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DEVELOPMENT OF STRIP EDM

DISSERTAION

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Abstract

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In this research, a strip-electrode system was developed to overcome the problem of electrode wear in electrical discharge machining (EDM). In general EDM, electrode wear causes shape errors to the workpiece. High production costs must be incurred to resolve such errors. Strip EDM makes efficient use of the electrode, eliminating the need for additional machining processes or methods to resolve shape errors. The strip electrode moves continuously along the electrode guide, creating the same conditions found in wire EDM, where the worn electrode is immediately replaced with a new one. The strip slides along the surface of an electrode guide in the strip-EDM system. During the actual machining process, the entire guide system moves along the tool path. The electrode guide acts like a block electrode in general EDM and the strip acts like the surface of an electrode. This effectively eliminates concern about tool electrode wear during machining. Using the machining system developed, three major applications were tested in this study:

milling, turning, and V-grooving. When the strip machining system was applied to ED-milling, grooves and curved structures were fabricated without having to compensate for electrode wear. Strip EDM was applied to turning and the results promise excellent accuracy at a high machining speed. V-grooving to make several types of cutting angles was also investigated and the strip-EDM method was successfully used to cut various shapes from a stainless steel workpiece.

Keywords: Electrical discharge machining, Electrode wear, Strip electrode, Strip EDM

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1

Introduction

Today, various machining technologies are being advanced in both traditional and non-traditional machining fields. Although the machining methods are being developed using advanced tool materials and coating technologies in the traditional field, non-conventional methods of machining are still required to handle hard-to-cut materials. Electrical discharge machining (EDM) is a type of non-traditional machining method, along with processes such as electrochemical machining, laser beam machining, and water jet machining. These are in contrast to the traditional group of methods that use cutting processes, such as milling, turning, drilling, and grinding, which are based on mechanical force by tools. Of all the exotic metalworking processes, none has gained greater industry-wide acceptance than EDM [1, 2]. This machining method is useful for making complex shapes or very small sized figures on a hard-to-cut workpiece. Its machining mechanism uses electro-thermal energy, which is generated by the discharge sparks that occur between the electrode and a workpiece. The sparks cause great heat and the thermal energy created can melt or vaporize metals. This process can only deal with conductive metals, since the energy source of the sparks is an electrical power generator and the current supplied by the generator must flow through an electrode and the workpiece. Therefore, the materials used for EDM are limited; nevertheless, this method can machine almost all types of industrial materials, since they are conductive metals in the actual field. Moreover, EDM is not concerned with the mechanical properties of a workpiece, such as hardness and strength, because there is no physical contact between the tool electrode and workpiece [1-3].

During the EDM process, a large number of discharge sparks occur in the machining gap between the electrode and workpiece. The discharge sparks not only remove materials from the workpiece surface, but materials from the electrode as well. The erosion of the workpiece is referred to as machining and a higher erosion rate of the workpiece helps the machining process. However, a high erosion rate for the electrode must be avoided. This erosion phenomenon of the electrode is referred to as electrode wear. Electrode wear is one of the most serious problems in the

EDM process, since it affects dimensional accuracy and the shape produced [1, 4]. The electrode shape is disfigured by wear and is a direct cause of shape error on the machined portion.

In order to prevent or reduce shape error caused by electrode wear, practical machining processes can be implemented. One process is a compensated tool path. As the EDM process is applied to milling, an electrode travels along the tool path both horizontally and vertically. The servo system moves the electrode vertically along the length of the worn portion continuously or intermittently [5-8]. However, this compensation method actually has a weakness; it is impossible to compensate for the side wear of the electrode or to determine an accurate amount of wear during the machining. The second solution for overcoming shape errors is to break up the machining process into several steps, consisting of rough cutting and finish cutting [9-11]. Each machining step requires a new electrode and its own machining conditions. However, this machining method increases machining time and decreases productivity. Moreover, all machining steps create partial electrode wear.

In general die-sinking EDM, kerosene is used as a working fluid and a long pulse-on time is applied in order to reduce electrode wear. During long pulse-on periods, carbon is dissociated from the kerosene and is deposited on the electrode surface as a result of electrode polarity. The carbon layer protects the surface of the electrode from the high temperature of the discharge sparks. As a result, the electrode wear is reduced [4, 9]. Although the electrical pulse in die-sinking EDM has the effect of reducing wear problems, electrode wear cannot be completely prevented, and the machined surface becomes rough due to the high electrical energy of the long pulse-on time [12-14]. Moreover, EDM with kerosene has the significant disadvantage of slowing down machining speed. In contrast, the use of deionized water as the working fluid increases machining speed, but large electrode wear can occur because of a lack of any effect on the carbon layer.

If the electrode can be continuously replaced during the machining, there would be no wear problems. Additionally, a faster machining speed could be achieved using deionized waster rather than kerosene. The EDM with these characteristics is referred to as wire EDM [1, 2]. Wire EDM uses thin wire as an electrode. While there are no electrode wear issues with wire EDM, the machined shape should be pierced through the workpiece and the wire electrode is easily broken by arc discharge and vibrated by the turbulence of the working fluid [15, 16].

Electrode-wear problems result from low productivity and affect shape precision. In this research, the use of a strip electrode during the EDM process is suggested as way to overcome the problems noted above. The strip-EDM system is a combination of a block electrode and a wire electrode. The total electrode system moves like the block electrode in general EDM and the worn electrode surface is continuously replaced with new a surface, as with wire EDM. In fact, the strip-EDM method is not a no-wear EDM process; the electrode strip is subject to wear. However, electrode wear need not be considered during machining because the strip electrode is continuously fed by a strip-supplying mechanism in the machining system [17, 18].

The purpose of this research is the development of strip-EDM systems. Based on the above, a strip-electrode apparatus was designed and produced. This machining system was also applied to milling, turning, and V-grooving. Therefore, various shapes can be machined on hard metal without electrode wear problems.

This dissertation consists of seven chapters.

Chapter 1 introduces the purpose of this study, namely, to overcome electrode wear problems in the EDM process.

In chapter 2, the principle of EDM is reviewed and includes a description of the three major types of EDM: die-sinking EDM, electrical discharge drilling (ED-drilling), and wire EDM. Electrode wear, one of the main topics in this dissertation, is expounded upon from both a microscopic and macroscopic standpoint. From a microscopic point of view, wear is caused from the thermal energy of ions and electrons. The ions and electrons generate great heat when they strike metal surfaces. From a macroscopic point of view, wear affects dimensional accuracy and the shape produced. As a result, machining efficiency and productivity of the EDM process decrease.

Chapter 3 introduces the strip-EDM system developed in this research. It consists of a strip-electrode apparatus and EDM machinery. For practical machining tests, the strip-electrode system was adapted for use with a commercial wire-EDM machine.

Chapter 4 presents the main experimental study of strip ED-milling under machining conditions. The major machining factors are electrode material, peak current, depth of cut, and strip feed speed. Experiments to compare the general ED-milling method to the strip EDM were conducted. The experiments conducted using the general ED-milling process used die-sinking EDM with kerosene as a working fluid. Since the strip EDM was developed with wire EDM, the working fluid of strip EDM is deionized water. In this chapter, several machining examples are shown, including simple pockets, multi-step grooves, prism arrays, and pyramid patterns.

In chapter 5, strip EDM is applied to turning. For this application, a turning unit was designed and produced. Using the turning system, the strip ED-turning is tested according to machining conditions. Its machining result is also compared to a general ED-turning. Wire EDM has been used as the general method. Additionally, complex shapes are machined using applications of strip ED-turning.

Chapter 6 introduces adjustable V-grooving, using a special strip-electrode guide. To make various V-grooves with only one guide system, an adjustable V-groove guide was developed. The guide can define various tip angles for the V-shapes. Since the surface of the electrode is also a strip, there is no concerned about wear problems. In the experiments, several V-grooves are completed with different tip angles.

In chapter 7, conclusions and discussion of this research are presented.

This dissertation cites forty references comprised of journal papers, patents, books, and articles from technical magazines. These references were chosen to create a research project that is based not only on theoretical study, but that is also practical and demonstrates an actual machining process.

2

Electrical Discharge Machining

During World War II, EDM was developed in both the Union of Soviet Socialist Republics (USSR) and the United States, respectively. In USSR, B. R. Lazarenko and N. I. Lazarenko developed a new machining method based on an RC (resistor and capacitor) discharge circuit [19]. Today, this type of EDM is widely applied to ED-drilling and micro EDM. A different type of EDM was invented in the United States at about the same time. H. Stark, V. Harding, and J. Beaver made an EDM system using a vacuum tube. This was the origin of TR (transistor) type EDM. Today, TR type EDM is broadly adopted for die-sinking EDM, EDM drilling, and wire EDM [20].

Early in EDM history, EDM process used a block or a rod type of electrode and is called die-sinking EDM. Later, a wire EDM was developed using a spooling wire electrode. The die-sinking EDM is used to machine a mold shape on a workpiece and the wire EDM can make a die shape that is being pierced on a workpiece. These two types of EDM have become indispensable machining processes in today's industries. Since the material removal mechanism uses discharge sparks between an electrode and a workpiece instead of a cutting tool, there is no mechanical force or contact between the electrode and the workpiece. Therefore, EDM can deal with almost every metal or hard-to-cut material regardless of mechanical properties such as hardness and strength. Moreover, it is compatible for use where shape or location of the detail cannot be easily machined by conventional methods [4]. Today, industries require stronger machine parts that are both macro and micro in size. Given current industrial demand levels for machining, EDM is the most useful and powerful machining solution.

This chapter introduces the principles of EDM. A basic mechanism is explained and three major EDM types, die-sinking EDM, ED-drilling, and wire EDM, are reviewed. Electrode wear is one of the most important problems in the EDM process. This study also considers electrode wear problems. Therefore, the principle of electrode wear is also discussed in this chapter.

2.1 Principles of EDM

EDM is the process of electro-thermally removing material from any conductive workpiece. The machining mechanism uses discharge sparks as a tool. The EDM consists of four major components: electrode, workpiece, power source, and working fluid, as shown in figure 1. A power source supplies electrical energy to the electrode and workpiece. The amount of electrical energy required is directly related to the machining characteristics, such as machining speed and surface quality. The electrode and the workpiece are submerged into a working fluid and the machining gap between the electrode and the workpiece is filled by the fluid. The fluid plays an important role as an insulator before a spark occurs and as a conductor during sparking. After sparking, the working fluid acts as a debris remover and as a coolant [21].

The machining mechanism consists of several steps. Assuming an electrode is negatively charged and the workpiece is positive (or vice-versa), the electrode is advanced into the workpiece. When the gap distance becomes very narrow, a discharge spark occurs. Figure 2 shows the spark sequence of the EDM process [4, 9, 22]. Since the electrode and workpiece are charged with a potentially high-voltage, an intense electromagnetic flux or energy column is formed at the narrowest points of the electrode and the workpiece. Subsequently, this electrical field eventually breaks down the isolation and the north and south poles are held apart. At this time, the grain of trapped ions is aligned with polarity and the resistivity of the working fluid is reduced. This phenomenon causes a spark to flow through the ionized flux column and strike the workpiece and electrode surfaces. The voltage drops rapidly as a current is produced. The discharge spark melts or vaporizes anything in contact with it, including the electrode surface, the workpiece surface, and the working fluid. The portion of the workpiece surface affected by the spark is melted and vaporized. The working fluid expands rapidly due to the heat of the spark. The expansion moves away the melted or vaporized workpiece particle and a crater are left on the surfaces of the workpiece and the electrode. The debris generated from the workpiece and electrode is removed from the machining gap through flushing. Voltage rises as resistivity increases and the current drops as the working fluid can no longer sustain a stable spark. At this point, the current must be switched off. The EDM method makes the desired shape on a workpiece by repeating the above-described spark process [9, 10].

There are primarily three types of EDM methods according to electrode types: die-sinking EDM, ED-drilling, and wire EDM. Each method has its own application, depending on the purpose of the work.

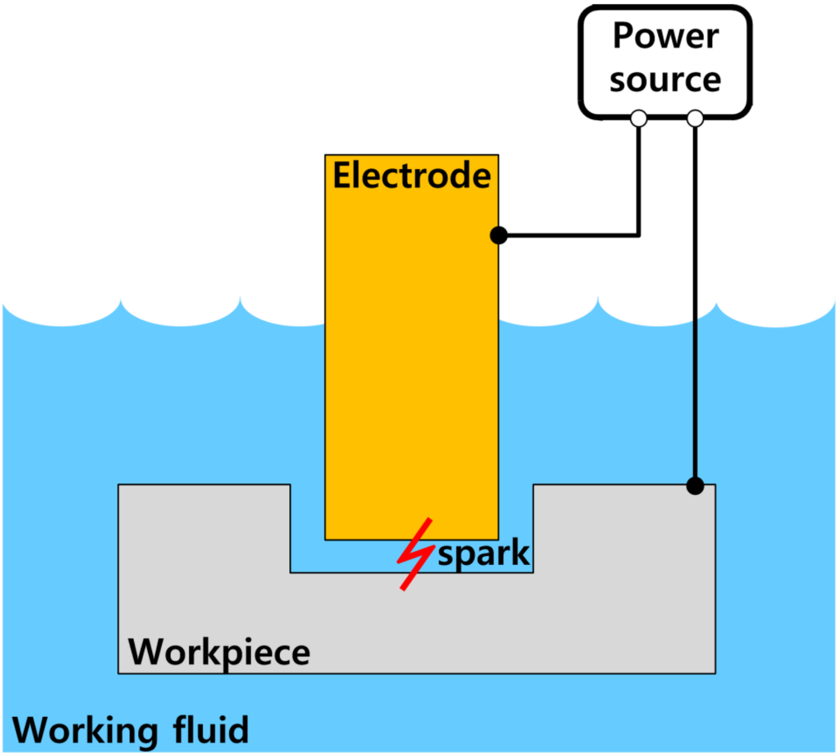
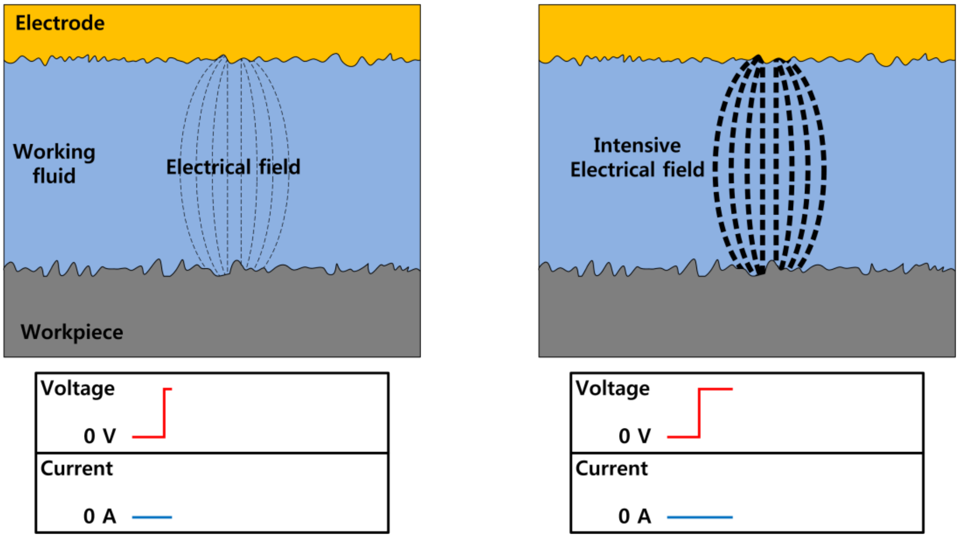
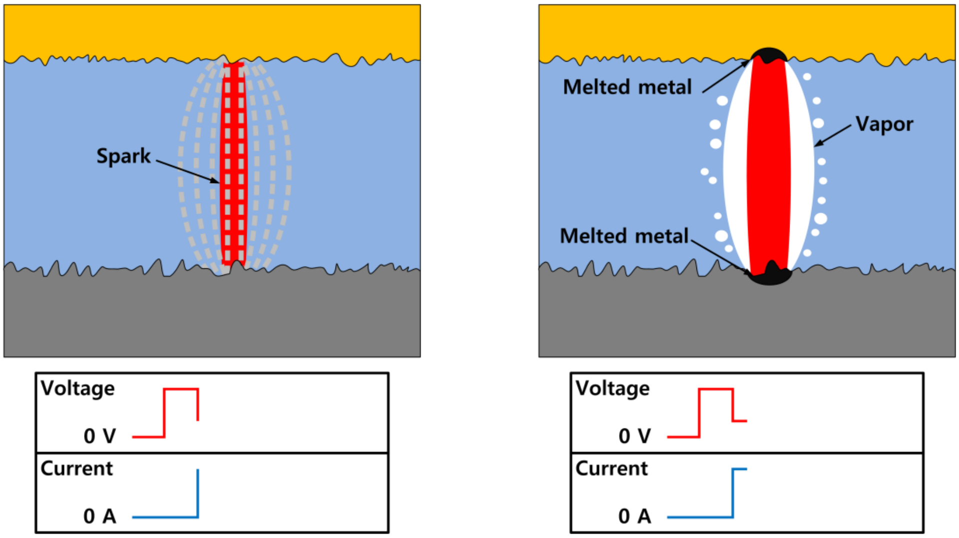


Figure 1 A schematic diagram of an EDM system



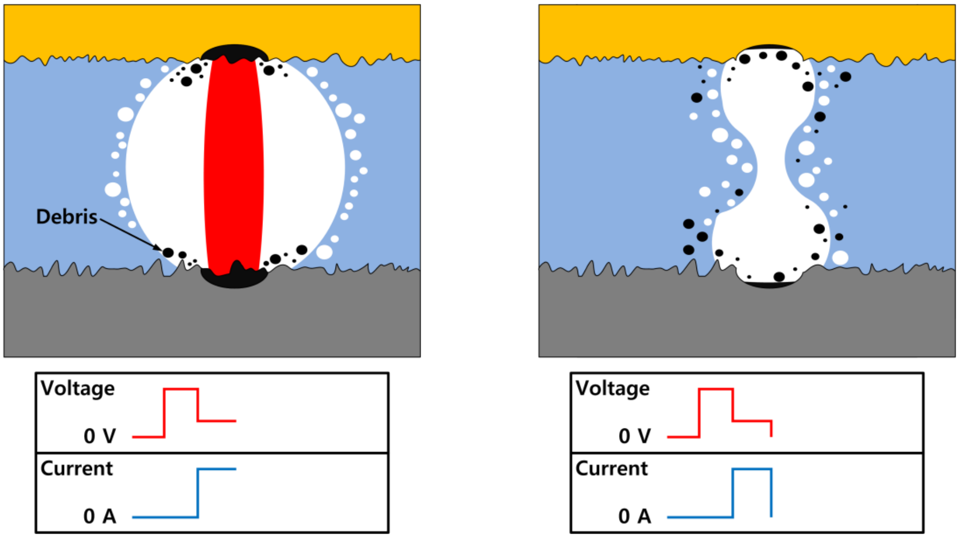
(a) Open gap

(b) Electric field



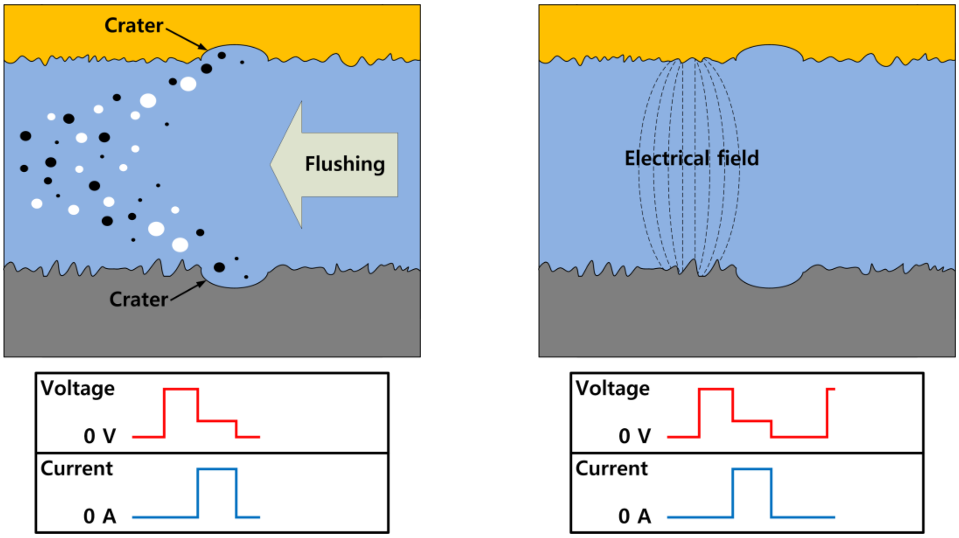
(c) Beginning a spark

(d) Melted and vaporized workpiece



(e) Bubble expanding

(f) Removal of spark



(g) Flushing and dielectric recovery

(h) Ready for another spark

Figure 2 The spark sequence of EDM

2.1.1 Die-sinking EDM

Die-sinking EDM, also known as general EDM, ram EDM, and vertical EDM, is applied to fabricate blind shapes on a workpiece. Before starting the machining process of die-sinking EDM, a formed electrode is machined to the desired shape by a general cutting process or wire EDM. Figure 3 shows the machining system of the die-sinking EDM. A preformed electrode is held on the Z-column of the machine and moves vertically. The electrode and workpiece are submerged into the working fluid. The fluid is usually kerosene, paraffin, or hydrocarbon-based oils. When a voltage is applied to the electrode and workpiece, the oil becomes ionized and sparks occur at the narrow machining gap. The controlled sparks partially melt or vaporize the workpiece surface [10]. Once the sparking process is completed, the working fluid removes debris from the gap and cools the surface of the workpiece and the electrode. Since the dielectric characteristic of the oil is not changed by the discharge sparks, the fluid is reused after filtering out the debris. During machining, an electrode not only follows a tool path, but also vibrates or makes jump-like motions. The additional movement of the electrode is needed to improve flushing, since the oil has high viscosity [9-11].

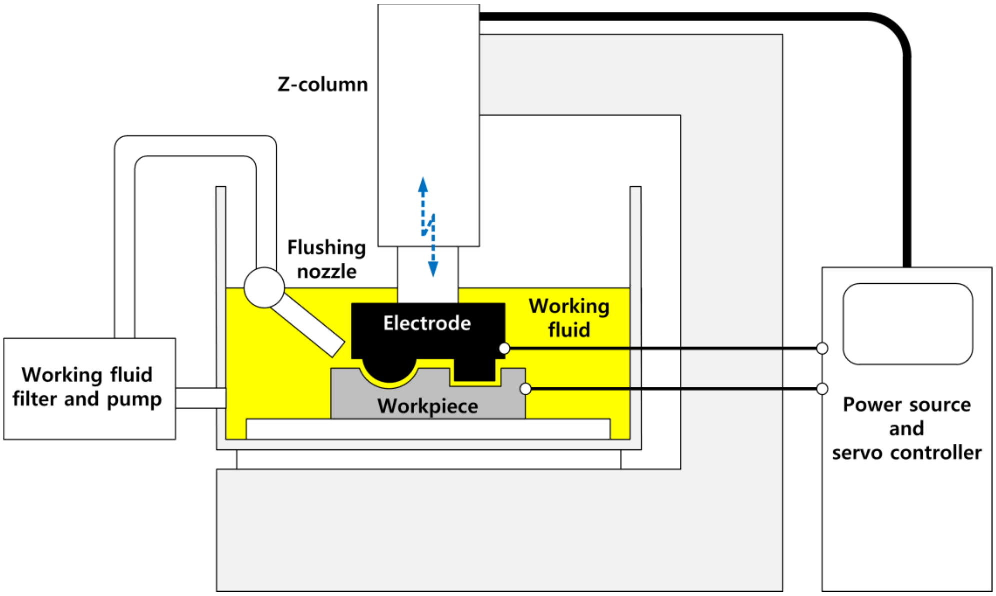


Figure 3 Schematics of die-sinking EDM

2.1.2 ED-drilling

ED-drilling, also known as small-hole EDM, is applied to make small holes or high-aspect-ratio holes on a workpiece. This machining method uses tube electrodes to increase machining performance. It is difficult to ensure that there is an adequate supply of working fluid in a machining gap as the depth of the machined hole increases, which can cause ineffective flushing. To overcome this flushing problem, the working fluid is supplied through a hollow in the tube electrode as shown in figure 4. The waste fluid and debris are removed through a narrow gap between the outside of the electrode and the inside of the machine hole. The working fluid is water or kerosene. Water facilitates a high machining speed, but electrolytic corrosion occurs on the workpiece [23-24]. On the other hand, a precise hole can be bored without corrosion when kerosene is used as the working fluid, but machining speed is relatively low.

Since this machining process has no contact between a tool electrode and the workpiece, it is used to make a small hole on hard metals and to drill a precise hole on a curved surface. Early in the development of ED-drilling, this process was usually used to bore a start hole for wire EDM. However, today it is widely used to complete small holes on special parts such as the nozzle of a fuel injector, cooling holes on a gas turbine blade, and optical parts.

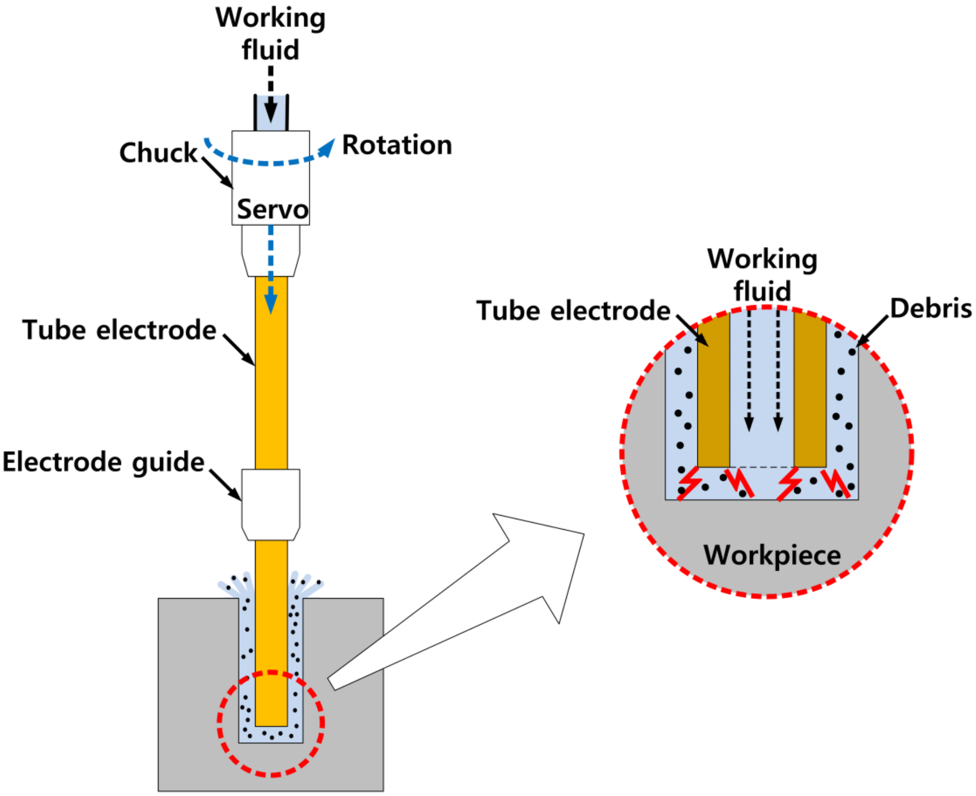


Figure 4 Schematic of ED-drilling

2.1.3 Wire EDM

Figure 5 illustrates the process of wire EDM. It is applied to make pierced shapes in a workpiece. This method uses a thin wire as an electrode. The wire electrode is continuously fed to the machining gap and moves along a tool path. All EDM processes suffer from electrode wear. However, wire EDM is not concerned with a wear problem because the worn wire is removed immediately and a new one is supplied continuously.

Water is used as the working fluid in wire EDM. Pure water is an insulator, but regular water contains ions that cause the conductivity of water to be too high. Therefore, electrolyzation occurs in regular water. In order to create a discharge spark, the ions must be removed. The wire-EDM system has a special filter with a deionization resin that transforms regular water into deionized water. Since deionized water is similar to pure water, it can act as a working fluid for EDM. When sufficient voltage is applied to the electrode and the workpiece, the fluid ionizes and a discharge spark occurs at the machining gap. After sparking, the deionized water loses it isolated characteristic and is transformed to regular water. The waste fluid passes through a filter to remove the debris. The ions in the water are then removed by the resin and the fluid is reused as deionized water.

In wire EDM, the wire electrode is easily broken by overheating [25]. If the spark period is long, as with the die-sinking EDM process, the wire will be broken. To prevent the wire from breaking, wire EDM uses a relatively shorter spark time compared to die-sinking EDM. Wire EDM has applications in die-making processes and tool repair. Moreover, it does not require use of preformed electrodes. Generating a tool path is sufficient for making a desired shape. Recently, an application of wire EDM was successfully used in turning. It is a useful machining method for completing small-sized and precise turning with difficult-to-cut materials.

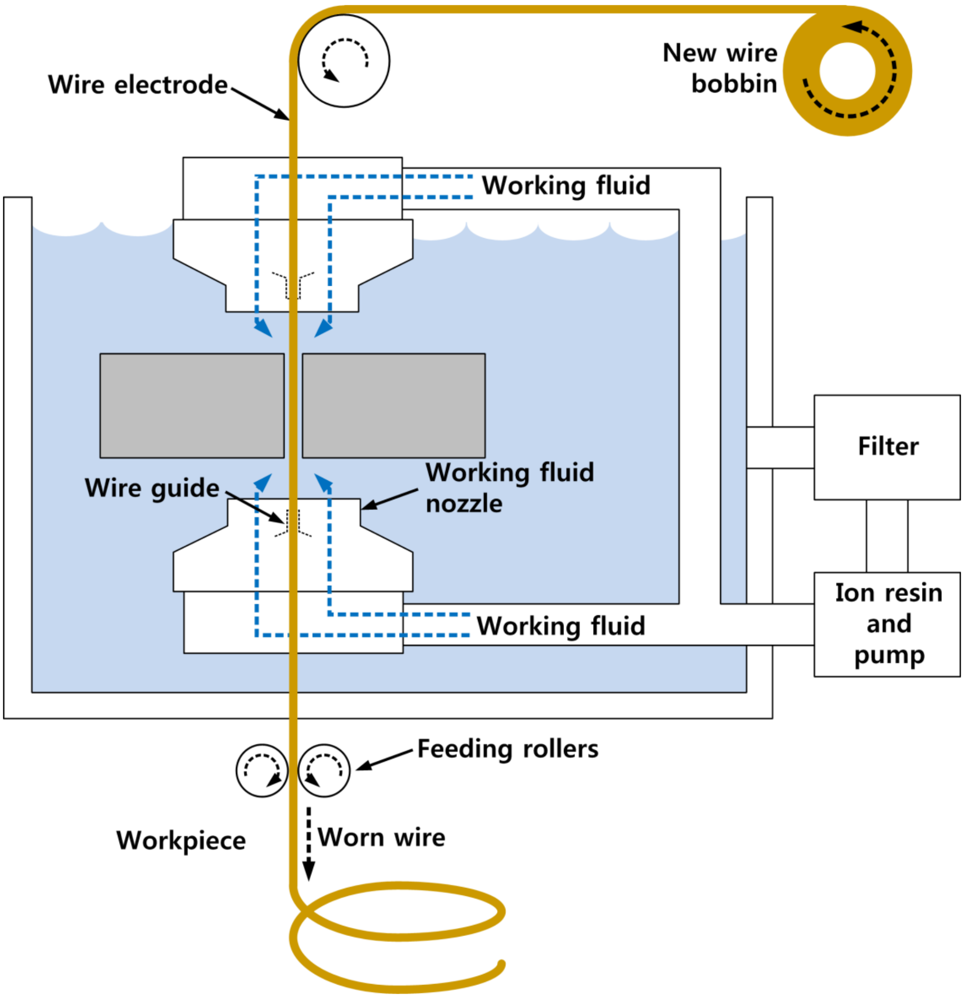


Figure 5 Schematics of wire EDM

2.2 Principles of electrode wear in the EDM process

A discharge spark consists of electrons and positive ions as shown in figure 6. Assuming the electrode is negatively charged and the workpiece is positively charged (or vice-versa), an electron comes out of the electrode surface. The electron travels to the oppositely charged workpiece through the machining gap, which has been filled with the working fluid. As the electron moves, it collides with an atom in the working fluid causing the atom to lose an electron and become a positive ion. The initial electron and the new electron generated by the bombardment are accelerated by the electrical field and continue to travel to the workpiece. They then collide with other atoms. As this process is repeated, a large number of electrons and positive ions are generated [26, 27]. Finally, the positive ions and the electrons strike the surface of the electrode and the workpiece. Given the light weight of an electron, it accelerates much faster than a positive ion. Therefore, many more electrons bombard the surface during sparking. For this reason, electrons are considered the primary source of energy for EDM material removal [4]. The bombardments cause the surface materials of both the electrode and workpiece to melt or vaporize with each spark. The phenomenon occurring on the surface of the workpiece is referred to as machining of the workpiece and the phenomenon occurring to the electrode is referred to as electrode wear.

There three types of electrode wear during EDM: bottom wear, edge wear, and side wear. The extent of bottom wear is determined by the difference between the length of an electrode before and after machining. The discharge sparks occur mainly on the bottom surface of the electrode when die-sinking EDM or ED-drilling operations have a vertical tool path. Therefore, the bottom surface experiences more wear during machining. The extent of edge wear is determined by comparing the initial edge length with the point on the electrode edge that did not experience wear at the end of the machining process. As the machining process advances, shape error increases due to the dull edge of an electrode, which is caused by edge wear. The extent of side wear is determined by the difference between the width of the initial electrode and the used electrode. Side wear is greater on the bottom portion of the electrode because that area suffers more discharge sparks. Figure 7 illustrates the different types of electrode wear. Electrode wear is directly related to the number of sparks on the electrode surface. Figure 8 shows the number of sparks required to produce a flat surface as compared to the number required to produce a right angle corner on a workpiece. Each spark on the flat surface of the electrode machines a corresponding point on the workpiece surface. On the other hand, many sparks must originate from the edge of the electrode to produce a corner shape on the workpiece. Since discharge sparks remove material from the workpiece and electrode, more material is removed from the edge corner of the electrode than the flat surface of the electrode. For this reason, the edges of an electrode are worn more than the flat surface of the electrode. The above is based on the vertical tool path of a general

EDM known as die-sinking EDM. ED-drilling also comes creates this kind of wear. If the tool path is changed to a horizontal motion or a combination of vertical and horizontal motion, the location of the electrode wear changes according to operating conditions.

As amounts of electrode wear are compared quantitatively according to machining conditions, the volume of removed material is usually measured and this measurement is used to compare the electrode volume before and after machining. The electrode wear ratio is also used for studying and analyzing the EDM process. The ratio is calculated by volumetric electrode wear and machined volume of a workpiece.

$$\text{Electrode wear ratio}[\%] = \frac{\text{Volumetric wear of electrode}}{\text{Machined volume of workpiece}} \times 100[\%] \qquad (2.1)$$

The electrode wear ratio is an important index for explaining machining characteristics of a specific electrode, workpiece, and machining conditions.

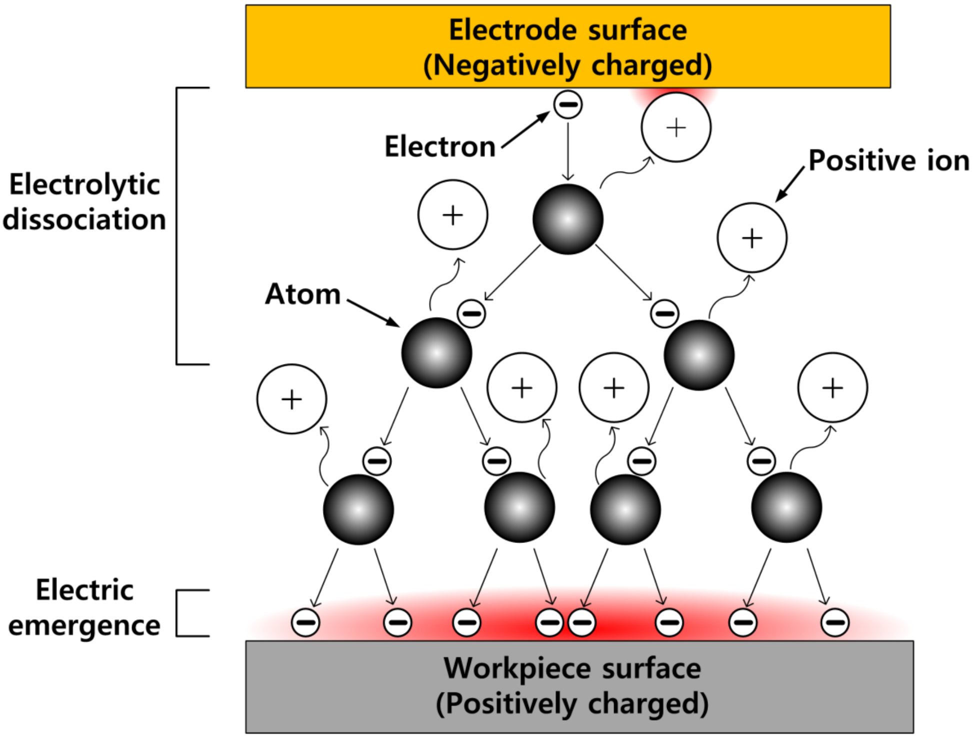


Figure 6 A spark in a machining gap of the EDM process

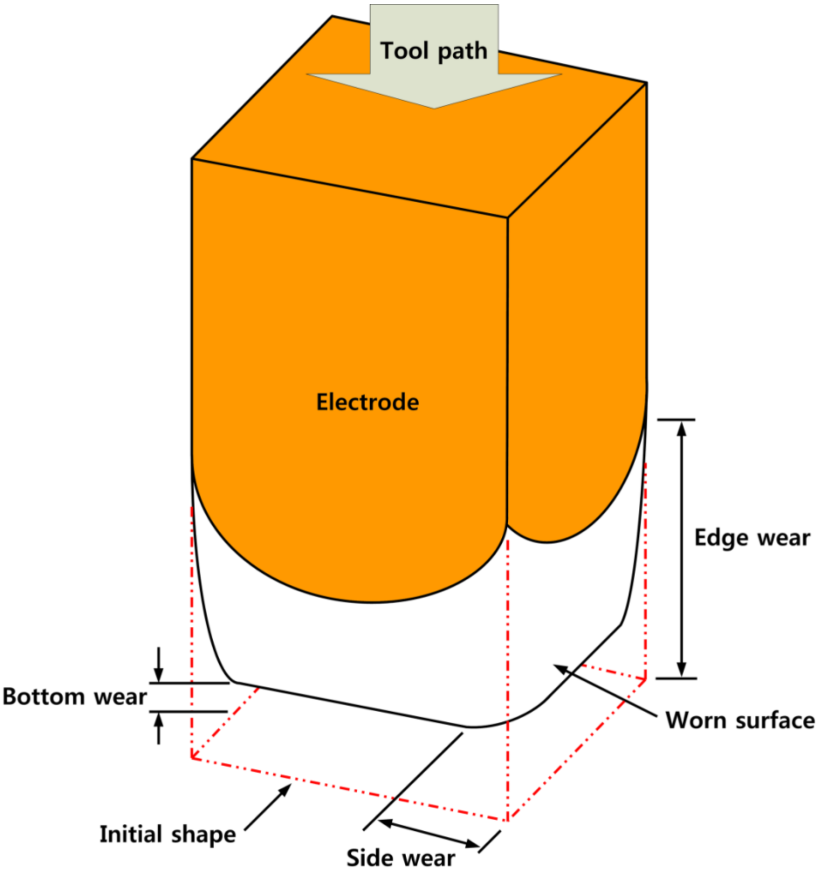


Figure 7 The different types of electrode wear

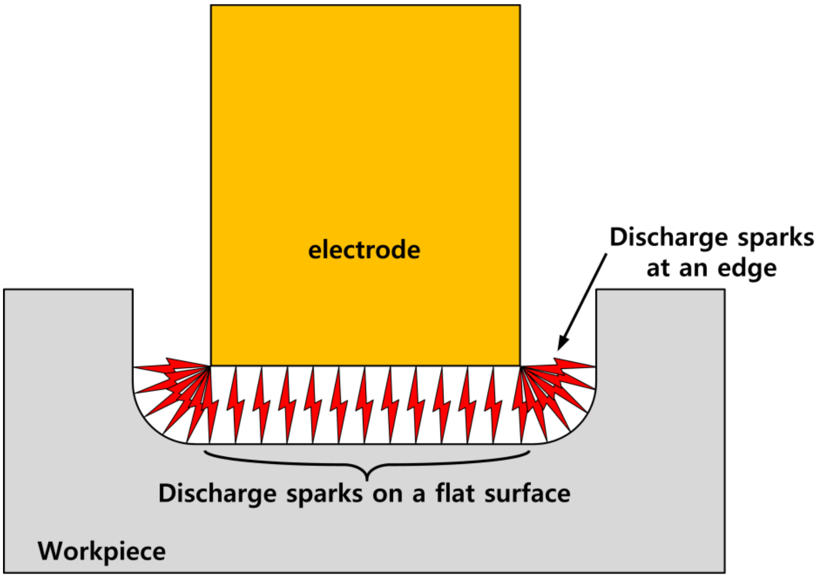


Figure 8 Sparks required to produce edges and flat surfaces

2.3 Electrode wears according to types of EDM

All types of EDM suffer from electrode wear during the machining process, as shown in figure 9. Die-sinking EDM uses a block-type electrode. Electrode wear starts from machining surfaces of the electrode. However, the edge of the electrode is worn more than the flat surface from the concentration of discharge sparks. Although a die-sinking EDM can reduce wear using the special machining condition with long pulse-on time that was mentioned in chapter 1, the initial shape of the electrode is also disfigured. In the case of ED-drilling, a length of electrode becomes shorter as machining time is increased. This results in a more serious problem of bottom wear than edge or side wear because it is difficult to monitor how deeply a hole has been drilled into a workpiece. Since the tip shape of the tube electrode deforms to the shape of a hemisphere or cone, there is a difference between the inlet and outlet diameters of the machined hole. As compared to die-sinking EDM and ED-drilling, electrode wear problems are not of concern in wire EDM. Although wear of a wire electrode is also caused by discharge sparks during the machining process, the worn wire is immediately removed and a new wire is sequentially supplied to the machining gap by an electrode feeding mechanism.

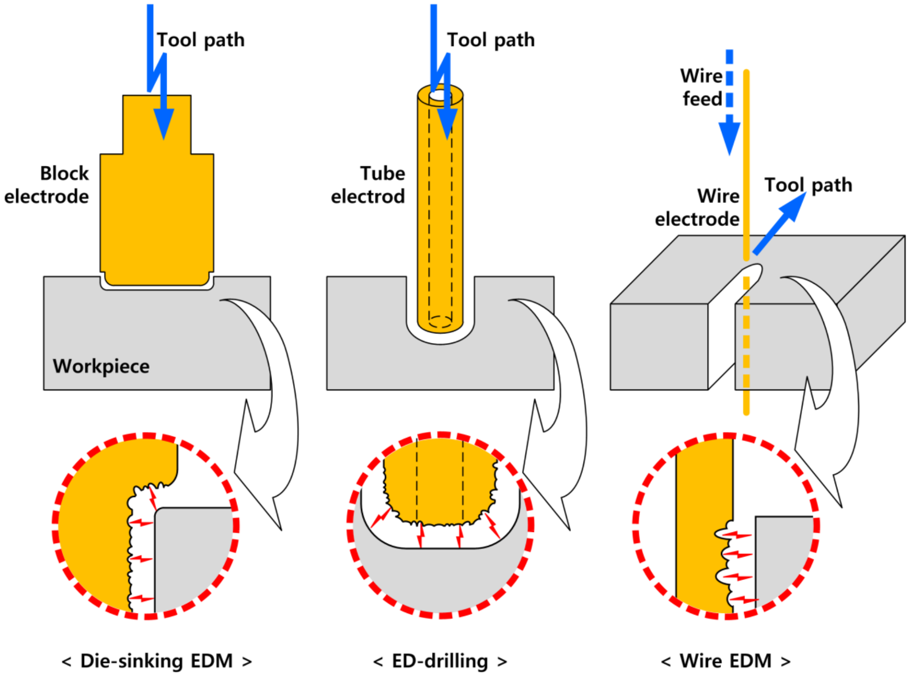
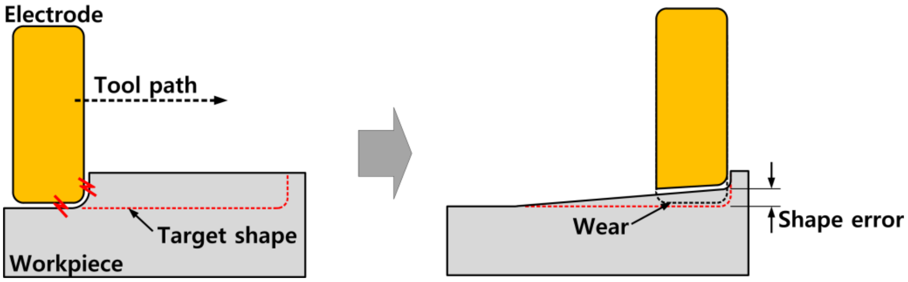


Figure 9 Electrode wear according to EDM types

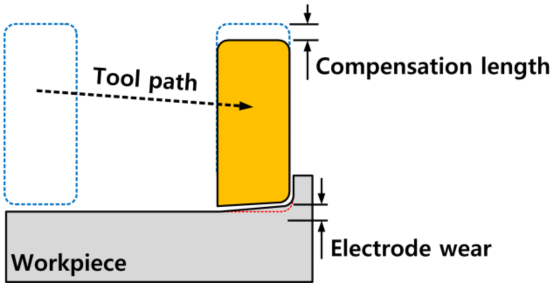
2.4 General method for reducing electrode wear problems

2.4.1 Compensative tool path

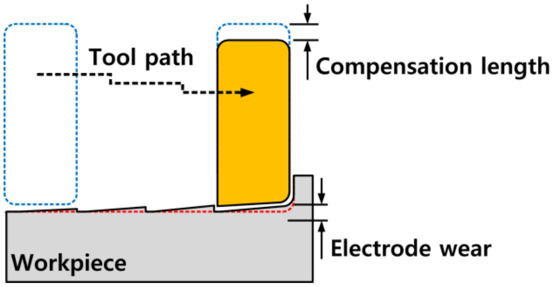
When an electrode moves along the horizontal tool path during the machining process, wear starts to occur on the bottom surface of the electrode. Figure 10 (a) illustrates that machining process. The length of the electrode becomes shorter than the initial shape, with the result that the machined portion has shape error. This error is the difference between the target shape and the actual machined shape. To compensate for the error, the electrode moves not only along the tool path but also the direction of wear. There are two compensation methods: the continuously compensated path and the intermittently compensated path [28-31]. The first method continuously moves in the compensated direction as shown in figure 10 (b). Although this method can complete machined parts with minimal shape error, it is difficult to predict continuous electrode wear during the machining process. Another compensation method checks the electrode wear periodically (not continuously) as shown in figure 10 (c). However, it causes relatively large shape error on a machined part and machining time increases.



(a) Electrode wear along the tool path



(b) Continuously compensated tool path

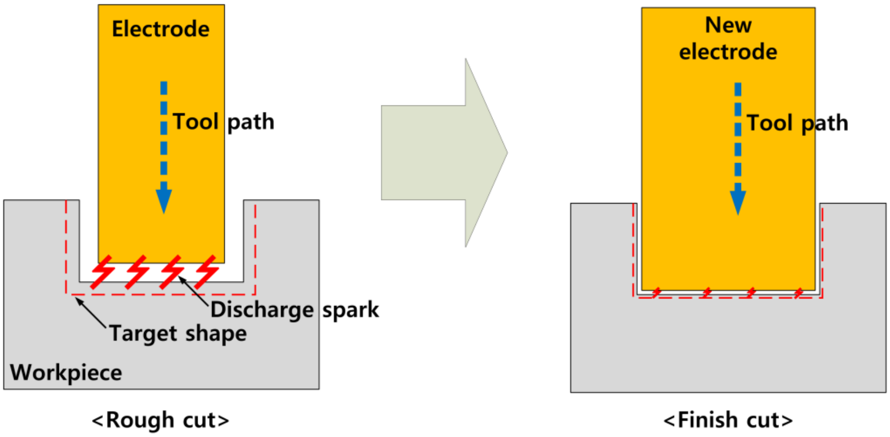


(c) Intermittently compensated tool path

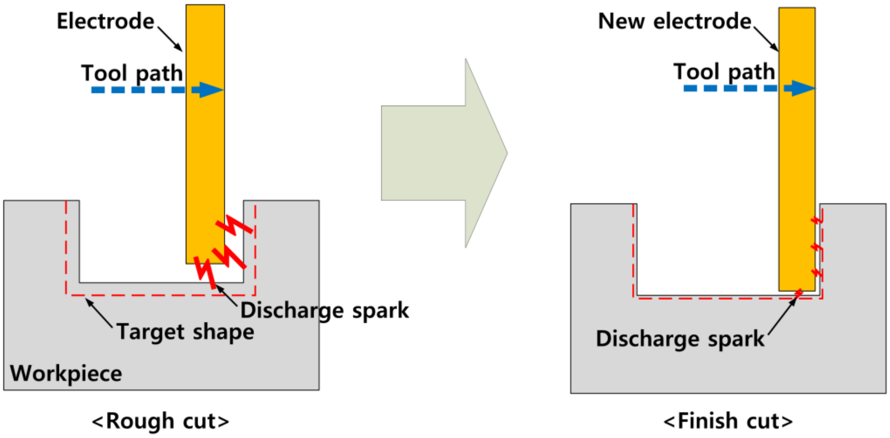
Figure 10 Compensated tool path methods

2.4.2 Finish cut process with a new electrode

From a practical point of view, the machining process is usually broken down into several steps and each step has its own machining conditions and electrode. This is simpler and more practical. Figure 11 illustrates the process. To complete a target shape, a workpiece is machined using rough cut conditions with an electrode. The rough cut removes large parts of the workpiece. After this first step, the workpiece is machined again using different machining conditions and electrodes. The number of finish cuts required can be just one or several, depending on the desired shape. This machining method cannot prevent shape error problems completely because the finish cuts also have electrode wear.



(a) Die-sinking EDM



(b) ED-milling

Figure 11 Finish cut processes using new electrodes

2.4.3 Long pulse-on time in kerosene

In a general EDM process using a die-sinking EDM machine and kerosene, a practical method for reducing electrode wear is available. The key is to set up machining with positive electrode polarity and long pulse-on time [4, 9, 10]. When discharge sparks flow through kerosene, carbon is generated in the working fluid as shown in figure 12. The carbon is deposited on the electrode surface and forms a layer. This carbon layer protects the electrode surface from the high temperature of the discharge sparks. Although this machining condition reduces electrode wear, positive polarity of an electrode usually removes workpiece material at a lower machining speed than when there is negative electrode polarity. Moreover, the machined surface becomes rougher due to the high discharge energy of a long pulse-on time. This machining condition is generally applied to the rough cutting process of die-sinking EDM and is an option when the electrode material is copper or graphite.

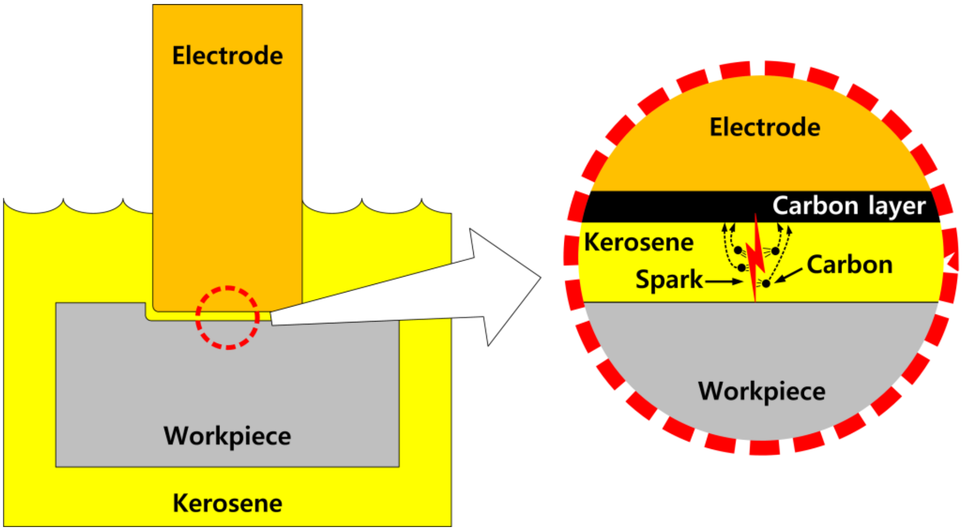


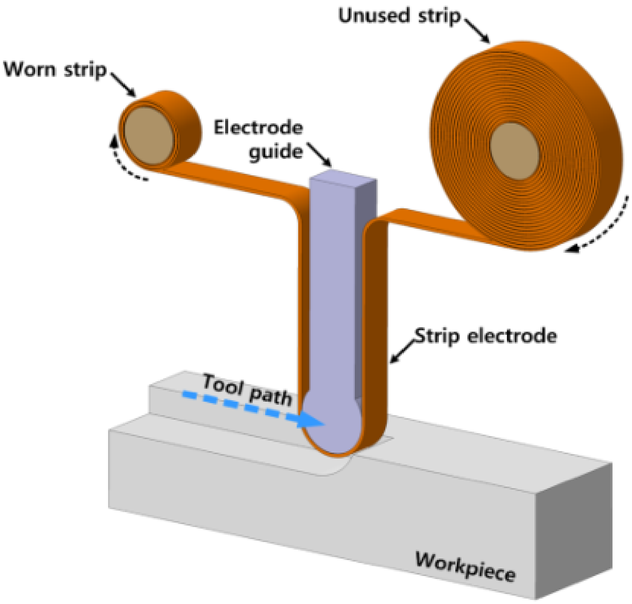
Figure 12 Low wear process in general EDM

3

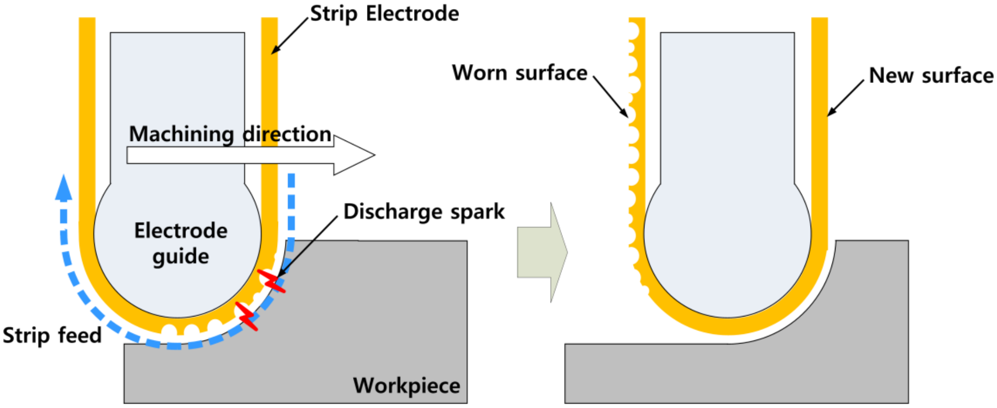
Development of the Strip-EDM System

Wear compensation is important for completing the EDM process without causing problems due to electrode wear. In fact, it is impossible to obtain an electrode wear value of zero, but it is possible to simulate zero electrode wear if a special type of EDM is used. Wire EDM is not a concern with wear problems. A new wire electrode is supplied continuously and the worn wire is immediately removed from the machining gap. However, wire EDM can only make contour parts or die shapes from a workpiece. Grooves or molds that are blind pockets can be machined using die-sinking EDM or ED-milling, which have problems related to tool electrode wear [17].

Strip EDM can overcome electrode wear problems in a general ED-milling process. In this method, the tool electrode consists of an electrode guide and a conductive strip. The strip travels continuously on the surface of the electrode guide and discharges sparks in the gap between the surfaces of the strip and the workpiece. Figure 13 (a) illustrates the concept of the strip EDM. During the machining process, the worn surface of the strip is immediately replaced with a new unworn surface, as shown in figure 13 (b). Electrode wear occurs mainly on the surface in the direction of the tool path. In strip EDM, the tool electrode can continuously maintain a new surface by a continuous-feed strip. As a result, the strip-EDM process is not a concern with electrode wear, much like the wire-EDM process. Also, the suggested machining method does not require compensation of tool path or a new electrode for a finish cutting process. In this study, the strip-electrode system uses a wire-EDM machine. Since water is the working fluid, the EDM process can achieve high machining speed compared to general EDM.



(a) The concept of the strip EDM



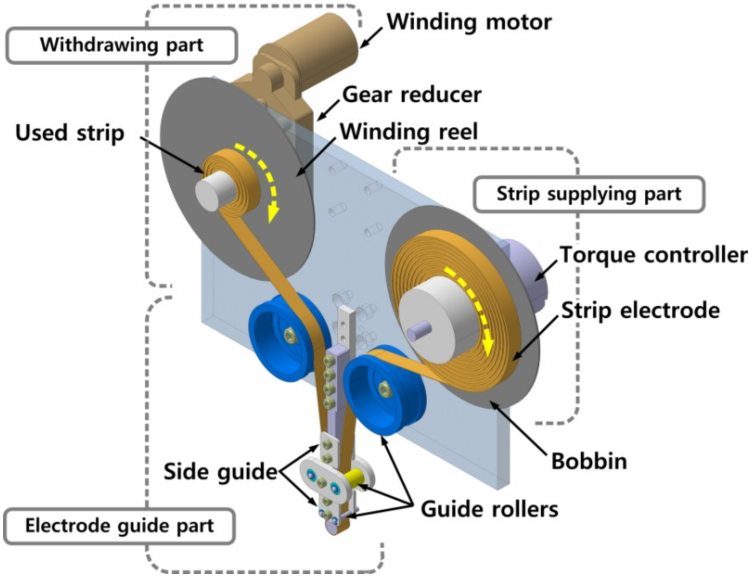
(b) The machining process

Figure 13 The principle of the strip EDM

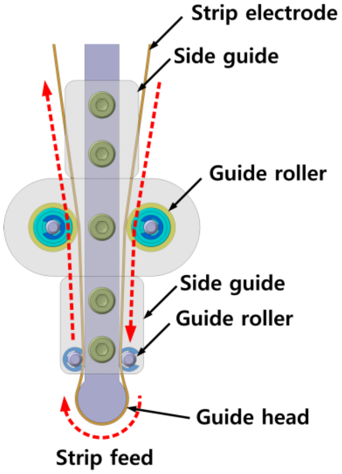
3.1 Development of the strip-electrode system

Strip EDM is a combination of general EDM and wire EDM. The electrode guide system serves as the block electrode for general EDM and a strip on the guide acts as an electrode surface. It moves continuously, like a wire EDM. Figure 14 illustrates a strip-electrode apparatus designed in this study. It consists of 3 major parts: an electrode supplying part, an electrode guide part, and a withdrawing part. The electrode supplying part has a strip bobbin and a torque controller as shown in figure 15 (a). The thin strip winds around the bobbin that is connected to the torque controller. It creates a momentary resistance from running opposite to the rotational direction of the bobbin and prevents wrinkling of the strip electrode. The strip travels from the bobbin to the winding reel through the electrode guide part. The electrode guide part consists of several guide rollers, side guides, and a guide head as shown in figure 15 (b). The guide rollers prevent vibration of the strip and the side guides prevent derailment from the guide head. The head is a semicircle with a 5 mm radius, allowing the strip to slide smoothly across the surface of the guide. The material of the guide is duralumin and is connected to the power source of the EDM machine. The guide also acts as a connecter between the strip electrode and the power source. Figure 15 (c) shows the withdrawing part with a DC motor, a reducer, and a winding reel. The winding motor drives the winding reel and defines the feed speed of the strip electrode during machining. The feed speed is in the range of 2 mm/s to 8 mm/s, which is the operative capacity of the motor and the motor controller. The specifications of each mechanical element are listed in table 1.

The developed electrode system is installed on a wire-EDM machine. The electrode unit is set on the Z-column of the machine and moves relative to the workpiece. The workpiece is submerged in the working fluid of a work tank. Since the electrode apparatus does not need to be fully submerged, only part of the guide head is submerged in the working fluid. During the machining, deionized water is injected into the machining gap between the electrode and workpiece through a nozzle. Figure 16 shows the completed setup of the strip-EDM system on the machine.

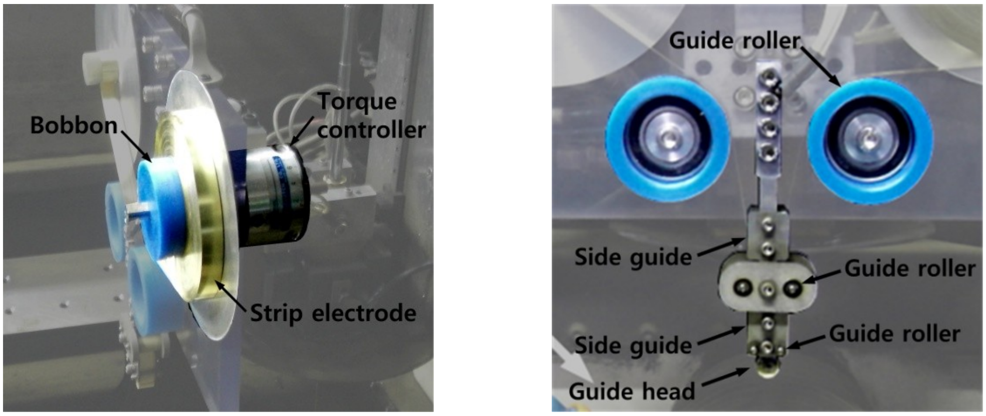


(a) Schematic of strip-electrode apparatus



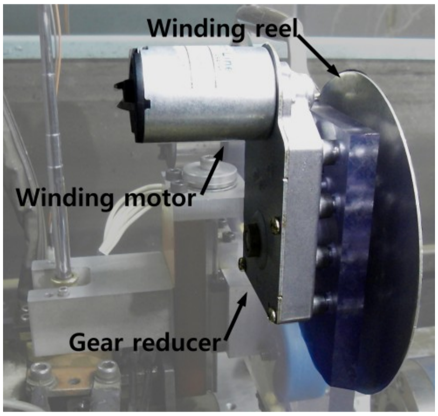
(b) Electrode guide part

Figure 14 The strip-electrode apparatus designed in this study



(a) Strip supplying part

(b) Electrode guide part

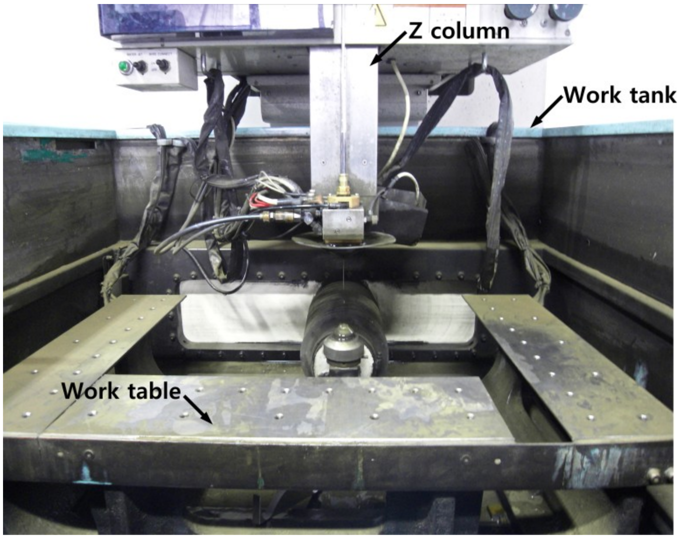


(c) Withdrawing part

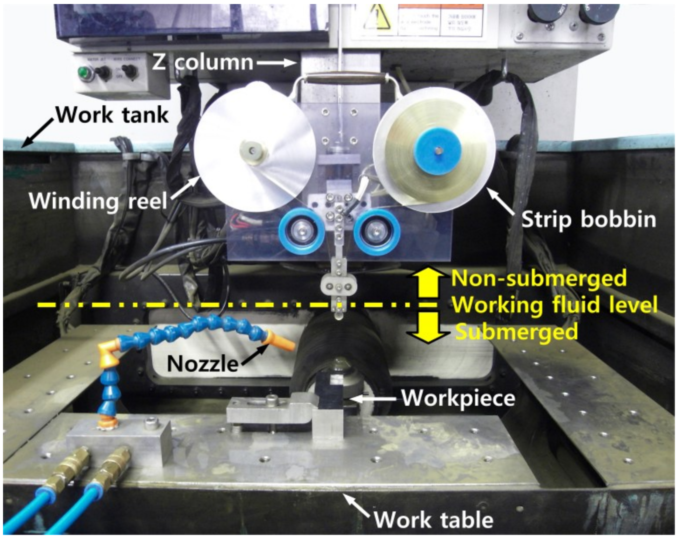
Figure 15 Three major parts of the strip-electrode system

Table 1 Specifications of parts in the strip-electrode apparatus

Part name (Model, maker)	Specification
Motor (MF56-3448-GM, Motor Line Co., Ltd.)	DC +24 V 5000 RPM
Reducer	Reduction ratio: 1/750
Motor controller (DC200C-24VC, Sunjin Motor Tech Corp.)	PWM type control circuit Output: + 24 V pulse
Torque controller (PHT 1.2D, Ogura Clutch Co., Ltd.)	Torque gain: 0.2~0.7 $g_f \cdot$cm/RPM



(a) Before setup



(b) After setup

Figure 16 Setup of a strip-electrode apparatus on the machine

3.2 Machining system used in this study

A commercial wire-EDM machine (EZ20S, SPM Co., Ltd.) was modified for the experiments. Figure 17 is the machine used in this study. The detailed specifications of the machine are listed in table 2. The developed strip-electrode system is attached to the Z-column of the machine, and the workpiece is clamped onto the work table in a tank. All axes are moved by a computer numerical controller (CNC) and the resolution is 1 μm. The working fluid is deionized water, which is typically used for a wire EDM. A nozzle is used to inject the water into the machining gap between the workpiece and the tool electrode. Waste water is reused after filtering and completion of the deionization process. Figure 18 illustrates the total machining system used in this study. The discharge power source consists of two electrical systems: a detecting pulse circuit and a main power source. The electrode approaches the workpiece and the detecting pulse circuit generates bipolar pulses, as shown in figure 19 (a). The bipolar pulse is suitable for preventing corrosion when deionized water is used [32-34]. The pulse was 12.8 kHz with a voltage of +140 V and -80 V. The main power source supplies a high current for the machining when the discharge spark occurs. Figure 19 (b) shows the diagram and the waveform of the main discharge spark during the machining process.

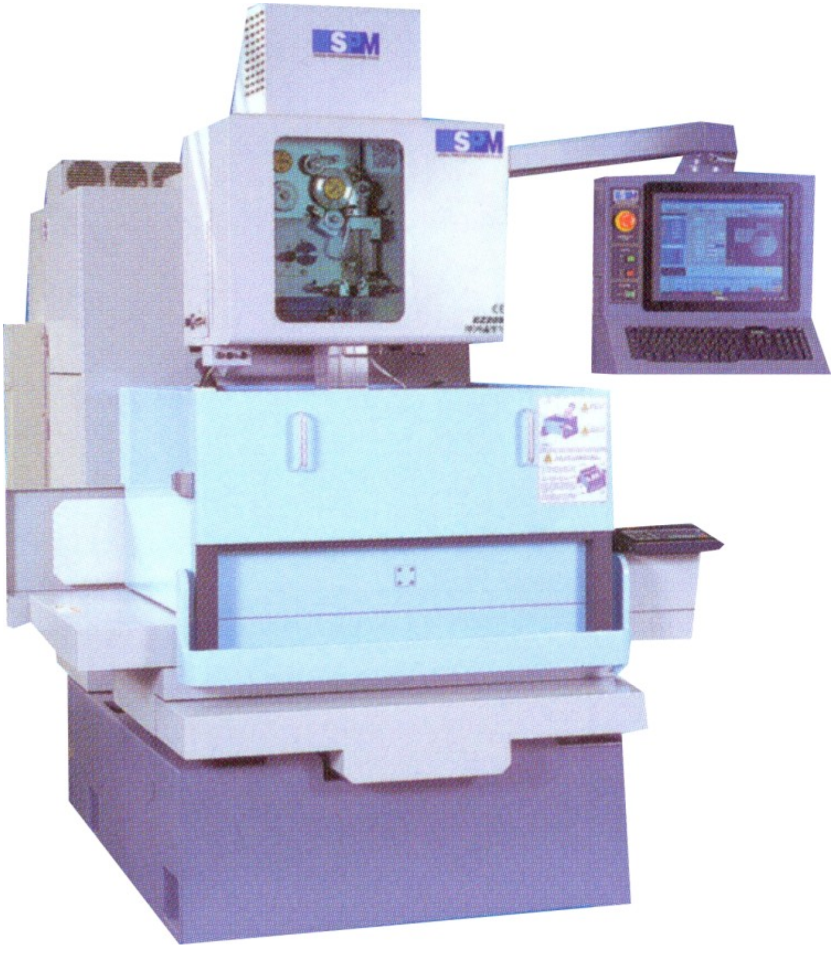


Figure 17 The EDM machine used in this study (Courtesy SPM Co., Ltd.)

Table 2 Specifications of the wire-EDM machine used in this study

Model	EZ 20S
Maker	SPM Co., Ltd.
Size of table	784 mm x 466 mm
X, Y, Z stroke	500 mm x 300 mm x 260 mm
The maximum speed of table	1300 mm/min
The maximum capable load on table	600 kg
The maximum capable size of workpiece	700 mm x 450 mm

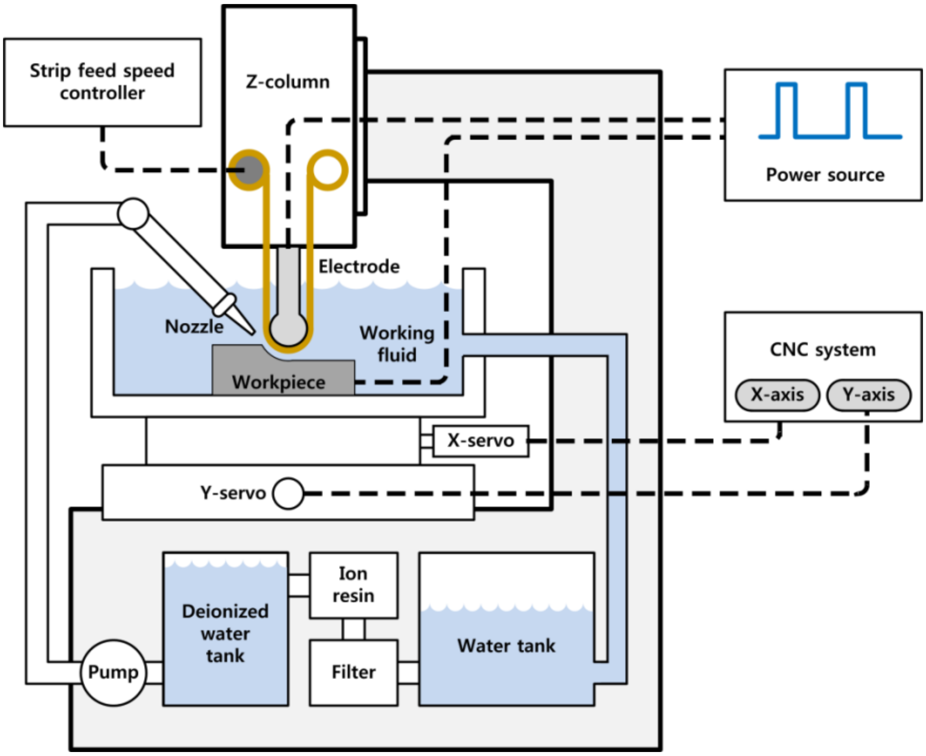
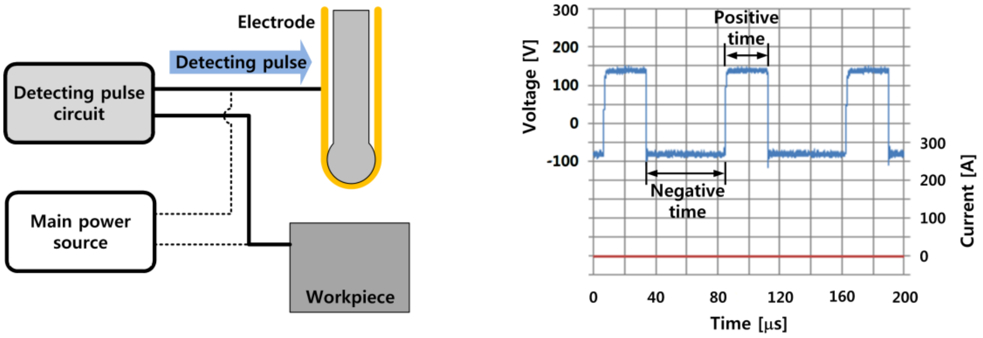
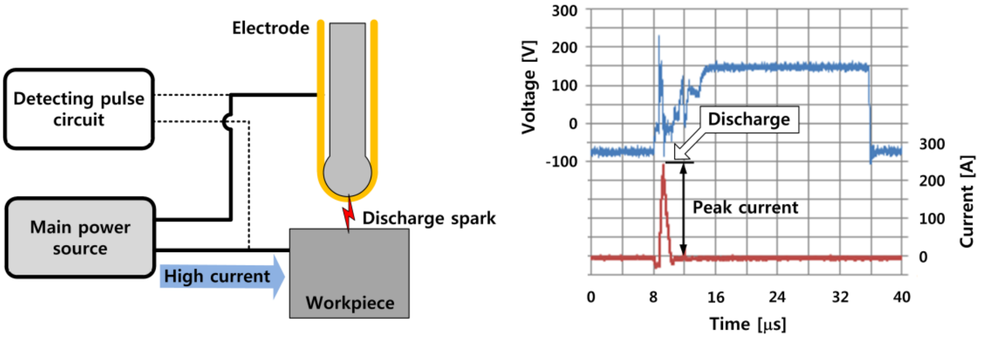


Figure 18 Schematic of machining system used in this study



(a) Operation of the detecting pulse circuit and its waveforms



(b) Operation of the main power source and its wave forms

Figure 19 The electrical power system of the machining system

4

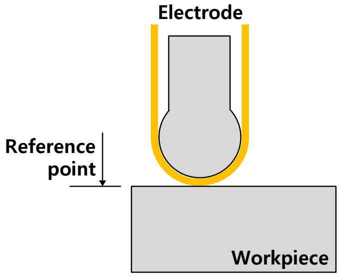
Strip EDM for the Milling Process

ED-milling is a useful process to machine a workpiece using a simple shape electrode. In a general EDM process, electrode wear causes shape error on the machined part as shown in figure 10 (a). As mentioned in chapter 2, there are some practical solutions: create a compensative tool path, finish the cut with new electrodes, or implement a long pulse-on time with kerosene. However, these methods cannot perfectly prevent electrode wear. On the other hand, wear problems are not a concern with strip EDM. While electrode wear does occur on the surface of the strip, the worn surface is immediately and continuously replaced with a new surface during machining. Therefore, the strip EDM does not require additional processes to correct wear problems.

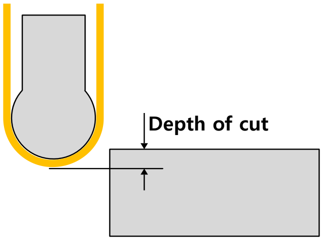
In this chapter, the strip-EDM method is discussed as applied to ED-milling. Machining characteristics such as material removal rate (MRR), surface roughness, arc problem, and size effect are investigated according to machining conditions. The major machining conditions of interest here are strip material, discharge energy, strip feed speed, and machining area. Finally, the machining results are compared to the general EDM method.

4.1 Milling procedure

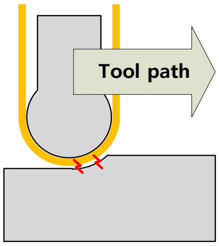
Figure 16 (b) shows the system setup of strip ED-milling. The workpiece is fixed on the work table of the machine and the strip-electrode apparatus is attached vertically on the Z-column. Before beginning the machining process, the electrode guide is moved to the desired cut depth. The reference position is defined by the top surface of the workpiece touching the bottom surface of the strip electrode. After that, the electrode moves along the tool path. During the machining process, the servo system of the machine controls the gap distance between the surface of the electrode and the workpiece to prevent a short circuit which results from contact between the electrode and the workpiece. Figure 20 illustrates the experimental process in this study.



(a) Defining a reference zero-point



(b) Move to a depth of cut



(c) Beginning machining

Figure 20 Process of strip ED-milling

4.2 Machining conditions in strip ED-milling

The strip electrodes used were composed of two different materials, copper and brass. The thickness of each strip was 0.1 mm and the width was 10 mm. The strip feed speed was 2 mm/s, which is the minimum feed speed of the withdrawing system. The workpiece material was stainless steel 304 and was submerged in a working fluid. Deionized water was used as the working fluid and was injected into the machining gap between the electrode and the workpiece. The resistivity of the deionized water was 2.3 MΩ·m. The power source generates bipolar pulses of 12.8 kHz. The pulse condition consists of a positive time of 28 μs with +140 V and a negative time of 50 μs with -80 V. During sparking, high current flows occurred in the discharge gap. The peak current is in the range of 95 A to 320 A. The machining conditions used in the experiment are detailed in table 3.

Table 3 The machining conditions of strip ED-milling experiments

Strip electrode materials	Copper or Brass
Workpiece material	Stainless steel 304
Working fluid	Deionized water (Resistivity: 2.3 MΩ·m)
Open-gap voltage	-80, 140 V
Positive time	28 μs
Negative time	50 μs
Peak current	95, 145, 240, 320 A
Depth of cut	1, 2, 3, 4 mm

4.3 Effect of electrode material

Copper and brass are widely used for EDM electrodes. In order to investigate machining characteristics that exist with the use of different electrode materials, milling experiments were conducted using a depth cut of 1 mm.

4.3.1 Material removal rate

Figure 21 shows MRR according to peak current. It indicates the discharge energy of a spark because the discharge energy is defined by the value of the peak current. The MRR increased with increased peak current. Since the copper electrode was used, MRR was higher. There is less electrical loss during the discharge process because copper has a higher electrical conductivity than brass. This means that the actual spark strength of the copper electrode is higher than that of brass. Therefore, the quantity of material removed from a workpiece is significant. However, the peak current could not be increased above 240 A because the copper strip was used. The copper made it easy for an arc discharge to occur [13]. Figure 22 shows the machined surface of the workpiece and the used surface of the copper strip. The arc welded the electrode surface and the machined surface on the workpiece. Consequently, the EDM process did not advance due to an overabundance of shorts and the strip was derailed off of the electrode guide. In contrast, the brass strip could bear over 240 A because of stable discharge conditions in the machining gap.

Brass is a suitable electrode material for EDM when water is used as the working fluid [13]. Although the brass electrode caused a lower MRR, the peak current could be increased to over 240 A. As a result, the MRR could be larger than with a copper electrode because of the higher current peak.

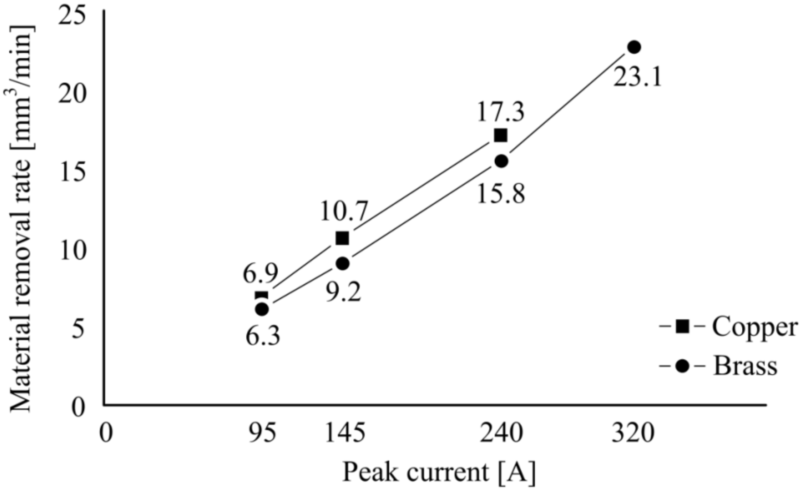


Figure 21 Material removal rate according to peak current

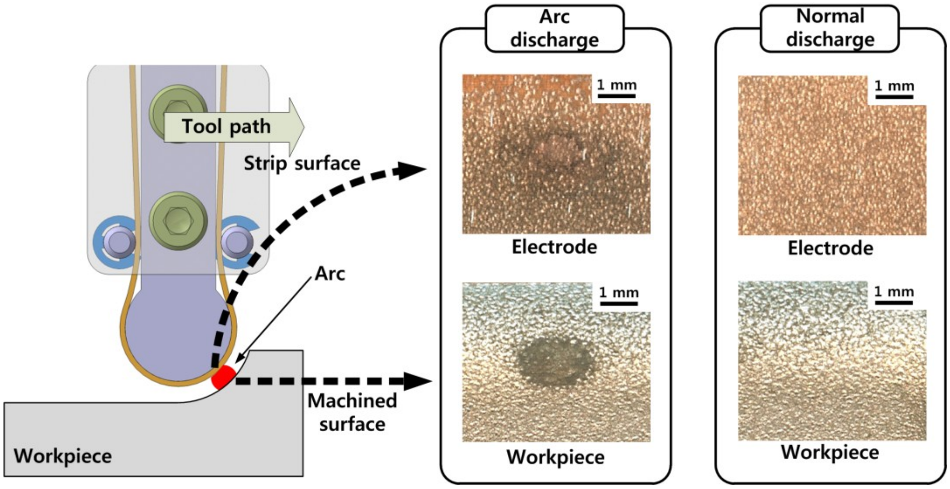


Figure 22 The arc problem with a copper strip

4.3.2 Surface quality

Surface roughness is one of the important factors used to appraise the quality of an EDM machine. The surface roughness of the machined portion was measured by a non-contact 3D surface profiler (NANO View-E1000, Nano system Co., Ltd.). The measured results are displayed in figure 23. The error bars indicate the maximum and minimum values. As the peak current increased, the surface became rougher. The higher discharge energy caused large craters on the machined surface. Therefore, the value of surface roughness was large when the electrical condition generated a high peak current [35]. Under the same electrical conditions, a smoother surface was achieved using the brass strip. As mentioned in section 4.3.1, the actual spark strength is smaller for brass, since using the brass strip results in more electrical loss.

Figure 24 and 25 show the machined surfaces according to the electrode materials with peak current of 240 A. With the copper strip, the corners of the machined portion showed red discoloration, as shown in figure 24 (a). To check the elements on the surface, energy-dispersive X-ray spectroscopy (EDS) analysis was used. Figure 24 (b) shows the results of the analysis. Copper, which is the major element of the electrode, was detected on 40% of the part, in addition to the workpiece components that are mainly made of iron and chrome, which consist of stainless steel 304. The copper, which is easy to deposit electrolytically, was attached at the machined surface because a strong electrical field forms at the edge of the electrode [36]. In comparison, the brass strip did not discolor the machined surface. Copper was detected on only 4% of the part, as shown in figure 25. The copper was released from the electrode material due to the discharge sparks. Before machining, there was no copper on the workpiece, as shown in figure 26.

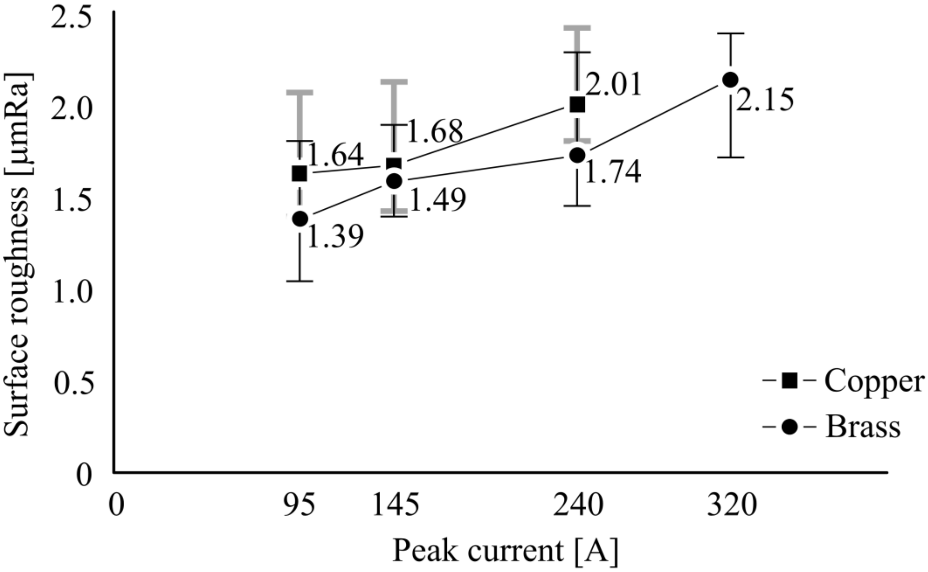
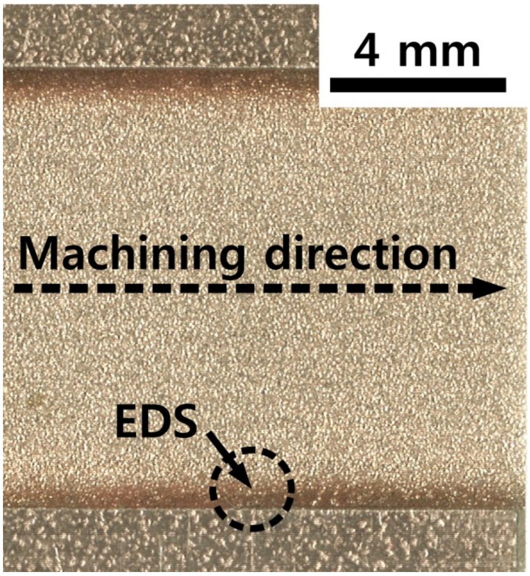
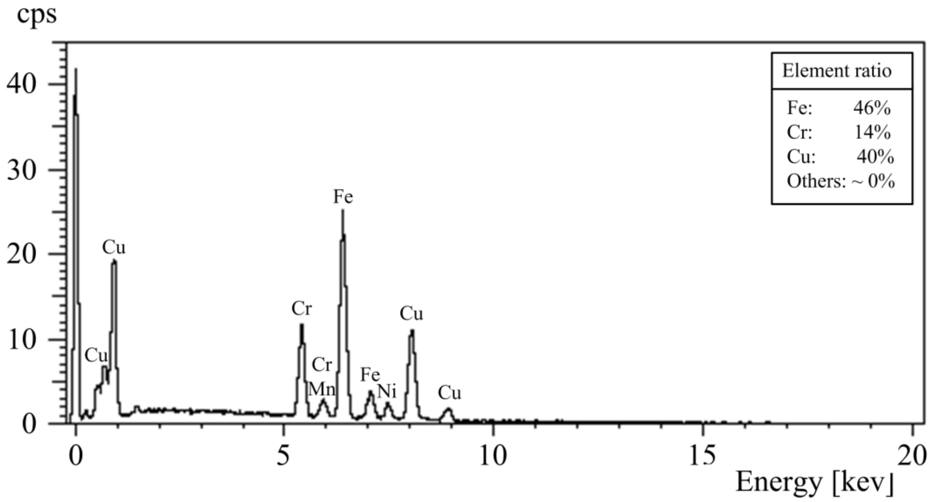


Figure 23 Surface roughness according to peak current

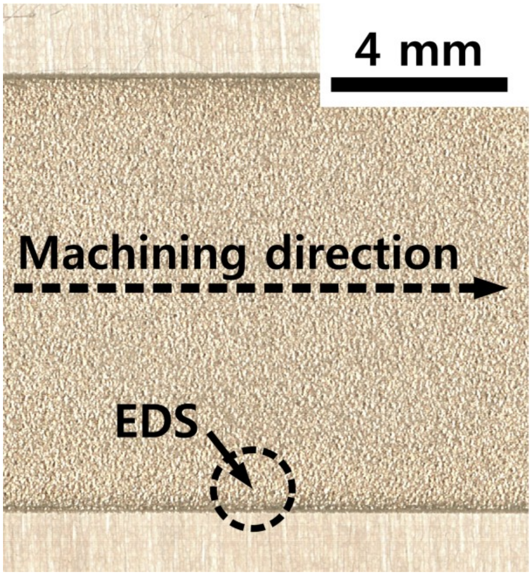


(a) Machined surface on the workpiece

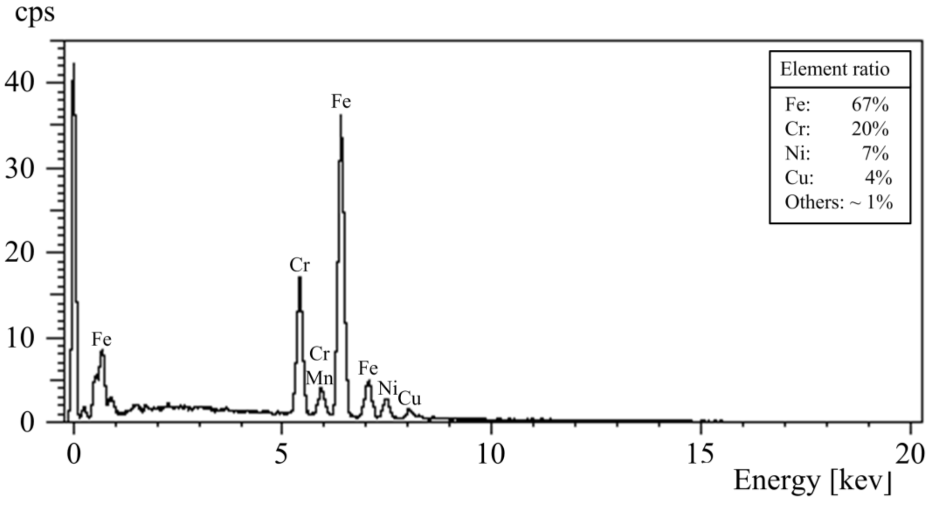


(b) The EDS analysis of (a)

Figure 24 Machined surface using a copper strip



(a) Machined surface on the workpiece



(b) The EDS analysis of (a)

Figure 25 Machined surface using a brass strip

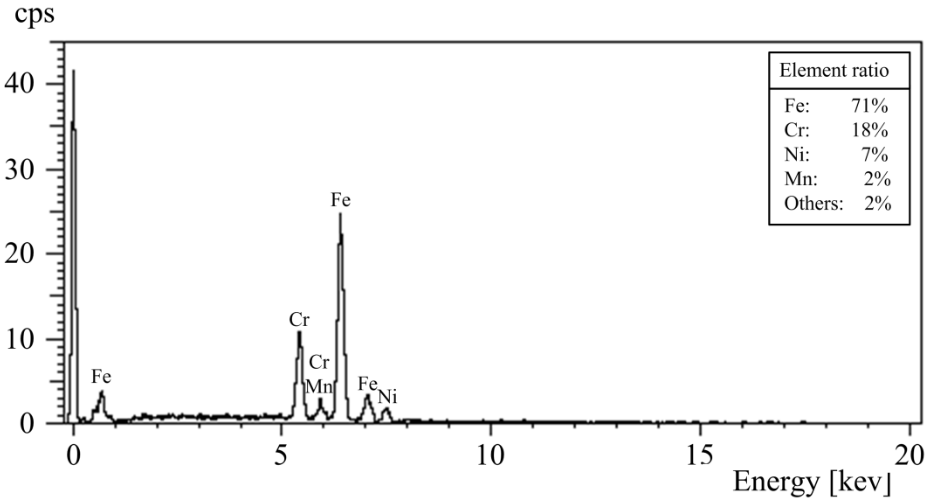


Figure 26 EDS analysis of initial surface of a workpiece

4.4 Effect of strip feed speed

The strip electrode moves on the guide during machining. Machining tests were conducted at various strip feed speeds to investigate machining characteristics at different strip feed speeds. The speeds ranged from 2 mm/s to 8 mm/s. A brass strip was used and the peak current was 320 A (table 3).

Figure 27 shows the results. The machining characteristics, such as MRR and surface roughness, were not significantly affected by the strip feed speed. Therefore, the low speed is more desirable from a practical point of view, as it will conserve electrode materials. In this research, the minimum feed speed is 2 mm/s of the withdrawing system.

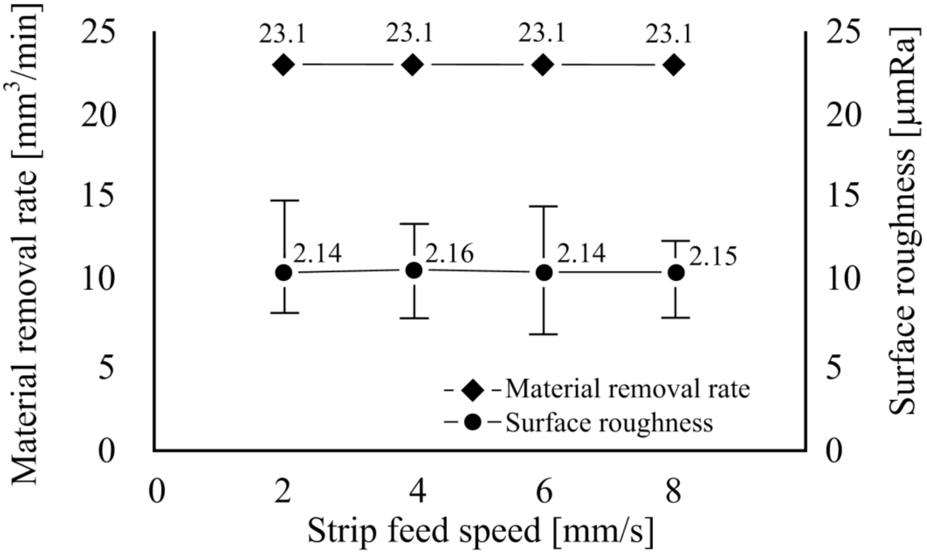


Figure 27 Effect of strip feed speed

4.5 Effect of machining area

The MRR can vary according to machining area, even when the same electrical conditions are applied to the electrode and workpiece. This characteristic is the area effect [13, 37]. In this section, the area effect of the strip EDM was investigated according to discharge energy.

4.5.1 Principle of area effect

Each electrical condition of the EDM process has an optimal machining area for achieving the highest MRR possible. The machining area is the sparking area on the electrode. The MRR decreases as the machining area varies from the optimal area value [13]. This trend can be displayed in a diagram and it is the area effect curve shown in figure 28. The machining speed increased rapidly with an increase in the machining area until the optimal point was reached. Past the optimal point on the effect curve, the machining speed decreased slowly. Low electrical energy causes a small optimal area and high electrical energy causes a large optimal area. Therefore, high electrical energy does not always cause an MRR that is higher than lower electrical conditions. The machining speed with low discharge energy is somewhat better than conditions with greater discharge energy when the machining area is small.

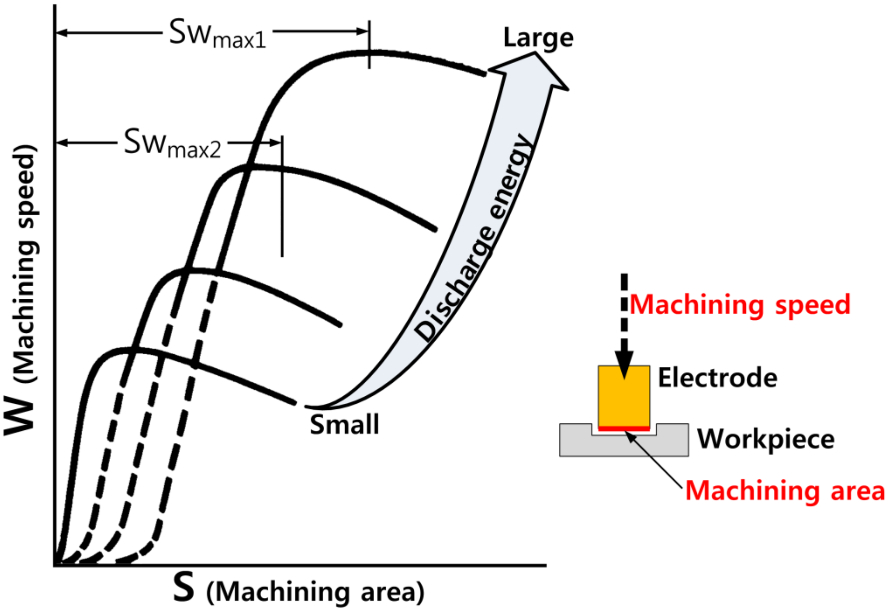


Figure 28 Area effect curve [13] (redrawn)

4.5.2 Area effect of strip ED-milling

The machining area on the electrode is defined by several factors as shown in figure 29. The area is calculated by the following equation:

$$A = (R+t)w\left(\cos^{-1}\frac{R+t-D}{R+t}\right) \tag{4.1}$$

In this research, the thickness and width of the strip were constant. The thickness was 0.1 mm and the width was 10 mm. In order to investigate area effect of the strip EDM, three major factors were considered: depth of cut, radius of the guide, and machining width. The actual experiments used the machining conditions with a brass strip and a peak current of 320 A (table 3).

The machining experiments were conducted according to the depth of cut. The calculated machining area increased as the depth of cut was increased, as shown in figure 30. The depth of cut considered was between 0.25 and 4 mm. The machining results are presented in figure 31. The MRR increased rapidly until MRR reached 23.1 mm^3/min, the maximum point for a 1 mm cut depth. After reaching the 1 mm depth of cut, the MRR decreased slowly.

The second set of machining experiments considered the radius of the guide. The machining area increased as the guide radius increased, while the depth of cut remained constant. Figure 32 illustrates the relationship between the machining area and the guide radius. These experiments used a guide radius of 5 mm. Additional machining tests used a radius of 7.5 mm and 10 mm. The resulting MRR according to guide radius is shown in figure 33. The results for a 5 mm radius (as shown in figure 31) are marked as gray points and the new results are marked as black square points on the graph. The MRR decreased slowly and showed a decreasing trend after reaching the maximum value.

The last consideration was the width of machining. In this research, the width of the strip was constant at 10 mm. In order to investigate the effects on MRR relative to machining width, the workpiece width was changed, rather than the strip (figure 34). The workpiece width ranged from 2 mm to 8 mm. The machining results are plotted in figure 35. Previous results are marked by gray points and the new results are marked by black square points on the graph. As shown in the results, the MRR decreased following the area effect curve.

With the above three experiments, the area effect curve can be completed as shown in figure 36 (a). The maximum MRR is 23.1 mm^3/min and the optimal area is 32.5 mm^2 at the maximum MRR. The area effect curves under different conditions were completed as shown in figure 36 (b) and (c). When the peak current was 240 A, the maximum MRR was 16.8 mm^3/min, with the optimal area of 19.5 mm^2. In this machining area, the peak current of 140 A caused higher MRR than at 320 A, even though a small peak current was used. The peak current of 145 A had a lower maximum MRR and optimal area of 10.6 mm^3/min and 16.0 mm^2, respectively.

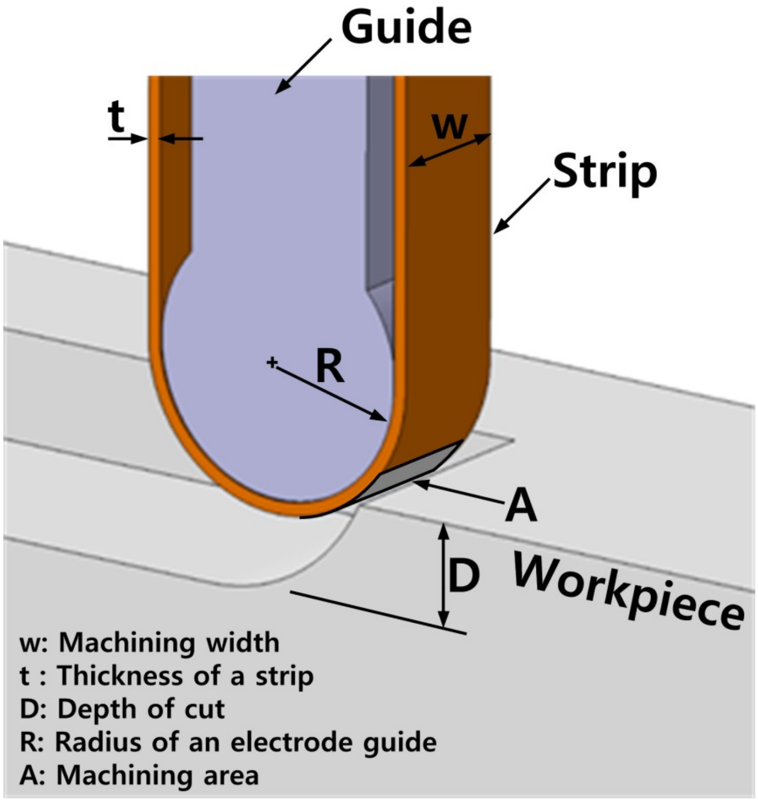


Figure 29 Machining area

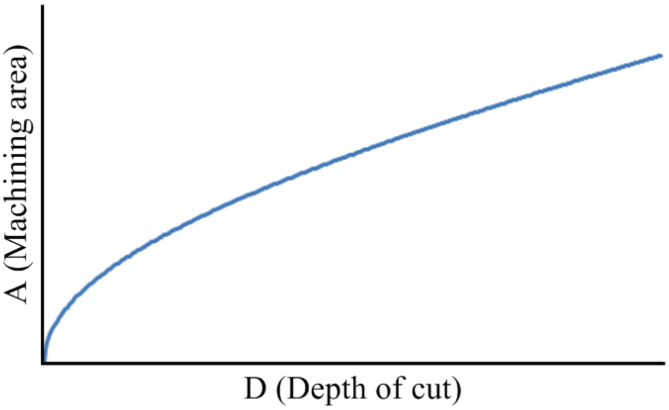


Figure 30 Machining area according to depth of cut

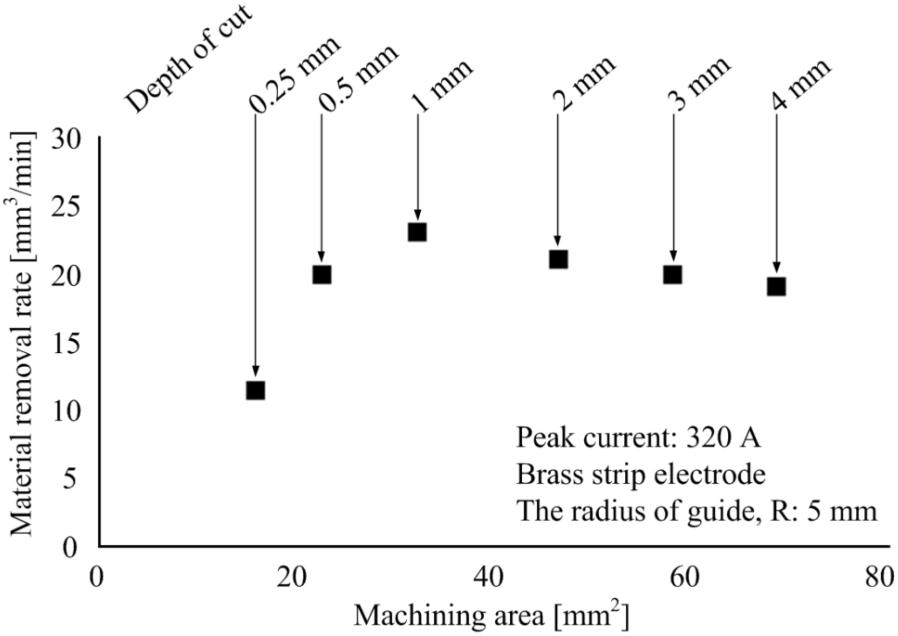
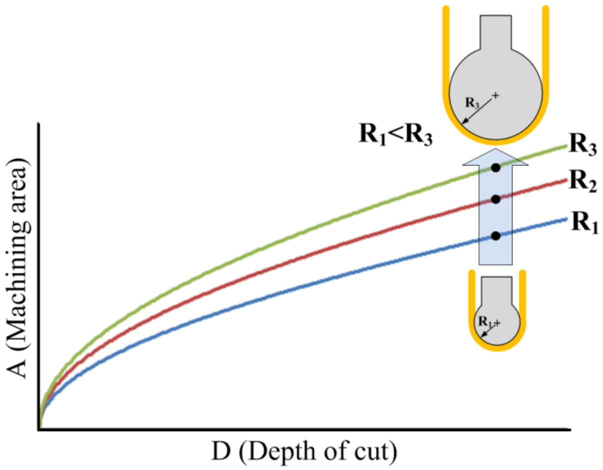
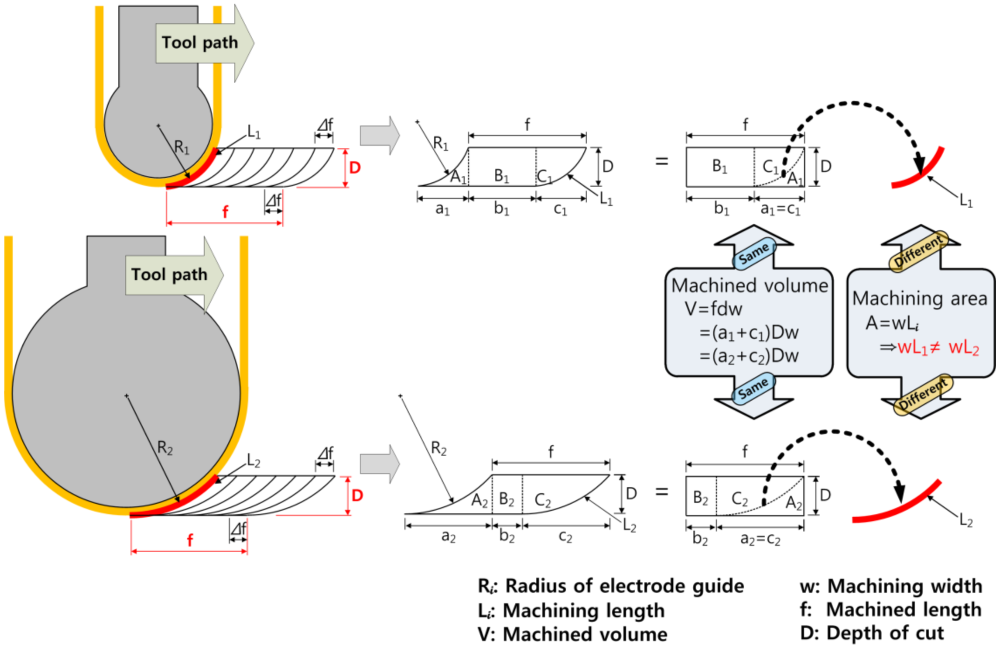


Figure 31 Material removal rate according to depth of cut



(a) Relationship between the machining area and the radius of guide



(b) Variation of the machining area in constant depth of cut

Figure 32 Machining area according to radius of guide

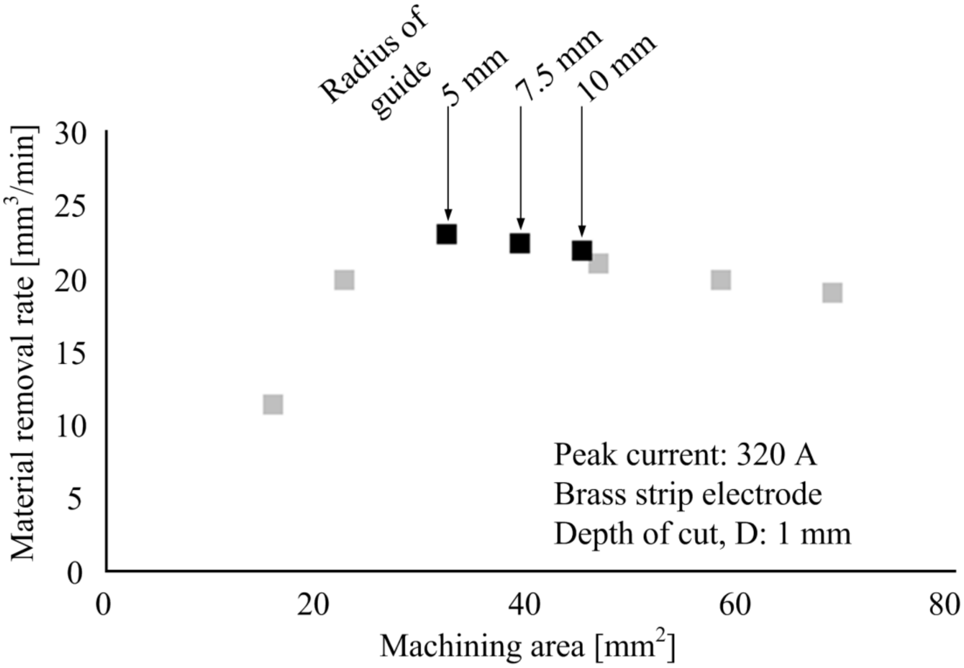


Figure 33 Material removal rate according to radius of guide

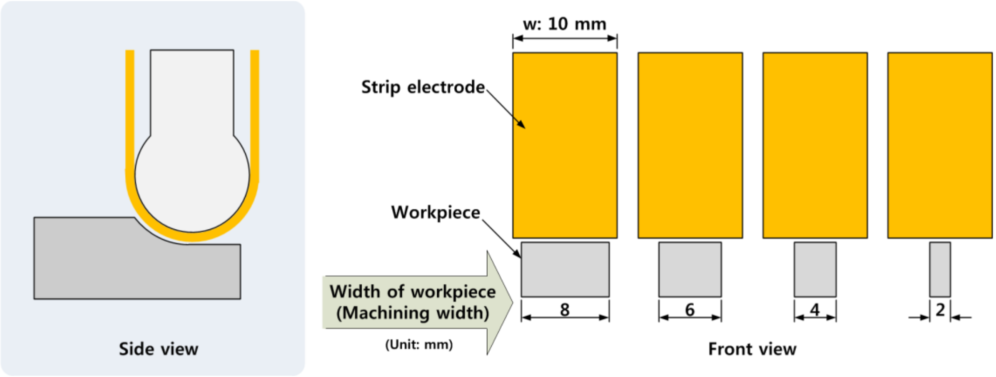


Figure 34 Experimental method for testing machining width

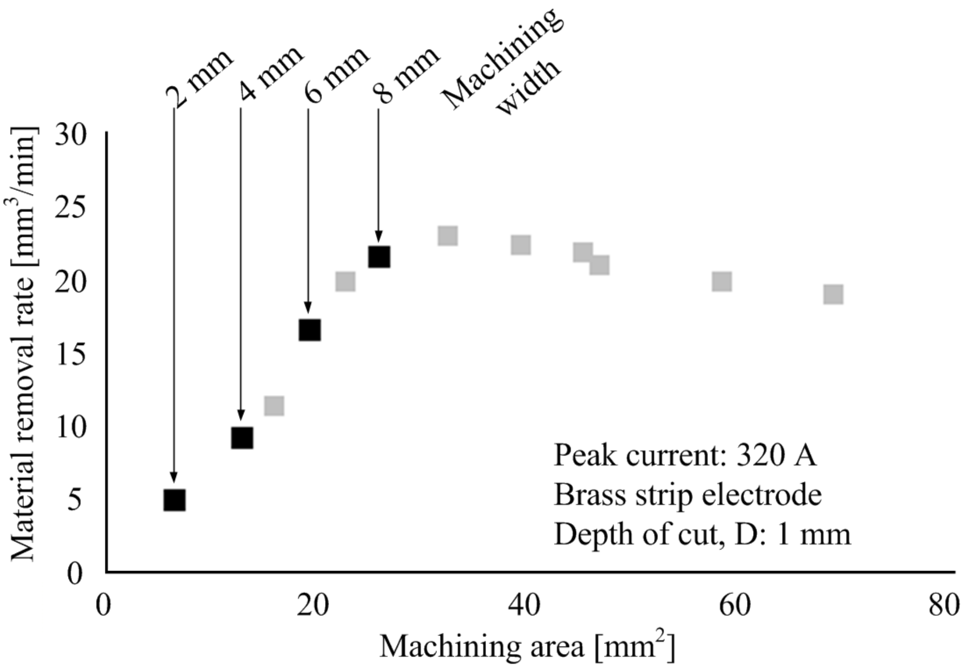
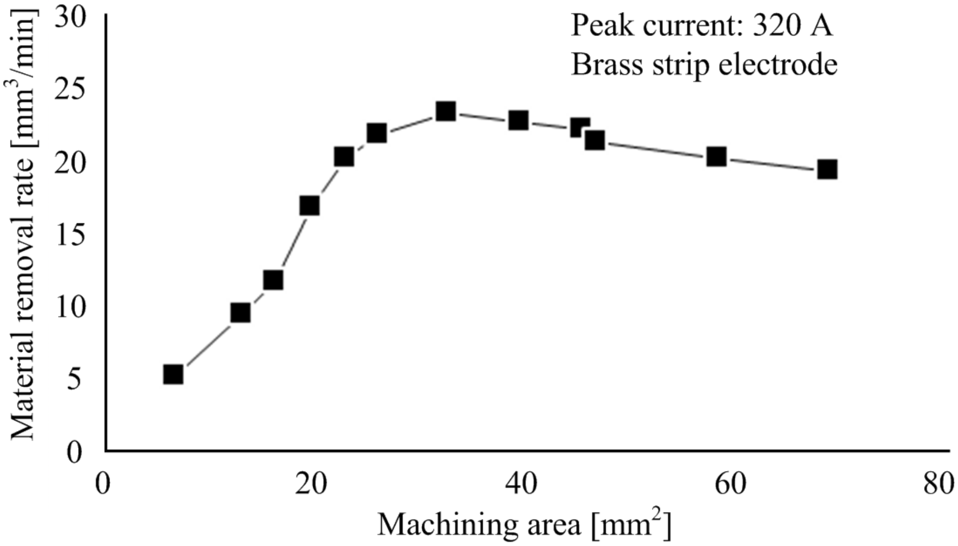
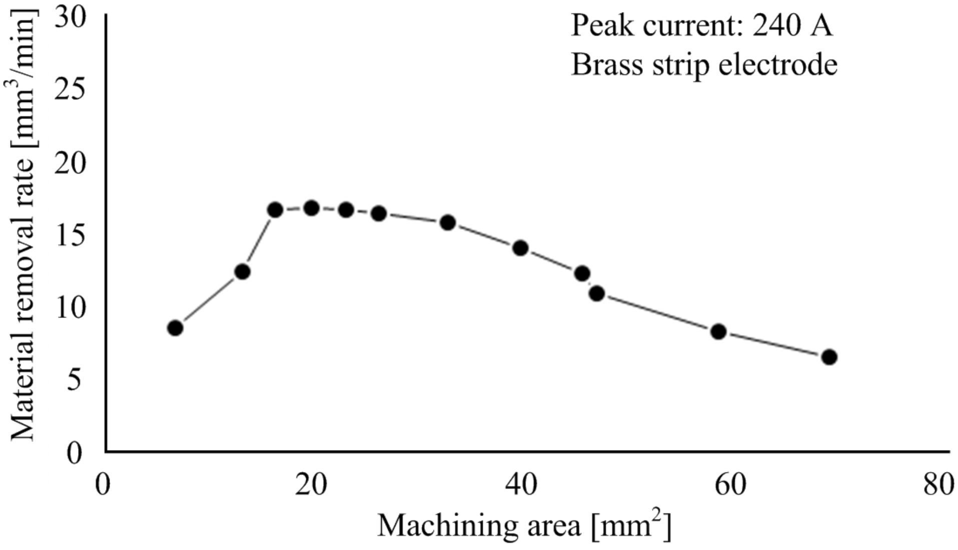


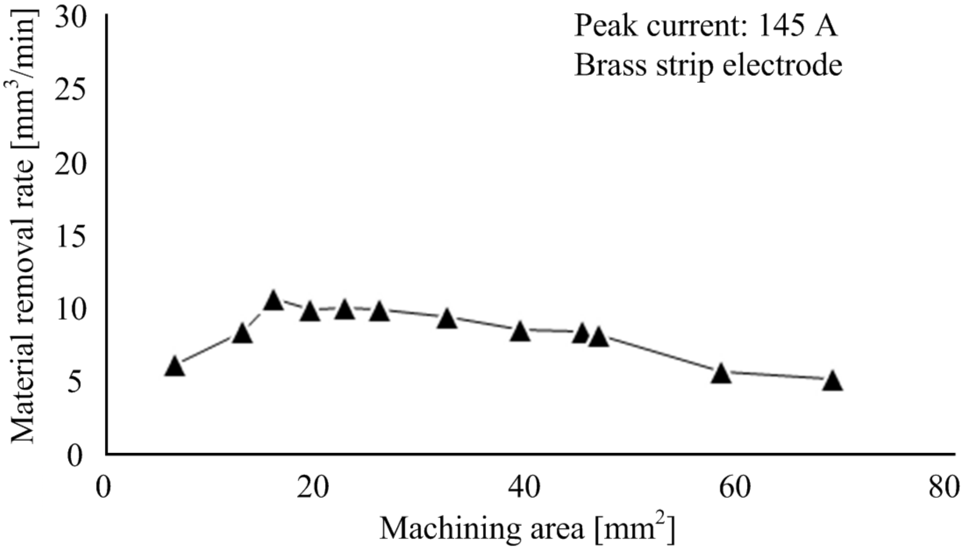
Figure 35 Material removal rate at different machining widths



(a) The area effect curve using a peak current of 320 A



(b) The area effect curve using a peak current of 240 A



(c) The area effect curve using a peak current of 145 A

Figure 36 Area effect curves at different peak currents

4.6 Comparison to general EDM

4.6.1 Use of block electrode

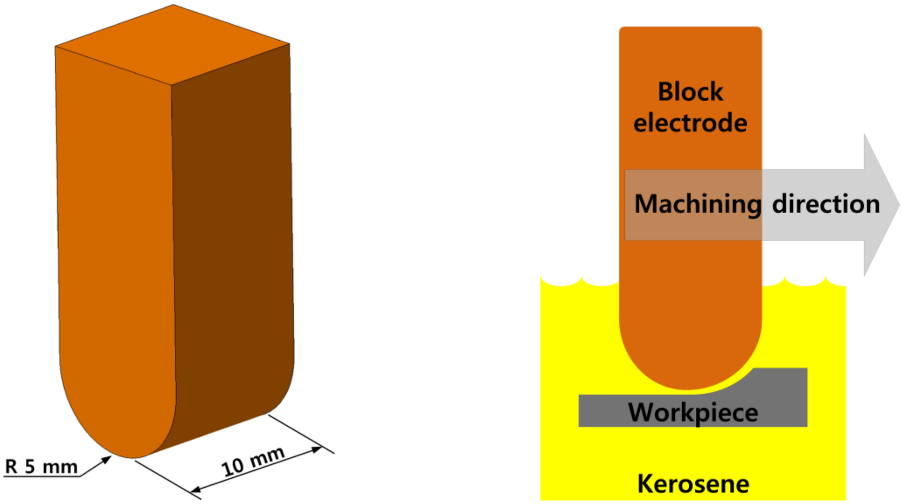
In a general ED-milling process, die-sinking EDM has been used with a copper electrode and kerosene as the working fluid. For the general ED-milling test, a commercial die-sinking EDM machine (MIC-432CS, Ecowin Corp.) was used. The electrode shape used in this study was the same used in the strip-electrode system, as shown in figure 37. The recommended electrical conditions, which were optimized by the machine maker, are applicable to minimum-electrode-wear machining. The condition had a long pulse-on time to reduce electrode wear, as mentioned in chapter 2. The detailed factors are listed in table 4. Using these machining conditions, a groove was machined with a 200 mm length. Figure 38 shows the electrode before and after the general ED-milling experiment. The part of the electrode that was exposed to the discharge area was worn. The electrode wear can be explained as a ratio of the volume of the electrode wear to the volume of the machined portion. In this experiment, it was difficult to directly measure the volume of electrode wear because the worn portion of the electrode was complex and small in shape. To ascertain the volume of the electrode wear, the difference between its weight before and after machining was determined using a precision scale (HM-202, A&D Co., Ltd.) with a resolution of 0.01 mg. The value was then converted to a volume measurement using the density value for copper. The electrode wear ratio of the ED-milling was determined to be 6.5%. In this process, long pulse-on time was required for low electrode wear. However, the machined surface became rougher due to high levels of discharge energy. Figure 39 compares the results from the general EDM method and the strip EDM method. The strip process used a peak current of 320 A. Although the peak current of the strip-EDM process was 16 times greater than for general EDM, the surface roughness of general EDM was rougher. The main reason for this difference is that the pulse-on time was long. Figure 40 shows the waveforms of voltage and current during a single discharge spark. Based on the measured waveform, the discharge energy can be calculated by the following equation.

$$\varepsilon = \int_0^{\tau_d} V(t) \cdot I(t) dt \qquad (4.2)$$

Where, ε is discharge energy and τ_d is the time for a single discharge. The voltage, *V(t)*, and current, *I(t)*, are variable over time. The calculated energy of the general process is 1.36×10^{-1} J, while the single discharge energy is 9.58×10^{-3} J for strip EDM. Therefore, the surface of the strip EDM process was smoother due to the low energy of a single discharge.

Although the strip EDM used a lower rate of discharge energy, its MRR was higher than the general process, as shown in figure 41. In the strip-EDM process, discharge occurred more frequently due to the high-frequency power source.

An additional machining test was conducted with a brass block electrode under the same conditions as for the strip EDM. All conditions were the same as those noted in table 3. The peak current was 320 A. The electrode size was the same as shown in figure 37 and the material used was brass, as for the strip electrode test. The electrode wear ratio was determined to be 327%. Under these machining conditions, electrode wear increased rapidly because there was no effect from the carbon layer. Figure 42 shows the brass electrode used in this machining test.

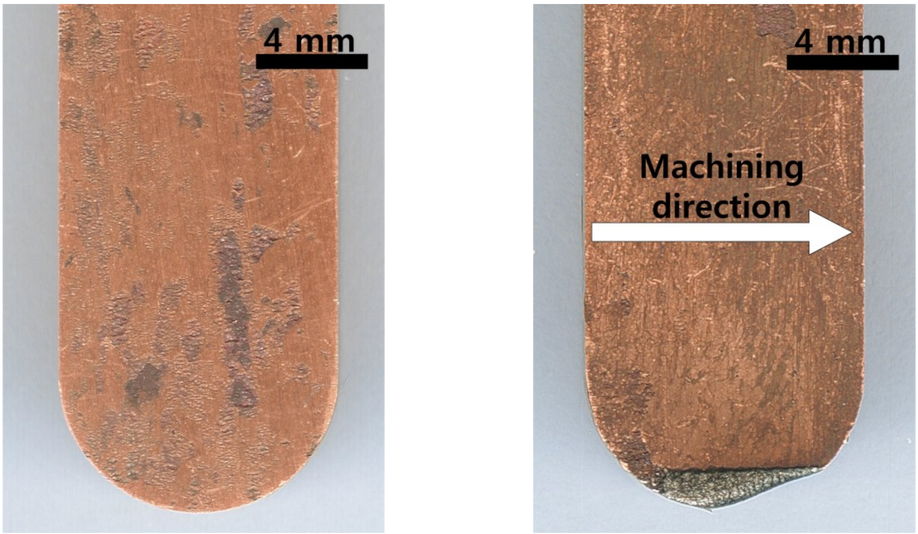


(a) The size of the electrode (b) A schematic of the machining

Figure 37 The electrode for the general ED-milling

Table 4 Machining conditions of the general ED-milling

Electrode Type	Block
Electrode Material	Copper
Working fluid	Kerosene
Open-gap voltage	200 V
Pulse-on time	200 μs
Pulse-off time	200 μs
Peak current	20 A
Workpiece	Stainless steel 304
Depth of cut	1 mm



(a) Before the machining (b) After the machining

Figure 38 The electrode wear of general ED-milling using kerosene

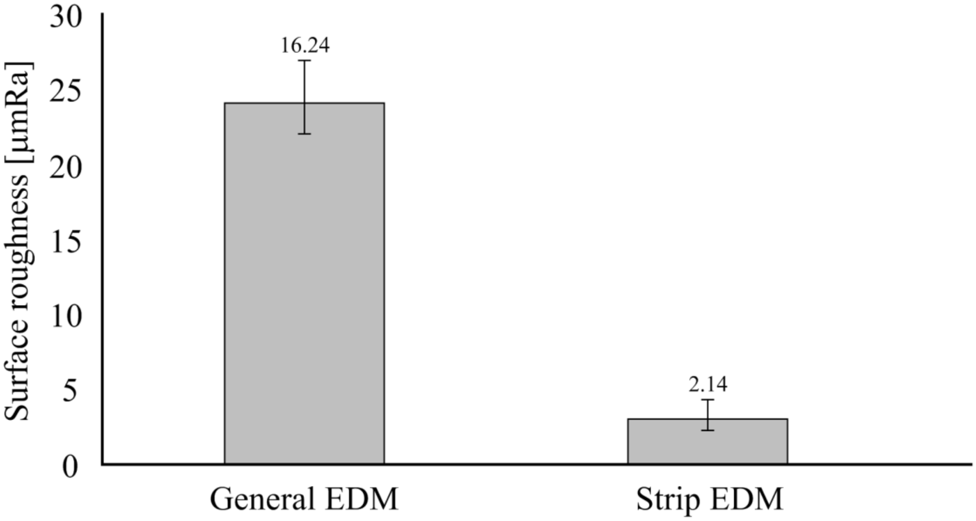
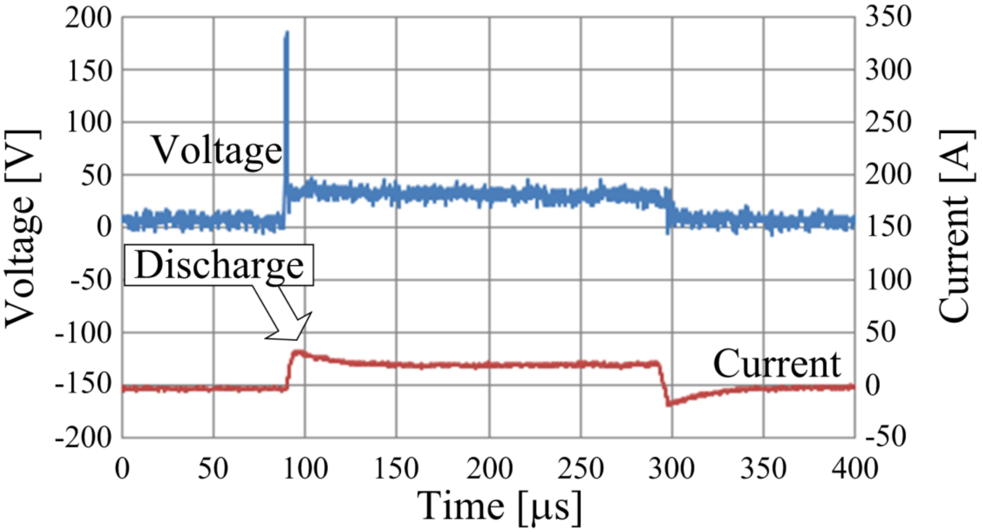
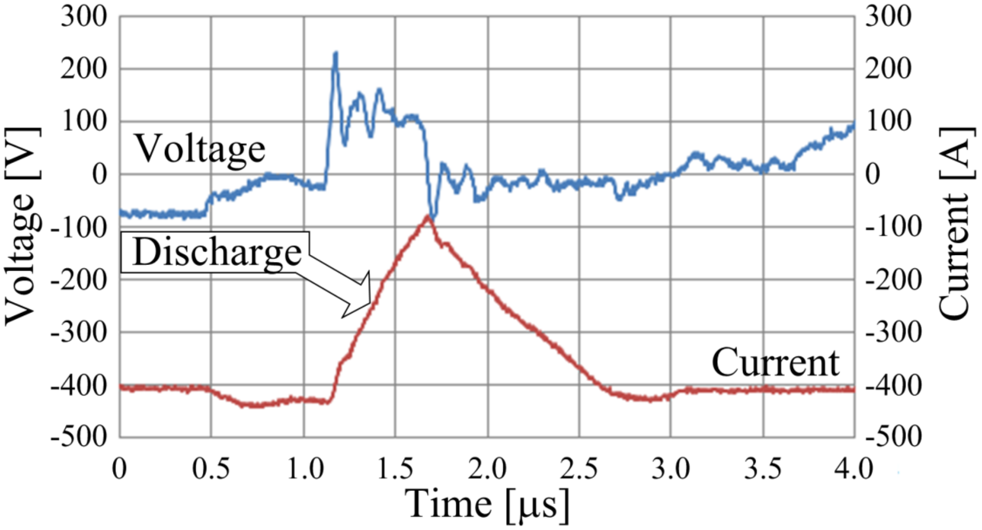


Figure 39 Surface roughness according to EDM method



(a) Waveforms of the general EDM



(b) Waveforms of the strip EDM

Figure 40 The voltage and current waveforms during a single spark

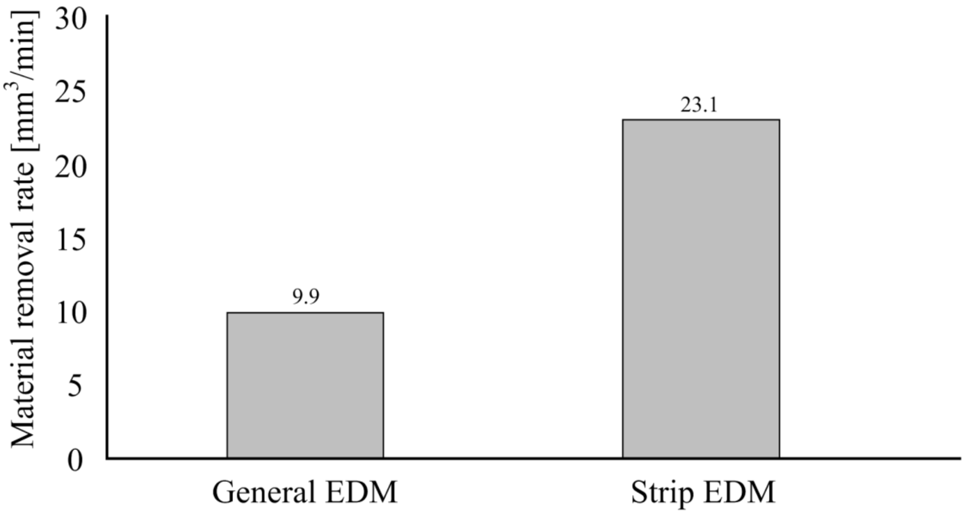
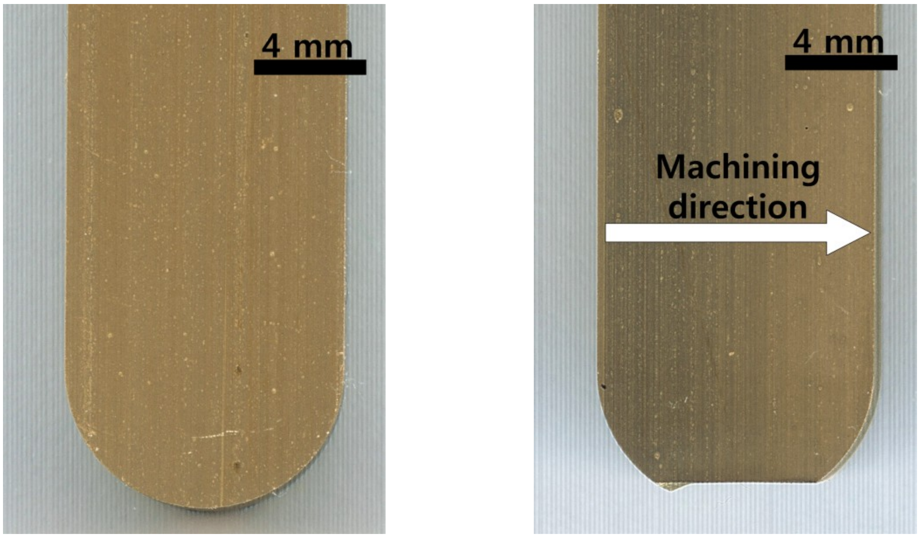


Figure 41 The material removal rates according to EDM method



(a) Before the machining (b) After the machining

Figure 42 The electrode wear of general ED-milling using water

4.6.2 Use of a wire electrode

The machining system of the strip EDM was based on the wire-EDM machine. In order to compare strip EDM with wire EDM, the machining experiments were conducted with a wire electrode. The machining conditions were the same as those shown in table 3 and the peak current was 320 A. The workpiece was stainless steel 304 and the three thicknesses used were 9.3, 18.4, and 29.8 mm. Figure 43 is a schematic of the wire-EDM experiment.

The machining results are noted on the area effect curves for the results of the strip EDM in figure 44. The MRR of the wire EDM were close to the area effect curves when the same machining area and the same electrical conditions were used.

Both strip EDM and wire EDM advance their machining processes by expending their electrode materials. A comparative factor k was defined to compare their machining characteristics. It is the ratio of the electrode consumptive rate to MRR, as explained by following equation.

$$\begin{aligned} \mathrm{k} &= \frac{\text{Electrode consumptive rate}}{\text{Material removal rate}} \\ &= \frac{A[mm^2] \times f\,[mm/min]}{MRR\,[mm^3/min]} \end{aligned} \tag{4.3}$$

Where A is the cross-section area of an electrode and f is the feed speed of an electrode, such as a wire or a strip. The small k value means that a small quantity of electrode material is needed for unit MRR or machining speed. In the wire-EDM process, the wire feed speed was 100 mm/s (6000 mm/min), which was the minimum speed that could be attained without the wire being broken by discharge sparks. For the strip EDM, the feed speed was 2 mm/s (120 mm/min). It was possible to have a slower strip feed speed than for a wire because the strip had a larger cross-section area and lower tension. The values of k under each of the machining conditions are noted in figure 44. Although the MRR of strip EDM was similar to wire EDM under the same machining conditions and with a similar machining area, the k value of the strip EDM was much smaller than was the case for the wire EDM. Therefore, the strip EDM needed less electrode material to achieve a similar machining performance as for wire EDM. When the machining conditions used the peak current of 320 A and the workpiece thickness of 9.3 mm, the wire electrode was broken due to overheating.

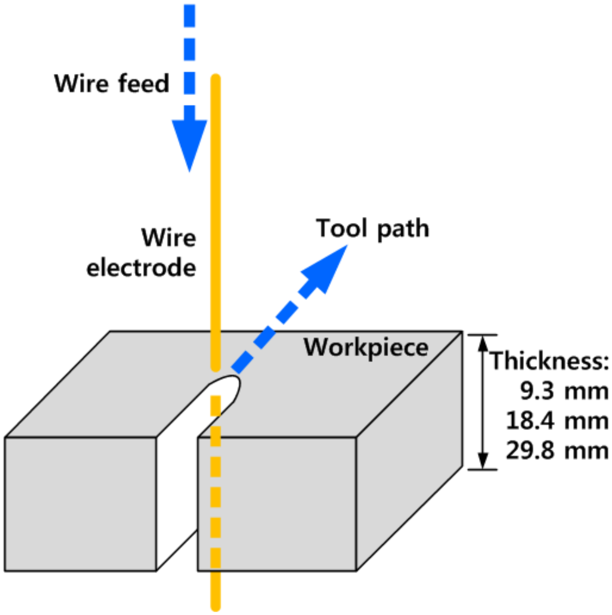
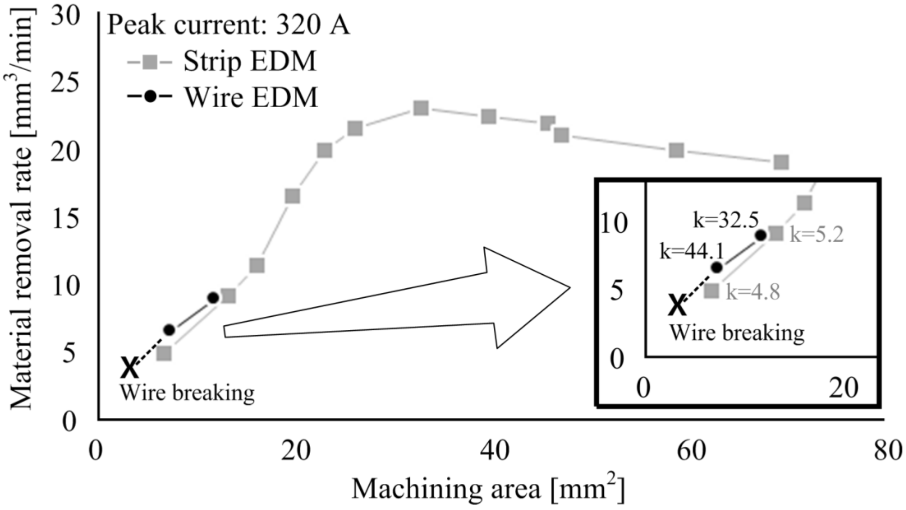
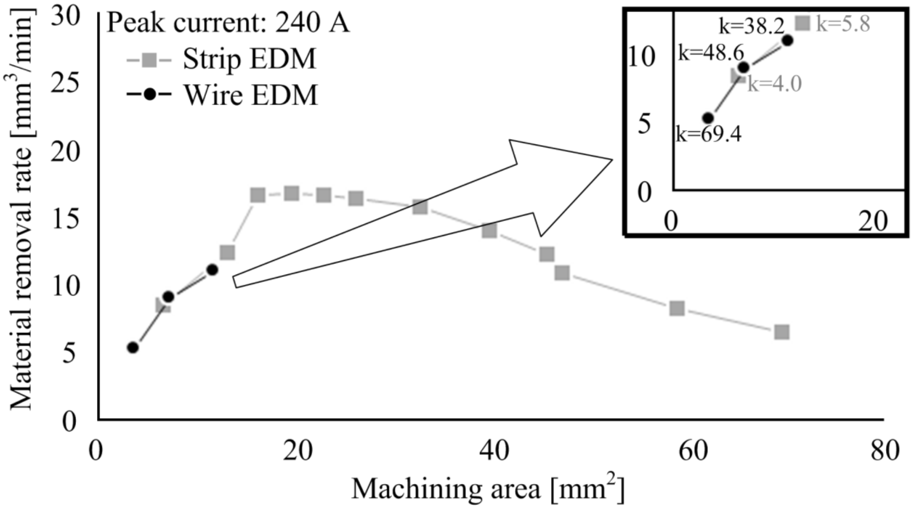


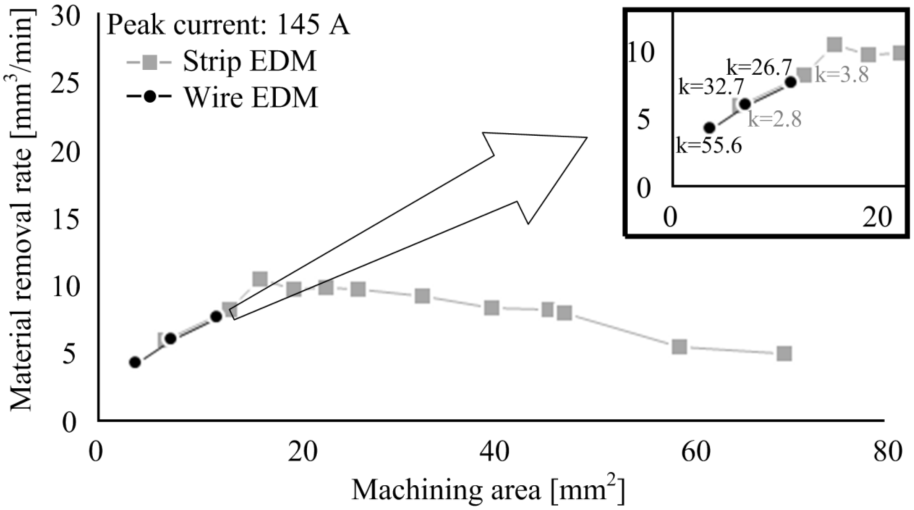
Figure 43 The experimental process of wire EDM



(a) The area effect curve using a peak current of 320 A



(b) The area effect curve using a peak current of 240 A



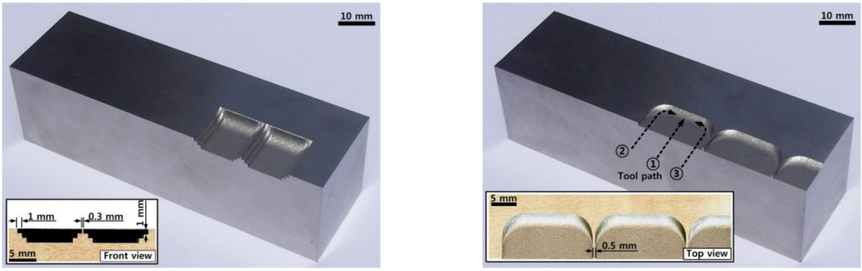
(c) The area effect curve using a peak current of 145 A

Figure 44 Comparing wire EDM to strip EDM

4.7 Applications of strip ED-milling

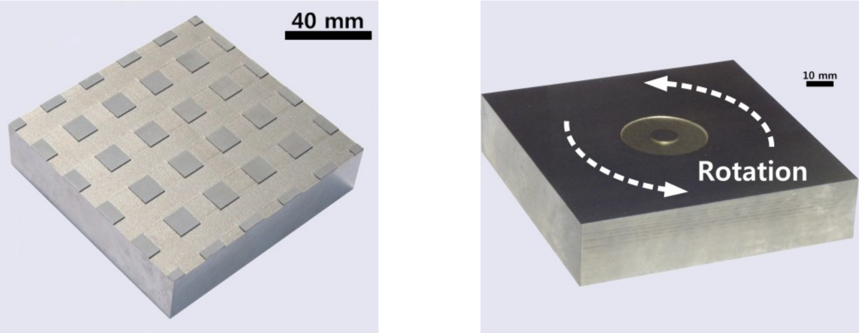
4.7.1 Normal milling

Figure 45 shows several machining examples of strip ED-milling. The workpiece material was stainless steel 304. Figure 45 (a) shows multi-layer shapes at the edge of the workpiece. The electrode moved layer by layer during the machining. As the electrode moved along the curved tool path, the round corner pocket could be completed. Figure 45 (b) is the machining result of the curved tool path. Figure 45 (c) is the square patterns on the workpiece. Its tool paths intersected at right angles. Figure 45 (d) shows axial-symmetric groove on the workpiece, which was fabricated by rotating the workpiece.



(a) Multi-layer shapes with a thin wall

(b) Round-contour shapes



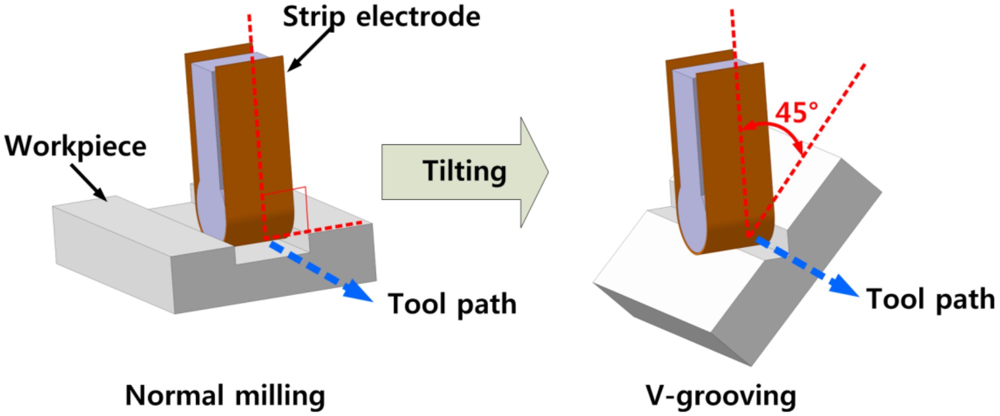
(c) Square patterns

(d) Axial-symmetry pocket

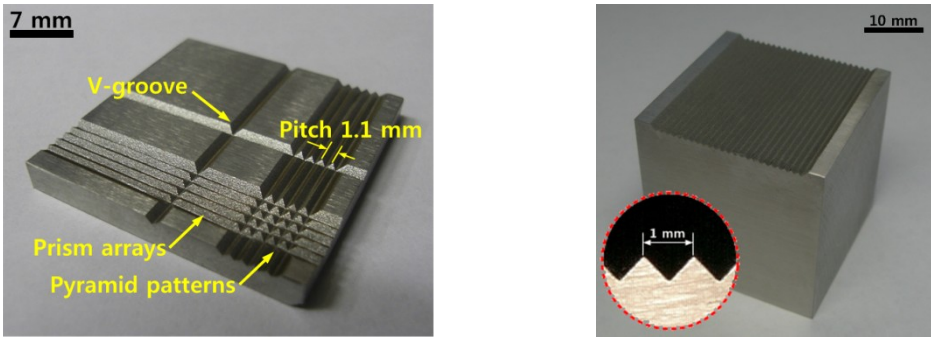
Figure 45 Machining examples of strip ED-milling

4.7.2 V-grooving

The strip ED-milling can be applied to V-grooving. In the normal process, the electrode stands vertically against a workpiece. Since the workpiece is tilted at 45 degrees, a V-groove can be machined as shown in figure 46 (a). In this process, only the edge corner of the strip electrode is related to machining a workpiece. Figure 46 (b) and (c) are the machining results of V-grooving. The workpieces were also stainless steel 304. Using this method, a V-groove, prism arrays, and pyramid patterns were machined on the workpiece.



(a) Concept of V-grooving using strip EDM



(b) Various V-groove patterns

(c) Prism mold

Figure 46 V-grooving process using strip EDM

5

Strip EDM for the Turning Process

EDM can be applied to the turning process because it is a useful method for dealing with hard-to-machine metals [38-40]. Generally, ED-turning uses a wire electrode because electrode wear is not a concern with wire EDM. However, wire EDM has issues concerning rough surface, wire breakage, and low machining speed. The workpiece of the ED-turning process is cylindrical in shape and the machining area with discharge sparks is relatively small. It is easy for a thin wire to be broken by overheating because of the small discharge area. Moreover, the cylindrical workpiece must rotate at a high rotation speed because a slow rotation of the workpiece causes an irregular helical shape of the machined part. However, rotational instability can occur during the machining process and this disturbs machining of a workpiece.

In contrast, a strip EDM has the advantages of providing a smooth machined surface, high MRR, and electrode breakage is not an issue because of the large machining area. Also, strip ED-turning does not require a high rotation speed of the workpiece. Therefore, rotational instability is also not an issue.

In this chapter, the process of applying the strip EDM to ED-turning is introduced. To complete a turning process, a turning unit was designed and the machining characteristics, such as MRR and surface roughness, were investigated relative to specific machining conditions. Additionally, the processes were compared to the wire ED-turning method. In the advanced application section, complex shapes were machined on a workpiece.

5.1 Turning procedure

5.1.1 Machining process

The machining concept of strip ED-turning is illustrated in figure 47. The strip electrode is fed continuously, similar to the ED-milling setup, and the workpiece was rotated at a low RPM. Figure 48 shows the machining process step by step. First, the electrode is set up for the desired radial depth of cut. Next, the servo system moves the electrode guide in the tangential direction of the rod, which does not rotate. In the third step, the electrode guide stops moving at the center of the rod workpiece and the workpiece itself starts to rotate at a constant RPM. To complete the target shape, the rod only rotates during machining, as shown in the fourth and fifth steps. Finally, the electrode guide moves back after one rotation of the rod workpiece. The axial-symmetric shape can be completely fabricated through these six steps.

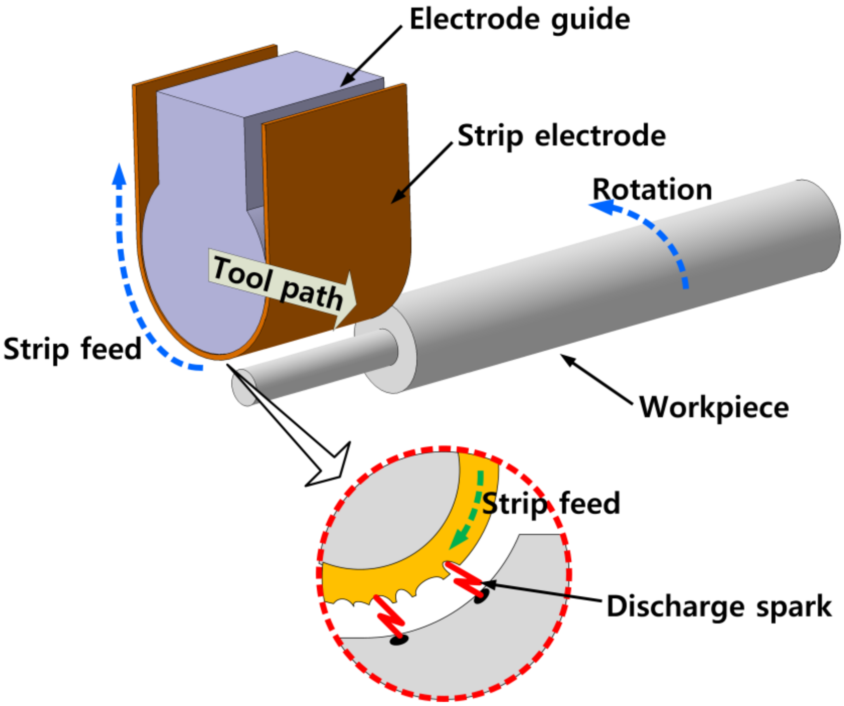


Figure 47 Concept of the strip ED-turning

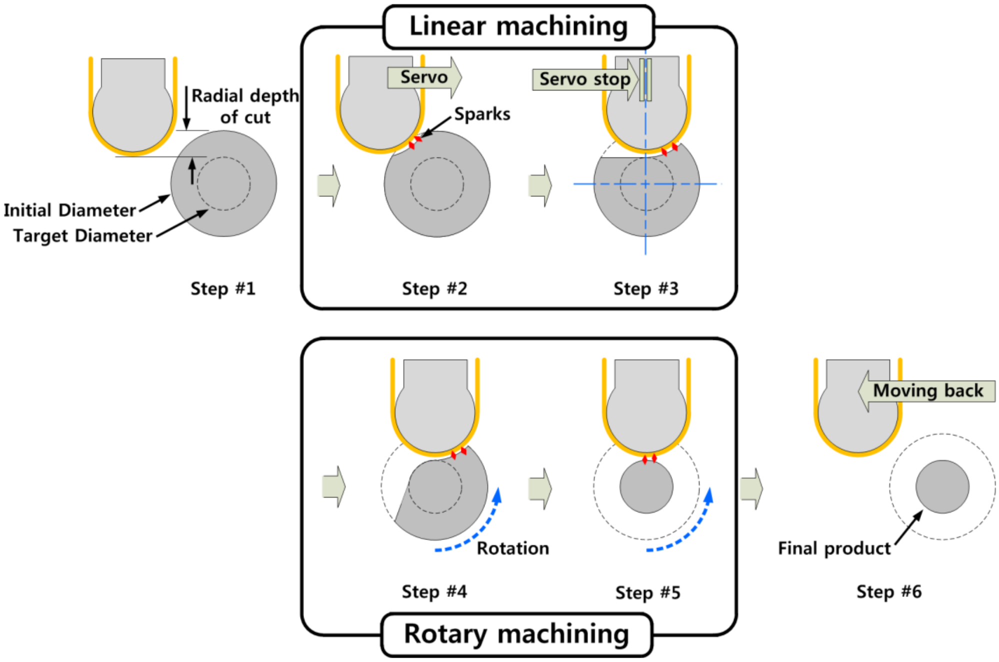


Figure 48 Process of strip ED-turning

5.1.2 Turning system

In the ED-turning process, a workpiece rotates while submerged in a working fluid. Figure 49 illustrates the turning unit designed in this study. The workpiece is fixed on a chuck of the spindle. It is attached to the spindle housing using several bearings. To prevent a water leak in the housing, bearing covers and contact seals were used to isolate the parts located in the housing. A timing belt between the spindle and the motor delivers the turning force of the induction motor, which is located outside the working fluid and is attached to the isolation plate. The spindle speed is controlled to a resolution of 0.1 RPM. The current flows to the spindle via carbon brushes. The actual machining system is shown in figure 50.

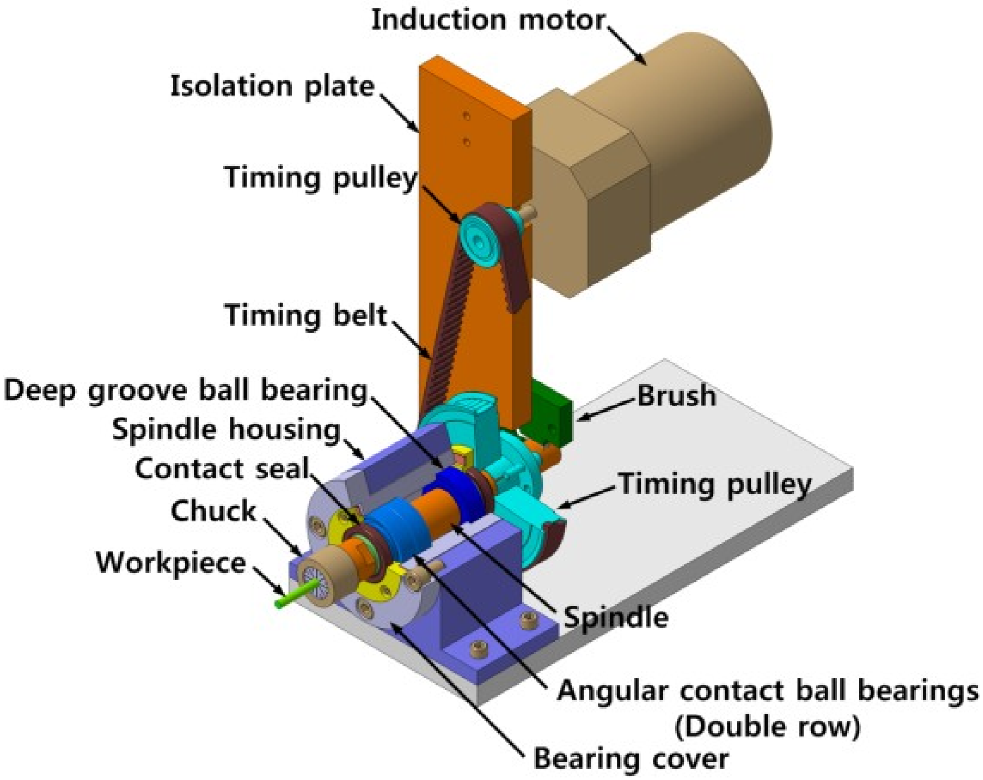


Figure 49 A cutaway view of the turning unit of the strip EDM

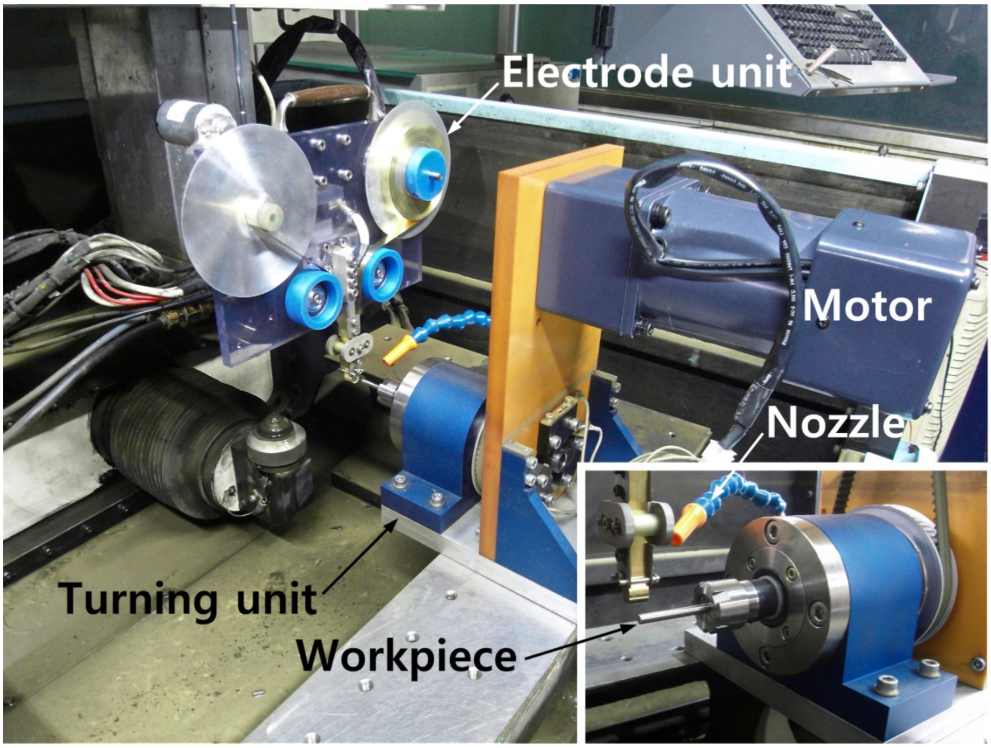


Figure 50 The strip ED-turning system used in this study

5.2 Machining conditions of strip ED-turning

The workpiece used was a stainless steel 304 rod and the tool electrode was a brass strip. The electrical conditions were similar to the milling experiment. To investigate the machining characteristics relative to discharge energy, the peak current used in the experiments was between 195 A and 320 A. For the machining test, the ϕ0.3 mm rod was machined to a smaller diameter. The radial depth of cut was 0.5 mm. Therefore, the machining process created a shaft workpiece with a diameter of 2 mm. The machining conditions used in the experiment are detailed in table 5.

Table 5 The machining conditions of strip ED-turning experiments

Electrode	Brass strip Thickness: 0.1 mm Width: 10 mm Feed speed: 2 mm/s
Workpiece	Stainless steel 304 Diameter: 3.0 mm
Working fluid	Deionized water
Open-gap voltage	-80, 140 V
Positive time	28 μs
Negative time	50 μs
Peak current	195, 270, 300, 320 A
Radial depth of cut	0.5 mm

5.3 Machining results

Peak current is one of the most important factors used to define MRR and surface roughness in the EDM process. To investigate machining characteristics according to peak current, several peak current values were applied to the machining. During the turning process, the spindle rotated at a constant RPM via the motor. To determine the permissible RPM relative to peak current, the rotation speed was increased until an electrical short occurred between the electrode and the workpiece. The radial depth of the cut was 0.5 mm; the other conditions are listed in table 5. The results of the test are listed in table 6. When the peak current was 195 A, a short circuit occurred at 0.4 RPM; therefore, 0.3 is the permissible rotation speed under these electrical conditions. However, RPM could increase to 0.6 when the peak current reaches 320 A. In conclusion, the rotation speed directly related to the MRR increased as the peak current increased.

Table 6 Permissible rotation speed according to peak current

Peak current [A]	195	270	300	320
Permissible rotation speed [RPM]	0.3	0.4	0.5	0.6

Figure 51 shows MRR according to peak current. This was calculated using the ratio of removed volume to machining time. The removed volume of the workpiece was determined by measuring its size difference before and after machining. As shown in figure 52, the machining time is of 2 types: linear machining, shown in steps 2 and 3, and rotation machining, shown in steps 4 and 5 of figure 48. During linear machining, the tool electrode machines a workpiece without spindle rotation. The machining time is short because the tool path is short. During the process of rotation machining, the machining time is defined by the RPMs of the spindle because the rotation speed is constant according to the machining conditions shown in table 6. Based on the total machining time, MRR can be calculated. As the peak current increased from 195 A to 320 A, MRR also increased. Although the machining speed increased with the increase in electrical energy, the machined surface became rougher, as shown in figure 53.

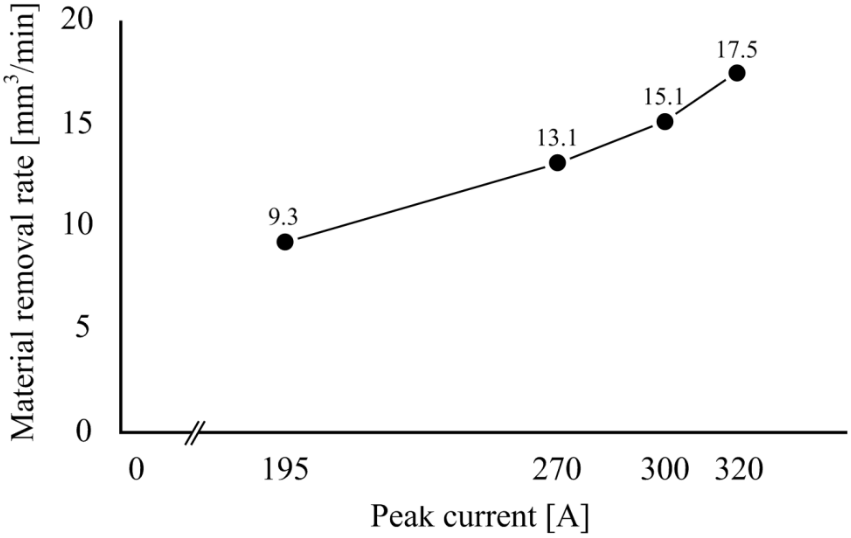


Figure 51 Material removal rate according to peak current

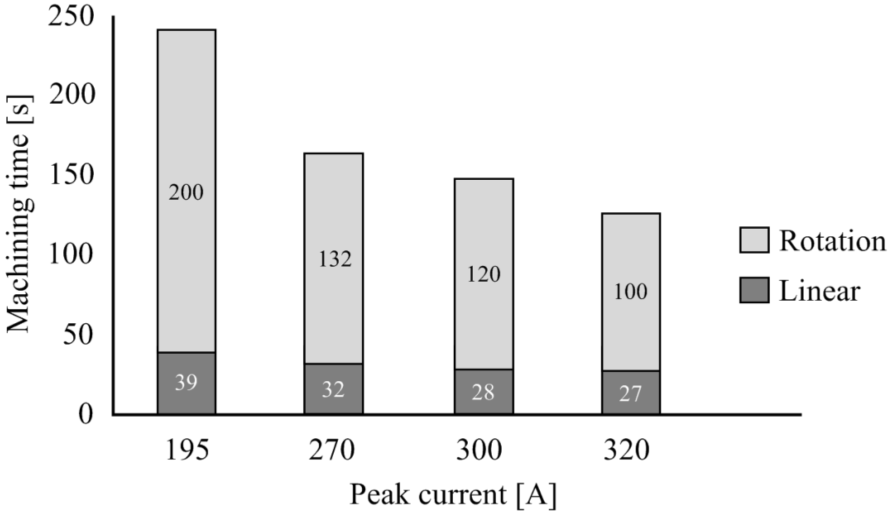


Figure 52 Machining time according to peak current

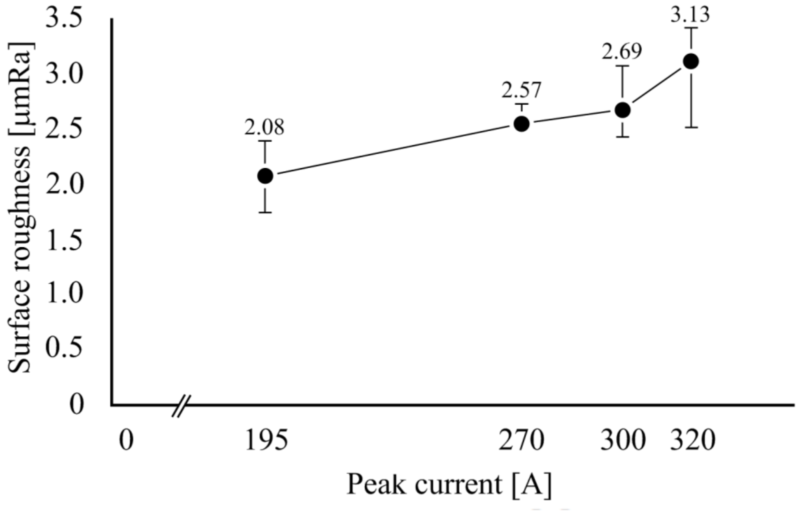


Figure 53 Surface roughness according to peak current

5.4 Comparison to wire ED-turning

Wire EDM has been used for ED-turning because there is no need to consider electrode wear during machining. In this study, wire ED-turning was conducted to compare the results to the strip ED-turning. The peak current was 270 A. When the peak current exceeded 270 A, the wire electrode was broken due to overheating. A wire easily breaks when machining conditions utilize a small diameter wire with a high current. The tool path of the wire electrode is the same as the axial of the workpiece, shown in figure 54. The workpiece was rotated at a constant RPM. In the strip method, the spindle is rotated for only one full revolution at a low RPM; however, wire ED-turning makes a helical shape if a low rotation speed is used. To obtain cylindrical shapes, wire ED-turning requires a higher RPM. Therefore, 60 and 90 RPMs were used in the experiments. The electrode was a brass wire with a diameter of 0.25 mm and a radial depth of cut of 0.5 mm. The machining conditions are listed in table 7.

The wire ED-turnings had identical MRRs under both RPM conditions, as shown in figure 55. The MRR of the wire ED-turning was 42.6% lower than the strip method under the same machining conditions, with a 0.5 mm radial depth of cut. The MRR values of the strip ED-turning shown in figure 55 were taken from figure 51.

The machined surfaces were observed using a scanning electron microscope (SEM), shown in figure 56. In wire ED-turning, irregular cusp areas were found on the surfaces, see figures 56 (a) and (b). Owing to the cusp on the machined surface, the values of surface roughness were 11.51 μmRa and 12.53 μmRa respectively. In contrast, the strip ED-turning did not leave a cusp on the machined surface, shown in figure 56 (c). The surface roughness was over 4.6 times smoother than for the wire method.

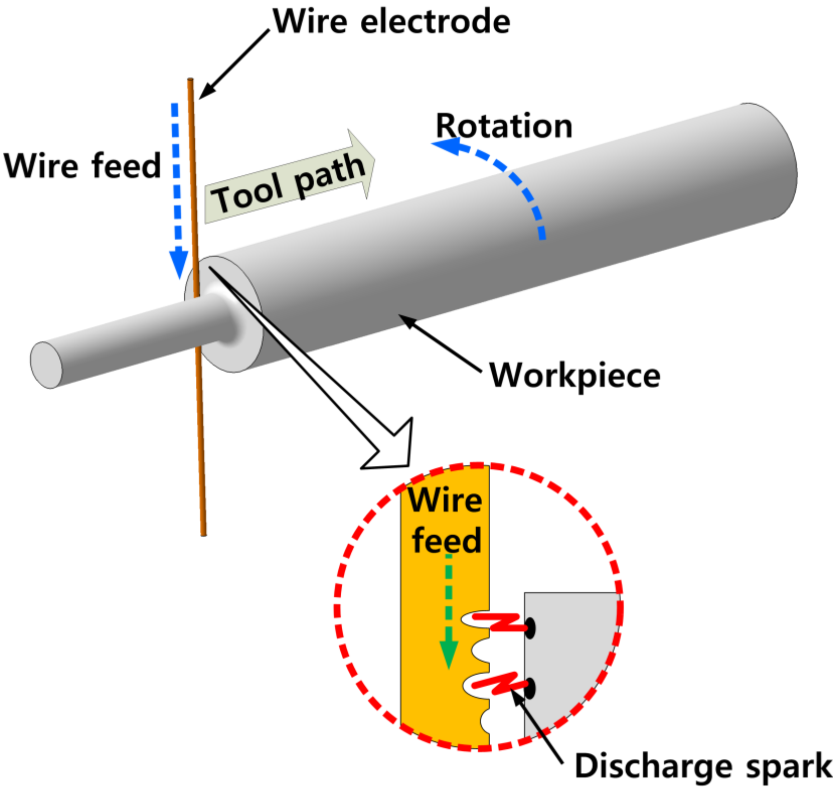


Figure 54 Schematics of wire ED-turning

Table 7 Machining conditions for wire ED-turning

Electrode	Brass wire Diameter: 0.25 mm
Workpiece	Stainless steel 304 Diameter: 3.0 mm
Rotation speed	60, 90 RPM
Peak current	270 A
Radial depth of cut	0.5 mm

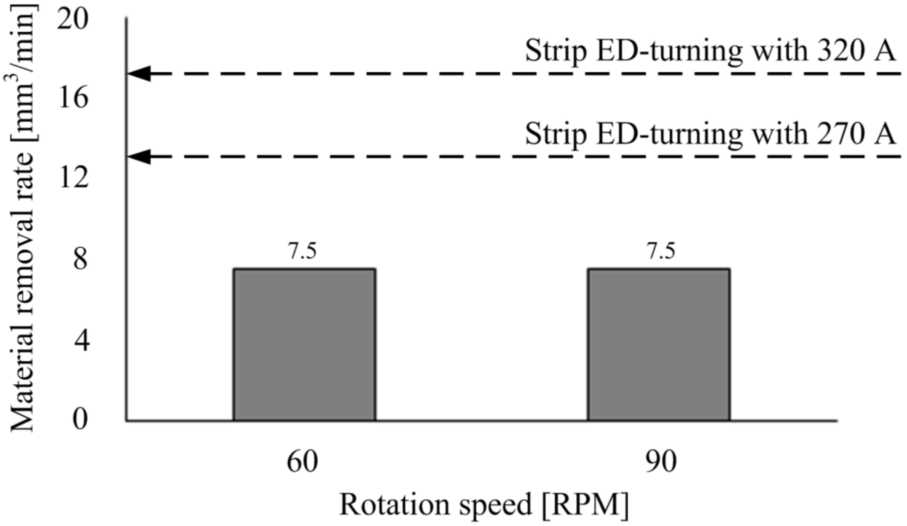
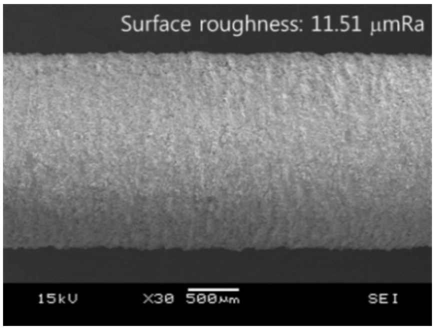
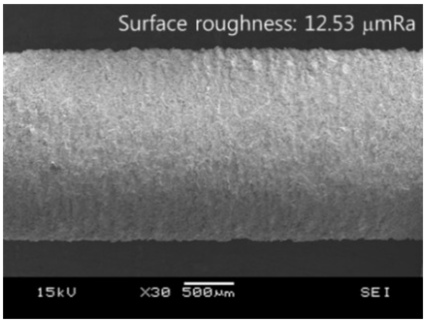


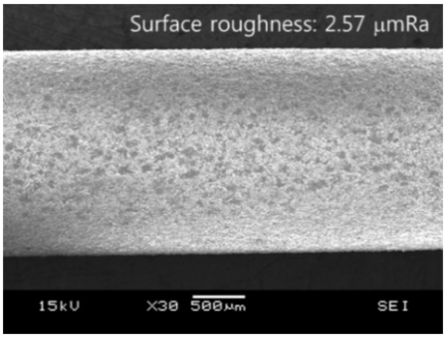
Figure 55 Comparison of the MRR of wire ED-turning to that of strip ED-turning



(a) 60 RPM of the wire-EDM



(b) 90 RPM of the wire-EDM



(c) The strip ED-turning

Figure 56 The SEM images of the machined surfaces

5.5 Application machining using strip ED-turning

Strip ED-turning can be applied to machine various turning products. A turning example was conducted to evaluate the performance of strip ED-turning. This process can be classified into three machining modes. The first is normal turning that reduces the diameter of a workpiece. The second mode is taper turning, which can manufacture a cone shape when a strip electrode is set up at a constant angle. Finally, the index mode can be applied to make polygons. The workpiece does not rotate continuously in index mode. After machining the face of the desired polygon, the spindle rotates to create an interior angle of the polygon. Repeating this machining step several times, the polygon can be manufactured in index mode. Figure 57 shows the example, which used all three modes in the practical machining process at a peak current of 320 A. The end tip was machined using the taper-turning mode with a taper angle of 15 degrees. The middle part of the cylinder was completed using the normal turning mode. Finally, the octagon was formed using the index mode.

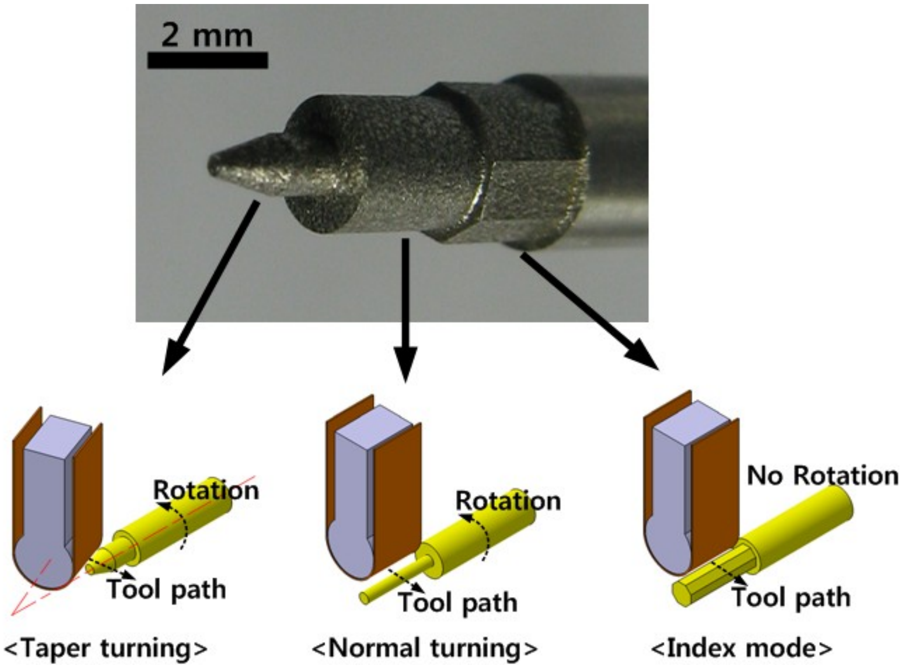


Figure 57 The product created using three kinds of strip ED-turning

6

Adjustable V-grooving

The EDM process needs its own electrode that has a preformed shape to obtain the desired shape on a workpiece. With V-grooving on hard metals, EDM can be applied to the machining process. In the general EDM method, there is an electrode wear problem and its own electrode is needed to obtain the desired shape. In contrast, the strip-EDM method does not have a wear problem and only one electrode guide system is sufficient to machine various shapes on a workpiece. Figure 58 illustrates the concept of the suggested machining method. In this chapter, adjustable V-grooving is suggested for making various V-grooves using only one guide system based on use of a strip electrode. The adjustable V-grooving electrode was developed and the machining characteristics were investigated using the guide system.

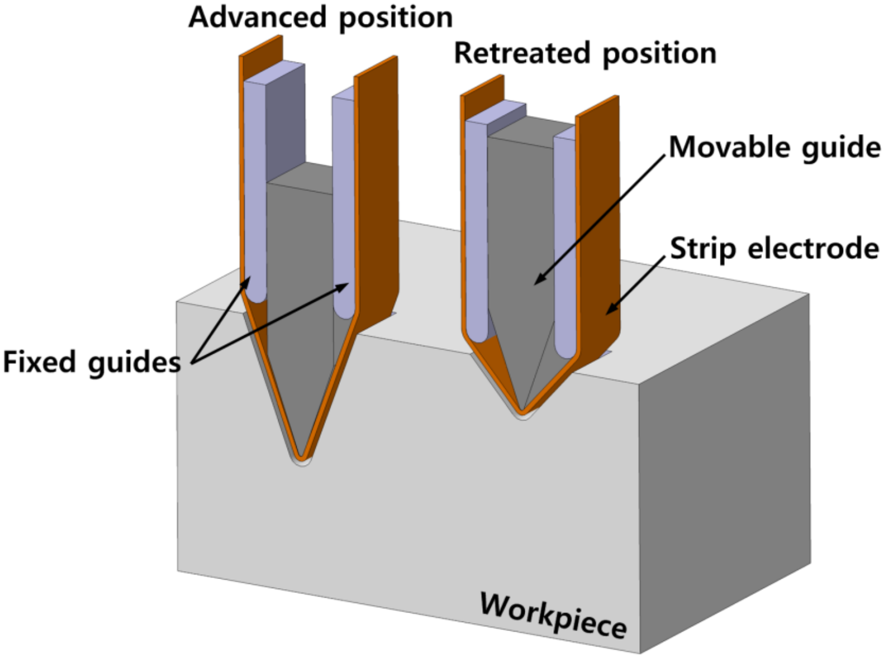


Figure 58 The concept of adjustable V-grooving

6.1 Adjustable V-grooving procedure

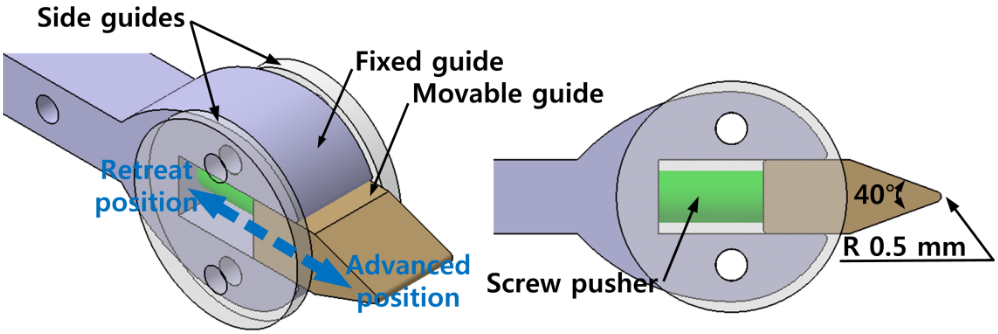
6.1.1 Machining process

Adjustable V-grooving is similar to the die-sinking EDM process. The suggested machining method forms a V-shape determining the position of the movable guide as shown in figure 58. When the movable guide is located at the advanced position, the tip angle of V-shape is small. If the movable guide retreats, the angle becomes large. After fixing the angle of the V-groove, the whole guide system moves along the tool path. During the machining process, the strip is supported by both the movable guide and the fixed guides. In this way, the electrode maintains the V-shape without deformation from electrode wear.

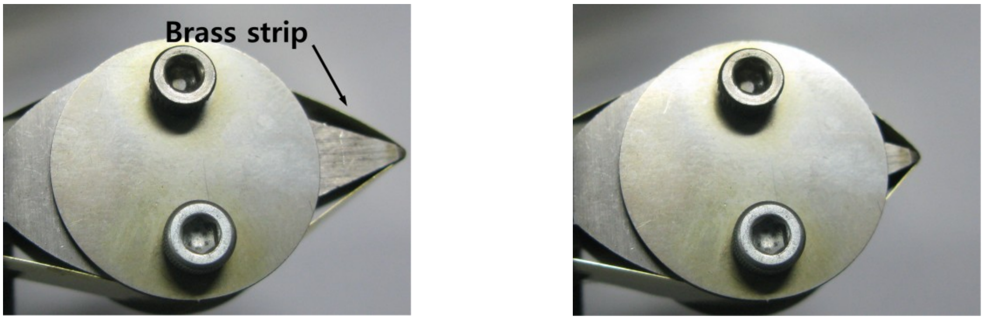
6.1.2 Machining system

Figure 59 (a) shows the electrode guide apparatus of the adjustable V-grooving. The movable guide is located within the fixed guide and the screw pusher moves the movable guide back and forth. When the movable guide is at the advanced position, the electrode makes a small tip-angle V-groove as shown in figure 59 (b). A V-groove with a large angle is obtained when the movable guide retreats as shown in figure 59 (c).

The side guides prevent the strip electrode from being derailed. The tip radius of the movable guide was established at 0.5 mm to ensure a smooth feed of the thin strip. The tip angle is determined by the position of the movable guide before beginning the machining. After setup, the whole electrode apparatus moves to machine a workpiece as shown in figure 60.



(a) Schematic of designed electrode guide apparatus



(b) Small angle mode

(c) Large angle mode

Figure 59 Electrode guide of adjustable V-grooving

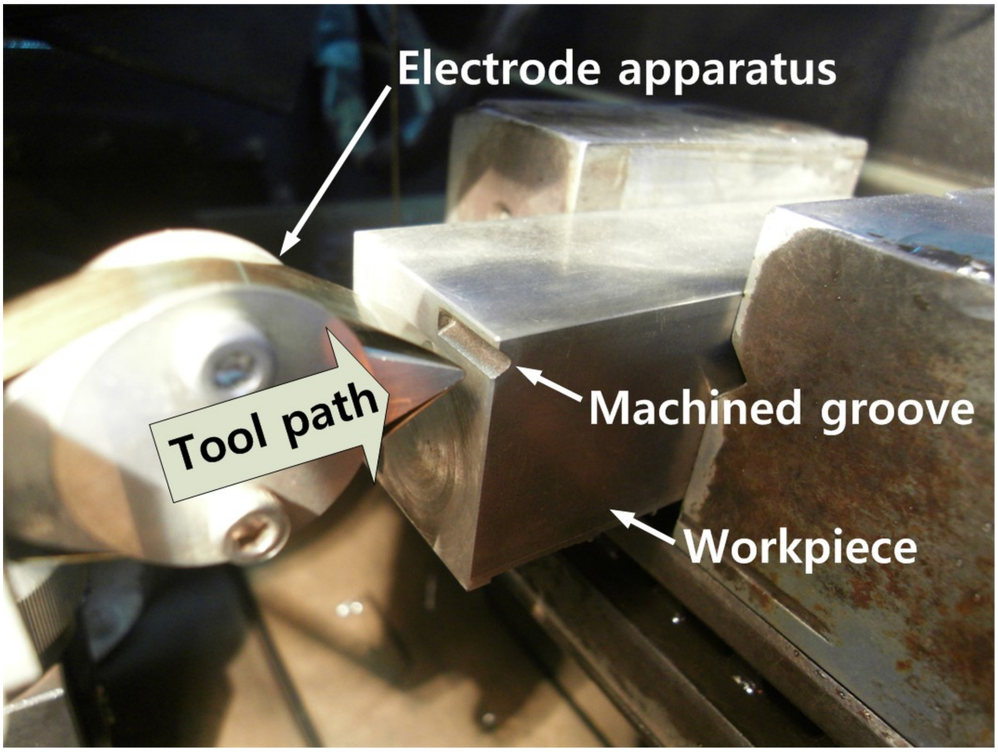


Figure 60 Machining setup

6.2 Machining conditions of adjustable V-grooving

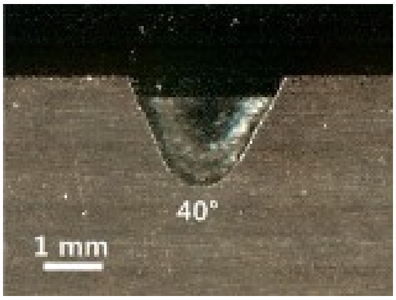
To fabricate various V-grooves, the tip angle of the V-groove is determined by the position of the movable guide. The angles used in the machining experiments were 40, 60, and 80 degrees. The electrical condition was set at a peak current of 320 A and other electrical factors were the same as noted in table 3. The machining conditions are listed in table 8. Using these machining conditions, the V-groove with a depth of 2 mm was machined on the stainless steel workpiece.

Table 8 Machining conditions of the adjustable V-grooving experiments

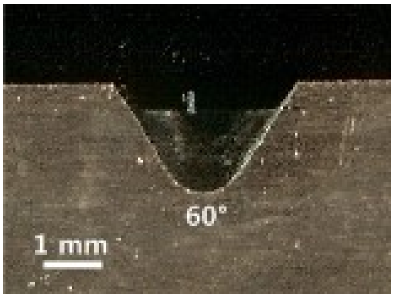
Electrode	Brass strip Thickness: 0.1 mm Width: 10 mm Feed speed: 2 mm/s
Workpiece	Stainless steel 304
Tip angle	40°, 60°, 80°
Peak current	320 A
Machining depth	2 mm

6.3 Machining results

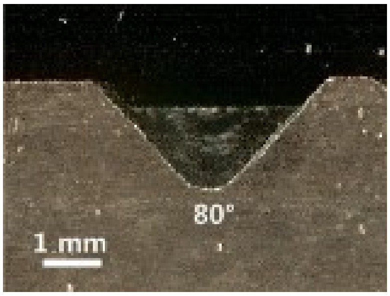
The machined grooves are shown in figure 61. Each groove is 2 mm in depth. All were fabricated using only one electrode guide system. The machining time to complete a groove is graphically presented in figure 62. When machined grooves have consistent depth, the machined volumes increase as the tip angles increase. Therefore, the MRR of machining at 80 degrees is the highest, as shown in figure 63.



(a) 40°



(b) 60°



(c) 80°

Figure 61 Machined grooves according to tip angle

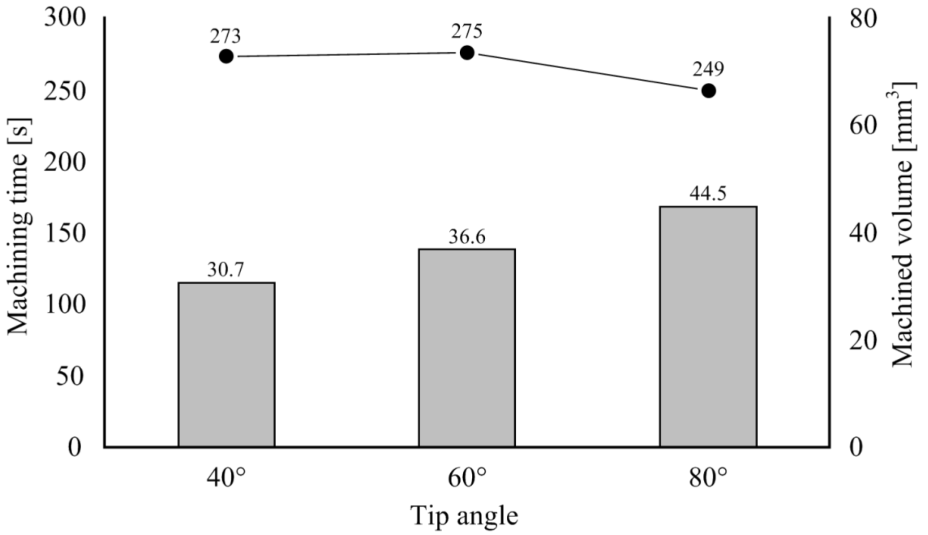


Figure 62 Machining time and machined volume according to tip angle

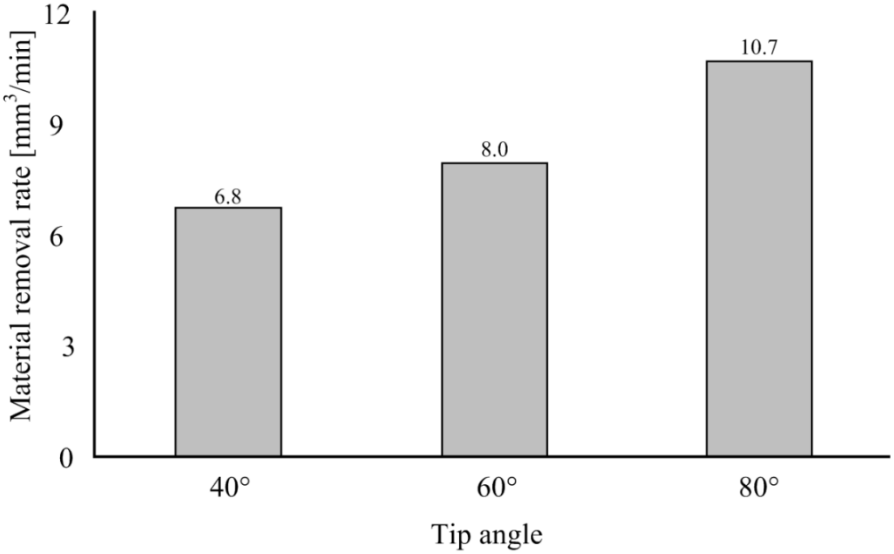


Figure 63 Material removal rates according to tip angles

7

Conclusion

The general EDM process has electrode wear problems. To overcome the problems, additional machining processes are needed to create a compensated tool path and several new electrodes are required during the finish. In this study, a strip-EDM method was suggested as a way to overcome the disadvantages inherent in the general EDM process. There is no concern for electrode wear in strip EDM. As a tool electrode, the conductive strip travels on the surface of the electrode guide and the portion of the strip that becomes worn is automatically replaced with a fresh portion of the strip via the feed mechanism. In the experimental studies, copper and brass electrode strips were used. Under the same machining conditions, the copper strip was found to have a higher MRR than the brass strip. However, the machined surface created by using a copper strip was rougher and the machining current could not exceed 240 A, otherwise an arc would occur. The brass strip did not create an arc until the peak current reached 320 A. Therefore, the machining speed could be increased. The copper electrode strip left copper on the machined surface, which produced a red discoloration, but the brass electrode did not discolor the surface. In practical machining, multi-step pockets, round-contour pockets, and square patterns were completed by using the strip EDM process with a variety of tool paths. None of the strip-EDM processes required a compensated tool path or new electrodes to achieve a finish cut.

In this study, strip EDM was also utilized for turning. It proved useful because electrode wear was not an issue and a large area could be machined. Machining characteristics such as MRR and surface roughness were investigated relative to discharge energy. The MRR and surface roughness increased as the peak current increased due to the high energy discharge. Unlike wire ED-turning, the strip-EDM method did not create broken-electrode problems and cusps on the machined surface. In addition, the surface roughness was also smoother. Under the same machining conditions, the MRR of the strip ED-turning was 74.3% higher than the MRR of wire ED-turning. Using the new process, complex shapes (a taper pin, a cylinder, and a polygon) were fabricated on the rod workpiece

The strip-EDM method can be applied to fabricate V-grooves. The strip electrode can be set to various V-shapes relative to guide shape because the thin strip is very flexible. Based on this characteristic, the adjustable V-grooving electrode apparatus was designed and completed. This electrode unit can make various angles of V-grooves according to the position of the movable guide.

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Abstract in Korean

본 연구에서는 방전가공 시 발생하는 전극마모 문제를 해결하고자 스트립 전극 시스템을 이용하였다. 일반적으로 방전가공에서 발생하는 전극마모는 가공품의 형상정밀도를 저하시키고 오차 보정을 위해 추가적인 공정이 필요하게 되어 생산성 측면에서 비용을 증가시킨다. 반면에 본 연구에서 다룬 스트립 전극을 이용한 방전가공은 전극마모를 고려하지 않아도 된다. 그러므로 앞에서 언급한 전극마모로 인한 문제가 발생하지 않는다. 스트립 전극은 가공 중에 와이어 방전가공에서의 와이어 전극처럼 연속적으로 가공 간극에 공급된다. 이 때 얇은 스트립은 전극 가이드 위를 미끄러져 이동 한다. 전극가이드는 일반적인 방전가공에서의 블록 전극과 같은 역할을 하고 스트립 전극은 전극의 표면 역할을 한다. 그러므로 전체적인 가공은 전극마모가 발생하지 않는 블록 전극과 같이 작용한다. 이와 같은 원리를 이용하여 가공 시스템이 구성되었으며 방전 밀링, 터닝, V그루빙에 적용되었다. 본 연구에서의 가공 실험을 바탕으로 스트립 전극을 이용하여 다양한 형상이 스테인레스 스틸 공작물에 가공되었다.

주요어: 방전가공, 전극마모, 스트립 전극, 스트립 방전가공

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