision machining of all types of conductive materials such as metals, metallic alloys, graphite [1-3]. It is also known as an 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, where the temperature increases up to 10,000 °C and allows the material to be removed from the machining area [3-4]. WEDM is particularly valuable for applications involving manufacture of stamping dies, extrusion dies, aerospace parts such as micro gas turbine blades, and electronic components [5-6]. Without WEDM, the fabrication of precision workpiece requires many hours of manual grinding and polishing [5].

In WEDM, the performance measures are the indicators used to observe the quality of the finished parts, whereas, the process parameters are the variables that influence the machining process. The most significant performance measures in WEDM are surface finish, material removal rate, and kerf. All of these performance measures are usually affected by the process parameters such as pulse on-time, open voltage, servo voltage, wire feed, dielectric pressure, and wire tension. These parameters have the ability to produce better quality machined surface with less cracks and surface damages [7]. Surface roughness is used to control the quality of the finished part while kerf is used to determine the accuracy of dimension. According to previous studies, the surface roughness improves when the pulse duration and the discharge current decreases [8].

Kerf is a width of the machined slots, where it also measures the amount of the material that is wasted during machining. It determines the dimensional accuracy of the finishing part. Kerf limits the internal corner radius during machining of the workpiece [3, 9-10]. Open voltage and wire tension are some of the main parameters that can control the kerf and precision of the machined part [8, 11]. It is because open voltage can control the wire vibration and breakdown distance. The corner errors and kerf variations mainly caused by the wire tool deflection and vibration in the discharge gap, these are the main factors that influence the machining accuracy. A study has been carried out to examine the kerf variations and the discharge gap (25-75  $\mu$ m) usually achieved in conventional WEDM

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[5]. Hence, the objective of this paper is to investigate the effect of WEDM process parameters on surface roughness and kerf of stainless steel using distilled water as the dielectric fluid and brass wire as the tool electrode.

## 2 METHODOLOGY

The experimental investigation was performed using the Mitsubishi FX10K CNC Wire EDM. The workpiece material, which was stainless steel S304, was prepared in desired dimension of 150 mm × 8 mm × 10 mm with flat surface finish. Stainless steel is commonly used almost in all industrial applications and it accounts for approximately 50% of the world's steel production and consumption. This is because of its aesthetic view in architectures, resistance against corrosion and chemicals, high hardenability, and well mechanical property. As a result, it has become the most preferred material [8, 12]. Brass wire with 0.2 mm diameter was used as the tool electrode whereas distilled water as the dielectric fluid. The experimental parameters are listed in Table 1.

The parameters were selected based on the type of machining material, tool material, height of the workpiece, and the capability of the machine. The controlled parameters were voltage open, wire speed, wire tension, voltage gap, and off time. Mitutoyo SurfTest (SV-514) was used to measure the surface roughness ( $R_a$ ). The tester used a cut-off length of 2 mm and evaluation length of 0.8 mm with a Surfpak V4.10 (2) software having a resolution of 0.01  $\mu\text{m}$  and stylus speed of 0.10 mm/sec. Measurements of  $R_a$  were repeated three times and the average of  $R_a$  were calculated. On the other hand, scanning electron microscope, SEM (Jeol JSM-5600) was used to measure the kerf of the workpiece. The measurements of kerf were taken at three different places and the average of the kerf was calculated.

The experiments were based on the Taguchi's  $L_{16}$  orthogonal array design. The experimental results in Table 2 are analysed using signal-to-noise (S/N) ratio and analysis of variance (ANOVA) approach. The S/N ratio is used as a measurable value instead of standard deviation. This is because of the fact that as the mean decreases, the standard deviation also will decrease and vice versa. The S/N ratio depends on the type of characteristic, where the higher value that represents a better machining performance such as MRR is known as higher is better. On the other hands, the characteristic that have lower value that represents a better machining performance, such as surface roughness and kerf is called lower is better as shown in Eqn. 1 [13-14].

$$\frac{S}{N} = -10 \log \left( \frac{1}{n} \sum_{i=1}^n y_i^2 \right) \quad (1)$$

Where,  $n$  is the number of iteration and  $y$  is the experimental result.

## 3 RESULTS AND DISCUSSION

### 3.1 Surface Roughness, $R_a$

**Signal-to-Noise (S/N) ratio.** The S/N ratio according to Taguchi method is the ratio of signal to noise where signal represents the desirable value and noise represents the undesirable value. The S/N ratio for the experiments conducted is shown in Table 2 meanwhile the mean of S/N ratio for  $R_a$  is presented for four levels are tabulated in Table 3. Figure 1 shows the effects of process parameters on mean S/N ratio for  $R_a$ . According to Taguchi method, minimizing average  $R_a$  would be better for precision manufacturing. Hence, "smaller-the better" type problems would give a smaller values for average  $R_a$  in order to get a better quality of finish parts [15]. Based on Table 3 and Figure 1, it was found that S/N ratio for  $R_a$  decreases when the wire speed, wire tension, and voltage gap are at level 4. The wire vibration tends to reduce when the wire tension increases which helps the surface roughness to improve [16]. However, the S/N ratio for  $R_a$  increases when the off time is at level 4 and level 3 for voltage open. Voltage open should be kept as low as possible in order to get a better surface roughness. It is to avoid powerful explosion to occur which can cause deep crater on the machined surface and resulting to poor surface quality at the machined area [16].

**Analysis of variance (ANOVA).** An empirical model as expressed in Eqn. 2 is developed by ANOVA. Based on Table 4, the model F-value of 102.38 implies that the model is significant. There is only a 0.14% chance of noise that could occur in the model F-value. The prob>F values less than 0.0500 indicates that the model terms A (voltage open), B (off time), E (voltage gap), AB (voltage open and off time), AC (voltage open and wire speed), BD (off time and wire tension), BE (off time and voltage gap), CD (wire speed and wire tension), CE (wire speed and voltage gap), and DE (wire tension and voltage gap) are significant. The most significant factor that affects the  $R_a$  is B (off time) with 77.57 F-value. However, values that are greater than 0.1000 indicates the model terms are not significant. If there are many insignificant model terms, then the model reduction may improve the model. Factors C (wire speed) and D (wire tension) are the most uninfluenced factors since their prob>F are 0.5508 and 0.9052 respectively. Nevertheless, when factor C (wire speed) interacts with factor A (voltage open), D (wire tension), and E (voltage gap), the model terms becomes significant. Hence, it means that factor C (wire speed) cannot be removed from the hierarchy, even though it is not significant if it is stand-alone. Similarly for factor D (wire tension), the model terms become significant when it interacts with factor B (off time), C (wire speed), and E (voltage gap). The Predicted  $R^2$  of 0.8133 is in reasonable agreement with the Adjusted  $R^2$  of 0.9878. Adequate precision measures the S/N ratio,

where the ratio greater than 4 is desirable. The ratio of 44.649 indicates that the signal is adequate. This model can be used to navigate the design space.

$$R_a = 3.755 + 0.831A - 1.063B + 1.949C - 2.314D - 0.199E - 0.096AB - 0.058AC + 0.206BD + 0.011BE - 0.035CD - 0.019CE + 0.044DE \tag{2}$$

Where,  $R_a$  = surface roughness ( $\mu\text{m}$ ),  $A$  = voltage open (V),  $B$  = off time ( $\mu\text{s}$ ),  $C$  = wire speed (m/min),  $D$  = wire tension (N), and  $E$  = voltage gap (V).

**Table 1:** Experimental parameters of WEDM

Control Parameters	Factors	Level			
		I	II	III	IV
Voltage open (V)	A	10	12	14	16
Off time ( $\mu\text{s}$ )	B	1	2	3	4
Wire speed (m/min)	C	6	8	10	12
Wire tension (N)	D	6	7	8	9
Voltage gap (V)	E	40	45	50	55
<b>Fixed Parameters:</b>					
Workpiece material	Stainless steel S304				
Tool electrode	Brass wire ( $\varnothing$ 0.2 mm)				
Dielectric fluid	Distilled water				

**Table 2:** Experimental result for average surface roughness and average kerf

Run	Process parameters					Performance measures			
	Voltage open (V)	OFF time ( $\mu\text{s}$ )	Wire speed (m/min)	Wire tension (N)	Voltage gap (V)	Average surface roughness $R_a$ ( $\mu\text{m}$ )	S/N value Average surface roughness	Average kerf (mm)	S/N value Average kerf
1	14.00	3.00	6.00	7.00	55.00	3.22	-10.1571	0.274	11.2450
2	10.00	3.00	10.00	8.00	50.00	3.13	-9.9109	0.268	11.4373
3	14.00	4.00	8.00	6.00	50.00	2.05	-6.2351	0.277	11.1504
4	16.00	3.00	8.00	9.00	40.00	2.79	-8.9121	0.28	11.0568
5	12.00	3.00	12.00	6.00	45.00	3.45	-10.7564	0.245	12.2167
6	12.00	2.00	6.00	9.00	50.00	3.11	-9.8552	0.269	11.4050
7	14.00	2.00	12.00	8.00	40.00	3.44	-10.7312	0.293	10.6626
8	16.00	4.00	6.00	8.00	45.00	2.96	-9.4258	0.272	11.3086
9	16.00	2.00	10.00	6.00	55.00	2.73	-8.7233	0.274	11.2450
10	10.00	2.00	8.00	7.00	45.00	2.72	-8.6914	0.274	11.2450
11	10.00	4.00	12.00	9.00	55.00	3.86	-11.7317	0.278	11.1191
12	16.00	1.00	12.00	7.00	50.00	3.51	-10.9061	0.284	10.9336
13	12.00	4.00	10.00	7.00	40.00	2.97	-9.4551	0.274	11.2450
14	14.00	1.00	10.00	9.00	45.00	3.01	-9.5713	0.192	14.3340
15	10.00	1.00	6.00	6.00	40.00	2.82	-9.0050	0.282	10.9950
16	12.00	1.00	8.00	8.00	55.00	3.09	-9.7992	0.265	11.5351

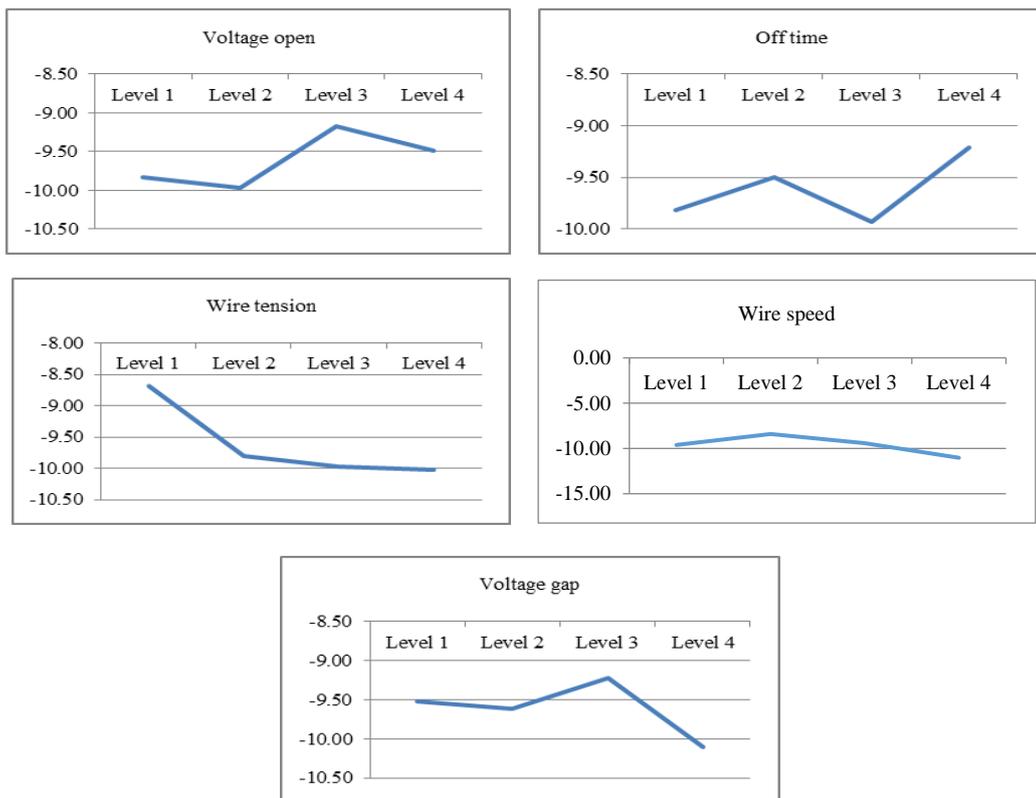
**Table 3:** S/N ratio means for  $R_a$

Process parameters	S/N Ratio mean				Delta	Rank
	Level 1	Level 2	Level 3	Level 4		
Voltage open (V)	-9.8347	-9.9665	-9.1737	-9.4918	0.7928	4
OFF time ( $\mu\text{s}$ )	-9.8204	-9.5003	-9.9341	-9.2119	0.7222	5
Wire speed (m/min)	-9.6108	-8.4094	-9.4151	-11.0314	2.6220	1
Wire tension (N)	-8.6799	-9.8024	-9.9668	10.0176	1.3377	2
Voltage gap (V)	-9.5258	-9.6112	-9.2268	10.1028	0.8760	3

**Table 4:** ANOVA for average Ra

Source	Sum of Square	Degree of Freedom (DF)	Mean Square	F Value	Prob>F	Percentage Contribution (%)
Model	2.56	12	0.21	102.38	0.0014	
A	0.12	1	0.12	55.36	0.0050	5.82
B	0.16	1	0.16	77.57	0.0031	7.76
C	9.364E-004	1	9.364E-004	0.45	0.5508	0.045
D	3.491E-005	1	3.491E-005	0.017	0.9052	1.69E-3
E	0.026	1	0.026	12.62	0.0380	1.26
AB	0.098	1	0.098	47.14	0.0063	4.75
AC	0.14	1	0.14	69.43	0.0036	6.79
BD	0.54	1	0.54	259.29	0.0005	26.19
BE	0.040	1	0.040	19.05	0.0222	1.94
CD	0.061	1	0.061	29.29	0.0124	2.96
CE	0.48	1	0.48	231.98	0.0006	23.28
DE	0.39	1	0.39	185.59	0.0009	18.91
Residual	6.256E-003	3	2.085E-003			
Cor Total	2.57	15				
Total	2.062	15				

Standard deviation	0.046	R <sup>2</sup>	0.9976
Mean	3.05	Adjusted R <sup>2</sup>	0.9878
Coefficient of variation	1.50	Predicted R <sup>2</sup>	0.8133
Predicted residual error of sum of square (PRESS)	0.48	Adequate precision	44.649



**Figure 1:** Effects of process parameters on mean S/N ratio for Ra

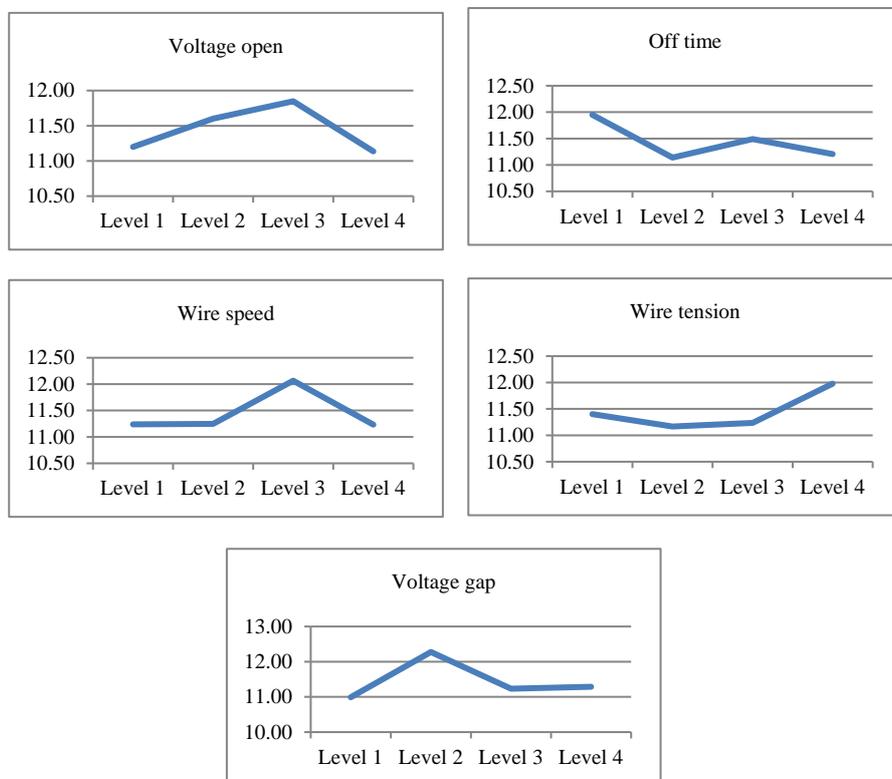
### 3.2 Kerf

**Signal-to-Noise (S/N) ratio.** The equation used to calculate the average kerf is the same used for the average  $R_a$  in order to attain better accuracy for the finish parts. Figure 2 shows the effects of process parameters on mean S/N ratio for kerf while Table 5 shows the S/N ratio means for kerf. Based on Table 5 and Figure 2, it shows that S/N ratio for kerf decreases when the level of voltage open and wire speed are at level 4 while wire tension is at level 2. However, according to previous research studies, it is inferred that kerf decreases when the wire tension increases. This is because wire vibration is expected to reduce with the increase of wire tension which will lead to reduction of kerf (16). Conversely, the S/N ratio for kerf increases when the levels of off time and voltage gap are at level 1 and level 2 respectively.

**Analysis of variance (ANOVA).** An empirical model as expressed in Eqn. 3 is developed by ANOVA. Based on Table 6, the model F-value of 68.71 implies the model is significant. There is only a 0.25% chance of noise that could occur in the model F-value. Values of prob > F less than 0.0500 indicate model terms are significant. In this case B (off time), C (wire speed), D (wire tension), E (voltage gap), AB (voltage open and off time), AC (voltage open and wire speed), AD (voltage open and wire tension), BD (off time and wire tension), BE (off time and voltage gap), CE (wire speed and voltage gap) are significant model terms. Values greater than 0.1000 indicate the model terms are not significant. If there are many insignificant model terms (not counting those required to support hierarchy), then the model reduction may improve the model. Factor A (voltage open) is the most uninfluenced factor and factor B (off time) is the most influenced factor. However, when factor A (voltage open) interact with factor B (off time), then it is significant. It is the same concept for AC (voltage open and wire speed) and AD (voltage open and wire tension). Thus, it means that factor A (voltage open) cannot be removed as it is significant when there is an interaction with B (off time), C (wire speed), and D (wire tension) even though it is not significant if it is stand-alone. The Predicted  $R^2$  and PRESS are not defined. Adequate precision measures the S/N ratio, where the ratio greater than 4 is desirable. The ratio of 36.342 indicates that the signal is adequate. This model can be used to navigate the design space.

$$Kerf = 1.596 - 0.151A - 0.193B - 0.089C - 0.089D + 0.015E + 0.012AB + 0.010AC + 4.125 \times 10^{-3}AD + 0.016BD - 7.547 \times 10^{-4}BE + 1.238 \times 10^{-3}CD - 8.481 \times 10^{-4}CE \quad (3)$$

Where,  $Kerf$  = kerf (mm),  $A$  = voltage open (V),  $B$  = off time ( $\mu s$ ),  $C$  = wire speed (m/min),  $D$  = wire tension (N), and  $E$  = voltage gap (V).



**Figure 2:** Effects of process parameters on mean S/N ratio for kerf

**Table 5:** S/N ratio means for kerf

Process parameters	S/N Ratio mean				Delta	Rank
	Level 1	Level 2	Level 3	Level 4		
Voltage Open (V <sub>o</sub> )	11.1991	11.6004	11.8480	11.1360	0.7120	5
OFF time ( $\mu$ s)	11.9494	11.1394	11.4890	11.2058	0.8100	4
Wire speed (m/min)	11.2384	11.2468	12.0653	11.2330	0.8323	2
Wire tension (g)	11.4018	11.1671	11.2359	11.9787	0.8116	3
Voltage gap (V)	10.9899	12.2761	11.2316	11.2860	1.2862	1

**Table 6:** ANOVA for average kerf

Source	Sum of Square	Degree of Freedom (DF)	Mean Square	F Value	Prob>F	Percentage Contribution (%)
Model	7.838E-003	12	6.532E-004	68.71	0.0025	
A	2.288E-005	1	2.288E-005	2.41	0.2186	0.16
B	2.700E-003	1	2.700E-003	284.05	0.0005	18.37
C	1.031E-003	1	1.031E-003	108.43	0.0019	7.01
D	1.232E-003	1	1.232E-003	129.62	0.0015	8.38
E	9.236E-004	1	9.236E-004	97.16	0.0022	6.28
AB	1.399E-003	1	1.399E-003	147.15	0.0012	9.52
AC	2.641E-003	1	2.641E-003	277.79	0.0005	17.97
AD	1.742E-004	1	1.742E-004	18.33	0.0234	1.19
BD	3.356E-003	1	3.356E-003	353.01	0.0003	22.83
BE	1.817E-004	1	1.817E-004	19.12	0.0221	1.24
CD	7.827E-005	1	7.827E-005	8.23	0.0641	0.53
CE	9.407E-004	1	9.407E-004	98.96	0.0022	6.39
Residual	2.852E-005	3				
Cor Total	7.866E-003	15	9.506E-006			
Total	0.0147	15				
Standard deviation		3.083E-003	R <sup>2</sup>		0.9964	
Mean		0.27	Adjusted R <sup>2</sup>		0.9819	
Coefficient of variation		1.15	Predicted R <sup>2</sup>		N/A	
Predicted residual error of sum of square (PRESS)		N/A	Adequate precision		36.342	

#### 4 MULTIPLE OPTIMIZATIONS

The ANOVA-based optimization was done in order to get the optimum values of the process parameters for minimum  $R_a$  and kerf. Minimum  $R_a$  (2.56  $\mu$ m) and kerf (0.212 mm) can be achieved at 10 V voltage open, 2.84  $\mu$ s off time, 12 m/min wire speed, 6.3 N wire tension, and 54.91 V voltage gap. Experiments were conducted to validate the results obtained from the optimization. Based on the experiment, the actual  $R_a$  (2.76  $\mu$ m) and kerf (0.23 mm) were higher compared to the optimize  $R_a$  and kerf with maximum error of 7.81% and 8.49% respectively. The percentage error for minimum  $R_a$  and kerf are relatively small which shows the empirical equations are valid.

#### 5 CONCLUSIONS

In this paper, process parameters of WEDM on surface roughness and kerf were analysed using stainless steel (S304) as the workpiece, brass wire as the tool electrode, and distilled water as the dielectric fluid. All of the process parameters that have been used for the investigation were found to have influence on the surface roughness and kerf. The following conclusions are drawn from the experimental study:

1. From S/N ratio, it can be inferred that wire speed, wire tension, and voltage gap should be at the highest level, which is level 4 while voltage open and off time should be at level 3 and 4 respectively to obtain low surface roughness. As for the kerf, it can be concluded that to get minimum kerf, voltage open and wire speed should be at level 4 while off time, wire tension, and voltage gap should be at level 2, level 2, and level 1 respectively.
2. Based on ANOVA, the most significant factor that influences the surface roughness and kerf is off time.
3. The minimum surface roughness and minimum kerf can be achieved when 2.56  $\mu$ m at 10 V voltage open, 2.84  $\mu$ s off time, 12 m/min wire speed, 6.3 N wire tension, and 54.91 V voltage gap are considered as the optimum process parameters for WEDM of stainless steel.
4. The predicted value and experimental  $R_a$  and kerf value are within 7.81% and 8.49% error respectively.

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