STUDY OF THE SURFACE INTEGRITY OF THE MACHINED WORKPIECE IN THE WEDM OF TUNGSTEN CARBIDE

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ABSTRACT

This paper presented a study on the surface integrity of the machined surface of tungsten carbide (WC-15%Co) using wire electro-discharge machining (WEDM). WEDM tests on a WC-15%Co workpiece were conducted on a Sodick WEDM 5-axes series AQ537L, with the pulse duration (ON), pulse interval (OFF), peak current (IP) and servo voltage (SV) varied. The WEDMed surface roughness and thickness of recast layer were examined with a Scanning Electron Microscope XL40. The Full Factorial Design of Experiment (DOE) approach with two-level was used to formulate the experimental layout and to evaluate the effects on two machining responses consisting of surface roughness and thickness of recast layer. It is found that pulse duration has appeared to be the significant effect to both responses. It is also observed that there was almost no presence of microcracks in this study. The recast layer has distinguished microstructure from its parental material which consists of a lot of pockmarks, voids and globules of debris on its surface. Based on the observation done, the WEDM conditions have no effect on the microstructure of the bulk workpiece material. This means that damage caused by WEDM on the WEDMed surface is limited to certain depth only. Overall, the results showed that the thickness of recast layer and surface roughness of machined surface were improved when pulse duration and peak current were set at low values.

Keywords: Tungsten carbide, WEDM, surface integrity, DOE

INTRODUCTION

Wire electro-discharge machining (WEDM) is a specialized thermal machining process capable of accurately machining parts with varying hardness or complex shapes, which have sharp edges that are very difficult to be machined by the main stream machining processes. Since the introduction of the process, WEDM has evolved from a simple means of making tools and dies to the best alternative of producing micro-scale parts with the highest degree of dimensional accuracy and surface finish quality. Some of the common applications of WEDM are including the fabrication of the stamping and extrusion tools and dies, fixtures and gauges, prototypes, medical parts and so on [1]. However, further improvements are still required to meet the increasing demand of product precision in those sectors of manufacturing.

Recently, this process is significantly used in producing punches, mould and dies for production of high quality and high accuracy parts which made of carbide (WC-Co) material [2]. Therefore, the results in achieving good surface quality of WEDMed surface have become the most desirable performances in this process. During the WEDM process, both workpiece and the tool undergo surface modification. Many researchers [3-12] have looked at the modification of steel workpieces, but few have examined the modification of the tungsten carbide materials. The plasticity of tungsten carbide is high and in comparison with steel, its modulus of elasticity is three times greater [13].

In this study, a full factorial design with two-level was selected with the aid of the DOE of WEDMing of tungsten carbide using brass wire. DOE is a powerful analysis tool for modeling and analyzing the influence of process variables over some specific variables. This approach was used to determine the significant WEDM process variables which affecting the responses such as surface roughness and recast layer, under a wide range of machining conditions. The insignificant variables will be identified and will be segregated but are not considered during actual or confirmation experiments.

METHODOLOGY

1.1 Experimental set-up

During this study, a series of experiments on WEDM of tungsten carbide was conducted on a Sodick 5-axes machine series AQ537L to examine the effects of input machining parameters such as the pulse duration (ON), pulse interval (OFF), peak current (IP) and servo voltage (SV), on the surface roughness and thickness of recast layer. In the tests, surface roughness and thickness of recast layer were measured using different techniques and equipments.

1.2 Machine tool

The Sodick 5-axes series AQ537L machine is a wire-cut machine manufactured by Sodick Technologies. The dielectric fluid used in the experiments was deionized water with the flushing rate remain constant for all the tests conducted.

1.3 Workpiece material

The workpiece material used in this study was tungsten carbide with composition of 85% tungsten and 15% cobalt content. The size of tungsten carbide workpiece initially was a rectangular with dimension of 100mm x 50mm x15mm. The properties of workpiece are shown in Table 1.

1.4 Electrode material

The tool electrode used in this research was brass wire (hard brass) with 0.2mm diameter. The composition of the brass wire was 63% Cu and 37% Zn. For all the experiments on tungsten carbide were carried out using the same type of brass wire but with different machining parameters settings.

TABLE 1 Workpiece material properties.

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

1.5 Experimental procedure

In this investigation, randomization of the run order and analysis sequences were done according to the run order generated in Design Expert software. The Full Factorial Design of Experiment (DOE) approach was chosen with two-levels each, consisting of 16 runs with four center points added which gave the total of 20 runs all together. The setting of the machining parameters used to run the 24 trials are shown in Table 2.

After WEDM operations, the machined surface were cut into small parts perpendicular to the EDMed surface using the same wire-cut machine. This is to reveal the section of EDMed surface layer for measuring the surface roughness and thickness of recast layer. The machined surface roughness was then measured using Mitutoyo Formtracer CS-5000 and the other cut surfaces were then sanded with emery papers of reducing grain sizes. 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 using SEM (Philips XL40) at different magnifications to determine the width of damaged layer caused by WEDM. The workpieces were also subjected to energy dispersive X-ray (EDX) to investigate their structure composition that might be altered during WEDM process.

TABLE 2 The machining parameters and their levels.

Machining Parameters	Levels	
	1	2
	Low	High
Pulse Duration, A (μs)	2	6
Pulse Interval, B (μs)	24	40

Peak Current, IP (ampere)	10	15
Servo Voltage, SV (volt)	15	48

RESULTS AND DISCUSSION

In this study, the machining responses that were analyzed were surface roughness (Ra) and recast layer (RL). As mentioned earlier, 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.

2.1 Effect on Surface Roughness (Ra)

Based on the analysis results obtained from the Design Expert software, pulse on (ON) and servo voltage (SV) were the main factors that affecting the Ra. According to the analysis conducted in this study, Ra was increased rapidly with the increment of pulse on while, the servo voltage affect the Ra in the inverse relation.

FIGURE 1 Main effects plot of Ra.

As shown in Figure 1, it was clearly indicates that whenever ON increased from 2 μs to 6 μs, the value of Ra also increased dramatically. The projecting increment of Ra is approximately 14%. Meanwhile, opposite manner was observed for SV effect as the graph showed that Ra decreased when SV increased from 15 volt to 48 volt. The decrement that Ra experienced is about 13.1% when SV is setting at 48 volt. Based on the ANOVA analysis, ON and SV were affecting Ra individually without any interaction with other factors. From the correlations obtained in this investigation, judgement in terms of selecting the most suitable settings for both ON and SV for future optimization can be made. Therefore, in order to get better Ra during machining, ON should be set at 2 μs while SV at 48 volt.

From the examination of WEDMed surfaces that conducted in this study, the surface topography reveals that Ra was caused by an uneven fusing structure, globules of debris, shallow craters, pockmarks and voids. These effects might become more pronounced as the ON increase and SV decreased as shown in Figure 2 and Figure 3. This phenomenon can be explained due to the fact that as the SV decreases, electric discharges will strike the surface of the workpiece more intensely, and resulting worsened erosion effect which leads to deterioration of the surface roughness. Furthermore, as the pulse on increases, the amount of heat transferred to the machined surface also increases and consequently more material will melts. As mentioned before, Ra might become worst if the molten material is not swept away from the surface by the dielectric fluid because later, it will solidify during cooling process on the machined surface and form a white layer which also known as recast layer. The effect of this white layer also contributes in increasing the Ra.

FIGURE 2 SEM micrographs showing globules of debris and pockmarks on WEDMed surface of tungsten carbide. Conditions: pulse on, ON = 2 μs and servo voltage, SV = 48 V.

FIGURE 3 SEM micrographs showing shallow craters and voids on WEDMed surface of tungsten carbide. Conditions: pulse on, ON = 6 μs and servo voltage, SV = 15 V.

2.2 Effect on Recast Layer (RL)

The results obtained from the ANOVA analysis clearly showed that the most significant factor in affecting recast layer (RL) was pulse duration (ON) and followed by peak current (IP). As shown in main effect plotted graph (refer Figure 4), the thickness of RL increased when both factors, ON and IP were directly increased. Beside these two factors, there were also other factors that greatly influenced the thickness of RL (refer Figure 5 and Figure 6).

FIGURE 4 Main effects plot of RL.

FIGURE 5 3D interaction plot of OFF*IP for RL.

FIGURE 6 3D interaction plot of ON*OFF for RL.

According to Figure 5, when OFF was set up at low level, the thickness of recast layer achieved to the maximum thickness as IP was set at higher level. However, when OFF increased to 40 µs, the thickness of RL decreased to 26%. This happened probably because of the setting for off time was too short, and so disintegrated particles from the gap between the electrode and workpiece were not able to remove sufficiently during the cutting operation. Therefore, these particles will stick to the machined surface and later formed into recast layer as more particles melts and stick on the cutting area. Furthermore, the higher discharge current applied, the higher will be the material removed but the thicker recast layer will be. That is why usually very high currents are not used as they often lead to heat damage of the workpiece and increased the depth of recast layer. Thus, in this case, to obtain the minimum thickness of RL, IP should be set to low setting compatible with OFF. As observed in Figure 6, it clearly showed that thickness of RL is mainly influenced by ON, as RL has increased rapidly when ON increased. This is explained by the fact that the more heat is transferred into the workpiece as ON increased, the harder for dielectric fluids to clear away the molten material, thus it builds up upon the machined surface of the workpiece during cooling period [11].

Generally, recast layer is considered as machining damage zone of microscopic defect [13, 14]. This is due to most of the defects such as shallow craters, voids, microcracks and globules of debris were observed in the recast layer. As shown in Figure 7, it was clear that recast layer has distinguished microstructure from its parental material and consist a lot of pockmarks and voids on its surface. It is also observed that damage caused by WEDM conditions have no effect on the microstructures of the bulk workpiece material. In the other words, RL was occurred within limited depth only. The overall thickness of RL examined in this experiment for 20 specimens are varies from 5 to 15 µm.

FIGURE 7 SEM of recast layer after undergone WEDM process.

For further analysis, energy disperse X-ray diffraction (EDX) was used to identify and analyzed the material compositions of the RL as shown in Figure 8. From the EDX analysis, it's showed that two additional elements, copper (Cu) and Zinc (Zn), were detected in the recast layer. 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. The same results was also obtained by Jun Qu et al. [15] when they examined the machined surface of tungsten carbide using the same equipments.

FIGURE 8 EDX analysis result for recast layer (after WEDM process).

CONCLUSIONS

An extensive experimental study has been conducted to investigate the effect of the machining parameters on machining characteristics in WEDM of tungsten carbide. The machining parameters are the pulse duration (ON), pulse interval (OFF), peak current (IP) and servo voltage (SV). While, the machining characteristics are the surface roughness (Ra) and recast layer (RL). Tentatively, the following conclusion may be drawn from the study.

1. Pulse on time (ON) was appeared to be the main effect for all two responses investigated in this study. This means that, ON is the most significant and dominant factor than other factors in affecting the machining characteristics such as Ra and RL. Thus, in order to minimize Ra when machining tungsten carbide, one can employ low pulse on and high servo voltage with respective, 0.2 µs and 48 volt. The results obtained from this investigation also reveals that Ra normally caused by an uneven fusing structure, globules of debris, shallow craters, pockmarks and voids. These effects become more evident when ON increased and SV decreased.
2. From the experimental results, the most significant factor for RL was pulse on, pulse off and peak current. The optimum condition for RL in order to minimize the thickness is, pulse on, pulse off and peak current should be set at 2 µs, 24 µs and 10 A. It as observed that thickness of RL rapidly increased when pulse on increased while pulse off decreased. This happened due to dielectric fluids could not flushed away the molten materials sufficiently, which later it builds up and resolidified on the machined surface during cooling period. Recast layer also contributed to the surface roughness during machining tungsten carbide.
3. Generally, recast layer known as the machining damage area because all the surface defects usually occurred within this limited depth of recast layer thickness. The defects such as shallow craters, voids, microcracks, pockmarks and globules of debris were more evident at higher peak current, pulse on and servo voltage, with low pulse off time. However, peak current is appeared to be the most dominant factor in affecting the thickness of RL.

ACKNOWLEDGEMENTS

I would like to express my deepest, sincerest gratitude to my supervisor of this project Associate Professor Hamidon Musa and Associate Professor Dr Safian Sharif for their guidance and advice. Very special thanks dedicated to my family members for always believing in me and continuously supporting me

throughout this research. Less but not least, I would also like to thank for those who have contributed directly or indirectly towards the success of this research study.

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