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Evaluation of the Effects of Ton, Toff and SV on Surface Roughness in WEDM of Cemented Carbide

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Abstract— *This study evaluates the effects of three machining parameters, namely pulse-on time (Ton), pulse-off time (Toff), and servo voltage (SV), on surface roughness (Ra) during the wire electrical discharge machining (WEDM) of cemented carbide. The experiments were designed using a Taguchi L9 orthogonal array with three input factors, each at three levels. The investigated output response was the average surface roughness Ra. The experimental results show that Ra varied from 2.285 µm to 3.503 µm. The lowest Ra value was obtained at Ton = 1 µs, Toff = 20 µs, and SV = 75 V. The analysis of mean effects and signal-to-noise (S/N) ratios indicates that the parameter combination capable of producing a lower surface roughness is Ton = 1 µs, Toff = 30 µs, and SV = 70 V. Analysis of variance (ANOVA) shows that Ton is the most influential factor affecting Ra, with a contribution of approximately 80.68%, followed by SV with 10.76% and Toff with 8.27%. The results indicate that reducing Ton, increasing Toff, and selecting a lower SV can improve surface quality in the WEDM of cemented carbide.*

Keywords— *WEDM, cemented carbide, WC-Co, surface roughness, Ra, Taguchi, ANOVA, Ton, Toff, SV.*

I. INTRODUCTION

Hard alloys, especially tungsten carbide–cobalt base materials, are widely used in the manufacture of molds, cutting tools, wear-resistant parts, and parts working under high load conditions. These materials have high hardness, good wear resistance, and high thermal stability. However, these very characteristics make hard alloys difficult to machine using traditional cutting methods due to high cutting forces, rapid tool wear, high machining costs, and difficulty in controlling surface quality. Therefore, non-traditional machining methods, including wire electrical discharge machining (EDM), are considered suitable solutions for machining high-hardness and complex-shaped conductive materials [1–3]. WEDM is a thermoelectric machining process capable of machining high-hardness or complex-shaped parts by means of material removal through electrical discharge instead of direct mechanical contact.

In WEDM, material is removed by thermal energy generated from electrical discharges between the wire electrode and the workpiece in a dielectric medium. The discharge energy melts and vaporizes part of the material in the machining zone. The molten material is then flushed out of the machining gap by the dielectric fluid. Because there is no direct mechanical cutting force, WEDM is particularly suitable for hard, brittle, and difficult-to-machine materials such as WC-Co. However, because the material removal mechanism is thermally based, the machined surface often exhibits features such as discharge craters, a recast layer, adhered material, and sometimes micro-cracks [4-8].

Surface roughness Ra is one of the important indicators for evaluating surface quality after machining. For components operating under friction, wear, or high-precision requirements, surface roughness directly affects functional performance, fatigue strength, wear resistance, and service life. A surface with high roughness is often associated with larger discharge craters, a non-uniform recast layer, and a higher possibility of surface defect formation [9-11].

Among WEDM process parameters, pulse-on time (Ton) has a direct effect on the energy of each discharge pulse. As Ton increases, the duration of spark action becomes longer, and the energy transferred to the workpiece increases, leading to more intense melting and vaporization of the material. This usually increases the size of discharge craters and results in higher surface roughness. In contrast, pulse-off time (Toff) determines the recovery period of the dielectric medium between two consecutive discharge pulses. If Toff is too short, debris and gas bubbles cannot be removed in time, causing unstable discharges and deteriorating the machined surface. Servo voltage (SV) is also important because it affects the discharge gap, machining gap stability, and spark density.

Many studies have used the Taguchi method, ANOVA, regression, response surface methodology, and optimization algorithms to evaluate the effects of WEDM parameters on machining quality [12-20]. However, for cemented carbide machining, especially in the low-parameter range used for finish machining, the simultaneous effects of Ton, Toff, and SV on Ra still need further clarification. Therefore, this study conducts experiments using a Taguchi L9 array to determine the influence trends of Ton, Toff, and SV on the surface roughness Ra in WEDM of cemented carbide. The results are analyzed through mean values, S/N ratios, and ANOVA to identify the dominant factors and propose a suitable parameter combination for reducing surface roughness.

II. EXPERIMENTAL METHOD

A. Material and Machining Process

The material used in the study was WC–Co hard alloy. The test specimens were machined using electrical discharge machining (EDM) on a Sodick AL80G machine. The electrode wire used was copper cutting wire, with a diameter of 0.2 mm. The dielectric medium was deionized water.

In this study, three machining parameters were investigated: pulse-on time (Ton), pulse-off time (Toff), and servo voltage (SV). Other parameters such as wire speed, wire tension, dielectric flushing pressure, and specimen height were kept constant throughout the experiments to clearly evaluate the effects of the three selected parameters.

B. Experimental Design

The experiments were arranged according to a Taguchi L9 orthogonal array with three input factors, each at three levels. The parameter levels are presented in Table 1.

TABLE 1. Machining parameters and investigated levels

Factor	**Symbol**	**Level 1**	**Level 2**	**Level 3**
Pulse-on time	Ton	1 µs	2 µs	3 µs
Pulse-off time	Toff	10 µs	20 µs	30 µs
Servo voltage	SV	70 V	75 V	80 V

The experimental matrix and measured Ra values are presented in Table 2.

TABLE 2. Experimental matrix and measured Ra values

Exp.	**Ton (µs)**	**Toff (µs)**	**SV (V)**	**Ra (µm)**
1	1	10	70	2.335
2	1	20	75	2.285
3	1	30	80	2.412
4	2	10	75	2.955
5	2	20	80	2.941
6	2	30	70	2.505
7	3	10	80	3.503
8	3	20	70	3.074
9	3	30	75	3.050

C. Surface Roughness Measurement

After machining, the surface roughness Ra was measured using a Mitutoyo SJ-210 instrument. Each sample was measured at three different locations on the machined surface, and the average value was taken as the representative result. Within the scope of this paper, Ra was chosen as the output parameter because it is a common parameter for evaluating surface quality after WEDM.

D. Data Analysis Method

Because the objective of this study is to reduce surface roughness, the "smaller-the-better" criterion was used in the Taguchi analysis. The signal-to-noise (S/N) ratio was calculated using the following equation:

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

Where yi is the measured Ra value and n is the number of repetitions. In addition, analysis of variance (ANOVA) was used to determine the influence level and percentage contribution of each machining parameter to Ra.

III. RESULTS

A. General Evaluation of the Experimental Results

As shown in Table 2, Ra varied from 2.285 µm to 3.503 µm. The minimum Ra value was obtained in experiment 2 at Ton = 1 µs, Toff = 20 µs, and SV = 75 V. The maximum Ra value occurred in experiment 7 at Ton = 3 µs, Toff = 10 µs, and SV = 80 V. The difference between the maximum and minimum Ra values was 1.218 µm, indicating that the machining parameters had a clear effect on surface quality.

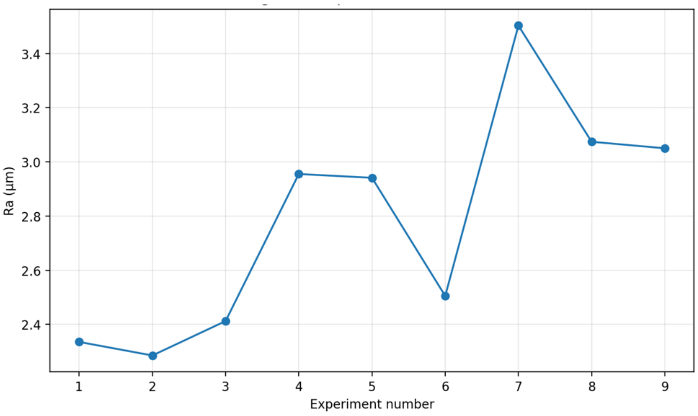

Figure 1. Surface roughness Ra values for each experiment.

Figure 1 shows that the experiments with low Ton generally produced lower Ra values, whereas the experiments with Ton = 3 µs produced higher Ra values. In particular, experiment 7 gave the highest Ra because it combined high Ton, low Toff, and high SV. This agrees with the thermal material removal mechanism in WEDM: when discharge energy is high and dielectric recovery time is short, the surface tends to become rougher.

B. Mean Effects of the Parameters on Ra

TABLE 3. Mean Ra values at the levels of the factors

Factor	**Level 1**	**Level 2**	**Level 3**	**Trend**
Ton	2.344	2.800	3.209	Ton increases → Ra increases
Toff	2.931	2.767	2.656	Toff increases → Ra decreases
SV	2.638	2.763	2.952	SV increases → Ra increases

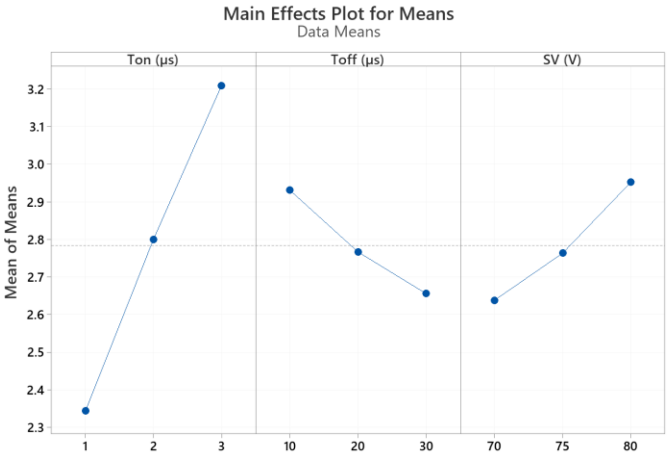

Figure 2. Main effects plot of Ton, Toff, and SV on the mean Ra value

Figure 2 shows that Ton has the steepest slope, indicating that it is the most influential parameter affecting Ra. When Ton increased from 1 µs to 3 µs, the mean Ra increased from 2.344 µm to 3.209 µm. This is because a higher Ton extends the discharge pulse duration, increases the energy transferred to the machining zone, and enlarges the discharge craters and recast region.

For Toff, as Toff increased from 10 µs to 30 µs, the mean Ra decreased from 2.931 µm to 2.656 µm. This indicates that a longer Toff improves cooling and debris flushing, thereby reducing abnormal discharges. For SV, when SV increased from 70 V to 80 V, Ra increased from 2.638 µm to 2.952 µm. Within the investigated range, a lower SV produced better surface quality.

C. Signal-to-Noise Ratio Analysis

TABLE 4. S/N response table for surface roughness Ra

Factor	Level 1	Level 2	Level 3	Delta	Rank
Ton	-7.397	-8.919	-10.110	2.713	1
Toff	-9.222	-8.767	-8.437	0.785	3
SV	-8.365	-8.758	-9.302	0.937	2

Figure 3. Main effects plot for S/N ratios.

For the “smaller-the-better” criterion, a higher S/N value indicates better surface quality. Figure 3 shows that the optimum levels based on the S/N ratio are Ton at level 1, Toff at level 3, and SV at level 1. Therefore, the predicted optimum parameter combination is Ton = 1 µs, Toff = 30 µs, and SV = 70 V. This result is consistent with the mean-value analysis: low Ton reduces discharge energy, high Toff supports dielectric recovery, and low SV helps maintain more stable discharge conditions within the investigated range.

D. Analysis of Variance (ANOVA)

TABLE 5. ANOVA results for Ra

Factor	SS	df	MS	F	P-value	Contribution (%)
Ton	1.123	2	0.562	279.18	0.0036	80.68
Toff	0.115	2	0.058	28.61	0.0338	8.27
SV	0.150	2	0.075	37.25	0.0261	10.76
Error	0.004	2	0.002			0.29
Total	1.393	8				100

Figure 4 shows that Ton contributed the most to the variation in Ra, reaching 80.68%. This confirms that Ton is the dominant parameter for surface quality within the surveyed area. SV contributed 10.76%, ranking second, while Toff contributed 8.27%. The error was only 0.29%, indicating that the ANOVA model explained most of the data's variability.

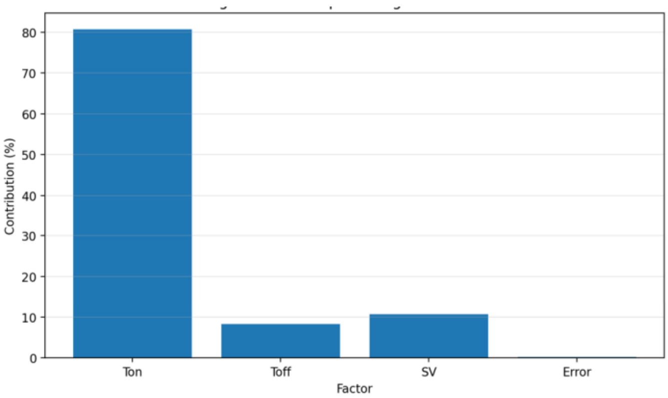

Figure 4. Percentage contribution of the factors based on ANOVA.

IV. DISCUSSION

Experimental results show that Ton has a dominant influence on Ra. This is a reasonable result because Ton is directly related to discharge energy. As Ton increases, the area of material that melts and vaporizes expands, leading to the formation of larger discharge pits. After rapid cooling, the material layer re-solidifies unevenly on the surface, increasing roughness.

Toff tends to decrease Ra when increasing from 10 µs to 30 µs. This mechanism can be explained by the resilience of the dielectric medium. Longer pulse interruption times help to remove the peeled product better, reducing short circuits or abnormal discharges, thereby improving the machined surface.

SV also affects surface roughness. Within the surveyed range, increasing SV increases Ra. This suggests that high gap voltage can change the discharge state towards creating a rougher surface. However, the influence of SV is much lower than that of Ton. Therefore, when selecting the machining mode for hard alloys, Ton should be prioritized for control first, then SV and Toff should be adjusted to achieve machining stability.

V. CONCLUSION

- The surface roughness Ra in the nine experiments varied from 2.285 µm to 3.503 µm. The lowest Ra value was obtained at Ton = 1 µs, Toff = 20 µs, and SV = 75 V.
- Ton was the most influential factor affecting Ra. When Ton increased from 1 µs to 3 µs, the mean Ra increased from 2.344 µm to 3.209 µm. This indicates that reducing Ton is an important solution for improving surface quality.
- Toff showed an opposite trend to Ra. When Toff increased from 10 µs to 30 µs, the mean Ra decreased from 2.931 µm to 2.656 µm, indicating that increasing Toff helps stabilize the discharge process and improve the machined surface.
- SV also had a significant effect on Ra. Within the investigated range, when SV increased from 70 V to 80 V, the mean Ra increased from 2.638 µm to 2.952 µm.
- The ANOVA results showed that Ton had the largest contribution, reaching 80.68%, followed by SV with 10.76% and Toff with 8.27%. All three factors had statistically significant effects on Ra at the 95% confidence level within the investigated data range.

- The predicted optimal parameter combination for reducing Ra is Ton = 1 µs, Toff = 30 µs, SV = 70 V. This combined Ra value is approximately 2.069 µm.

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