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Material Removal Rate, Kerf, and Surface Roughness of Tungsten Carbide Machined with Wire Electrical Discharge Machining

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In this article, the effects of varying seven different machining parameters in addition to varying the material thickness on the machining responses such as material removal rate, kerf, and surface roughness of tungsten carbide samples machined by wire electrical discharge machining (WEDM) were investigated. The design of experiments was based on a Taguchi orthogonal design with 8 control factors with three levels each, requiring a set of 27 experiments that were repeated three times. ANOVA was carried out after obtaining the responses to determine the significant factors. The work piece thickness was expected to have a major effect on the material removal rate but showed to be significant in the case of surface roughness only. Finally, optimization of the machining responses was carried out and models for the material removal rate, kerf, and surface roughness were created. The models were validated through confirmation experiments that showed significant improvements in machining performance for all investigated machining outcomes.

Keywords kerf, material removal rate, surface roughness, Taguchi method, tungsten carbide, wire EDM

1. Introduction

Tungsten carbide is part of the family of carbide ceramics such as silicon carbide, titanium carbide, tantalum carbide, and chromium carbide (Ref 1). Tungsten, titanium, and chromium carbide are known for their hardness and wear resistance properties, which makes them useful materials for cutting tool applications. Tungsten carbide combined with a metallic binder such as cobalt is called as a cemented carbide or cermet (WC). Due to the high material hardness, advanced ceramics such as WC are difficult to machine using conventional machining processes such as milling, turning, and grinding. In recent years, as an alternative method to machine WC, wire electrical discharge machining (WEDM) has gained wide acceptance.

Wire electrical discharge machining is an emerging non-conventional machining process for machining hard to machine materials that are electrically conductive (Ref 2). It is a highly precise, accurate, and one of the most popular machining processes in non-conventional machining (Ref 3). In this process, the material is removed by a series of discrete electrical discharges between the wire electrode and the work piece. The discharges, which are highly focused by the dielectric medium, cause rise in the local temperatures of the work piece near the point of introduction. The temperatures are high enough to melt and vaporize the material in the immediate vicinity of the electrical discharges. Since, there is no mechanical contact between the work piece and the electrode, material of any hardness can be machined as long as it is sufficiently electrically conductive (Ref 4). The most important machining responses of the process are the material removal rate, the surface roughness of the machined surfaces, and the kerf, which is the effective width of cut.

This article discusses in detail the machining of tungsten carbide cermet using WEDM. The WC used in this article has 88% WC and 12% cobalt. Several researchers in the past have studied the effect of EDM on tungsten carbide material. Jahan et al. studied the effect of different electrode materials on machining of WC in sinker EDM. Electrodes made from AgW (80% W-20% Ag) were found to yield the best surface finish in micro-EDM of tungsten carbide (Ref 5). Jahan et al. also investigated the effect of EDM machining using both transistor as well RC type pulse generators (Ref 6). It was found that a RC type pulse generator resulted in a better surface finish than a transistor type pulse generator. Saha et al. used a multi variable regression model and back-propagation neural network model to predict the surface roughness and cutting speed in WEDM of tungsten carbide (Ref 7). Lee and Li demonstrated that the surface integrity of an EDM machined surface remains intact when it is machined with peak currents of less than 16 A (Ref 8). It was found that at a peak current of 64 A, the damaged WC layer is around 25 microns in depth (Ref 8).

This article goes a step further and investigates in detail the effect of all critical WEDM parameters such as open voltage, servo voltage, pulse ON time, pulse OFF time, wire feed velocity, wire tension, dielectric pressure, and also thickness of WC material on machining characteristics such as material removal rate, surface roughness, and kerf. Three levels of

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thickness were machined under three levels of machining parameters.

2. Design of Experiments and Experimentation

In this study, a large number of control factors were considered in order to enhance the accuracy of the results. However, the peak current value was kept constant to a value of rough cutting assuming that its effect will match the effect produced by on-time. The design of experiments consisted of a total of 8 parameters with 3 levels each. The control factors are the material thickness (M_t), open voltage (O_v), pulse ON time (P_{ON}), pulse OFF time (P_{OFF}), servo voltage (S_v), wire feed velocity (W_v), wire tension (W_t), and dielectric pressure (D_p). The input parameters or the control factors along with the output parameters are depicted in Fig. 1 and their 3 levels are listed in Table 1.

Since there were 8 control factors each with three levels in the experiment, a full factorial experimental design would have required a large number of runs, making the study extremely time consuming and expensive. To reduce the number of runs required, a Taguchi-based design of experiment was implemented (Ref 9). Based on the assumption that each input parameter in this experiment is independent, a Taguchi orthogonal array L27 (3 by 13) was used. Of the 13 columns, 8 columns were assigned to 8 control factors and the remaining 5 columns were removed.

A wire-cut EDM machine G43S CHMER EDM CHING HUNG Machinery & Electric Industrial Co. Ltd. TAIWAN with distilled water as the dielectric was used for conducting the experiments with tungsten carbide plates (88% WC, 12% Co, grade DK 500 UF, 92.4 HRA) as the work pieces (anodes). A 250 μm diameter brass wire (tensile strength 800-1000 MPa) was used as the tool electrode (cathode). The cut completion time was directly obtained from the machine computer. Tosun and Cogun calculated the material removal rate (M_{rr}) based on measuring kerf, length, thickness, and cutting time or feed rate (Ref 10). In this study, the material removal rate was calculated based on weighing the samples before and after machining and then dividing the difference of weight by the cutting time and density of the material. The samples were weighed on a scale with an accuracy of 0.001 g. This was repeated three times for each sample and the average weight was obtained for a better accuracy.

The surface roughness characteristic was measured in terms of CLA values (R_a) using a surface texture meter by Taylor Hobson, UK. The surface finish was measured three times at the set cut off length and evaluation length of 0.8 and 4.0 mm, respectively, and then averaged. The measurement of other surface finish characteristics such as R_t and R_z were not undertaken because their trends of variation are almost similar as with R_a in wire EDM process (Ref 11). The kerf (K_f) was measured on a Universal Profile Projector (UK) with an accuracy of 0.001 mm. It was measured at three different points of the kerf in each run.

The Taguchi Orthogonal Array along with the levels used for each parameter and the results of the experiments are listed in Table 2.

3. Results, Analyses, and Discussion

Statistical analysis was divided into three phases. In the first phase, the SN ratio was calculated for three responses. In the second phase, ANOVA was carried out for determining the significant factors for each machining response. Finally, optimization of the machining responses was performed.

3.1 Analysis of Signal-to-Noise Ratio

In this study, M_{rr} is a machining outcome where larger values are desirable. Hence, according to the Taguchi

Table 1 Control parameters and their levels

Process parameters	Units	Level 1	Level 2	Level 3
Material thickness (M_t)	mm	25.4	50.8	76.2
Open voltage (O_v)	Volt	75	90	105
Pulse ON-time (P_{ON})	μs	3	4	5
Pulse OFF-time (P_{OFF})	μs	20	25	30
Servo voltage (S_v)	Volt	40	50	60
Wire feed velocity (W_v)	mm/s	30	60	90
Wire tension (W_t)	g	1000	1600	2200
Dielectric pressure (D_p)	kg/cm^2	10	12	14

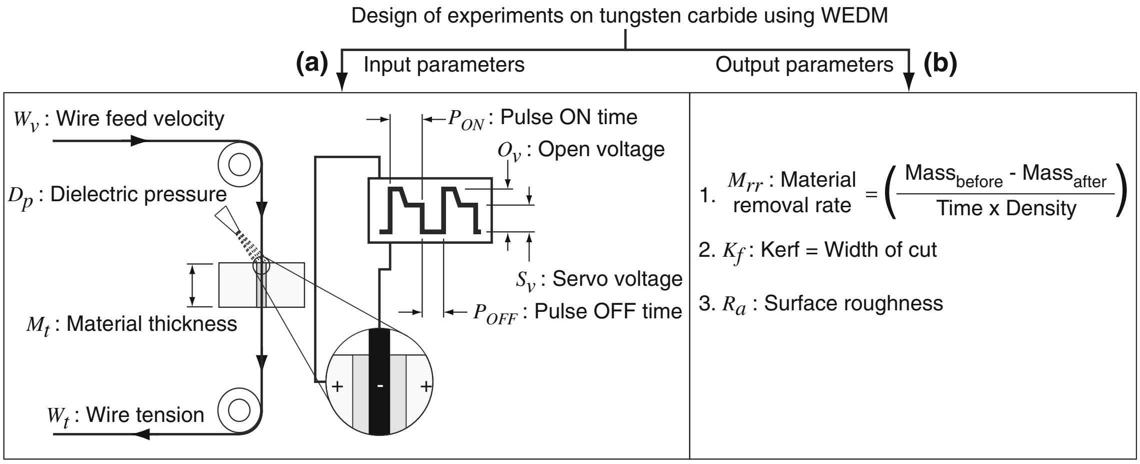

Fig. 1 Input (a) and output parameters (b) used in the design of experiments

Table 2 Taguchi orthogonal array and experimental results for material removal rate, kerf, and surface roughness

	Input parameters								Output parameters (Average)		
Exp. No.	M_t, mm	O_v, V	P_{ON}, µs	P_{OFF}, µs	S_v, V	W_v, mm/s	W_t, g	D_p, kg/cm^2	M_{rr}, mm^3/min	K_f, µm	R_a, µm
1	25.4	75	3	20	40	30	1000	10	2.7369	335	1.316
2	25.4	75	3	25	50	60	1600	12	4.3973	322	1.307
3	25.4	75	3	30	60	90	2200	14	1.489	312	1.244
4	25.4	90	4	20	40	30	1600	12	7.3108	315	1.642
5	25.4	90	4	25	50	60	2200	14	4.7340	322	1.558
6	25.4	90	4	30	60	90	1000	10	3.2319	337	1.420
7	25.4	105	5	20	40	30	2200	14	7.7297	333	1.811
8	25.4	105	5	25	50	60	1000	10	6.3535	341	1.593
9	25.4	105	5	30	60	90	1600	12	5.0706	331	1.747
10	50.8	90	5	20	50	90	1000	12	6.5523	351	1.502
11	50.8	90	5	25	60	30	1600	14	4.6899	331	1.551
12	50.8	90	5	30	40	60	2200	10	6.4456	314	1.711
13	50.8	105	3	20	50	90	1600	14	4.5649	306	1.511
14	50.8	105	3	25	60	30	2200	10	3.4235	298	1.556
15	50.8	105	3	30	40	60	1000	12	4.0003	317	1.464
16	50.8	75	4	20	50	90	2200	10	3.9489	326	1.324
17	50.8	75	4	25	60	30	1000	12	1.6787	323	1.422
18	50.8	75	4	30	40	60	1600	14	3.9655	330	1.473
19	76.2	105	4	20	60	60	1000	14	5.3004	336	1.596
20	76.2	105	4	25	40	90	1600	10	5.0862	320	1.456
21	76.2	105	4	30	50	30	2200	12	4.3195	299	1.456
22	76.2	75	5	20	60	60	1600	10	3.6028	338	1.489
23	76.2	75	5	25	40	90	2200	12	5.5052	326	1.627
24	76.2	75	5	30	50	30	1000	14	3.6514	345	1.436
25	76.2	90	3	20	60	60	2200	12	3.3139	315	1.324
26	76.2	90	3	25	40	90	1000	14	3.7811	312	1.320
27	76.2	90	3	30	50	30	1600	10	3.0792	307	1.244

technique, the larger-the-better SN ratio η as shown in Eq 1 was applied (Ref 12). For surface roughness and kerf, on the other hand, smaller values are desirable. Hence, the smaller-the-better SN ratio given as Eq 2 was applied (Ref 12).

$$\eta = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_1^2}\right] \quad \text{(Eq 1)}$$

$$\eta = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}y_1^2\right] \quad \text{(Eq 2)}$$

where n is the number of repetitions and y_i is the ith reading. The signal-to-noise ratios of all experiments are provided in Table 3.

3.2 ANOVA for Material Removal Rate (M_{rr}), kerf (K_f), and surface roughness (R_a)

After the SN ratios were obtained, the next step of the data analysis was to identify the control factors that have a significant effect on each of the machining responses. This was achieved by performing ANOVA and the results for material removal rate (M_{rr}), kerf (K_f), and surface roughness (R_a) are shown in Table 4, 5, and 6, respectively.

According to Phadke, a factor is significant if the F ratio for the factor is larger than 4 (Ref 12). In the case of material removal rate, the results show that the control factors such as open voltage (O_v), pulse ON time (P_{ON}), pulse OFF time (P_{OFF}), and servo voltage (S_v) are significant. The material thickness (M_t), wire feed velocity (W_v), wire tension (W_t), and dielectric pressure (D_p), on the other hand, are not significant.

Table 3 SN ratio for material removal rate, kerf, and surface roughness

	Output parameters SN ratios, dB		
Exp. No.	M_{rr}	K_f	R_a
1	8.745	−50.501	−2.382
2	12.864	−50.157	−2.323
3	3.458	−49.883	−1.900
4	17.279	−49.966	−4.309
5	13.505	−50.157	−3.850
6	10.189	−50.553	−3.046
7	17.763	−50.449	−5.159
8	16.059	−50.655	−4.046
9	14.101	−50.397	−4.844
10	16.328	−50.906	−3.535
11	13.423	−50.397	−3.813
12	16.185	−49.939	−4.666
13	13.189	−49.714	−3.586
14	10.689	−49.484	−3.838
15	12.042	−50.021	−3.313
16	11.93	−50.264	−2.441
17	4.499	−50.184	−3.059
18	11.966	−50.370	−3.366
19	14.486	−50.527	−4.058
20	14.128	−50.103	−3.261
21	12.709	−49.513	−3.261
22	11.133	−50.578	−3.457
23	14.816	−50.264	−4.226
24	11.249	−50.756	−3.140
25	10.407	−49.966	−2.441
26	11.552	−49.883	−2.411
27	9.769	−49.743	−1.900

Table 4 ANOVA and F test for material removal rate

Parameters	DF	Sum of squares	Mean squares	F ratio	Prob $> F$	% Contribution
Material thickness	1	1.628	1.628	3.137	0.093	2.65
Open voltage*	1	12.287	12.287	23.681	0.000	20.03
Pulse ON-time*	1	19.665	19.665	37.900	0.000	32.06
Pulse OFF-time*	1	5.344	5.344	10.299	0.005	8.71
Servo voltage*	1	12.104	12.104	23.329	0.000	19.73
Wire feed velocity	1	0.021	0.021	0.040	0.844	0.03
Wire tension	1	0.730	0.73	1.406	0.251	1.19
Dielectric pressure	1	0.222	0.222	0.428	0.521	0.36
Error	18	9.339	0.519	0.000	…	15.23
C. Total	26	61.339	…	…	…	100.00

* Significant factor (F ratio > 4)

Table 5 ANOVA and F test for kerf

Parameters	DF	Sum of squares	Mean squares	F ratio	Prob $> F$	% Contribution
Material thickness	1	138.889	138.889	2.880	0.107	2.86
Open voltage*	1	320.889	320.889	6.654	0.019	6.62
Pulse ON-time*	1	1922.000	1922.000	39.857	0.000	39.64
Pulse OFF-time*	1	220.500	220.500	4.573	0.046	4.55
Servo voltage	1	20.056	20.056	0.416	0.527	0.41
Wire feed velocity	1	68.056	68.056	1.411	0.250	1.40
Wire tension*	1	1283.556	1283.556	26.618	0.000	26.47
Dielectric pressure	1	6.722	6.722	0.139	0.713	0.14
Error	18	868	48.222	2.46E−05	…	17.90
C. Total	26	4848.667	…	…	…	100.00

* Significant factor (F ratio > 4)

Table 6 ANOVA and F test for surface roughness

Parameters	DF	Sum of squares	Mean squares	F ratio	Prob $> F$	% Contribution
Material thickness*	1	0.027	0.027	4.474	0.049	4.59
Open voltage*	1	0.134	0.134	22.535	0.000	23.11
Pulse ON-time*	1	0.264	0.264	44.513	0.000	45.66
Pulse OFF-time	1	0.006	0.006	0.959	0.340	0.98
Servo voltage	1	0.012	0.012	2.079	0.167	2.13
Wire feed velocity	1	0.004	0.004	0.746	0.399	0.77
Wire tension	1	0.016	0.016	2.754	0.114	2.82
Dielectric pressure	1	0.008	0.008	1.433	0.247	1.47
Error	18	0.107	0.006	0.000	…	18.46
C. Total	26	0.578	…	…	…	100.00

* Significant factor (F ratio > 4)

The mean parameters for the material removal rate are shown in Fig. 2. Here it can be seen that the material removal rate (M_{rr}) decreases with increase in material thickness (M_t), pulse off time (P_{OFF}), and servo voltage (S_v) while it increases with larger values in open voltage (O_v) and pulse on time (P_{ON}).

It is interesting to note that material thickness has very little effect on the material removal rate. Based on Luo's finding that the electrical energy available for material removal is uniformly distributed along the length of the wire, the material removal rate should not be affected by the material thickness (Ref 13). The experiments, however, indicate a decrease in M_{rr} for larger job thicknesses, which is most likely caused by inadequate flushing due to the longer kerf area.

ANOVA for kerf shows that the most significant factors are the pulse ON time (P_{ON}) and wire tension (W_t) followed to a lesser degree by open voltage (O_v) and pulse OFF time (P_{OFF}). The material thickness, servo voltage, wire feed velocity, and dielectric pressure are essentially irrelevant. From the mean parameters illustrated in Fig. 3 it can be seen that the kerf increases with increase in pulse on time (P_{ON}) but decreases with wire tension (W_t). This of course is the result of reduced wire vibration due to increased tension (Ref 14).

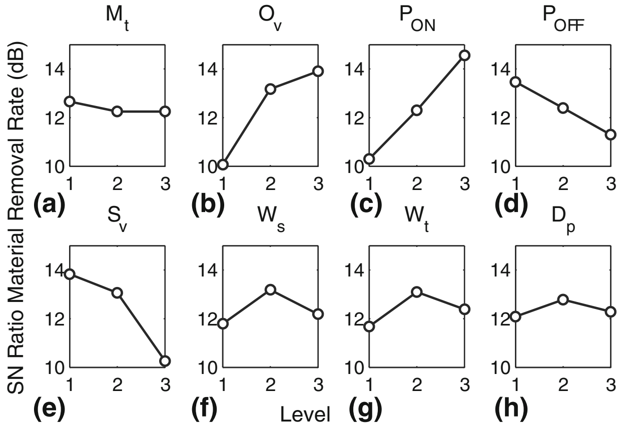

Fig. 2 Mean SN ratios for material removal rate

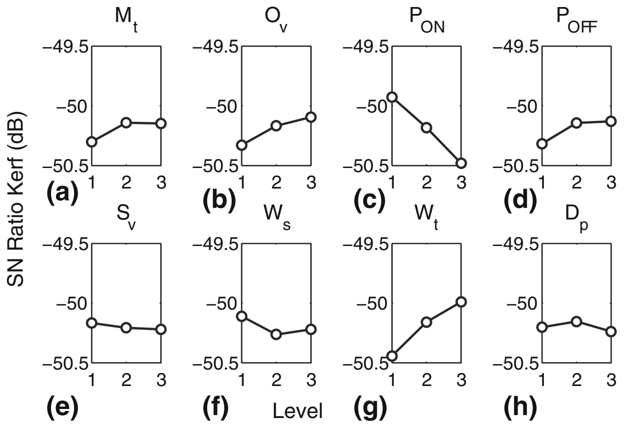

Fig. 3 Mean SN ratios for kerf

The surface roughness according to ANOVA is only affected by the material thickness, pulse ON time, and pulse OFF time. Figure 4 illustrates that a larger material thickness results in a better surface finish while increasing the open voltage and pulse ON time leads to a greater surface roughness. The open loop voltage is the driving force of electrical discharges, and a major factor determining how far the discharges range. Due to the cylindrical expansion of the discharges, far reaching discharges will have a lower density compared to near ranging discharges. The reduction in density is the most likely reason for the increase in surface roughness for larger values of open loop voltage. The pulse ON time also increases the surface roughness and that is caused by longer and more concentrated discharges that cause highly localized material erosion. The opposite effect is the result of reduced surface roughness with increased material thickness. The increased engagement length causes a reduction in spark energy distribution, which produces smaller and more highly distributed discharges.

3.3 Optimization of Response Variables

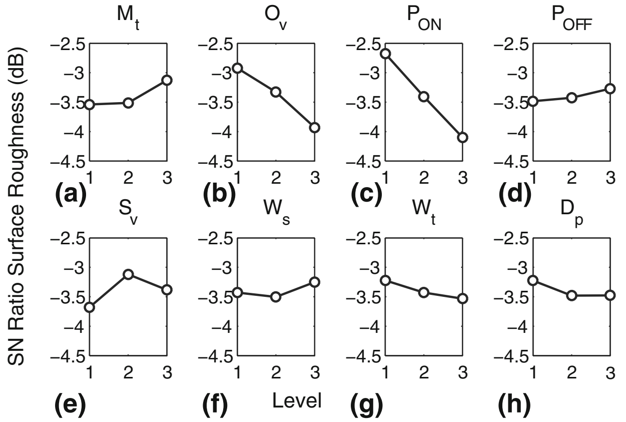

Fig. 4 Mean SN ratios for surface roughness

The ANOVA for all three responses provided the significant factors. Therefore, the optimal level of a significant control factor is at the level with the greatest SN ratio. Based on the orthogonal design of the experiments and assuming that the interactions between individual factors are negligible, the effect of each parameter at each of the three levels can be obtained. The mean SN ratio for the control parameters at levels 1, 2, and 3 can be obtained from Table 3 by taking the average of the SN ratios for the experiments 1-9, 10-18, and 19-27, respectively.

Optimizing the output parameters is achieved by selecting the significant control factors at their optimum level. Control factors that are not significant can be set at any level. Therefore, the material removal rate is maximized by setting the open voltage (O_v) and pulse ON time (P_{ON}) at level 3, and the servo voltage (S_v) and pulse OFF time (P_{OFF}) at level 1. Likewise for optimizing the kerf, where the optimum values for the significant control factors are the pulse ON time (P_{ON}) at level 1 and the wire tension (W_t) at level 3. The best surface finish is achieved by setting the open voltage (O_v) and pulse ON time (P_{ON}) at level 1, the servo voltage (S_v) at level 2, and the material thickness (M_t) at level 3.

After the optimal levels of the control factors have been determined, the next step is to predict and verify the improvement of the SN ratio. The SN ratio η_{pre} can be predicted as follows: (Ref 15, 16)

$$\begin{aligned}\eta_{pre} = \eta_{O_m} &+ (\eta_{M_t} - \eta_{O_m}) + (\eta_{O_v} - \eta_{O_m}) + (\eta_{P_{ON}} - \eta_{O_m}) \\ &+ (\eta_{P_{OFF}} - \eta_{O_m}) + (\eta_{S_v} - \eta_{O_m}) + (\eta_{W_v} - \eta_{O_m}) \\ &+ (\eta_{W_t} - \eta_{O_m}) + \left(\eta_{D_p} - \eta_{O_m}\right) \qquad \text{(Eq 3)}\end{aligned}$$

where η_{O_m} is the overall mean SN ratio and $\eta_{M_t}, \eta_{O_v}, \eta_{P_{ON}}, \eta_{P_{OFF}}, \eta_{S_v}, \eta_{W_v}, \eta_{W_t}$, and η_{D_p} are the SN ratios of the individual control factors at their optimum levels. Table 7 shows the comparison of the predicted and the actual responses obtained after executing optimal runs for each of the responses. The increase in SN ratio from the initial cutting parameters levels to the optimal cutting parameters levels are 6.82, 0.79, and 2.62 dB for M_{rr}, K_f, and R_a, respectively. The predicted and actually measured responses for all three machining outcomes are in excellent agreement, indicating that the use of Taguchi design for analyses and optimization of the control parameters was appropriate.

4. Conclusions

This article presents a comprehensive analysis of the effect of work piece thickness along with other important control

Table 7 Confirmation experiments for machining outcomes

Optimum control parameter level								M_{rr}, mm^3/min			M_{rr} SN ratio, dB		
M_t	O_v	P_{ON}	P_{OFF}	S_v	W_v	W_t	D_p	Initial (a)	Model	Actual	Initial (a)	Model	Actual
1	3	3	1	1	2	2	2	6.22	13.15	13.64	15.87	22.38	22.70
								K_f, µm			K_f SN ratio, dB		
								Initial (a)	Model	Actual	Initial (a)	Model	Actual
3	3	1	3	1	1	3	2	318.1	291.4	290.6	−50.05	−49.29	−49.26
								R_a, µm			R_a SN ratio, dB		
								Initial (a)	Model	Actual	Initial (a)	Model	Actual
3	1	1	3	3	3	1	1	1.53	1.13	1.11	−3.68	−1.06	−0.91

(a) Based on all control parameters set to level 2

factors on three critical machining outcomes of wire electrical discharge machining of tungsten carbide: material removal rate, kerf, and surface roughness. Based on a Taguchi design of experiments, it can be concluded that the material thickness has little effect on the material removal rate and kerf but is a significant factor in terms of surface roughness. For thinner work pieces, in order to obtain a fine surface finish, the spark energy will have to be reduced, which also reduces the material removal rate.

Optimization was performed and models for the three machining outcomes were developed that allow each of the outcomes to be optimized independently. However, the settings for optimum material removal rate generally increase both kerf and surface roughness. Therefore, in order to implement these models, it is necessary to make certain tradeoffs.

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