Wire Electrical Discharge Machining of Tungsten Carbide

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Abstract* – This paper presented a study on the machining of tungsten carbide (WC-15%Co) using wire electro-discharge machining (WEDM) with brass wire diameter of 0.2 mm used as the tool electrode. The main purposes of this study is to investigate the influenced of various parameters involved in WEDM on the machining characteristics, namely, sparking gap (Gap), cutting speed (CS) and microstructure after undergone WEDM process. The Full Factorial Design of Experiment (DOE) method with two-level was used to formulate the experimental layout, to analyze the effect of each parameter on the machining characteristics and to predict the optimal setting for each WEDM parameters such as pulse on (ON), pulse off (OFF), peak current (IP) and servo voltage (SV). Confirmation tests were also conducted for the optimum conditions for each machining characteristics, in order to verify and compared the results from the theoretical prediction (Design Expert) and experimental confirmation tests. In this investigation, the machining operation for tungsten carbide is performed using Sodick linear motor WEDM series AQ537L. Meanwhile, for the measurement equipments; Zeiss Axiotech High Power Optical Microscope is used to measure Gap and to examine the microstructures of the machined surface, Scanning Electron Microscope XL40 is carried out. Analysis done by DOE method reveals that in general, pulse on has appeared to be significant effect to all three responses investigated in this research. Overall, the results from the confirmation tests showed that the percentage of performance is acceptable due to all the results obtained were within the allowable values which is less than 10% of margin error.

Keywords – Tungsten carbide, WEDM, machining parameters, DOE

I. INTRODUCTION

Electrical discharge machining, commonly known as EDM, is a process that is used to remove metal through the action of an electrical discharge of short duration and high current density between the tool and the workpiece. There are no physical cutting forces between the tool and the workpiece involved. EDM has proved valuable especially in the machining of super-tough, electrically conductive materials such as the new space-age alloys. It can be used to produce parts with intricate shape that is impossible when using conventional cutting tools.

This machining process is continually finding further applications in the metal machining industry. It is being used extensively in the plastic industry to produce cavities of almost any shape in metal moulds. Other applications are also included such as producing critical parts for aerospace, electronics and medical industries [1-2]. Although the application of EDM is limited to the machining of electrically conductive workpiece materials, the process has the capability to cut these materials regardless of their hardness or toughness.

In this research, tungsten carbide is chosen to be the work material. Tungsten carbide (WC-Co) is an important material for tool and dies mostly because of its high hardness, strength and wear resistance over a wide range of temperature. It has high specific strength and cannot be fabricated easily by conventional machining techniques. Literature reports indicated that EDM can be successfully applied to a single-phase ceramics, cermets and ceramic-matrix composites, as far as they exhibit an electrical resistivity lower than values between 100 and 300?.cm [3]. Since EDM has been shown to be a versatile method for machining difficult-to-work materials and suitable in conforming WC-Co cemented carbides, therefore EDM process is chosen as a method to machine tungsten carbide in this study.

Although many studies have been conducted on EDM of tungsten carbide [1-4], investigations on the machining characteristics namely, sparking gap (Gap), cutting speed (CS) and microstructure of machined surface of tungsten carbide are still lacking. Hence, this study was attempts to investigate the effect of wire EDM parameters on the machining characteristics of tungsten carbide. The machining parameters are the input parameters of EDM process, namely voltage, peak current, pulse duration and interval time, which is believed have great influence to EDMed surface. Classical Design of Experiment (DOE) is used to investigate the effect of machining variables and to establish the relationship of certain responses.

II. METHODOLOGY

In this investigation, series of experiments on EDM of tungsten carbide were conducted on a Sodick WEDM 5-axis series AQ537L machine. The tool electrodes were made of brass wire with a combination of copper and zinc which is typically alloyed in the range of 63%-65% Cu and 35%-37% Zn. The workpiece was tungsten carbide of ISO Standards K-grade with the composition of 85% tungsten and 15% cobalt content. The specification of tungsten carbide used in this study is given as in Table 1. The size of tungsten carbide workpiece initially was a rectangular plate with dimension of 100mm x 50mm x 15mm. Then the workpiece material was cut to size using wire cut machine for 5mm length with the gap between two cutting experiments is 4mm (refer Figure 1). The spark gap was then measured using a Zeiss Axiotech High Power Optical Microscope with 100x magnification. The dielectric fluid used in the experiments was deionized water with the setting flushing pressure of 45 bar. As for the WEDM parameters, the peak current was from 10A to 15A, the pulse duration was from 2μs to 6μs, the pulse interval was from 24μs to 40μs and the servo voltage was from 15V to 48V.

In order to examine the microstructure of tungsten carbide after undergone WEDM operations, the workpiece was cut into smaller size of approximately 15mm x 3mm x 2mm, so that the section of the EDMed surface layer was revealed. The cut surfaces were then sanded with emery papers of reducing grain sizes. The sand paper grade used to grind the machined surface is 240, 320, 400, 600, 800, 1000 and 4000. This was followed by polishing with alumina (Al^2O^3) solution and etching under boiling condition. The cut surface morphology was then ready to be examined with SEM (Philips XL40) using different magnifications to investigate how its structure might be altered during the WEDM processes. The workpiece specimens were also subjected to energy dispersive X-ray (EDX) to examine the different of its structure composition before and after WEDM machining.

Table 1: Grade specifications of the workpiece.

Composition of the work piece	85%W, 15%Co
Grade (ISO Standard)	K grade
Grain size	Sub-micron (0.8μ)
Rockwell Hardness (HRC)	89.1-90.5
Transverse Rupture Strength (1000 psi)	600
Compressive Strength (1000 psi)	650
Application	Excellent wear/ edge strength

Figure 1: The diagram of work piece after cutting using WEDM.

III. RESULTS AND DISCUSSION

In this study, randomization of the run order to be carried out and analysis sequences were done according to the run order generated in the Design Expert software. The design of experiment chosen in this investigation was full factorial design of four factors with two levels each, consisting 16 runs plus four center points which gave the total number of runs are 20 trials. The machining responses that will be analyzed in this section were sparking gap (Gap) and cutting speed (CS). As mentioned easier, Design Expert software was used to analyze the results obtained in order to identify the significant factors and interactions between the factors that have been studied. Analysis of variance (ANOVA) table is commonly used to summarize the experimental results. These tables conclude information of analysis of variance and case statistics for further interpretation. The interpretations were done unilaterally, meaning that ANOVA analysis for all two responses was done separately at one time.

A. Analysis Results for Sparking Gap, Gap

Based on the analysis results obtained from the Design Expert software, it was obvious that pulse on was the only main effect factor which significantly influenced the WEDMing accuracy of the Gap. From Figure 2, pulse on (ON) showed an interesting plot with an increment of 41.3% as it increased from 2 μs to 6 μs. Based on the previous research, it is also expected that the sparking gap will keep on increasing if the range of pulse on is widen. Meanwhile, servo voltage (SV) seemed to be slightly increased as the setting increased from 15 volt to 48 volt. However, the increment was not high, since it is only 4.6%. This clearly has showed that the correlation of SV to Gap was not strong and significant when compared to pulse on.

Figure 2: Main effects plot of Gap.

However, based on interaction graph as shown in Figure 3, it was understood that generally Gap is rapidly increased when both factors were increasing simultaneously. The highest value of Gap was achieved when ON and SV were set up at 6μs and 15v respectively. The increment experienced by Gap was approximately 55%. This is due to when the smaller value is set for SV, the narrower the Gap will becomes which consequently leads to the increment number of electrical sparks. As the number of electrical sparks increased, the higher voltage power is supplied therefore, the larger Gap will be obtained. Although by applying the smaller value of SV can increased the machining rate but this condition may leads to machining state at the gap become unstable and later resulting in wire breakage. In directly, this condition has explained why the minimum value of Gap is obtained when ON = 2μs and SV = 15v.

As all the significant factors have been identified, the optimum parameters can be determined using the software in order to obtain the minimum value of the Gap. As the results, the margin error for all the experimental tests was acceptable because they were all less than 10% of allowable margin error (refer Table 2).

Figure 3: 3D interaction of ON*SV for Gap.

Table 2: Comparison test results for Gap.

No. of confirmation run	Prediction (Design	Experimental (Confirmation Test)	Error Margin (%)

	Expert)		
1	0.043	0.042	2.33
2	0.043	0.046	6.98
3	0.043	0.047	9.30

B. Analysis Results for Cutting Speed, CS

Results in Figure 4 showed that cutting speed, CS was affected by pulse on (ON), pulse off (OFF), peak current (IP) and servo voltage (SV). Based on the graph, CS increased dramatically from 0.5862 mm/min to 0.7716 mm/min as ON increased with approximately 32% of increment. So as IP, a slight increment of CS occurred when IP increased from 10 A to 15 A with percentage of 2.4%. Meanwhile, CS decreased as OFF and SV increased to 15% and 29.5% respectively. In this graph, SV indicated significant reduction of CS when SV managed to reduced CS from 0.7692 mm/min to 0.5938 mm/min. Since ON and SV showed the higher percentage compared to the other two factors, these factors can be considered to have more significant to the CS. Based on these relationship, maximum CS can be obtained at set up of ON = 6μs, OFF = 24μs, IP = 15A and SV = 15volt. For further analysis on this effect, the 3D interaction plot is used in this study as shown in Figure 5 to 7.

Figure 4: Main effects plot of CS.

According to Figure 5, increasing ON and SV improved the CS dramatically from 0.4413 mm/min to 0.7463 with the percentage increment of 70%. Increasing pulse on time means that the time for material removal is increased hence improving the CS. Although by setting SV at the high level decreased the electric sparks and slowed down the machining rate, the electric discharge was able to be stabilized when high level of pulse on time was applied. Although the graph indicated that CS increased rapidly when setting ON to 6μs and SV to 48v, it is not the highest CS achieved. Based on the graph given, the highest CS recorded for this interaction was 0.7983 mm/min with the setting parameter at 6μs and 15v for ON and SV respectively. This phenomenon occurred due to the longer machining time took place when ON increased and the increment of electric sparks and machining rate as SV increased. Therefore, the ideal solution for maximizing CS was to select high level of ON and low SV. However, too low setting for SV may cause the state of machining at the gap become unstable and resulting in wire breakage.

Figure 5: 3D interaction plot of ON*SV for CS.

Second interaction that have significant effect to CS, is interaction between OFF*SV. By increasing OFF and SV, the CS is slowed down by 7.4% and 25.2% respectively. Analogously, higher OFF caused less time for machining and slowed down the CS. This is because during pulse off time (OFF) the operating impulse is switched off and no current flow at this stage. Therefore, too long off time increased the machining time and reduce the CS simultaneously. Meanwhile, the higher SV able to low the machining rate thus, reduced the CS. Furthermore, since tungsten carbide has a very high melting and evaporation points with respectively, 2800 ºC and 6000 ºC [4], increasing the SV will only deteriorated the speed and even surface finish due to localized sparking and double sparking. However, too low value for SV resulting in wire failure thus, for better CS, OFF should be set at low level compatible with SV range.

Figure 6: 3D interaction plot of OFF*SV for CS.

Lastly is the analysis of interaction plot between ON*OFF for CS. Based on Figure 7, it was obvious that high CS can only be achieved by setting ON and OFF at the high level. This condition able to maximized the time for machining and consequently increased the CS. Although in general, increased OFF will reduce CS, but to set the sufficient pulse off time is important in speed of cutting operation. This is due to insufficient off time can lead to erratic cycling and retraction of the advancing servo, thus slowed down the operation cycle [2]. Therefore, it is important to set the off time at the compatible setting in order to stabilize the machining process and achieved the optimum CS.

As in previous response, after the optimum settings have been selected, confirmation runs for CS can be conducted. The results obtained from three trials of confirmation tests were all accepted as their values were less than

10% of the allowable margin error (refer Table 3).

Figure 7: 3D interaction plot of ON*OFF for CS.

Table 3: Comparison test results for CS.

No. of confirmation run	Prediction (Design Expert)	Experimental (Confirmation Test)	Error Margin (%)
1	0.7689	0.7963	3.56
2	0.7672	0.7243	5.59
3	0.7321	0.7134	2.55

C. Microstructure of the Machined Surface

The microstructures of WEDMed surfaces under different peak currents and pulse on are show in Figure 8 and 9. Under the lower peak current of IP = 10A and lower pulse on, ON = 2µs, there was no significant difference in the microstructures between the surface layer and those below it, as shown in Figure 8. While, under the higher peak current of IP = 15A and higher pulse on, ON = 6µs, the surface layer up to a depth of about 15µm was of a looser microstructure with shallow craters, voids and globules of debris on the machined surface, as shown in Figure 9.

It can be seen from the SEM micrographs that in cases under heavy WEDM conditions, there was a clear WEDM damaged layer on the machined surface, distinguished by the amount of WC grains and microstructures. The WC grains are sparsely distributed in the damaged layer caused by WEDM. Many of them must have been dislodged during the WEDM process.

Figure 8: Scanning electron micrograph showing the cross-sectional view of the microstructure of the WEDMed surface layer, under WEDM conditions: peak current, IP = 10A and pulse on, ON = 2µs.

Figure 9: Scanning electron micrograph showing the cross-sectional view of the microstructure of the WEDMed surface layer, under WEDM conditions: peak current, IP = 15A and pulse on, ON = 6µs.

From the examination of the WEDMed surfaces, it was observed that the machined workpiece surface texture after undergone WEDM operations became rougher and covered by shallow craters, globules of debris and pockmarks formed by entrapped gases escaping from the re-deposited material, as shown in Figure 10 and 11.

Figure 10: SEM micrographs showing molten material solidified on the WEDMed surface.

Figure 11: SEM micrographs showing pockmarks and voids on the WEDMed surface.

The compositions of the WEDMed surfaces also were examined by using EDX. Figure 12 showed that two additional elements, copper (Cu) and Zinc (Zn), were detected in the recast layer, on which EDX analyses were conducted. This can be explained by melting and resolidification of the brass wire electrode during WEDM spark erosion. The presence of oxygen in the recast layer probably due to oxidation occurred as the result of high temperature involved in the process.

For comparison, EDX analyses were also conducted on a workpiece surface before undergone WEDM process, as shown in Figure 13. It was found that there was no presence of Cu or Zn observed on the work material surface before undergone WEDM process. This is because the main elements of tungsten carbide normally contain tungsten (W), carbon (C) and cobalt (Co) [5].

Figure 12: EDX analysis result for recast layer (after WEDM process).

Figure 13: EDX analysis result for tungsten carbide workpiece surface before undergone WEDM process.

IV. CONCLUSIONS

It can be concluded from this study that:

1) In order to gain minimum Gap during WEDMing tungsten carbide, the setting parameters should be set up to low level for both significant factors namely, pulse on and servo voltage. The lowest Gap can be obtained from this setting was 0.0428 mm. It is important to ensure that both factors were set at the compatible setting due to improper setting of pulse on and servo voltage may leads to wire breakage thus, increased the machining time and production cost.

2) It was also observed that with longer pulse on and peak current, together with low setting level for pulse off and servo voltage, tends to increase the CS. The maximum CS achieved in this study was 0.8081 mm/min as the setting for pulse on, pulse off and servo voltage was set at 2 µs, 24 µs and 15 volt respectively.

3) It has been observed that the WEDM conditions have no effect on the microstructures of the workpiece material below the WEDM damaged layer. This means that WEDM causes damages on the WEDMed surface is limited to a certain depth only.

5) However, it has also been observed that the depth of the damaged layer increase with the peak current and pulse on. The damaged layer is minimized when the peak current and pulse on are set at low levels.

4) The margin error obtained from all responses studied in this research work were all accepted as the results indicated lower than the allowable set of margin error. In this case, the margin error was set below than 10%.

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REFERENCES

1] Mohd. Amri, L. (2002). “Study on Machining Parameters Optimization in EDM of Tungsten Carbide Using the Taguchi Method.” Universiti Teknologi Malaysia: Master Thesis.
2] Lee, S.H. and Li, X.P. (2001). “Study of the Effect of Machining Parameters on the Machining Characteristics in Electrical Discharge Machining of Tungsten Carbide.” Journal of Materials Processing Technology. 115: pg. 344-358.
3] Llanes, L., Idanez, E., Martinez, E., Casas, B. And Esteve, J. (2001). “Influence of electrical discharge machining on the sliding contact response of cemented carbides.” International Journal of Refractory Metals and Hard Materials. 19: pg. 35-40.
4] Mahdavinejad, R.A. and Mahdavinejad, A. (2005). “ED machining of WC-Co.” Journal of Materials Processing Technology. 162-163: pg. 637-643.
5] Fadi Namaan, A. N., Mohamed Abdullah, B., Sherif, S., Moataz, M. A. and Haitham, A. (1998). “High Performance Ceramics”. Engineering Department Unit: Engineering Materials. USA: Cairo.