APPLICATION OF THE TAGUCHI TECHNIQUE FOR WEDM

PARAMETERS FOR TUNGSTEN CARBIDE

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ABSTRACT

Relationships between material removal rate (MRR), surface roughness (SR) and surface crack density (SCD) were investigated for wire electrical discharge machining (WEDM) of pure tungsten to explore the significance of machine parameter variables such as voltage (Vo), peak current (Ip) and wire speed (Ws). An L9 orthogonal array Taguchi design of experiment (DOE) was used to determine the effect of different machine conditions. Data were statistically evaluated by analysis of variance (ANOVA). Results indicated that increase in discharge current and voltage increased MRR, SR and SCD. Specimens were observed by scanning electron microscopy to investigate surface response under different conditions. Characteristics of crack length distribution per unit area were optimized for surface crack density. Signal to noise ratio and ANOVA were utilized to analyze process responses. Results can be used to optimize cutting parameters for tungsten carbide manufacturing processes.

KEYWORDS: Tungsten Carbide, Wire-EDM, Taguchi Method, Material Removal Rate, Surface Roughness, Surface Crack Density (SCD), ANOVA

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1. INTRODUCTION

Wire electrical discharge machining (WEDM) provides an effective solution for hand cutting materials into intricate shapes with high accuracy and smooth surfaces (Dabade et al., 2016). Different factors and process parameters have been developed to optimize a large number of machine responses. WEDM mechanisms depend on wire electrical conductivity and the material used in the process (Singh et al., 2016). An electrical spark between the wire electrode and material to be cut as “spark gap” occurs for a short duration discharge which melts and removes particles from the workpiece by flushing with deionized water. Effects of machining process parameters such as voltage (Vo), discharge current (Ip), wire speed (Ws), and pulse on-off time correlate with performance characteristic of surface roughness (SR), material removal rate (MRR) and surface crack density (SCD). Sinter group materials as tungsten carbide (WC) with characteristics similar to diamond are attracting interest in the manufacturing industry as electronic lighting and cutting tools to perform a variety of component machine part functions (Upadhyaya, 1998). Tungsten carbide has excellent chemical and physical properties with a high melting point at $3,410 \pm 20^\circ\text{C}$, high strength and hardness (Selcuk et al., 2013). Tungsten (W) is a refractory metal with a bcc (body-centered cubic) structure, while cobalt (Co) is used as a binder material with stability up to 400°C . Cobalt, used as a binder for WC has a cubic lattice which cannot be transformed by annealing. Stabilization of the cubic modification by dissolved tungsten and carbon is produced by a hexagonal crystal structure phase of WC and Co (Upadhyaya, 1998). Tungsten-cobalt microstructure has a hardness similar to tungsten carbide, connected by an

obligation of cobalt (Co) called a skeleton, as shown in Figure 1 (Jangra, Grover, & Aggarwal, 2012).

Figure 1: Structure of Tungsten Carbide and Cobalt Binder

Srivastava et al. (2016) determined lowest surface roughness as $2.214\ \mu\text{m}$ when using WEDM at wire tension of $0.6\ \text{N}$, feed rate $10\ \text{m/min}$, flushing pressure $3\ \text{kg/cm}^2$ and $80\ \text{A}$ current by the Taguchi method, while Chen et al. found that machined finish for WEDM of tungsten carbide depended on cutting speed. However, pure tungsten is always brittle due to correlation between thermal and mechanical properties at low temperature. Grain growth leads to recrystallization with occurrence of grain boundaries (GBs) (Xie et al., 2018).

Hiong and Xiaoping (2003) studied EDM current with regard to microcracks on the tungsten surface. Their results showed that low melting point of cobalt caused the metal to melt and separate from the tungsten carbide matrix and development of microcracks and micropores as a result of thermal stress during the EDM process. Faleschini et al. (2007) used liquid nitrogen to reduce tungsten alloy temperature. Temperature changes when cooling the workpiece lead to stress during the operation and induce microcracks (Faleschini et al., 2007). Process parameters including cutting speed have been suggested as important for reducing microcracks and improving surface roughness of WC-Co. Discharge current and rate of dielectric fluid flow were also found to be inversely proportional to surface finish of WC-Co composites (Jangra et al., 2012).

Here, process parameters such as voltage (V_o), discharge current (I_p) and wire speed (W_s) were investigated and compared with performance characteristics of material removal rate, surface roughness and surface crack density of tungsten carbide using the Taguchi method.

2. METHOD

2.1 Material and Equipment

Experiments were conducted using a Mitsubishi FA10S wire electrical discharge machine (W-EDM) with deionized water based dielectric. Electrode material was a brass wire $0.25\ \text{mm}$ in diameter. The experiment was carried out on tungsten carbide (W73%C11%), and the workpiece was tested for chemical components by EDS (Figure 2). Chemical composition of tungsten carbide is shown in Table 1.

Figure 3 shows the experimental setup. Thickness of the workpiece was $2.0\ \text{mm}$. Experiments were carried out by main cut and trim cut using three parameters as open-circuit voltage (V_o), peak current (I_p) and wire speed (W_s) to investigate material removal rate (MRR) (mm^3/min), surface roughness (SR) and surface crack density (SCD).

Table 1: Chemical Composition of Tungsten Carbide

Element%	O	C	W	Na	K	Total
Weight%	14.58	11.08	72.98	0.45	0.90	100

Figure 2: EDS Test of Tungsten Carbide

Figure 3: W-EDM Experimental Set up

2.2 Experimental Design by Taguchi Method

A Taguchi L9 orthogonal array as a 3-level, 3 trial design of experiment (DOE) in the form of a table was used to investigate three parameters as voltage, current, and level of configuration (Table 2). ANOVA analysis was employed to determine the relative influence of processes parameters.

Table 2: Process Parameter Variable and their Levels

Factor	Sign	Unit	Level 1	Level 2	Level 3
Voltage Open	Vo	Volt	6	10	15
Peak current	Ip	Amp	5	7	8
Wire Speed	Ws	m/min	5	8	12

All experimental measurements were conducted in triplicate. An L9 orthogonal array for experimentation on wire EDM along with results of response are presented in Table 4.

2.3 Experimental Methodology

2.3.1 Material Removal Rate (MRR)

Effects of machining conditions were evaluated by MRR and SR on the effect of discharge current. Results showed that MRR significantly increased with increase in the rate of discharge current. MRR was calculated from the following equations (Arikatla et al., 2017) where V_c is the average feed in mm/min, H is workpiece thickness, k is the cutting width (offset) in mm and t is the time in seconds (Srinivasa Rao et al., 2016).

$$MRR = V_c \times H \times k \quad (1)$$

$$V_c = \frac{60}{t} \quad (2)$$

2.3.2 Surface Crack Density

Surface crack density (SCD) is defined as the average crack length per area ($\mu\text{m}/0.005 \mu\text{m}^2$) measured after the WEDM process by an SEM micrograph at 500 magnification. Length of cracks was measured on three randomly selected areas of each machined surface at 13,107.20 ($\mu\text{m}/\mu\text{m}^2$). Average crack length was divided to obtain SCD following equation (3) below (Bhaumik et al., 2017; Mohanty et al., 2014).

$$\text{Surface crack density} = \frac{CL_1 + CL_2 + CL_3}{3} \quad (3)$$

3. RESULTS AND DISCUSSIONS

3.1 Discharge Waveform of Analysis

Discharge energy of conventional WEDM at a current of 5, 7, and 8 A was controlled by the WEDM-CNC program. The spark occurs in the gap between the wire tool and material. If the gap distance is too narrow, spark and concentrated wave amplitude are not generated (Lin et al., 2014). Figure 4 a, b and c show a spark gap occurring. As mentioned above, stability of the WEDM process allows discharge waveforms to be monitored and determined. If the number of effective discharge waveforms increases, stability of the WEDM process improves and machining efficiency increases. When the elapsed machining time is extended, more machining debris is produced and suspended in the machining gap and wire breakage can occur. The debris accumulated also affects WEDM progress due to abnormal spark discharge (Lin et al., 2009; Zhou et al., 2018).

Figure 4: Discharge voltage waveform of conventional WEDM;
(a) $I_p=5$ A, $T_{on}=1$, $T_{off}=18$, (b) $I_p=7$ A, $T_{on}=1$, $T_{off}=18$, (c) $I_p=8$ A, $T_{on}=1$, $T_{off}=18$

3.2 Taguchi Method

Based on the Taguchi method, signal to noise ratio (S/N ratio) was calculated from the optimal parameter value. Table 3 shows the experimental result and mean of signal to noise ratios for various values of MRR, SR and SCD per L9 orthogonal array design. Minitab 18 was used to analyze “higher is better” values observed for MRR following equation (4) and “lower is better” values observed for SR and SCD following equation (5) (Ross, 1996).

$$\eta_{MRR} = -10 \log \left[\frac{1}{n} \sum_{i=1}^n y_i^2 \right] \quad (4)$$

$$\eta_{Ra, Crack} = -10 \log \left[\frac{1}{n} \sum_{i=1}^n y_i^2 \right] \quad (5)$$

Significance of experimental parameters on MRR, SR and SCD were shown by S/N ratios and summarized in Table 3. Analysis of variance (ANOVA) was used to optimize the desired response and determine parameters for MRR, SR and SCD integrity. ANOVA results were determined at 95% confidence level using MINITAB 18. A regression analysis summarized how significant process parameters V_o , I_p and W_s were affected by MRR, SR and SCD.

Experimental parameters of MRR, SR and SCD were ranked by the Taguchi technique. The first rank shows the optimal effect of machine settings with the main impact of MRR as peak current (I_p) and voltage (V_o) as the main effect for SR and SCD. Data were plotted as Figures 5, 6 and 7, respectively.

3.2.1 Effect of Process Parameters on MRR

Effect of WEDM parameters, as shown by the main plot of S/N ratio “larger is better”, focused on material removal rate. Table 4 shows the effects of process parameters on MRR performed by ANOVA. Figure 5a shows the main effects of parameters on MRR which was highest at the third level of open-circuit voltage (15 volts), the third level of peak current (8 A), and the first level of wire speed (5 m/min). Material removal rate increased with increasing open-circuit voltage and peak current at low wire speed. Main effect of MRR was optimized by average peak current, voltage increase and low wire speed. At high energy, the discharge current led to melting and evaporation of WC (Goswami et al., 2017; Rao et al., 2014).

Table 3: Experimental Result with Mean Responses and S/N Ratios of MRR, Surface Roughness and Crack Integrity

Exp. No.	Process Parameters			Mean of Responses			Mean of Main Effect Plot		
	Vo	Ip	Ws	MRR (mm ³ /min)	SR (μm)	SCD (μm/mm ²)	Mean of MRR	Mean of SR	Mean of SCD
1	6	5	5	3.69	31.83	0.0698	3.2633	31.9489	0.067723
2	6	7	8	6.04	32.51	0.0836	6.5417	34.5656	0.083886
3	6	8	12	8.09	38.03	0.0972	8.0143	35.8556	0.098979
4	10	5	8	4.89	31.57	0.1065	4.8121	29.3956	0.108325
5	10	7	12	8.86	32.51	0.1239	8.4361	32.6289	0.121745
6	10	8	5	13.93	44.54	0.0932	12.4314	46.5956	0.093526
7	15	5	12	6.30	36.17	0.1620	6.8040	38.2256	0.162319
8	15	7	5	11.03	56.31	0.1306	12.9508	54.1356	0.132427
9	15	8	8	12.50	54.69	0.1524	14.0778	54.8089	0.150264

Process parameter results of ANOVA analysis indicated confidence level at 95% significance when p-value was less than 0.05. Table 4 presents the result of ANOVA. Peak current was the major factor and significant parameter that affected MRR, voltage and wire speed, respectively.

Figure 5: Main Effect of the Parameter on (a) MRR, (b) SR and (c) SCD

Table 4: Analysis of Variance for MRR

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	113.973	37.9910	117.92	0.000
Vo	1	42.620	42.6197	132.29	0.000*
Ip	1	66.630	66.6295	206.81	0.000*
Ws	1	4.724	4.7237	14.66	0.012*
Error	5	1.611	0.3222		
Total	8	115.584			
S = 0.567602		R-sq = 98.61%	R-sq(adj) = 97.77%	R-sq(pred) = 94.89%	

*significance at p-value less than 0.05

3.2.2 Effect of Process Parameter on Surface Roughness

“Smaller is better” in the analysis of surface roughness (SR) which was measured using a roughness TIME series TR200 tester. An ANOVA was performed to determine the effects of process parameters on SR (Table 5 and Figure 5b). Results were lowest at the first level of open-circuit voltage, peak current and third level of wire speed. SR increased as voltage and peak current increased and wire speed decreased. With peak current and voltage increased, discharge current density eroded and melted the surface material. Mechanisms of voltage and peak current ejected and exploded material from the workpiece leading to the development of deep holes, craters, coral reefs, and micro-voids (Goyal, 2017). Surface roughness depends on the size of the craters, coral reef (Saha, Singha, Pal, & Saha, 2007) as shown by SEM micrographs (Figures 6 and 7).

A scanning electron microscope SEM (JEOL700) was used to measure SR and SCD. Figure 6a shows highest SR at $31.57 \mu\text{m}$ with MRR at $4.89 \text{ mm}^3/\text{min}$ and lowest crack density (SCD) at $0.1065 \mu\text{m}/\text{mm}^2$ using 10 volts, peak current 5 A and wire speed 8 m/min (Experiment no.4).

Figure 6b shows highest SR at $56.31 \mu\text{m}$ with MRR $11.03 \text{ mm}^3/\text{min}$ and SCD $0.1306 \mu\text{m}/\text{mm}^2$ using 15 volts, peak current 7 A and wire speed 5 m/min (Experiment no.8). Effects of increases in peak current, voltage and wire speed were assessed for SR and SCD. Experiment No.9 as Figure 6c shows SR and SCD increase, while SR and SCD melted when the workpiece was cut using a wire. Highest SR and SCD were $54.69 \mu\text{m}$ and $0.1524 \mu\text{m}/\text{mm}^2$, respectively.

SR and SCD increased when electrical discharge increased. Thermal conductivity allowed rapid dissipation of heat through the sample, instead of being concentrated on the surface. This caused larger discharge energy at the surface and produced deep areas of melting and larger craters which induced surface roughness on the workpiece. Surface smoothness was assessed by SEM (Figure 7). Experiment No.8 gave characteristic particles as debris granules and coral reefs.

Surface cracks on tungsten carbide probably occurred after the wire electrical discharge process during machine cooling, when WC entered a carbide phase. Boundary grain cracks occurred and reduced the surface roughness integrity (Bonny et al., 2009).

Figure 6(a): SEM Characteristic of SR (Exp. No. 4)

Figure 6(b): SEM Characteristic of SR (Exp. No. 8)

Figure 6(c): SEM Characteristic of SR and SCD (Exp. No. 9)

Figure 7: SEM Photograph of the Characteristic Surface Work Piece

Results of the ANOVA for a 95% minimum confidence interval of surface roughness are shown in Table 5. Major factors determining surface roughness were voltage, peak current and wire speed, respectively.

Table 5: Analysis of Variance for Surface Roughness

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	698.27	232.76	16.09	0.005
Vo	1	351.16	351.16	24.27	0.004*
Ip	1	236.22	236.22	16.33	0.010*
Ws	1	110.89	110.89	7.66	0.039*
Error	5	72.34	14.47		
Total	8	770.61			
S = 3.80368 R-sq = 90.61% R-sq(adj) = 84.98% R-sq(pred) = 65.30%					

*significance at p-value less than 0.05

3.2.3 Effect of Process Parameter on the Density of Surface Crack

Surface crack density was evaluated as “smaller is better” (Figure 5c) with analysis of variance shown in Table 6. Open-circuit voltage had the greatest effect followed by peak current and wire speed, respectively. Higher discharge energy resulted in increased melting, evaporation and erosion of the workpiece. Lower voltage, current and wire speed cause small gaps, and the difficulty of flushing waste material lead to the surface re-solidifying which generates cracks in material grains (Saha et al., 2007) and increases SCD (Goswami et al., 2017). Melting and re-solidification of the material causes formation of surface cracks because of temperature differential which increases surface stress levels and leads to cracks on the workpiece (Srinivasa Rao, Ramji, & Satyanarayana, 2016).

MRR, SR and SCD were determined by Minitab 18 as relatively significant individual factors for the WEDM process. Optimal parameters for the processing setup to investigate MRR, SR and SCD are shown in Table 7 as the predicted optimal condition and experimental result for each response variable.

Table 6: Analysis of Variance for SCD

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	3	0.007703	0.002568	142.62	0.000
Vo	1	0.006390	0.006390	354.94	0.000
Ip	1	0.000002	0.000002	0.13	0.731
Ws	1	0.001311	0.001311	72.79	0.000
Error	5	0.000090	0.000018		
Total	8	0.007793			
S = 0.0042431 R-sq = 98.84% R-sq(adj) = 98.15% R-sq(pred) = 96.50%					

*significance at p-value less than 0.05

Table 7: Confirmatory Experimental Results

Response	Optimal Condition	Experimental	Predicted Optimal Value	95% CI
MRR	15Vo8Ip8Ws	12.50	15Vo8 Ip5Ws	14.0031<MRR< 16.2000
SR	10Vo5 Ip8Ws	31.57	6Vo5 Ip12Ws	13.2557<SR< 28.9625
SCD	6Vo5 Ip5Ws	0.069	6Vo5 Ip5Ws	0.0586<SCD<0.0757

4. CONCLUSIONS

Significant input factors as MRR, SR and SCD were investigated to determine the WEDM of tungsten carbide. The Taguchi technique was used to optimize cutting conditions. Conclusions were as follows:

1. The most significant factor affecting MRR was peak current, followed by voltage and wire speed.
2. The most significant factor affecting SR was voltage following by peak current and wire speed.
3. The most significant factor affecting SCD was voltage followed by wire speed.

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REFERENCES

1. Anish Kumar, Vinod Kumar, & JatinderKumar. (2013). Multi-response optimization of process parameters based on response surface methodology for pure titanium using WEDM process. *The International Journal of Advanced Manufacturing Technology*, 68(9-12), 2645-2668. doi:10.1007/s00170-013-4861-9
2. Bhaumik, M., & Maity, K. (2017). Effect of process parameters on the surface crack density of AISI 304 in PMEDM. *World Journal of Engineering*, 14(6), 475-482. doi:10.1108/wje-08-2016-0051
3. Bonny, K., De Baets, P., Ost, W., Huang, S., Vleugels, J., Liu, W., & Lauwers, B. (2009). Influence of electrical discharge machining on the reciprocating sliding friction and wear response of WC-Co cemented carbides. *International Journal of Refractory Metals and Hard Materials*, 27(2), 350-359. doi:10.1016/j.ijrmhm.2008.09.002
4. Dabade, U. A., & Karidkar, S. S. (2016). Analysis of Response Variables in WEDM of Inconel 718 Using Taguchi Technique. *Procedia CIRP*, 41, 886-891. doi:10.1016/j.procir.2016.01.026
5. Faleschini, M., Kreuzer, H., Kiener, D., & Pippan, R. (2007). Fracture toughness investigations of tungsten alloys and SPD tungsten alloys. *Journal of Nuclear Materials*, 367-370, 800-805. doi:10.1016/j.jnucmat.2007.03.079
6. Goswami, A., & Kumar, J. (2017). Trim cut machining and surface integrity analysis of Nimonic 80A alloy using wire cut EDM. *Engineering Science and Technology, an International Journal*, 20(1), 175-186. doi:10.1016/j.jestch.2016.09.016
7. Goyal, A. (2017). Investigation of material removal rate and surface roughness during wire electrical discharge machining (WEDM) of Inconel 625 super alloy by cryogenic treated tool electrode. *Journal of King Saud University - Science*, 29(4), 528-535. doi:10.1016/j.jksus.2017.06.005
8. Hiong, L. S., & Xiaoping, L. (2003). Study of the surface integrity of the machined workpiece in the EDM of tungsten carbide. *Journal of Materials Processing Technology*, 139(1-3), 315-321. doi:10.1016/s0924-0136(03)00547-8

9. Jangra, K., Grover, S., & Aggarwal, A. (2012). Optimization of multi machining characteristics in WEDM of WC-5.3%Co composite using integrated approach of Taguchi, GRA and entropy method. *Frontiers of Mechanical Engineering*, 7(3), 288-299. doi:10.1007/s11465-012-0333-4
10. Lin, Y.-C., Chen, Y.-F., Wang, D.-A., & Lee, H.-S. (2009). Optimization of machining parameters in magnetic force assisted EDM based on Taguchi method. *Journal of Materials Processing Technology*, 209(7), 3374-3383. doi:10.1016/j.jmatprotec.2008.07.052
11. Lin, Y.-C., Chuang, F.-P., Wang, A. C., & Chow, H.-M. (2014). Machining characteristics of hybrid EDM with ultrasonic vibration and assisted magnetic force. *International Journal of Precision Engineering and Manufacturing*, 15(6), 1143-1149. doi:10.1007/s12541-014-0449-z
12. Mohanty, A., Talla, G., & Gangopadhyay, S. (2014). Experimental Investigation and Analysis of EDM Characteristics of Inconel 825. *Materials and Manufacturing Processes*, 29(5), 540-549. doi:10.1080/10426914.2014.901536
13. Rao, P. S., Ramji, K., & Satyanarayana, B. (2014). Experimental Investigation and Optimization of Wire EDM Parameters for Surface Roughness, MRR and White Layer in Machining of Aluminium Alloy. *Procedia Materials Science*, 5, 2197-2206. doi:10.1016/j.mspro.2014.07.426
14. Ross, P. J. (1996). *Taguchi Techniques for Quality Engineering*. United States of America.
15. Saha, P., Singha, A., Pal, S. K., & Saha, P. (2007). Soft computing models based prediction of cutting speed and surface roughness in wire electro-discharge machining of tungsten carbide cobalt composite. *The International Journal of Advanced Manufacturing Technology*, 39(1-2), 74-84. doi:10.1007/s00170-007-1200-z
16. Selcuk, C., Morley, N., & Wood, J. V. (2013). Porous tungsten with controlled porosity by low temperature sintering. *Powder Metallurgy*, 48(1), 17-22. doi:10.1179/003258905x37648
17. Singh, G. S., Jagdev, S., Harpreet, S., & Rupinder, S. (2011). Metallurgical and mechanical characteristics of cryogenically treated tungsten carbide (WC-Co). *The International Journal of Advanced Manufacturing Technology*, 58(1-4), 119-131. doi:10.1007/s00170-011-3369-4
18. Singh, V., Bhandari, R., & Yadav, V. K. (2016). An experimental investigation on machining parameters of AISI D2 steel using WEDM. *The International Journal of Advanced Manufacturing Technology*, 93(1-4), 203-214. doi:10.1007/s00170-016-8681-6
19. Srinivasa Rao, P., Ramji, K., & Satyanarayana, B. (2016). Effect of wire EDM conditions on generation of residual stresses in machining of aluminum 2014 T6 alloy. *Alexandria Engineering Journal*, 55(2), 1077-1084. doi:10.1016/j.aej.2016.03.014
20. Srivastava, T., Kumar, G., Tiwana, J. S., Singla, A., Rani, S., & Kakkar, S. (2016). Optimization of the machining parameters for EDM wire cutting of Tungsten Carbide. *MATEC Web of Conferences*, 57. doi:10.1051/mateconf/20165703006
21. Upadhyaya, G. S. (1998). *Cemented Tungsten Carbides*: Noyes publications.
22. Xie, Z. M., Miao, S., Zhang, T., Liu, R., Wang, X. P., Fang, Q. F., . . . Cai, L. H. (2018). Recrystallization behavior and thermal shock resistance of the W-1.0 wt% TaC alloy. *Journal of Nuclear Materials*, 501, 282-292. doi:10.1016/j.jnucmat.2018.01.042
23. Zhou, M., Wu, J., Xu, X., Mu, X., & Dou, Y. (2018). Significant improvements of electrical discharge machining performance by step-by-step updated adaptive control laws. *Mechanical Systems and Signal Processing*, 101, 480-497. doi:10.1016/j.ymssp.2017.06.041