Contents

Abstract

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Micro electrical discharge milling (ED-milling) is an effective process for machining of micro structures on hard metals. This method of machining generally uses kerosene or deionized water as a dielectric fluid, both of which are associated with some problems. Kerosene results in considerable electrode wear and deionized water causes electrolytic corrosion in workpiece. Cobalt-bonded tungsten carbide (WC-Co) has been recently used in many industry areas because of its superior mechanical characteristics such as high strength and wear resistance. However, it is difficult to machine WC-Co due to its characteristics. Moreover, it is impossible to make micro-sized figures on WC-Co workpiece using conventional machining methods. In this study, micro ED-milling was carried out using only bipolar pulsed power source to prevent electrolytic corrosion and electrode wear without additional methods. WC-Co was used for the workpiece and micro grooves were machined on the WC-Co workpiece. As a result, optimal pulse condition capable of eliminating electrolytic corrosion is found through the experiments and practical ED-milling was carried out using this condition.

Keywords : Micro EDM, Tungsten carbide, Electrolytic corrosion, Electrode wear, Bipolar pulse

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Chapter 1

Introduction

1.1 Research background

Recently, micro technology is required for higher efficiency and accuracy in micro structure with various materials and applications. Most of all, cobalt-bonded tungsten carbide (WC-Co) has been recently used in many industry areas because of its superior mechanical characteristics such as high strength and wear resistance. However, it is difficult to machine WC-Co due to its characteristics. Moreover, it is impossible to make micro-sized figures on WC-Co workpiece using conventional machining methods [1,2]. Of the micro non-conventional machining methods, electrochemical machining (ECM) and electrical discharge machining (EDM) have been typically considered as machining process. Micro ECM is not concerned with electrode wear, but machining speed is very slow. On the other hand, machining speed of micro EDM is faster than that of ECM, but electrode wear and electrolytic corrosion can occur during the machining. Dielectric fluids of micro EDM are classified with kerosene and deionized water, and these are one of the major factors which are affecting the machining results. When kerosene is used, electrolytic corrosion does not occur on a workpiece, but material removal rate is low and shape error occurs due to electrode wear. In comparison with kerosene, deionized water has advantages of fast machining speed and low electrode wear rate, but electrolytic corrosion occurs due to deionized water and power source. In micro EDM with WC-Co, the research on the use of bipolar pulse to prevent electrolytic corrosion is previously studied as the resistivity of deionized water, and various shapes of electrode with bipolar pulse system were used to machine electrolytic-corrosion-free holes in micro electrical discharge drilling (Micro ED-drilling), and mist-shaped, which is the mixture of air and water, dielectric fluid with bipolar pulse system was used to machine electrolytic-corrosion-free groove in micro ED-milling [3-6]. There has been considerable study on electrolytic corrosion in wire EDM and ED-drilling, but very few attempts have been made to prevent electrolytic corrosion on the WC-Co material during electrical discharge milling with deionized water. Also, the previous studies were used to prevent electrolytic corrosion with bipolar pulsed power source and additional devices.

1.2 Research objective and thesis overview

In this study, micro ED-milling on the surface of WC-Co was carried out using only bipolar pulsed power source to prevent electrolytic corrosion and electrode wear without additional methods. As a result, optimal pulse condition capable of eliminating electrolytic corrosion is found through the experiments and practical ED-milling was carried out using this condition without additional equipment.

In chapter 2, principle of micro electrical discharge machining (Micro EDM) is described. Then, cobalt bonded tungsten carbide (WC-Co) is also presented. Unlike the conventional EDM, micro ED-milling using bipolar pulse system is investigated.

In chapter 3, machining results are investigated. In this experimental setup, important factors such as electrolytic corrosion, electrode wear and material removal rate are also presented. Also, to compare the machining difference, tungsten electrode is used and results are described.

Finally, conclusion of this thesis was presented in chapter 4.

Chapter 2

Principle and experiments

2.1 Micro electrical discharge machining (Micro EDM)

Micro electrical discharge machining (Micro EDM) is one of the non-conventional machining process. A schematic figure which illustrates the principle of EDM is shown in figure 2.1. EDM process is that discharge sparks occur between the electrode and the workpiece in a dielectric fluid such as kerosene or water. At first, when the distance between the electrode and the workpiece is closed and power supply system is connected, the dielectric breaks down at a gap of distance and a discharge spark occurs. In this condition, the workpiece can be melted the temperature from 3,000 ˚C to 12,000 ˚C. Next, the high pressure of the dielectric fluid which is also locally heated by the discharge spark removes the melted and vaporized material. The removed part on the surface of the material forms a crater by one discharge spark, and the discharge gap restores the insulated state. Consequently, the craters accumulated on the surface of micro structures and this process is the repetition of these subsequent procedures. When machining feedrate is faster than craters by discharge process and the gap distance between electrode and workpiece is closed to zero, electrical shorts occur and moves back and gap distance is increased. However, when the machining feedrate increases too much, the electrode can be broken.

CHAPTER 2. PRINCIPLE AND EXPERIMENTS

In micro EDM, two types of discharge circuits are generally used as a discharge pulse generator: transistor circuit (TR) and resistance-capacitance (RC) circuit as shown in figure 2.2. The advantage of TR circuit is that an independent power supply type can force to cut off the discharge energy for the fast recovery as a switch. Moreover, it is possible to modify the pulse duration and down time in order to increase the duty ratio. On the other hand, repetition of charging and discharging in RC circuit depends on the distance between the two electrodes. Therefore, it is difficult to insulation state or achieve high duty factor since this circuit cannot manage the discharge current. However, in order to adapt EDM process for micro scale, the RC circuit is more suitable than the transistor circuit because of its short pulse duration under 0.1 μs and relatively high peak current against the input voltage. Miniaturization of the tool electrode is also an important problem in micro EDM. In General, EDM process is classified as drilling and milling. In this study, micro ED-milling is investigated to fabricate micro groove or 3D structures.

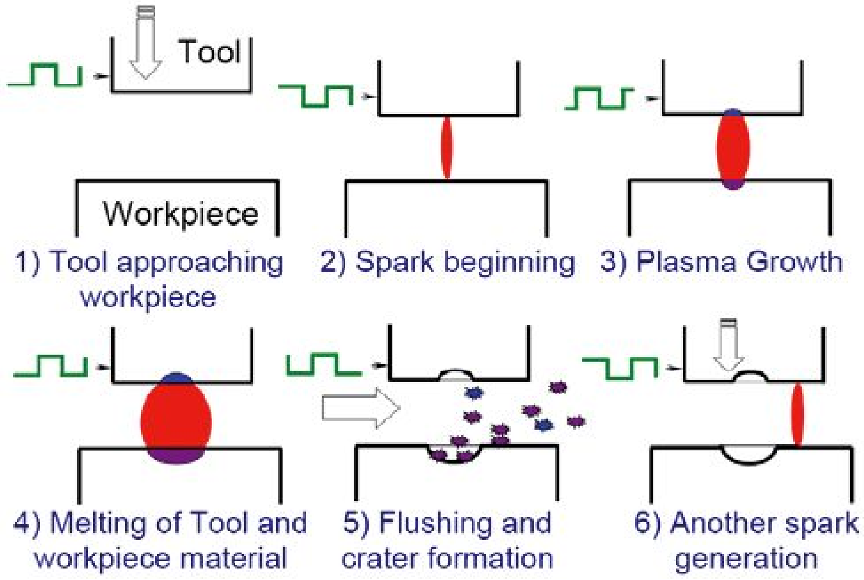


Figure 2.1 Principle of micro EDM process [7]

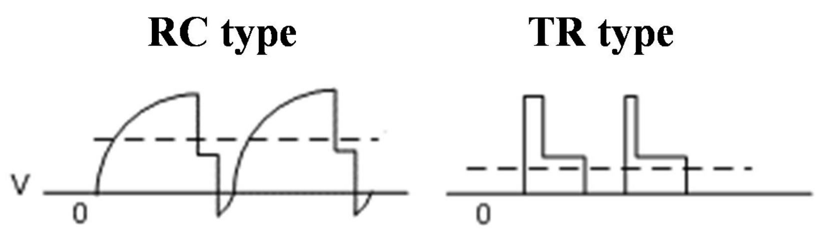


Figure 2.2 Discharge pulse types

2.2 Tungsten carbide with cobalt binder (WC-Co)

Tungsten carbide with cobalt binder (WC-Co) is one of extremely hard material which is used for various cutting tools and molds because of its high hardness and excellent wear resistance. Figure 2.3 shows that this material consists of WC-Co composition ranging from 3 to 30 % of Co matrix, and these properties which are 10.5 % Co workpiece and 13 % Co electrode are used in this study. WC-Co is usually produced by powder-metallurgy techniques. However, WC-Co is difficult to be machined with high accuracy by conventional machining processes. Generally, EDM process is one of non-conventional machining processes and widely used to machine hard material as shown in figure 2.4. In micro machining, micro EDM using kerosene is usually used to fabricate micro structures such as micro shafts, holes and 3D structures. WC-Co is based on the processing of two elements such as WC and Co which are different thermal characteristics. The cobalt matrix holding the tungsten particles has greater electrical conductivity than tungsten. Also, the melting point of tungsten carbide and cobalt is 2785~2830 °C and 1495 °C respectively. The cobalt binder has lower melting point and higher conductivity than tungsten carbide. Therefore, during EDM processes, the discharge energy removes the cobalt binder before melting of tungsten carbide. The EDM sparks tend to flow the tungsten particles and crash the cobalt binder. This procedure makes partially melted tungsten particles leave the surface, and tungsten particles are exposed to change the size and cause to failure problem.

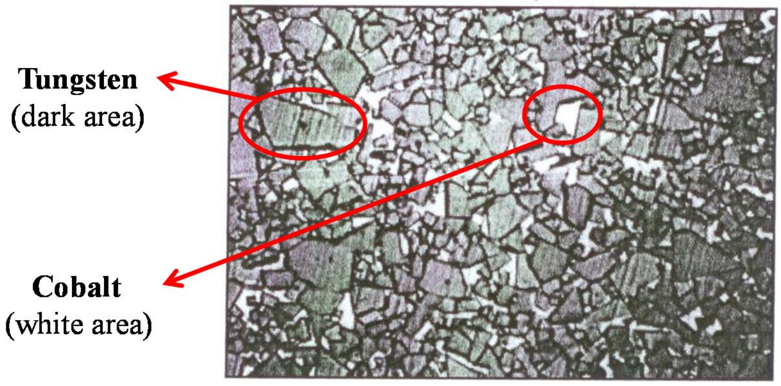


Figure 2.3 Schematic diagram of electrochemical reaction in WC-Co [2]

Figure 2.4 Example of micro WC-Co electrode using Wire EDM

2.3 Bipolar pulse

Figure 2.5 shows the example of bipolar pulsed circuit, and figure 2.6 shows the oscilloscope image of bipolar pulsed voltage condition : (+50 V, -15 V). To reduce electrolytic corrosion on the workpiece, a bipolar pulsed power source was used instead of a dc power source with the water-jet type of ED-milling. In the conventional EDM types, average voltage, which means the voltage level per one pulse, is higher than zero voltage due to the shortage of negative voltage level. On the other hand, the bipolar pulsed voltage type makes average voltage zero level, and does not make reverse-discharge sparks, although this power generator has both positive and negative voltage levels. In other words, the positive voltage level is high enough to make discharge sparks for machining but the negative voltage level is too low to discharge. However, as shown in figure 2.7, since the period of the negative voltage is longer than the positive time, the average voltage between a workpiece and a tool electrode is almost zero. Therefore, electrolytic corrosion can be reduced. In addition, average voltage levels are calculated as shown in figure 2.8.

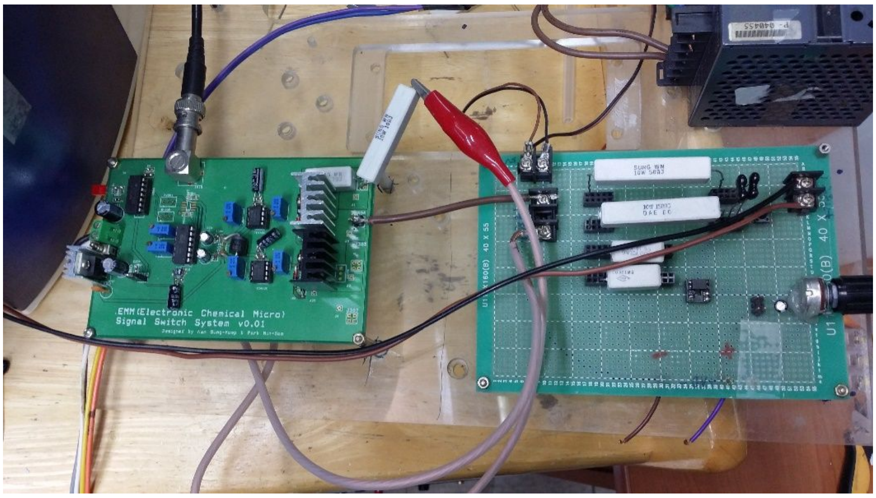


Figure 2.5 Bipolar pulse circuit

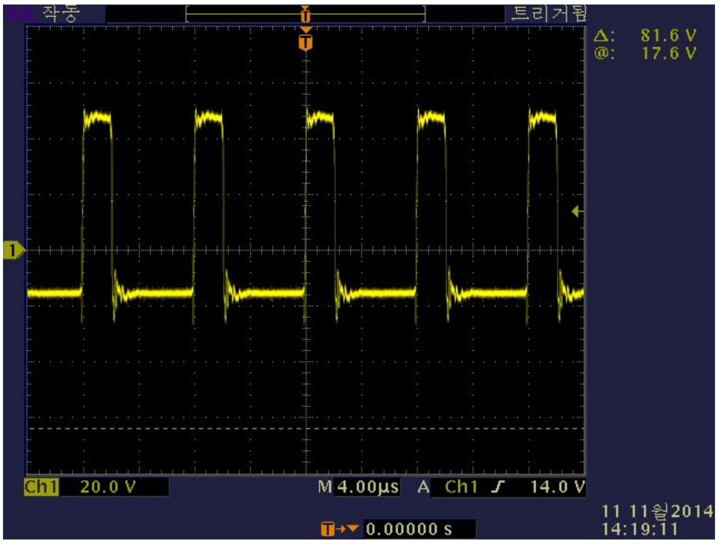


Figure 2.6 Oscilloscope image of bipolar pulsed voltage condition

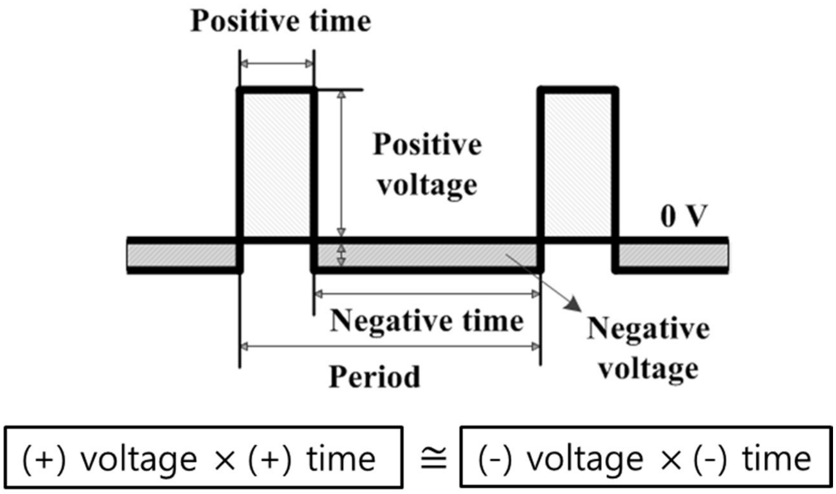


Figure 2.7 A merit of using bipolar pulsed voltage condition

		Negative voltage			
		0 V	-10 V	-15 V	-20 V
Positive voltage	40 V	10 V	2.5 V	-1.25 V	-5 V
	45 V	11.25 V	2.75 V	0 V	-3.75 V
	50 V	12.5 V	5 V	1.25 V	-2.5 V
	55 V	13.75 V	6.25 V	2.5 V	-1.25 V
	60 V	15 V	7.5 V	3.75 V	0 V

Figure 2.8 Average voltage calculation data

2.4 Deionized water

Generally, as a dielectric fluid in micro EDM, kerosene or deionized water is generally used in industrial fields. Kerosene is widely used in micro EDM as a dielectric fluid because it ensures a corrosion-free and high accuracy. However, it results in a low MRR, large electrode wear and unstable machining. On the other hand, deionized water can faster machining and lower tool wear, but the machining accuracy is deteriorated due to the electrolytic corrosion. Especially, tungsten carbide with cobalt binder (WC-Co) is suffered from the electrolytic corrosion severely in Eq.2.1 [3].

$$Workpiece : Co \rightarrow Co^{2+} + 2e^{-}$$

$$Working\ fluid : \frac{1}{2}O_2 + H_2O + 2e \rightarrow 2OH^- \tag{2.1}$$

Table 2.1 shows the properties of deionized water and kerosene. However, when a deionized water is used as a dielectric fluid, resistivity of deionized water should be constant level due to the difference of maintaining its resistivity with absorption of CO_2 from air and change of temperature [4]. Thus, during the machining process, small pump with water-jet nozzle is used for circulating the fresh water and maintaining high resistivity level. In this study, deionized water was used for micro ED-milling in order to a high machining efficiency with reducing electrode wear problem. Deionized water with high resistivity was obtained from a deionized water supplier (Simplicity, Millipore Corp.) as shown in figure 2.9, and the resistivity of water was measured by a resistivity meter (Alpha-RES 1000, Eutech instruments). This system produces Type 1 ultrapure water (18.2 MΩ·cm resistivity at 25 °C) on demand directly from potable tap water.

Table 2.1 Properties of deionized water and kerosene [7,8]

	Deionized water	**Kerosene**
Conductivity (μS/cm)	> 0.05	0.0017
Dielectric strength (MV/m)	13	14 ~ 22
Thermal conductivity (W/m-K)	0.606	0.149
Heat capacity (J/g-K)	4.19	2.16

Dynamic viscosity (g/m-s)	0.92	1.64

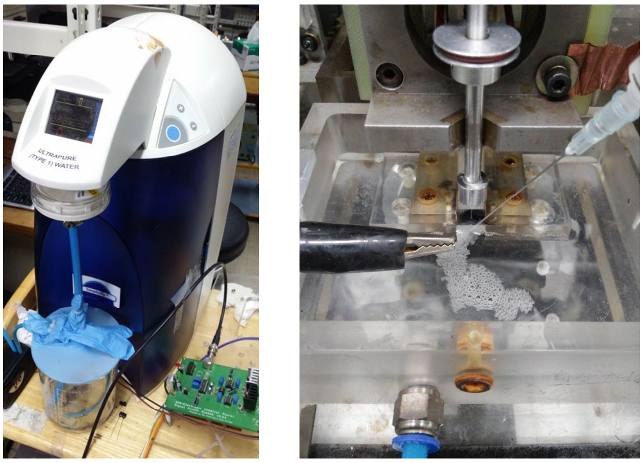


Figure 2.9 Type 1 deionized water and water-jet nozzle system

2.5 Experimental setup

The experimental systems containing wire EDM and micro ED-milling were constructed to control the rotation speed of an electrode and workpiece with precise location as shown in figure 2.10. Since a gap distance of the micro EDM process is about the range of several micrometers, a positioning and rotating system with a high accuracy is required. Also, fast responses with controlling position and rotation are also required because electrical short detection is operated by gap distance between an electrode and a workpiece.

Figure 2.11 shows a schematic system configuration of micro EDM, and figure 2.12 shows a schematic diagram of micro ED-Milling process using in this study. In this system, the Z stage is used for the tool electrode with vertical direction and the spindle rotation, and the X-Y stage is used for positioning the workpiece with horizontal direction. Work tank and tilting stage are equipped on the X-Y stage. The X-Y stage (315082AT, Parker Automation) and the Z stage (404200XR, Parker Automation) were used for three dimensional positioning which have 0.1 μm resolution. These stages are controlled by stepping motors (ZETA57-83, Parker Automation) and a programmable multi-axis controller (Turbo PMAC, Delta Tau) is used. Electrical and mechanical conditions in this experiment are shown in table 2.2.

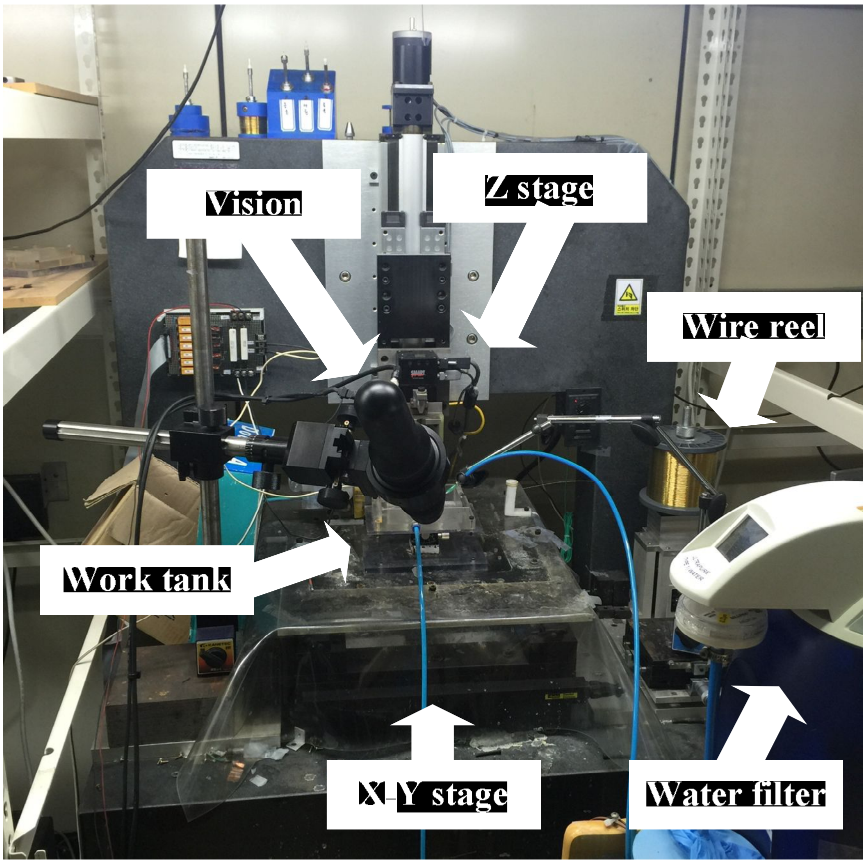


Figure 2.10 Micro machining system

Figure 2.11 Schematic system configuration of micro EDM

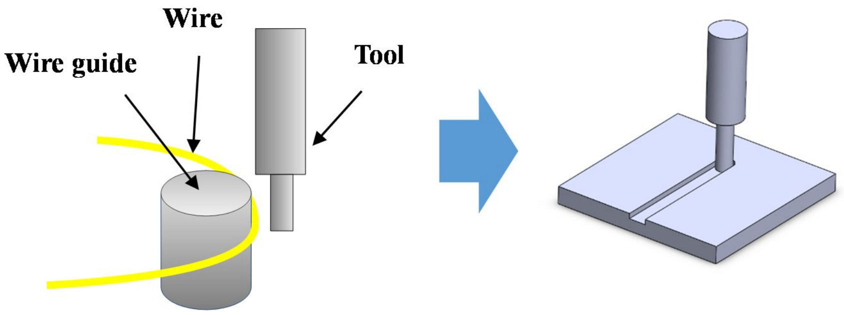


Figure 2.12 Schematic diagrams of micro ED-milling process

Table 2.2 Machining conditions using bipolar pulse

Electrical conditions	Frequency	125 KHz
	Capacitance	350 pF
	Duty factor	25%
	Positive duration	2 μs
	Negative duration	6 μs
Mechanical conditions	Workpiece	WC-Co (Cobalt 10.5 wt%)
	Electrode	WC-Co (Cobalt 13 wt%) Tungsten (W, 99.95 wt%)
	Electrode diameter	120 μm
	Depth of cut	30 μm
	Feedrate	3μm/s

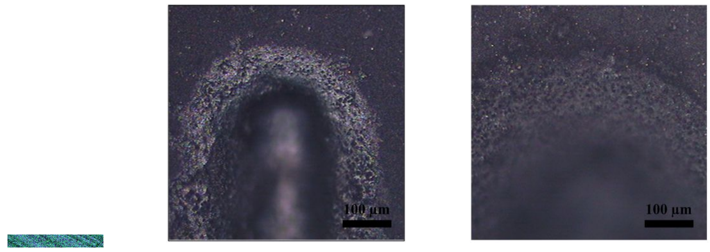
Chapter 3

Machining results

3.1 Electrolytic corrosion

Figure 3.1 shows the machining results with the DC power source. As a DC voltage increases in micro ED-milling process, the size of the electrolytic corroded zone is increased. Among the machining results, the maximum length of electrolytically corroded zone which refers to the maximum horizontal length in corroded zone is indicated in Figure 3.2 and 3.3. The length was measured by a microscope (Optiphot-100, Nikon Corp.) and calibrated measuring software (MVS-1000, SNU Precision Co., Ltd). The maximum length of electrolytic corrosion is within a 566 μm radius at 40 V and 652 μm radius at 70 V. In other words, as the voltage level is increased, the area of electrolytic corrosion increases. When the electrode and workpiece, which are sort of the electrode, are immersed in electrolyte, a very thin layer which is called the double layer exists at the interface between the electrode and the electrolyte. As voltage is applied between the two electrodes, the potential profile in the double layer becomes similar to the something of an equivalent circuit that consists of capacitors and resistors [9,10]. When a voltage is applied across two electrodes which are immersed in deionized water, electrochemical reaction occurs and a double layer which one layer is on the electrode side and the other is on the electrolyte was formed. It behaves as a two parallel plate capacitor. Thus, electric field was created at the inner area between an electrode and a workpiece, and it can influence the electrolytic corrosion.

Figure 3.4 shows the scanning electron microscope (SEM) images of machining results of WC-Co electrode under the bipolar pulsed power source; positive voltage is from 40 V to 60 V condition and negative voltage is from 0 V to -20 V condition. When the negative voltage condition is zero, electrolytic corrosion occurs not only on the edge of workpiece surface, but also on the machined surface with pausing electrical discharge. When the negative voltage condition is –20 V, the electrolyzation causes not only electrolytic corrosion, but also deteriorating degree of precise machining shape. Especially, in case of +40 V, -20 V voltage condition, a tool was severely worn out and machining process did not completed. In case of some experiments with WC-Co electrode, the milling process were not carried out to the end of machining due to the excessive short counts or severe electrode wear. Generally, as the positive voltage level gets increased at the same level of the negative voltage, the results of machined surface are gradually worse in terms of electrolytic corrosion. However, electrolytic corrosion gets less severe as the negative voltage level increases. However, as the positive voltage increases at the same negative voltage, the maximum length of electrolytically corroded zone is increased. In case of the same positive voltage, average voltage is decreased by improving the negative voltage. When the frequency and duty factor are fixed, higher voltage level is related to on-time discharge sparks. Therefore, the influence of electric field is magnified, and maximum length of electrolytically corroded zone is longer than that of low voltage level. To prevent this corrosion problem, the average gap voltage needs to zero for suppressing these electrochemical reaction. Figure 3.5 shows the comparison of maximum length of electrolytic corrosion according to average voltage. In this study, average voltage is calculated by multiplying positive and negative voltage level. The results show that as the average voltage is closed to zero, the tendency of maximum length of electrolytic corrosion is decreased.



(a) (b) (c)

Figure 3.1 Machining resu
deionized water: (a
+70 V

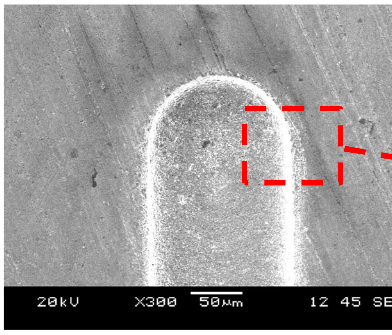


Figure 3.2 SEM image for me

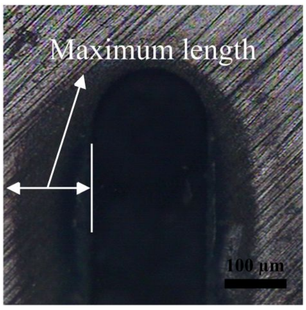


Figure 3.3 Example of maximum length of electrolytically corroded zone: tap water, (+40 V,-10 V)

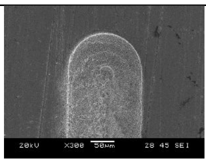
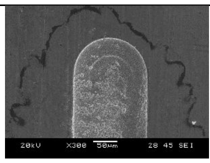
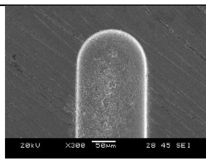
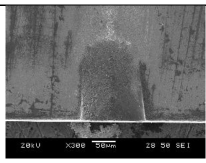
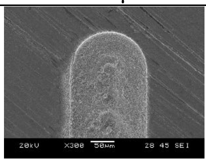
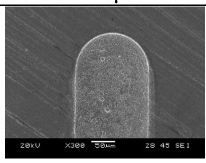
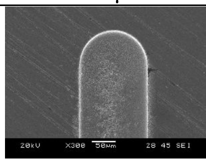
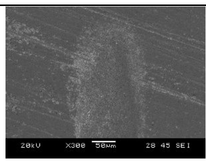
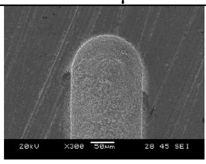
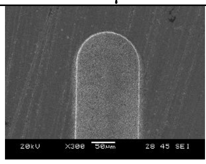
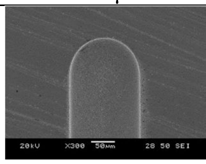
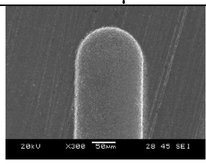
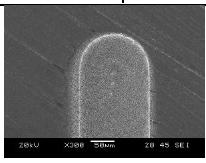
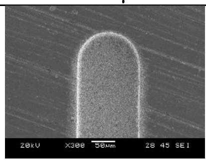
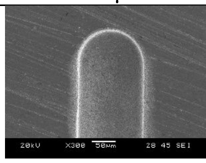
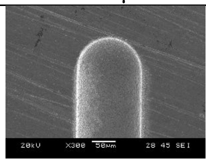
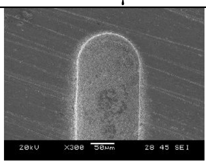
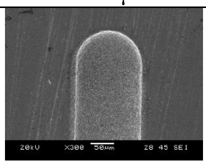
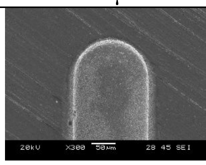
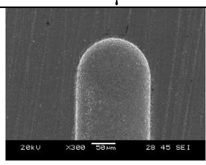
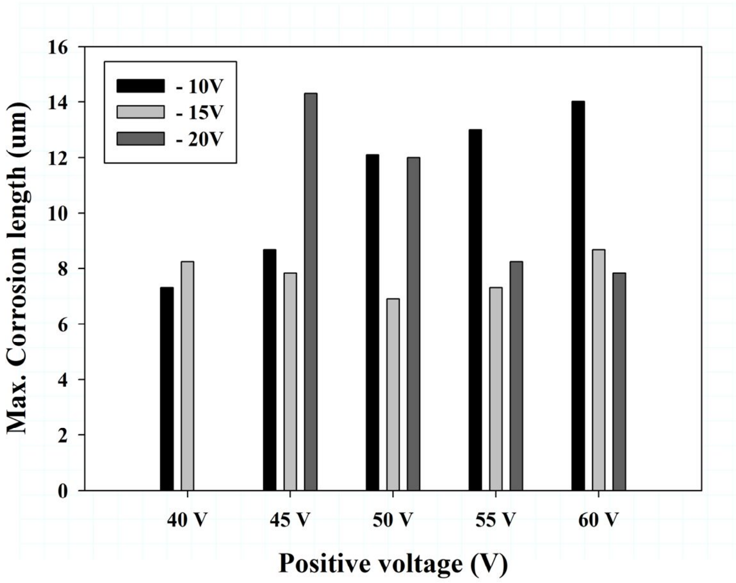
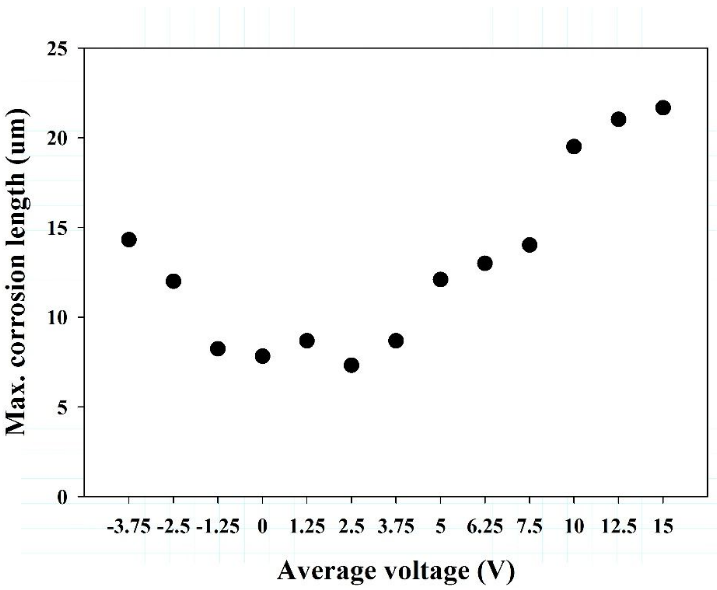
		(-) voltage			
		0 V	**10 V**	**15 V**	**20 V**
(+) voltage	**40 V**	 V_{avg} = +10 V, 19.50 μm	 V_{avg} = +2.5 V, 6.91 μm	 V_{avg} = –1.25 V, 8.24 μm	 V_{avg} = -5 V, inaccessible
	45 V	 V_{avg} = +11.25 V, 20.06 μm	 V_{avg} = +3.75 V, 7.32 μm	 V_{avg} = 0 V, 7.82 μm	 V_{avg} = -3.75 V, 14.31 μm
	50 V	 V_{avg} = +12.5 V, 21.02 μm	 V_{avg} = +5 V, 12.10 μm	 V_{avg} = +1.25 V, 6.91 μm	 V_{avg} = –2.5 V, 12.00 μm
	55 V	 V_{avg} = +13.75 V, 23.51 μm	 V_{avg} = +6.25 V, 13.00 μm	 V_{avg} = +2.5 V, 7.32 μm	 V_{avg} = -1.25 V, 8.24 μm
	60 V	 V_{avg} = +15 V, 21.67 μm	 V_{avg} = +7.5 V, 14.02 μm	 V_{avg} = +3.75 V, 8.68 μm	 V_{avg} = 0 V, 7.82 μm

Figure 3.4 SEM images of micro ED-milling with bipolar pulsed voltage conditions



(a)



(b)

Figure 3.5 Maximum length of electrolytic corrosion according to: (a) various voltage conditions, (b) average voltage conditions

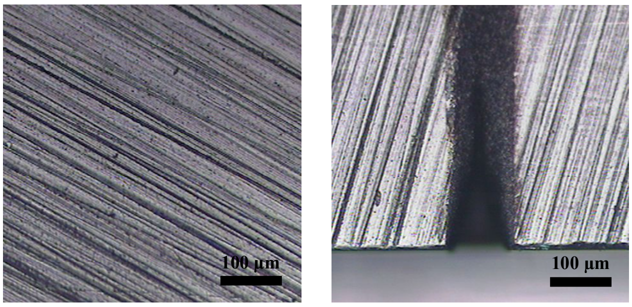
3.2 Electrode wear

Figure 3.6 shows the machining results of DC power source using kerosene as a dielectric fluid. In comparison with figure 3.1, electrode wear using kerosene was more severe than that of deionized water, and machining process could not be completed. The material removal is facilitated by melting and vaporization of the materials, and dielectric fluid carries out as a coolant for the electrode. By circulating the deionized water in micro ED-milling process with water-jet type, cooling and flushing effect are higher than that of kerosene.

In this study, electrode wear and electrolytically corrosion with bipolar pulsed power source are more alleviate than those of DC power source. However, electrode wear could occur in some occasions in the bipolar pulsed condition. Figure 3.7 and 3.8 show the wear of the electrode and workpiece after machining with bipolar pulsed condition under the +40 V, -30 V voltage and tap water condition. In this condition, both electrode and workpiece gradually decreased in width. The wear behavior of the electrode is influenced by the polarity except the specifications of the tool electrode material. Since the electrode wear rate is the ratio of the removed volume of the electrode, electrode wear with volumetric measurement was calculated to compare the differences of volumes before and after machining. Figure 3.9 shows the electrode wear ratio of negative voltage according to positive voltage in this experiments. By comparing machined volume with the workpiece and the electrode, electrode wear ratio is acquired and reduced comparing a DC power source with kerosene. Under the impact of negative voltage condition, wear of WC-Co electrode occurred considerably up to 96 % in the +40 V, -20 V condition.

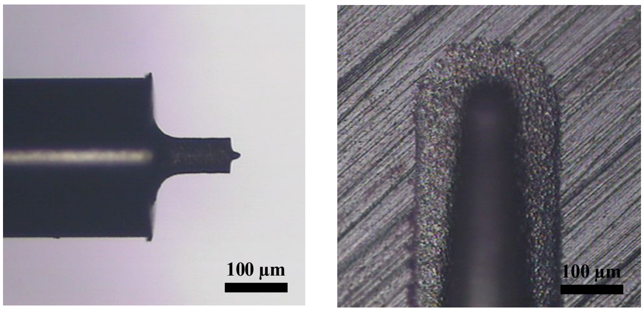
CHAPTER 3.2. ELECTRODE WEAR

As the level of positive voltage increased, electrode wear rate increased under -10 V voltage condition because energy of machining is increased. On the other hand, electrode wear decreases under -20 V voltage condition. Also, when the average voltage value approaches to 0 V, electrode wear rate is close to zero percent. It can be seen that electric field between electrode and workpiece occurs under the reverse voltage condition and these conditions affect a damaging electrode wear. Generally, discharge spark did not occur under – 40 V with positively charged electrode and a negatively charged workpiece since the average voltage level was not high enough to discharge between the electrode and workpiece. Electrode wear is caused to high-density electron impingement, thermal effect and mechanical vibrations. In these conditions, the electrons and negative ions strike the tool electrode surface and an electrode material with higher melting point wears less [11]. Hence, higher dimensional micro ED-milling accuracy can be acquired considering average voltage condition using bipolar pulsed voltage.



(a) (b)

Figure 3.6 Machining results in kerosene with the DC power source at 70 V: (a) Before, (b) After



(a) **(b)**

Figure 3.7 Electrode wear problem and workpiece after ED-milling

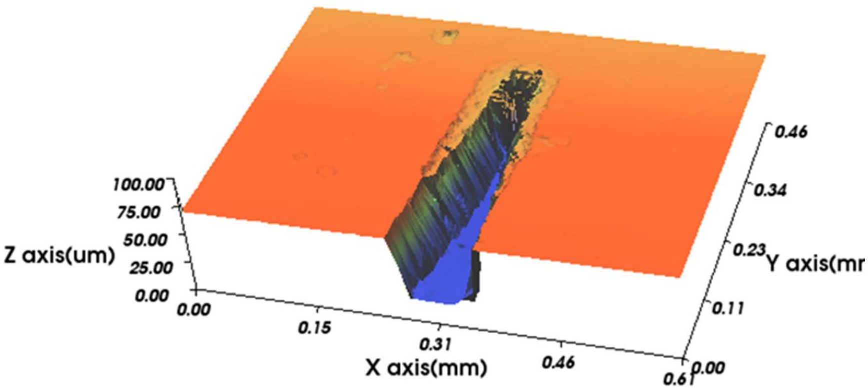


Figure 3.8 3D surface profile of electrode wear in workpiece

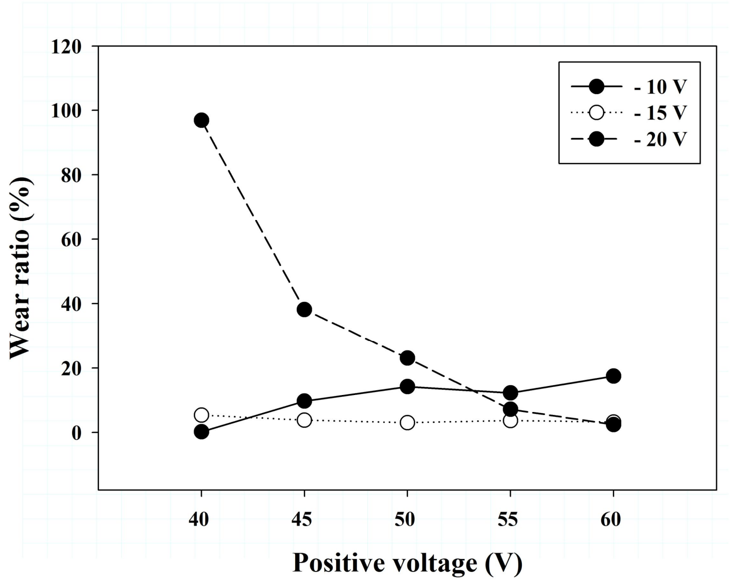


Figure 3.9 Electrode wear ratio of negative voltage according to positive voltage

3.3 Material removal rate

In this study, material removal rate (MRR) is that electrode wear values have been calculated by the volume difference of the workpiece before and after machining the EDM process, as shown in Eq.3.1.

$$MRR = \frac{Volume\ of\ material\ removed\ from\ part}{Machining\ time} \tag{3.1}$$

Figure 3.10 shows the image of a 3D surface profile of the machined part by a commercial non-contact measuring equipment (NANO View-E100, Nano system Co., Ltd.). In this voltage condition, the edge of the groove is sharp at the overall area, and the top surface near the machined area is maintained before machining process even though electrolytic corrosion occurs in the EDM with water-jet type. Figure 3.11 shows the comparison of MRR versus negative voltage with fixed positive voltage. The results show that as the absolute value of negative voltage is increased, the MRR is decreased. Under the bipolar voltage condition of +40 V, -20 V, MRR was not measured because machining was not completed. It can be seen that off-time voltage can decrease electrolytic corrosion, but the influence of negative voltage decreases MRR due to an electrode wear and discharge spark energy. In addition, when the average voltage decrease under the zero, reduction rate of MRR has increasing tendency with increasing an absolute value of average voltage.

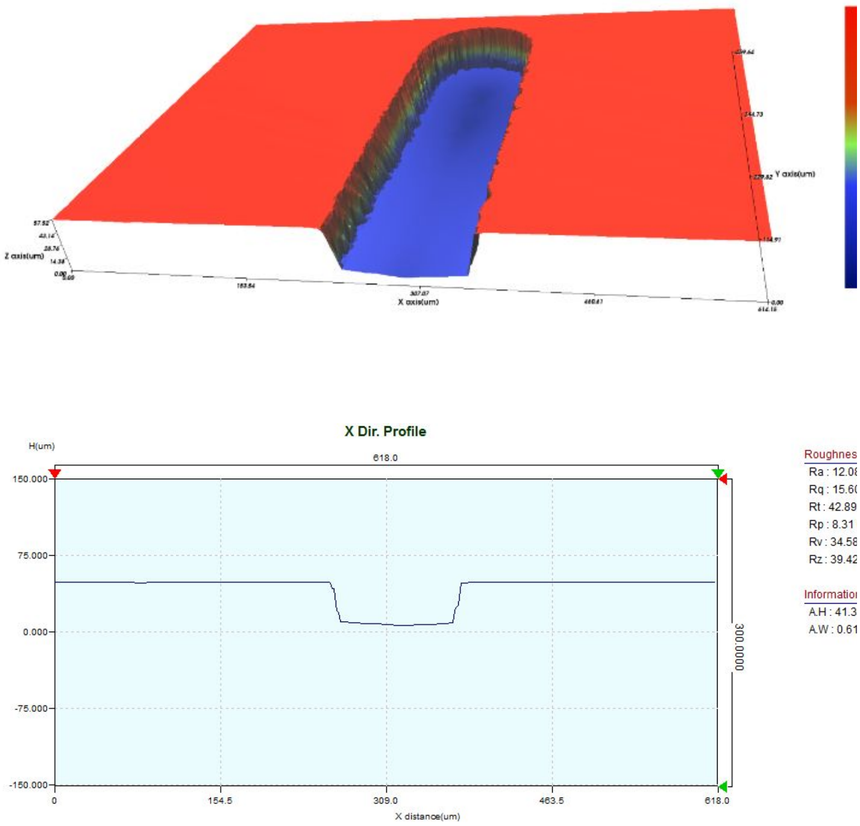


Figure 3.10 3D surface and X-direction axis profiles of machined part (+50V,-15V)

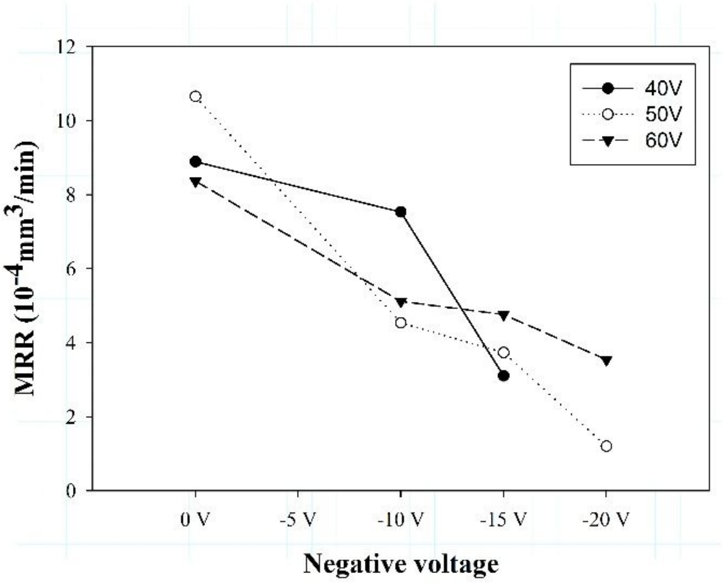


Figure 3.11 MRR according to negative voltage condition

In addition, figure 3.12 shows the optimum machining result in this experiment and machining parameters are shown in a table 3.1. Comparing with various voltage level, the conditions with a positive voltage of 50 V and with a negative voltage of –15 V was chosen in respect of surface integrity. Also, 3D machining results with layer-by-layer and hemispherical shape are shown in figure 3.13.

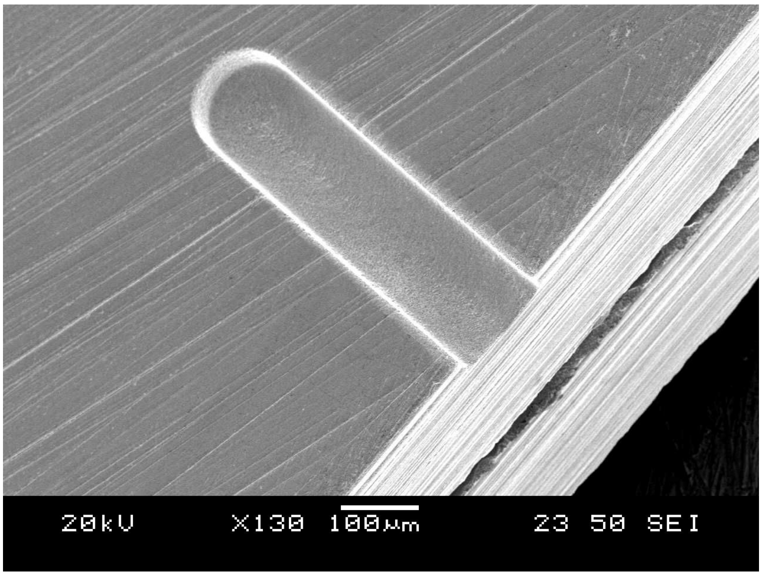


Figure 3.12 SEM image of optimal machining result with bipolar pulse

Table 3.1 Optimal machining parameters using bipolar pulse

Parameters (units)	**Value**
Bipolar voltage condition (V)	+50, -15
Machining time (sec)	292
Maximum length of corrosion (µm)	3.55
Electrode wear ratio (%)	3.05
Material removal rate (10^{-4} * mm^3/min)	3.32

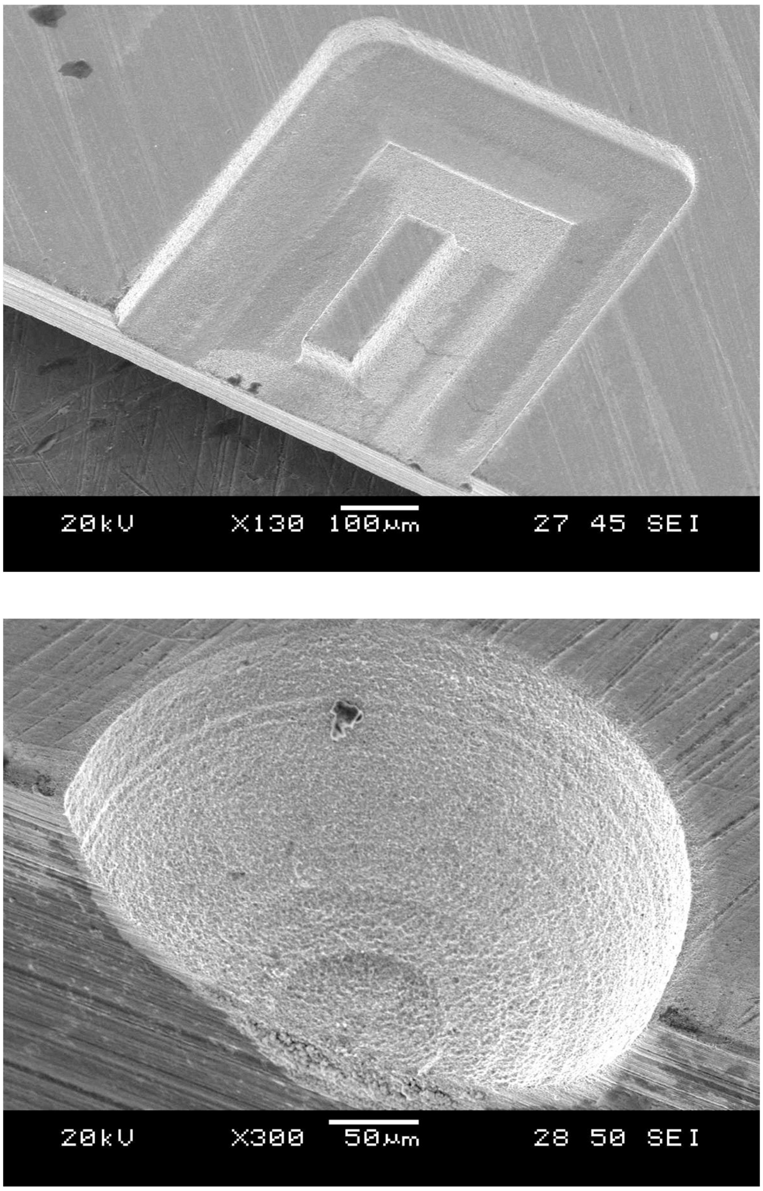


Figure 3.13 Layer-by-layer and 3D machining results

3.4 Tungsten electrode

In general, tungsten electrode is widely used in micro EDM as a tool electrode. In case of comparing tungsten and WC-Co with material properties, cobalt material is considered as a target instead of WC-Co material. It is because WC-Co mainly consists of two materials: tungsten carbide (WC) and cobalt (Co). When the EDM is progressed, electrical resistivity of cobalt, which is a binder, is lower than WC. In other words, cobalt is more conductive than WC, and electrical sparks tend to flow cobalt. As shown in table 3.2, electric resistivity of cobalt is higher than that of tungsten. On the other hand, melting point and thermal conductivity of cobalt are lower than tungsten material. It means that heat transfer occurs at a higher rate across materials of high thermal conductivity than across materials of low thermal conductivity [12]. Thus, it seems that energy loss of WC-Co is more than tungsten electrode, and discharge spark energy of tungsten is more powerful at the same machining condition.

Figure 3.14 shows the micro ED-milling results of tungsten electrode and figure 3.15 shows the micro ED-milling results of WC-Co electrode with low-resistivity deionized water. In this water condition, the machining result of WC-Co electrode with a positive voltage of 40 V and with a negative voltage of –10 V was chosen for optimal machining condition in respect of surface integrity. Unlike the tungsten electrode, in case of conditions using WC-Co electrode, the milling process was not carried out to the end of machining due to the excessive short counts or severe electrode wear. These results come from the difference of the mechanical structure and electrical conductivity with cobalt and tungsten. As the positive voltage level gets increased at the same level of the negative voltage, the results of machined surface are gradually worse in terms of electrolytic corrosion. However, electrolytic corrosion gets less severe as the negative voltage level increases.

Figure 3.17 shows maximum corrosion length and MRR according to various voltage conditions using tungsten electrode. Comparing machining results between WC-Co electrode as shown in chapter 3.1 and tungsten electrode as shown in figure 3.16 in the high resistivity of deionized water condition, overall length of maximum electrolytic corrosion with WC-Co is longer than that of tungsten electrode. However, overall wear ratio of WC-Co is lower than that of tungsten electrode. It seems that more discharge energy causes electrode wear problem severely. Also, material removal rate is similar to these electrodes. Consequently, WC-Co electrode is more suitable for micro EDM on the WC-Co workpiece with bipolar pulse system.

Table 3.2 Electrical and thermal properties of tungsten and WC-Co

		Melting point (◦C)	**Electrical resistivity (Ω·m)**	**Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)**
Tungsten		3422	5.60×10^{-8}	173
WC-Co	**WC**	2785 ~ 2830	13×10^{-8}	105
	Cobalt (Binder)	1495	6.24×10^{-8}	100

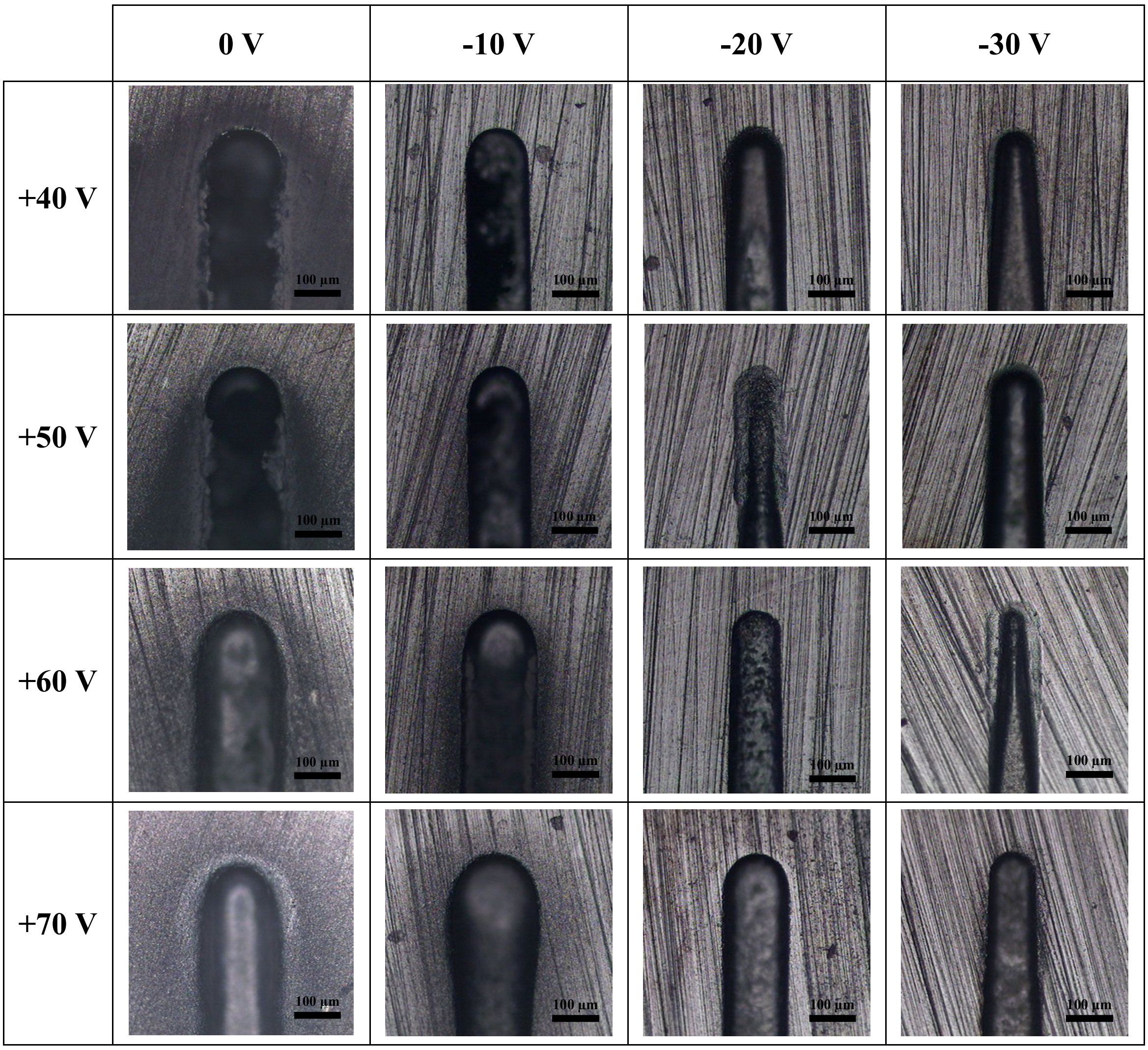


Figure 3.14 Micro ED-milling results of tungsten electrode with low-resistivity deionized water

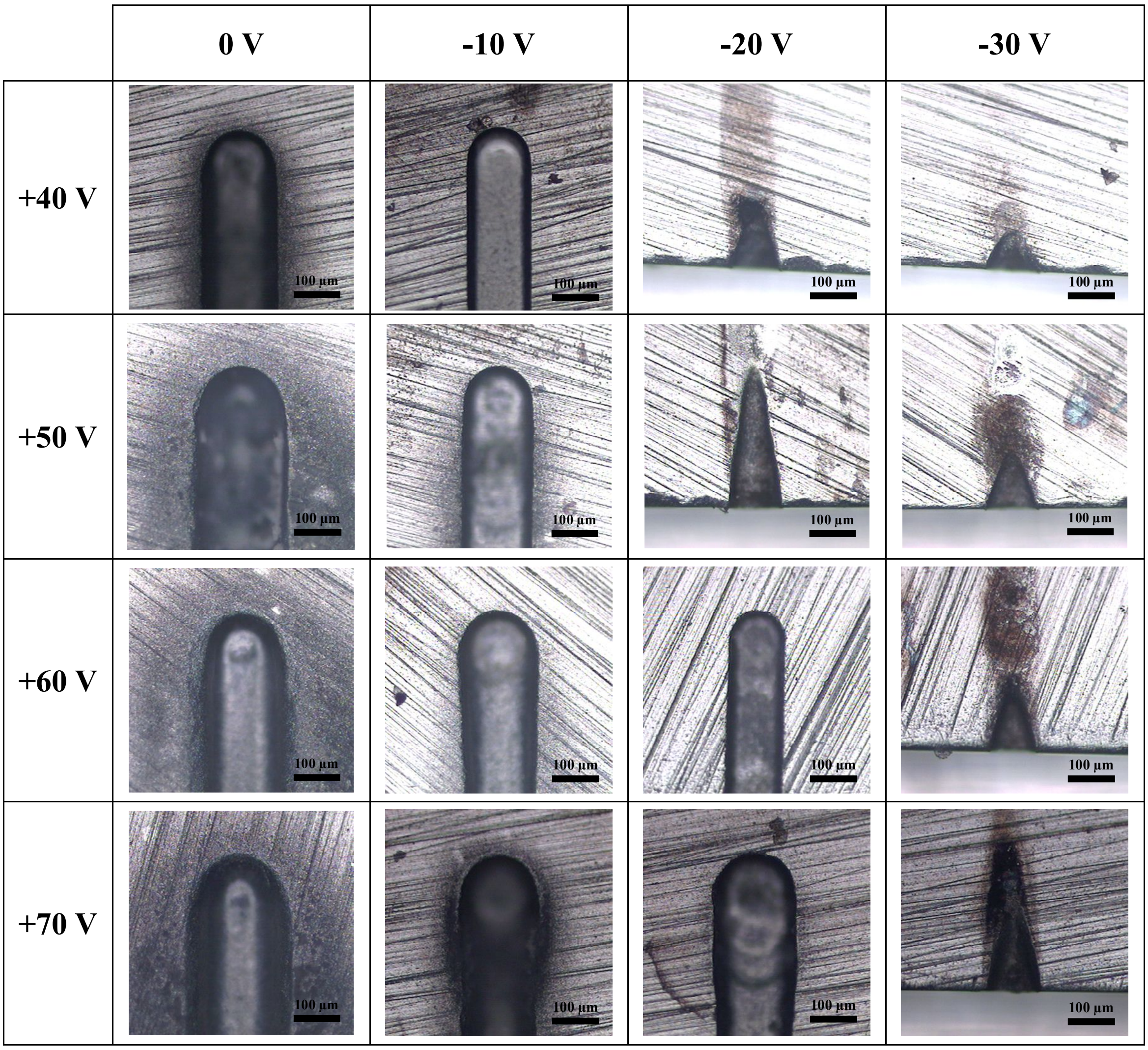


Figure 3.15 Micro ED-milling results of WC-Co electrode with low-resistivity deionized water

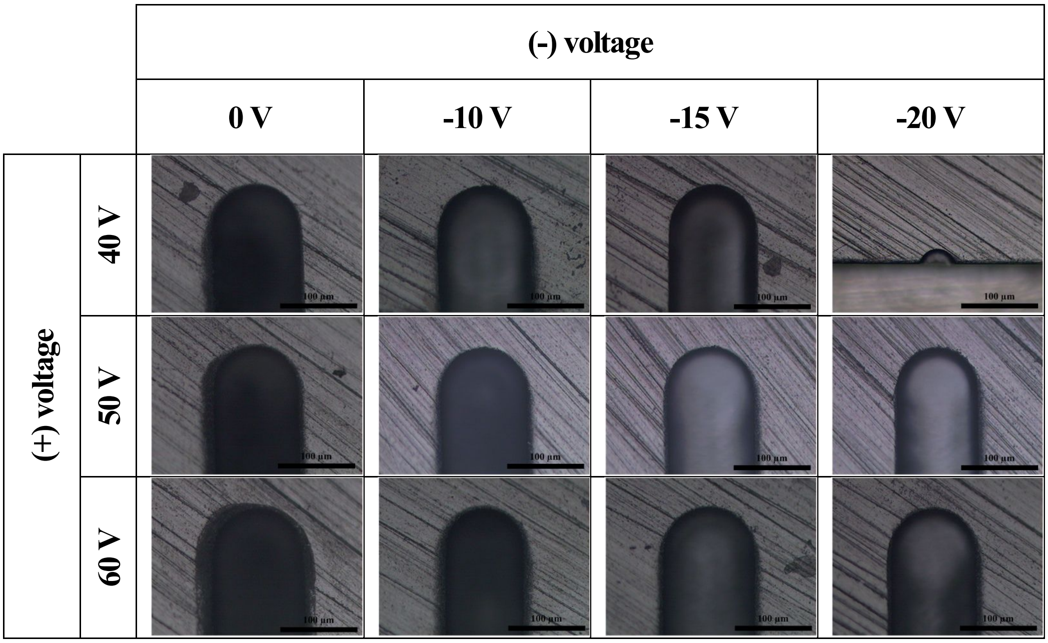


Figure 3.16 Machining results of tungsten carbide with high resistivity deionized water

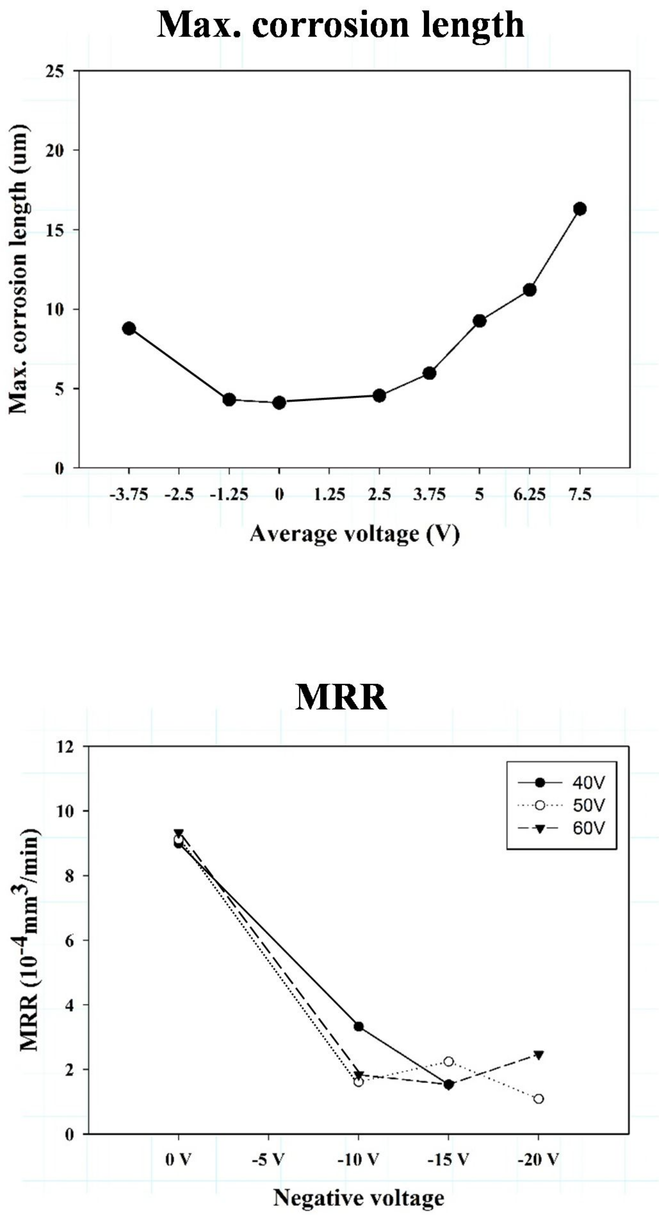


Figure 3.17 Maximum corrosion length and MRR according to various voltage

Chapter 4

Conclusion

In this study, micro ED-milling of WC-Co workpiece has been investigated to minimize electrolytic corrosion and electrode wear using deionized water and bipolar pulsed power source. Except for the bipolar pulsed power source and deionized water, there are no additional apparatuses to prevent electrolytic corrosion and electrode wear. It could be possible to produce good results for an RC discharge circuit using a bipolar pulsed power source and deionized water as compared with the DC or AC power sources and dielectric fluid of kerosene. However, since the electrode wear or electrolytic corrosion occur in some voltage conditions, it is important for micro ED-milling to choose the appropriate variables. As a result, the positive voltage of +50 V and the negative voltage of -15 V had less maximum length of electrolytic corrosion and electrode wear with optimal machining quality in these experiments: electrode wear rate was a 3.05 %, maximum length of electrolytic corroded zone was about 10 μm, and MRR was $3.73 * 10^{-4}$ mm^3/min.

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국문초록

초경 합금 (WC-Co, tungsten carbide with cobalt binder)은 현재 다양한 산업에서 사용되고 있으며 높은 강도와 내부식성과 같은 특징을 갖고 있는 금속으로 대두되고 있다. 하지만 이러한 특징으로 인하여 미세 단위의 전극이나 몰드, 삼차원 형상 등의 제작에 있어서 많은 어려움이 있다. 특수 가공 중에서 미세 방전 가공 (Micro EDM, micro electrical discharge machining)은 초경합금과 같은 금속의 가공에 있어서 효과적이고 경제적인 가공 방법이라고 할 수 있다. 방전가공에서 사용되는 가공액 (Dielectric fluid)을 구분하면 크게 등유 (Kerosene)와 탈이온수 (Deionized water)의 두 가지로 분류할 수 있다. 전통적인 가공액이라고 할 수 있는 등유를 사용하면 전해 부식 (Electrolytic corrosion)이 발생하지 않지만 전극 마모 (Electrode wear) 현상의 증가와 가공 시간 증가 등의 문제점이 발생한다. 이에 반해 절연액으로 탈이온수를 사용하면 가공 속도 향상 및 전극 마모 문제가 감소하지만, 전해 부식 문제가 발생한다. 본 논문에서는 탈이온수 사용 시 발생하는 전해 부식 현상과 기존의 존재하는 전극 마모 문제를 동시에 해결하기 위해 기존의 DC 전원과 AC 전원 대신에 양전압 전원과 음전압 전원이 독립적으로 연결되어 전압 조절이 가능한 바이폴라 펄스 (Bipolar pulse) 전원 장치를 이용하여 실험 및 연구를 진행하였다.

또한 초경 합금 가공에 있어서 기존의 같은 금속 재질인 초경합금 전극 대신에 텅스텐 전극을 사용하여 비교 실험을 진행함으로써 가공 결과를 비교 분석하였다. 그리고 전압 조건 조정 및 그에 따른 결과 등을 분석하여 최적의 가공 조건을 도출하고 미세 밀링 가공 및 3차원 형상 등을 제작하기 위한 연구를 수행하였다.

주요어: 미세 방전 밀링, 초경 합금, 전해 부식, 전극 마모, 바이폴라 펄스 전원