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공학석사 학위논문

Studies on tool feed length and tool pause period of gap control for improvement of micro electrical discharge drilling

전극 이송 거리 및 정지 시간 연구를 통한

미세 방전 드릴링의 개선

2017 년 2 월

서울대학교 대학원

기계항공공학부

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지도교수 주 종 남

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Abstract

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This study aims to show the method for improvement of micro electrical discharge drilling by manipulating tool feed length and tool pause period of gap control. Micro electrical discharge machining (micro EDM) is the process of removing material in a closely controlled manner from an electrically conductive material immersed in a dielectric fluid with a series of nonstationary and transient discrete electric sparking discharges. Micro EDM provides one of the best alternatives, or sometimes the only alternative, to machine a growing number of high strength and corrosion-and-wear-resistant materials into complex shapes. However, it also has its own disadvantages such as its slow machining speed and high tool wear. The gap control is one of the method to improve both drawbacks. In this paper, design factors derived from the algorithm of gap control, and changes of machining performance by manipulating these factors are studied. Material removal rate (MRR), tool wear rate (TWR) and tool wear ratio

(TWRatio) were measured to observe its own trend of change. As the tool feed length shortens, MRR and TWR increase and machining time and TWRatio decrease. When the tool pause period decreases, MRR and TWR are increased and machining time is decreased.

Keyword : Electrical discharge machining, Gap control, Material removal rate, Tool wear rate, Tool wear ratio

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Chapter 1.

Introduction

Electrical discharge machining (EDM) has its advantage, which is non-contact machining process by the thermal energy caused by plasma. With its non-contact characteristic, there is no need to consider the fracture or vibration of the tool caused by the contact between tool and workpiece, which is why EDM is suitable for micromachining.

Nevertheless, slow machining speed and high tool wear is main disadvantage to the micro EDM, which make precision machining hard to achieve. To improve both machining speed and tool wear, there are several methods for micro EDM, and the gap control is one of them. The gap control is the process for maintaining of gap between tool and workpiece, which can achieve high-speed machining and low tool wear. Process for indirect measuring of gap, which is hard to be direct-measured, and development of algorithm for gap control process mainly conducted as studies of gap control [1, 2]. However, there has never conducted about the study of design factors of gap control. Design factors can affect the performance of machining process, such as machining speed and tool wear ratio. By this reason, it is important to reveal the relation between design factors and the gap control method.

In this paper, design factors derived from the algorithm of gap control, and changes of machining performance by manipulating these factors are studied. Material removal rate (MRR), tool wear rate (TWR) and tool wear ratio (TWRatio) measured to observe its own trend of change.

1.1. Study Background

- **Micro electrical discharge machining (micro EDM)**

The micro EDM process is based on the thermoelectric energy created between a workpiece and a tool submerged in a dielectric fluid. When the workpiece and the tool are separated by a specific small gap, the so-called 'discharge gap', a pulsed discharge occurs which removes material from the workpiece through melting and evaporation. Fig. 1 shows the concept of the electrical discharge machining and discharge gap.

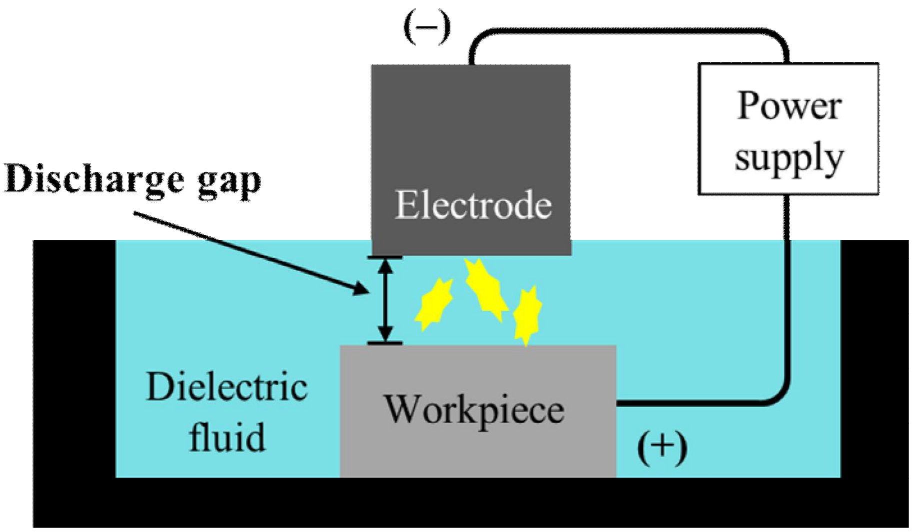


Fig. 1 Schematic of the electrical discharge machining

In recent years, numerous developments in micro EDM have focused on the production of micro-features. This has become possible due to the availability of new CNC systems and advanced spark generators that have helped to improve machined surface quality. Also, the very small process forces and good repeatability of the process results have made micro EDM the best means for achieving high-aspect-ratio micro-features.

Many papers target ways of optimizing EDM performance measures like the material removal rate (MRR), tool wear rate (TWR) and surface quality (SQ) [3]. Process parameters for micro-EDM are still at the development stage and their effects on performance measures have yet to be clarified. Because of the stochastic thermal nature of the EDM process, it is difficult to explain all of those effects fully. The optimization of parameters is based on process analysis to reveal the influence of each process variable on the desired machining characteristic [3]. The lack of information in this field is the main reason for the inability to develop knowledge-based systems to help the planning of micro-EDM operations.

Despite the use of advanced CNC controllers and the high degree of automation of EDM machines, there is still a lack of CAM tools to support micro-EDM. One of the main reasons for the limited application of micro-EDM milling to the machining of complex 3D cavities is the difficulty of generating tool paths using existing CAM systems. In particular, those systems do not permit tool wear compensation, nor support variation of the slice thickness or allow the direction of cut to vary with each slice. Attempts to address these issues have been reported [4].

- **Tool wear**

Tool wear becomes an important issue when employing tools with micro-features in die-sinking as the combination of micro-features and macro-features on one tool will introduce different wear ratios. The sparking area will change as the tool moves down, which will bring different sparking conditions during the process and will reduce quality. Fig. 2 shows the tool wear during electrical discharge machining.

In micro EDM drilling, there are problems when producing blind holes because wear constantly reduces the length of the tool. As a result, when eroding down to a fixed depth, the real depth of the hole will be significantly smaller.

A method to achieve a specific depth in this case is to compensate for wear of the tool by constant tool feeding in the Z-axis [5]. This method requires an accurate model for estimating the volumetric wear ratio (the ratio of tool wear and workpiece wear). Certain factors affecting the wear ratio are difficult to assess and control, like flushing conditions in a deep hole for instance. This could easily result in wrong estimation of the wear ratio and therefore in errors in the produced depth.

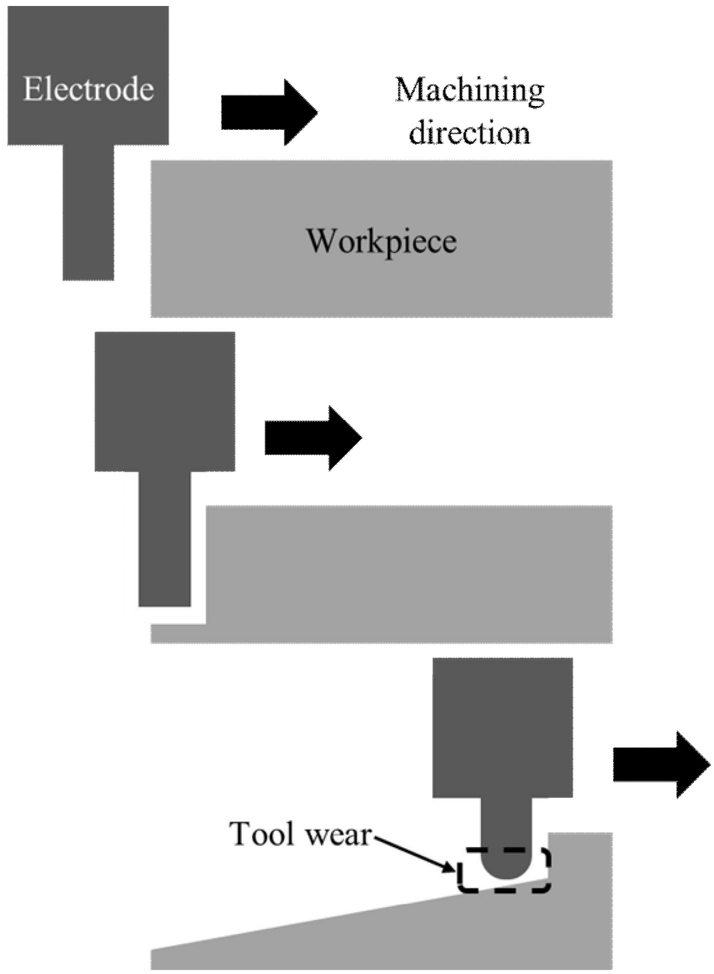


Fig. 2 Tool wear of electrical discharge machining

One solution is to repeat the process a number of times with new or reground micro-tools until the required profile is obtained. This is called the multiple tool strategy. The main drawback is that it can be time consuming and difficult to predict the number of needed tools.

The problems created by tool wear become more complicated when machining complex 3D micro-cavities. Either wear is too severe to allow the use of complex-shape-tools in a classical die-sinking process or tool geometry is impossible. Thus, for the production of micro-3D cavities, the use of micro-EDM milling with simple shape-tools might be the preferred strategy.

A basic method is to use a layer-by-layer machining strategy that compensates for wear during the machining of each layer by constant tool feeding in the Z-axis, based on estimation of the wear ratio. It is assumed that eroding of sufficiently thin layers would ensure that wear only occurs on the face of the tool but not on the sides. Very accurate estimation of the amount of wear is required, because an error in the estimation would have a cumulative effect through the layers. However, even when using a very small layer thickness, side wear is not negligible and introduces errors in the machined profile.

- **Gap control**

The control of EDM process is different from conventional machining process [6]. An additional gap control loop besides the servo control loop is needed in the EDM control. The average voltage during discharge, gap voltage, is constantly monitored, and the feed rate is overridden based on the difference between the reference gap voltage and monitored voltage. Therefore, the feed rate is constantly changing in EDM. Much work has been done to determine the output value of the manual feed rate override (MFO) function. Chang [7] developed a variable structure system (VSS) to enhance the robustness of the gap distance control. Zhang et al. [8] developed an adaptive fuzzy controller for the gap distance control. Kao et al. [9] and [10] also developed fuzzy controller using piezo stage for micro EDM hole drilling. Currently, research in gap control based on fuzzy control is becoming more popular since it utilizes the know-how of skilled operators [4]. However, the drawback of fuzzy controller is that it only controls the feed rate.

In conventional EDM, machine is controlled by retracting tool along a commanded trajectory based on the gap voltage regardless of type of EDM process. This gap control strategy is adequate for these EDM configurations since the direction of retraction is always orthogonal to the main discharge region. The tool retraction direction being orthogonal to the main discharge plane maximizes the efficiency of gap enlargement, which then leads to better debris flushing.

1.2. Purpose of Research

Process for indirect measuring of gap, which is hard to be direct-measured, and development of algorithm for gap control process mainly conducted as studies of gap control. However, the study of design factors of gap control has never conducted. Design factors can affect the performance of machining process, such as machining speed and tool wear ratio. By this reason, it is important to reveal the relation between design factors and the gap control method.

Chapter 2.

Principle and experiments

2.1. Two types of pulse generator of EDM

An RC pulse generators(Fig. 3) have easily provided a very short pulse on-time of a several dozen nanoseconds in micro EDM. However, high discharge frequency cannot be obtained by using an RC pulse generator, due to the time needed to charge the capacitor, which can severely affect the machining efficiency. Moreover, the RC pulse generator has no way to control the pulse interval, so the the workpiece can easily become subject to thermal damage if the dielectric strength is not recovered after the previous discharge and the current continues to flow through the same plasma channel in the gap without charging the capacitor [11].

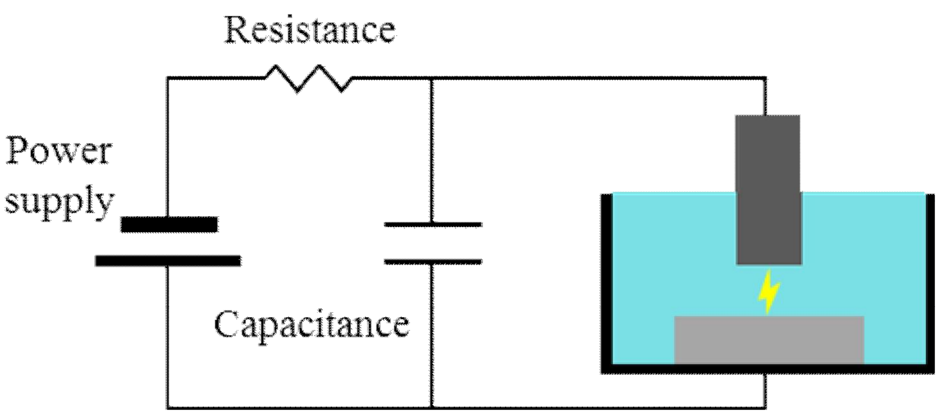


Fig. 3 Schematic of RC pulse generator

On the other hand, transistor type pulse generators(Fig. 4) are already widely used in conventional EDM but not in micro EDM. For transistor type pulse generators, the pulse discharge is achieved with the on/off of the switching component, and it is unnecessary to charge any capacitor. As a result, this type of pulse generator has a higher discharge frequency than the RC pulse generator, and thus can obtain a higher removal rate. Moreover, the discharge process can be easily controlled by detecting gap state in the gap in the transistor type pulse generator. However, due to the delay of the transmission of the switching component and the pulse control circuit components, the traditional transistor type pulse generator cannot easily generate the pulse of a several dozen nanoseconds needed in micro EDM.

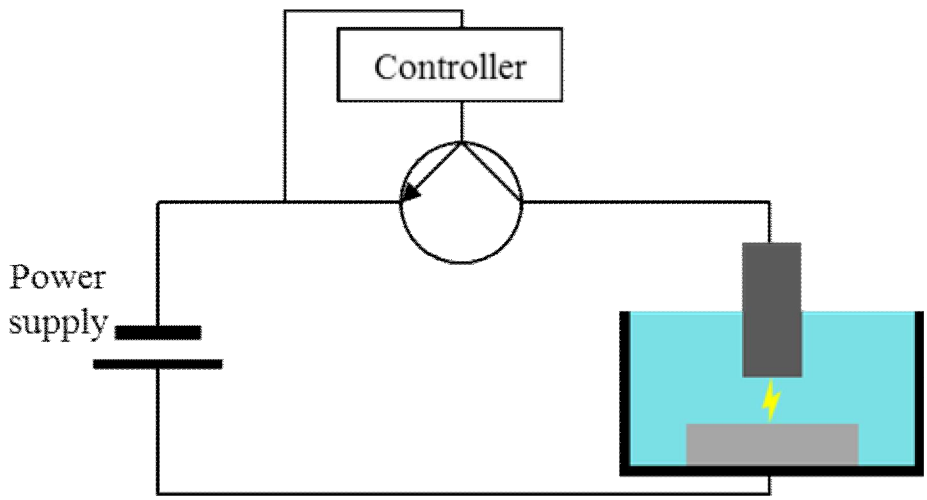


Fig. 4 Schematic of transistor pulse generator

2.2. Discharge gap

A proper "gap" is necessary to generate sparks between an tool and a workpiece. This gap is called "discharge gap". The lightning spark occurs at very long distances from the cloud to the ground, and the voltage reaches millions volts. In EDM, the voltage supplied is approximately 50 to 300 volts because higher voltage is not suitable for high precision machining.

Sparks do not occur in the condition that a tool and work touch each other (i.e. discharge gap = 0), and the machining does not proceed. EDM moves a tool up and down minutely depending on progress of the machining, and adjusts the tool position to make the discharge gap suitable for sparking.

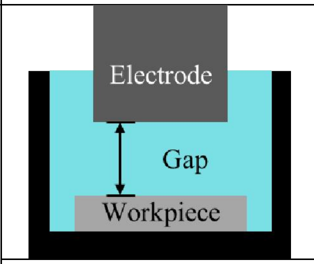
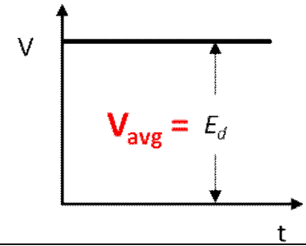
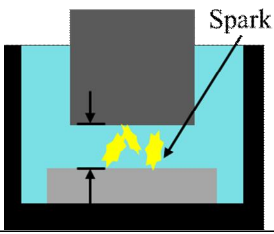
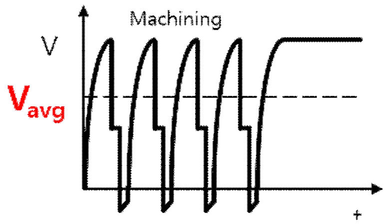
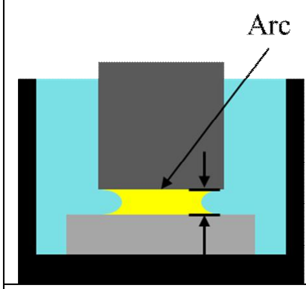
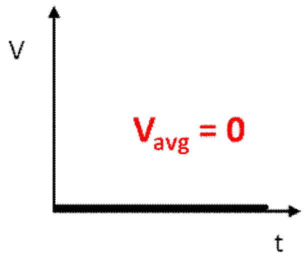
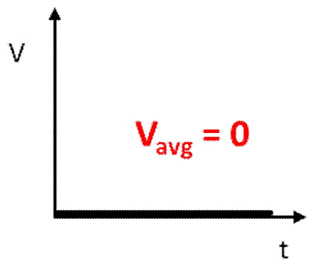
Table 1 shows the gap states classified by the length of the gap. When the gap is far enough to prevent of the discharge, it is 'excessive' state. At this state, voltage needed to break the dielectric between the gap is much higher than supplied voltage. This voltage is derived from the environmental condition of the gap such as the dielectric strength of dielectric fluid. For example, the dielectric strength of the distilled water is 65 ~ 70 MV/m and the voltage need to break the 1-μm-gap filled with distilled water is 65 ~ 70 V. At this condition, the 'excessive' gap state is the gap bigger than 1 μm. The voltage measured from the gap won't change.

By the time tool get close to the workpiece, discharge can occur between the gap. And this state of the gap is 'proper' gap state. By breaking the insulation of the dielectric fluid, the plasma channel is created between the gap. This plasma channel can melt the workpiece with its extremely high temperature, which is the main mechanism of electrical discharge machining. After the end of the discharge, flow of the fluid disconnect the channel, reestablishing the insulation. With the proper gap, this process can be occurred.

However, when the gap is narrower than the proper state, flow of the dielectric fluid can’t insulate the gap at the end of the discharge, meaning endless of the flow of current. This situation of the gap is called ‘insufficient’ gap.

The classification of these 3 kinds of gap state is important to evaluate total machining quality through the machining process. For the good quality of machining, maintaining proper gap is important than any other conditions.

Table 1 Gap state

<table>
<tr><th>Physical state</th><th colspan="2">Electrical state</th></tr>
<tr><td rowspan="2">Excessive gap</td><td>
</td><td>
</td></tr>
<tr><td colspan="2">Insulated</td></tr>
<tr><td rowspan="2">Proper gap</td><td>
</td><td>
</td></tr>
<tr><td colspan="2">Discharge</td></tr>
<tr><td rowspan="4">Insufficient gap</td><td>
</td><td>
</td></tr>
<tr><td colspan="2">Arc occurred</td></tr>
<tr><td></td><td>
</td></tr>
<tr><td colspan="2">Touch</td></tr>
</table>

2.3. Gap control and design factor

When unnecessary gap states are occurred during the machining process, gap adjustment is processed by manipulating the tool move forward and backward. This procedure is gap control. Proper gap control should be performed during the electrical discharge machining for maintaining the proper gap. In general, gap control is triggered by measuring average gap voltage. Average gap voltage represents the gap state. The algorithm of the gap control procedure is shown on the Fig. 5.

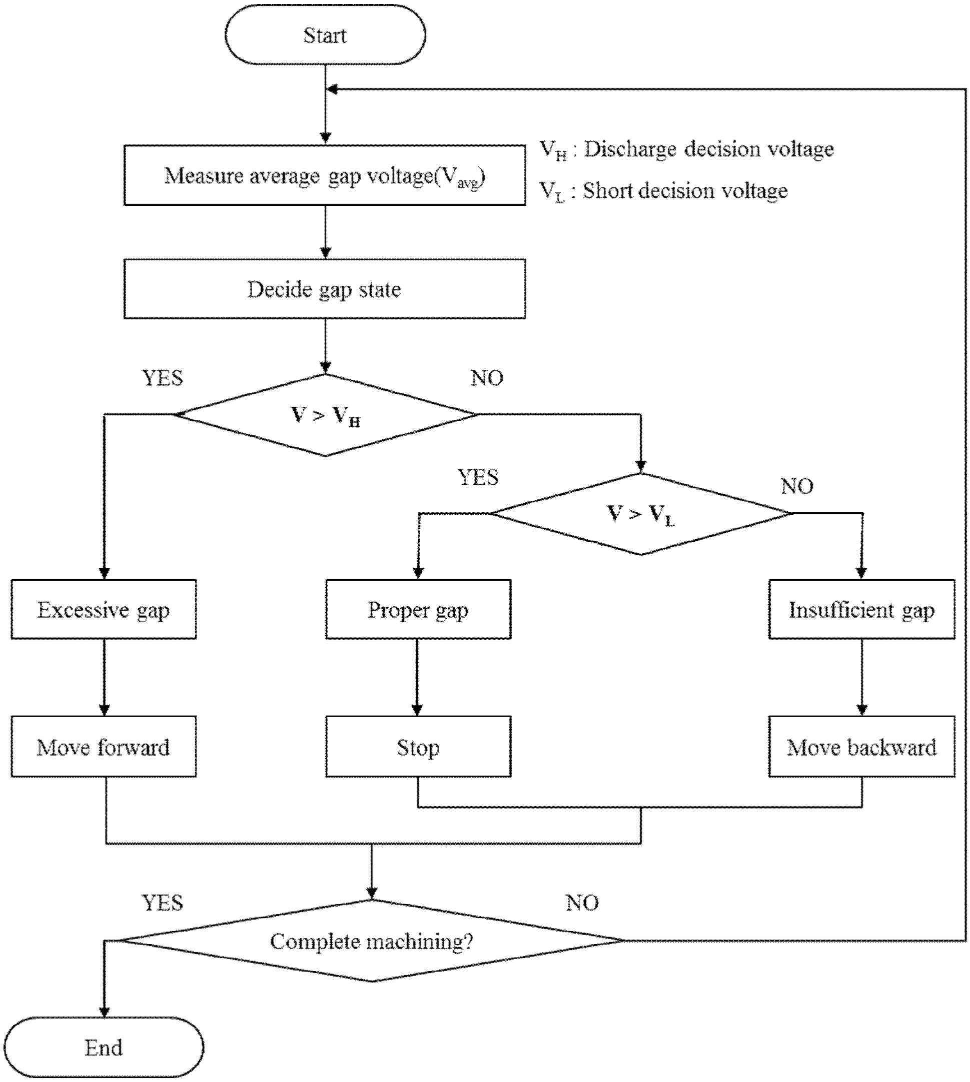


Fig. 5 Algorithm of the gap control procedure

At first, average voltage(V_{avg}) between the tool and workpiece is measured for counted preset number per second. The machining system compares the voltage with discharge voltage(V_H) or short voltage(V_L). When the gap state is decided, this comparison lead the movement of the tool to either forward, backward with tool feed rate(u) and tool feed length(d) or stop for tool pause period(t_s). After the movement of the tool, completion of machining is checked for feedback of the algorithm. Fig. 6 shows the relation between design factors and electrical discharge machining.

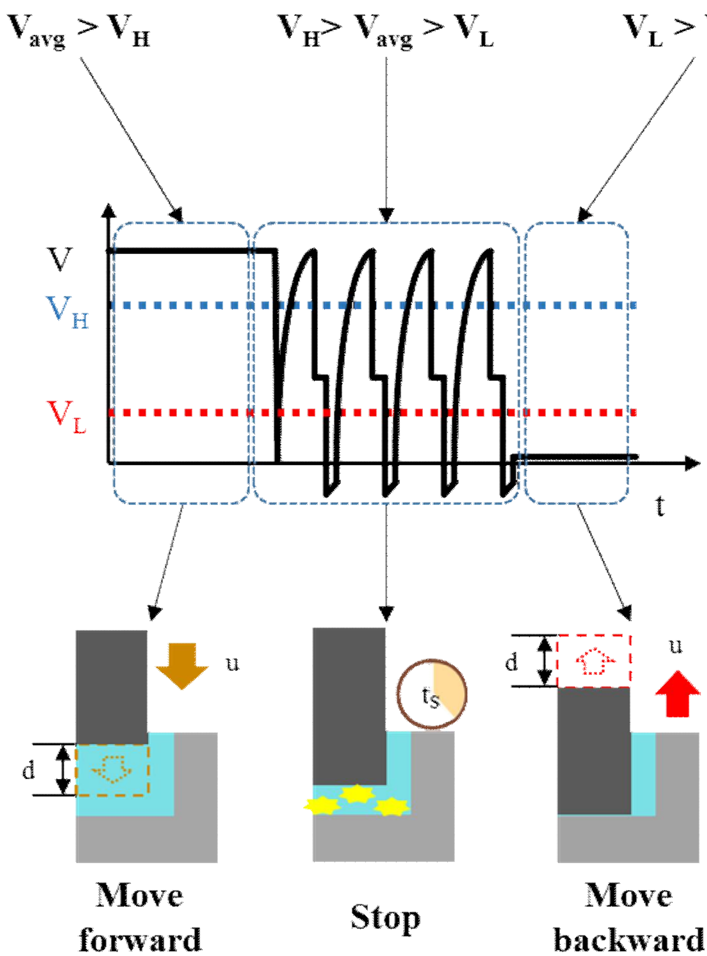


Fig. 6 Relation between design factors and electrical discharge machining.

According to the algorithm, there are several design factors for gap control procedure. Preset number for the average voltage, discharge and short voltage for comparison, tool speed during the movement, period time during tool stop are the selected design factors for the study. For the study, the preset number and the discharge/short voltage was fixed. The discharge and short voltage is mainly decided by the environmental condition such as the dielectric fluid, material of tool or workpiece. Preset number is also established as small as possible for prevention of the collision between tool and workpiece.

2.4. MRR, TWR, and TWRatio

For precise result analyzation, conversion of the result as dimensionless factor is important because each raw results can be affected by each other. Generally in machining, there are several factors such as material removal rate(MRR), tool wear rate(TWR) and tool wear ratio(TWRatio).

MRR means the machined workpiece volume per unit machining time. That is, high MRR is better for machining.

In contrast, TWR is the tool wear volume per unit time. Low TWR is better for machining. However, if the tool wear volume is same and machining time is excessively long, TWR can also be lowered. As a result, comparison of TWR always need to check its own machining time.

Tool wear ratio(TWRatio) is the tool wear volume per machined workpice volume. It is the same value of the result of TWR divided by MRR. For better machining condition, this value needs to be lowered. Fig. 7 shows the concept of the MRR, TWR and TWRatio.

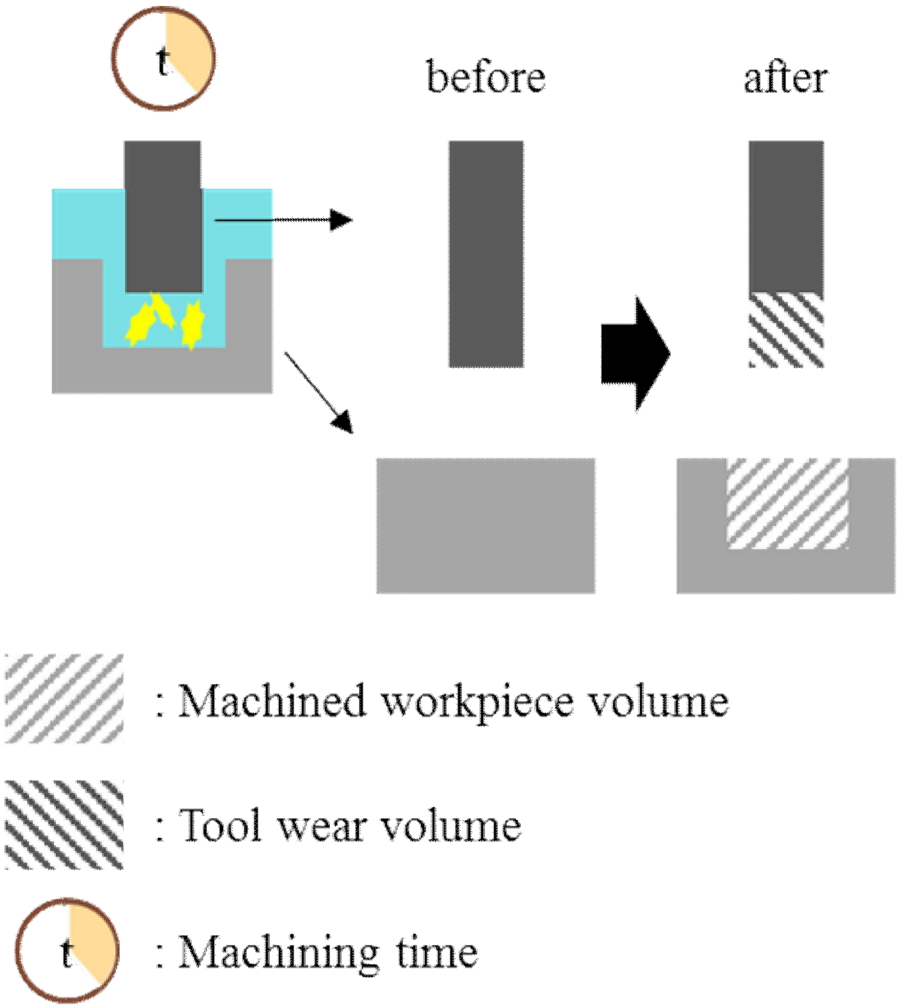


Fig. 7 Concept of MRR, TWR and TWRatio

Chapter 3.

Machining behavior through design factors

3.1. Experimental system

In this study, all the experiment was performed under this common condition shown in Table 2. Electrical discharge machining system composed of RC discharge pulse generator, machining bathtub with X-Y direction stage, Z direction stage with motor for rotation of the tool, DC power supply. The schematics of this system and components are shown on the Fig. 8. The pictures of the tool-motor assembly attached to the Z direction stage, machining bathtub, and RC discharge pulse generator used in the experiment are also shown in the Fig. 9 (a) ~ (c).

Table 2 Common condition of experiment

Voltage	100 V
Capacitance	6 nF
Tool material	WC-Co Φ 300 μm
Workpiece	STS 304, 1mm
Total tool move length	750 μm
Dielectric fluid	Kerosene

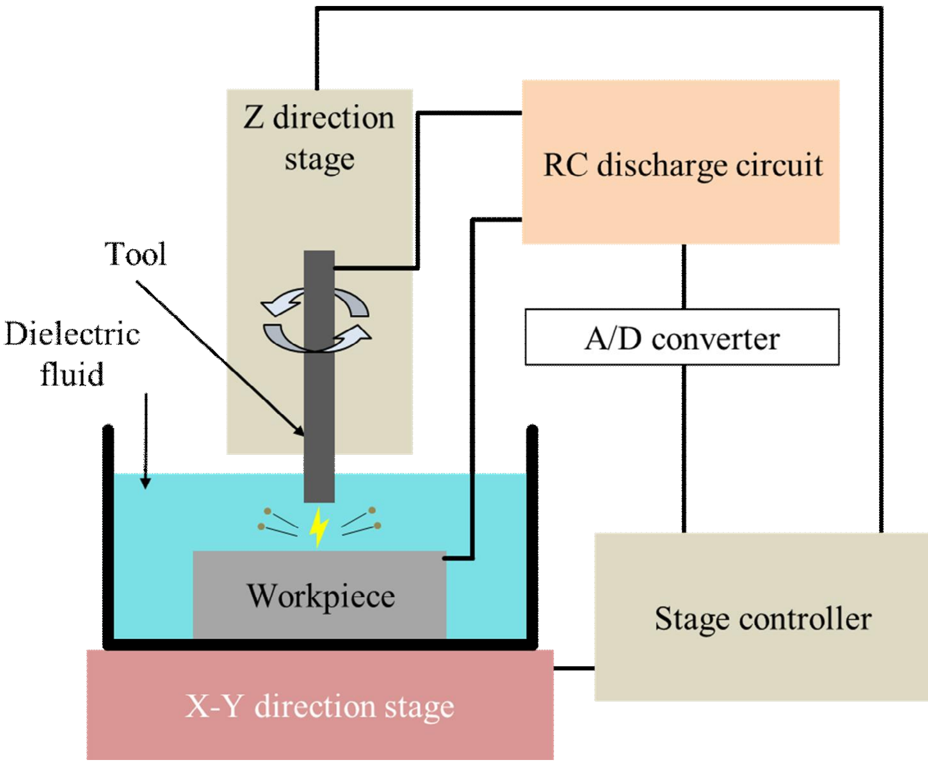
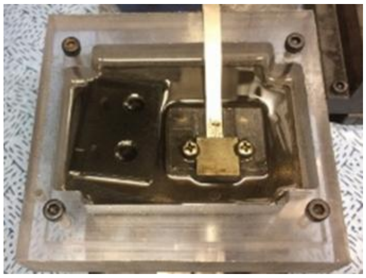
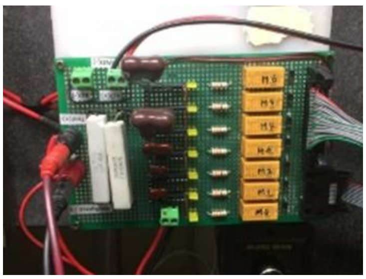


Fig. 8 Schematic of the electrical discharge machining system

(a)



(b)



(c)

Fig. 9 Components used in the experiment (a) : tool-motor assembly, (b) : machining bathtub, (c) : RC discharge pulse generator

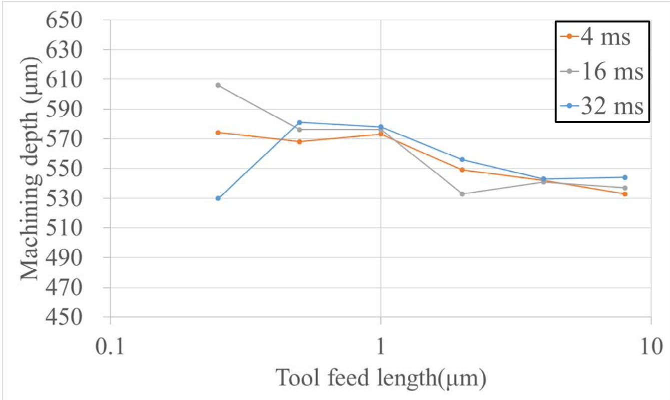
3.2. Experimental result

Experiment result of the tool feed length and tool pause period manipulation was performed to observe the machining behavior. Machining depth, tool wear length and machining time were measured for each experiment.

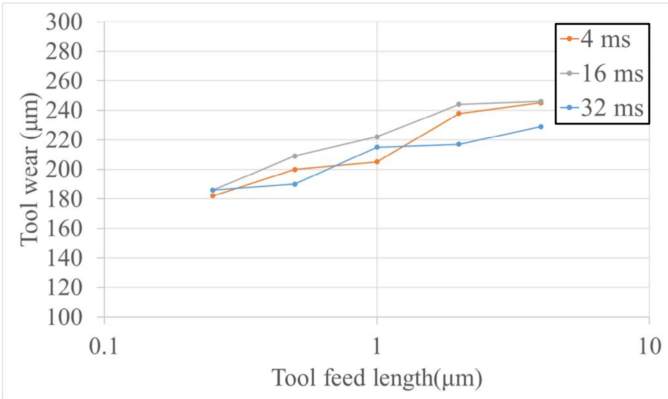
- **Tool feed length and machining behavior**

Fig. 10 shows the experiment result of the tool feed length manipulation. Length variation was 0.25, 0.5, 1, 2, 4, 8 μm. Each experiment by the length variation was conducted under the pause period condition as 4, 16, 32 msec. Machining depth decreases as the length increases. Tool wear and machining time increases depending on the length increase. However, some results of each experiment is far from the result tendency such as machining depth of the 0.25 μm – 32 msec or 2 μm – 16 msec condition. To compensate the result as a quantified dimensionless factor, material removal rate(MRR), tool wear rate(TWR) and tool wear ratio(TWRatio) was calculated.

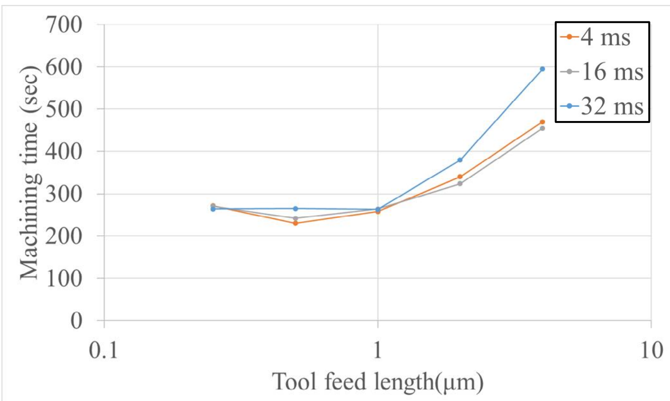
MRR, TWR and TWRatio calculated from machining depth, tool wear length and machining time is shown on Fig. 11. Almost all result of each experiment meets the result tendency through the length variation. When the length increases, MRR and TWR decreases and TWRatio increases. At the length 0.25, the MRR and TWR is slightly out of the result tendency. This result is because of the limit feed accuracy of the stage. Those feed length was much near the limit of the stage used in the experiment than other length conditions.



(a) Machining depth

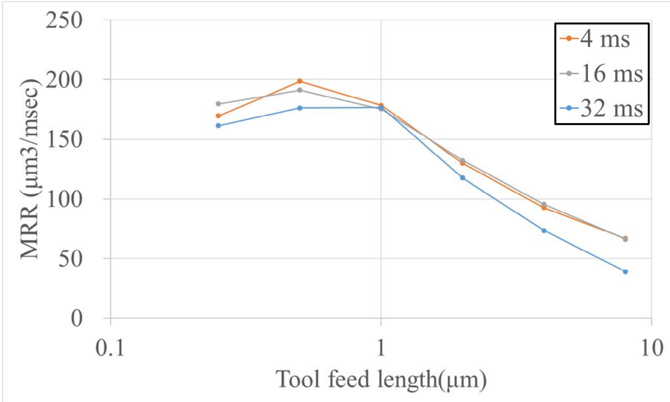


(b) Tool wear

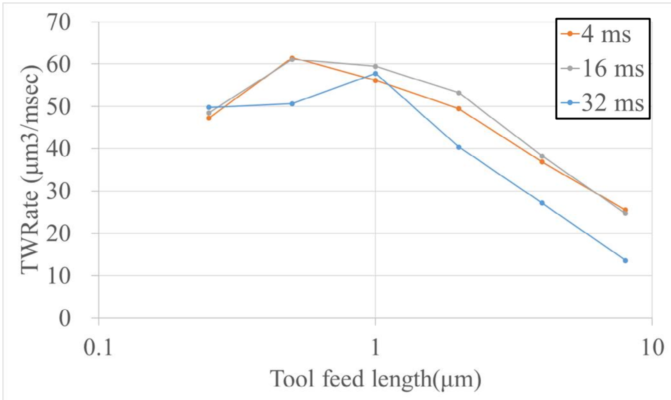


(c) Machining time

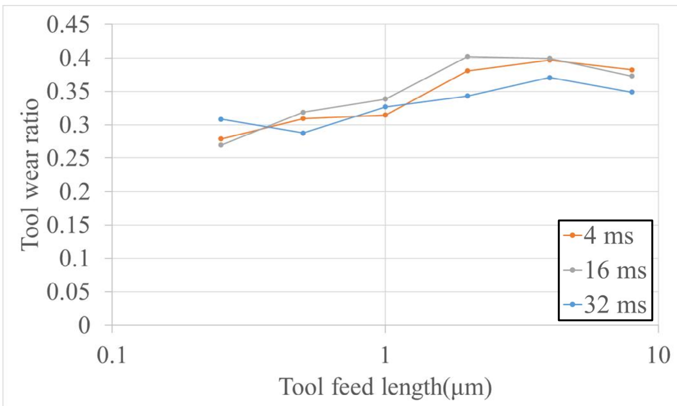
Fig. 10 Result of the tool feed length manipulation experiment



(a) Material removal rate



(b) Tool wear rate



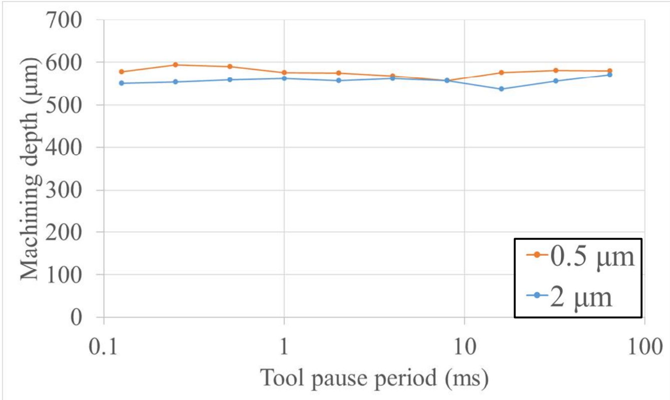
(c) Tool wear ratio

Fig. 11 MRR, TWR and TWRatio of the tool feed length manipulation experiment

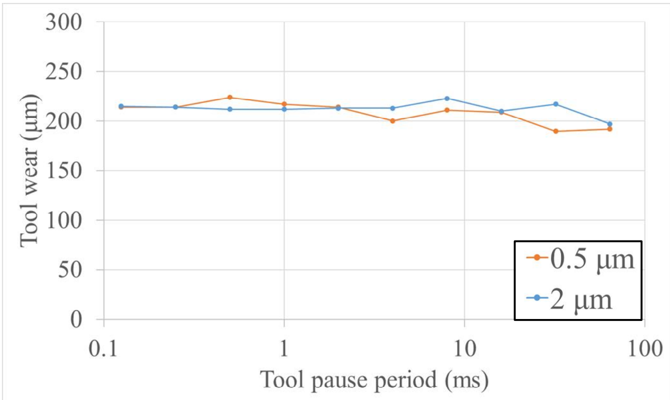
- **Tool pause period and machining behavior**

Fig. 12 shows the experiment result of the tool pause period manipulation. Period variation was from 0.125 to 64 msec. Each experiment by the period variation was conducted under the feed length condition as 0.5 and 2 μm. Machining depth and tool wear has no difference in spite of the period increases. Machining time increases depending on the period increase. Different from the length variation condition, almost every results are not far from the result tendency except for the machining time, 0.25 msec – 0.5 μm. Between the two length variation, there is the only tendency difference on machining time.

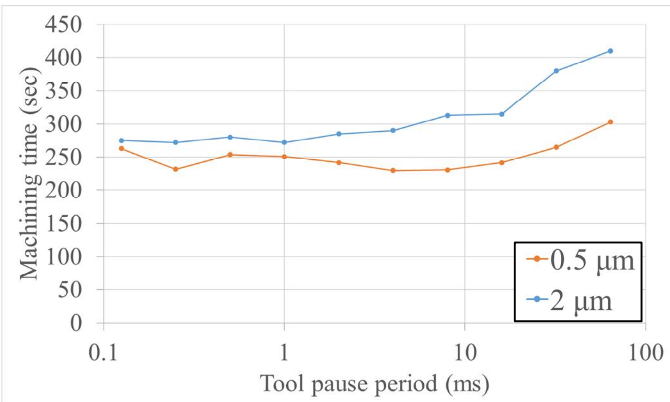
MRR, TWR and TWRatio calculated from machining depth, tool wear length and machining time is shown on Fig. 13. At this time almost all result of each experiment meets the result tendency through the length variation. When the period increases, MRR and TWR decreases and TWRatio has no difference.



(a) Machining depth

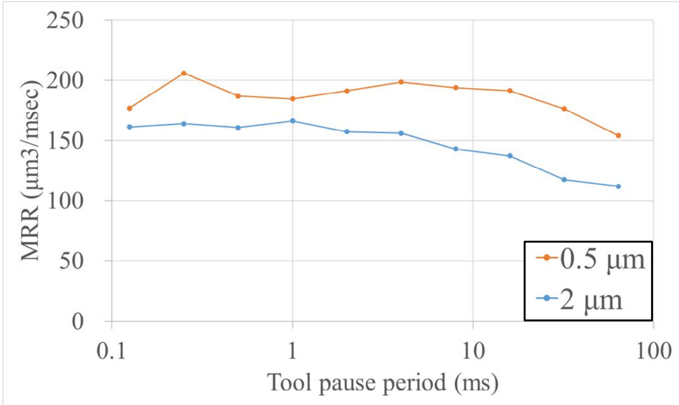


(b) Tool wear

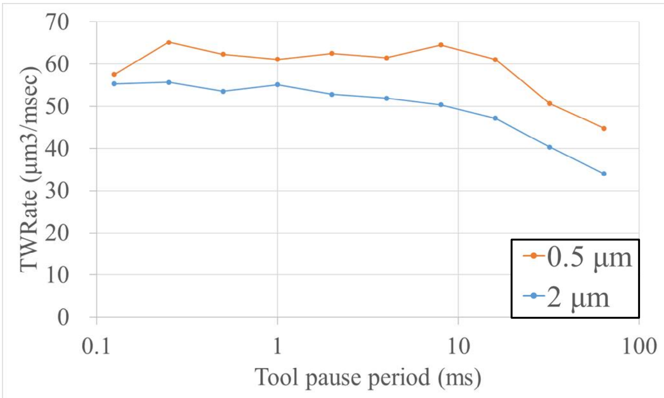


(c) Machining time

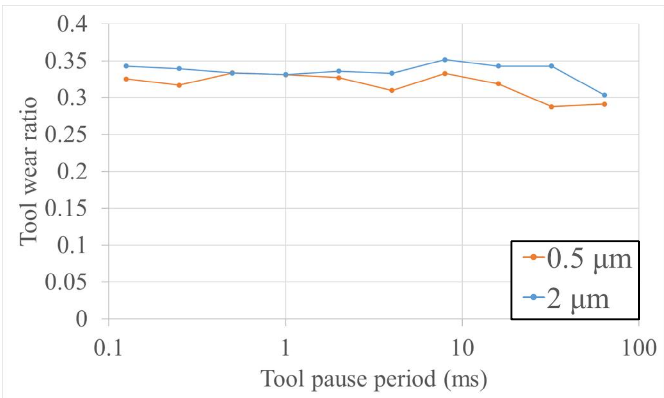
Fig. 12 Result of the tool pause period manipulation experiment



(a) Material removal rate



(b) Tool wear rate



(c) Tool wear ratio

Fig. 13 MRR, TWR and TWRatio of the tool pause period manipulation experiment

3.3. Discussion

The result of the tool feed length experiment is relevant to the number of tool backward movement. When the last sequence of the stop order ended, the gap state goes to the excessive gap, ordering the tool move forward. As the tool feed length goes larger, excessive feed can cause the gap state to be insufficient gap. This occurs unnecessary arc and collision and is shown in Fig. 14. Caused by this reason, tool goes backward more repeatedly than shorter feed length. Fig. 15 shows the numbers of backward movement by the tool feed length.

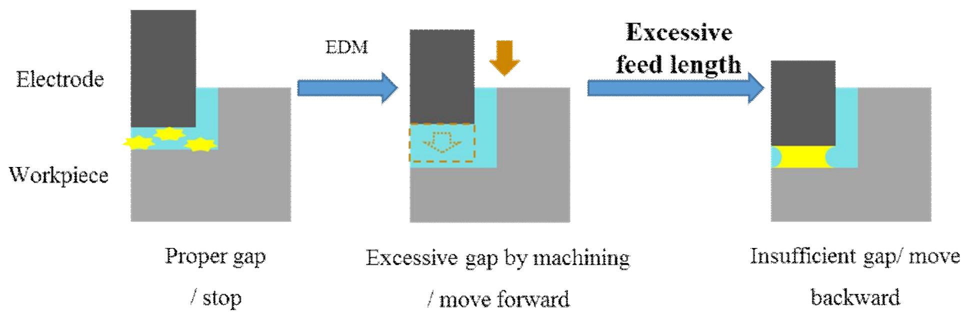


Fig. 14 Change of the machining process by excessive feed length

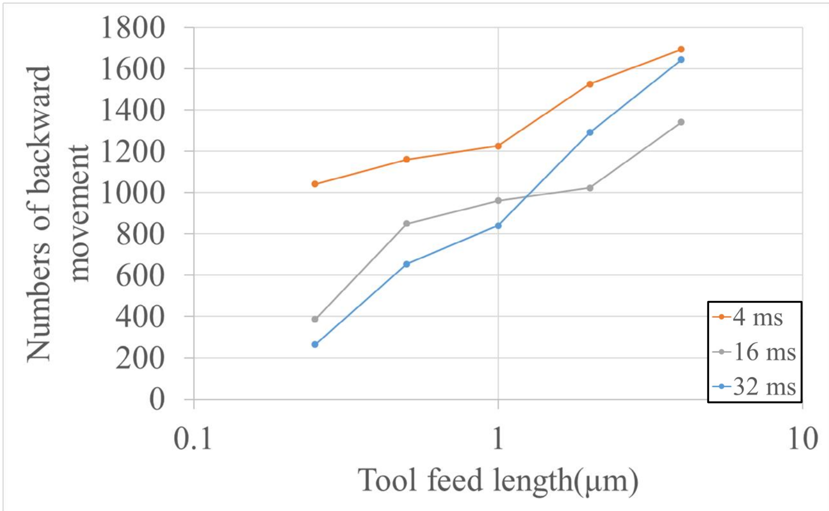


Fig. 15 Numbers of tool backward movement by the tool feed length

If the tool goes backward, tool have to move forward again for machining, but too much backward sequence can cause machining time consuming. And arc can damage the tool. By repeating the tool movement, arc can occur easily that can wear enormously the tool. As a result, TWRatio decreases when the feed length increases.

The result of the pause period variation experiment is relevant to the unnecessary rest time. Under the proper condition of design factor, stop order for tool movement occurs as the proper gap is measured. The tool may stop the movement for pause period. At the end of the period, measurement of the gap state performs again. This sequence repeats unless the state changes as excessive gap. When the final stop order is conducted and before the new order of forward movement, the gap finally becomes the excessive state, and the tool yet stay still, neither forward nor backward. This period is rest time. Fig. 16 shows this phenomenon.

As the tool pause period goes longer, unnecessary rest time increases, causing machining time increased. MRR and TWR decreases but TWR remains almost same, which means there is no difference in machined workpiece volume and tool wear volume. As a result, tool pause period only can affect to the machining time, without any harmful influence to the machining quality or precision.

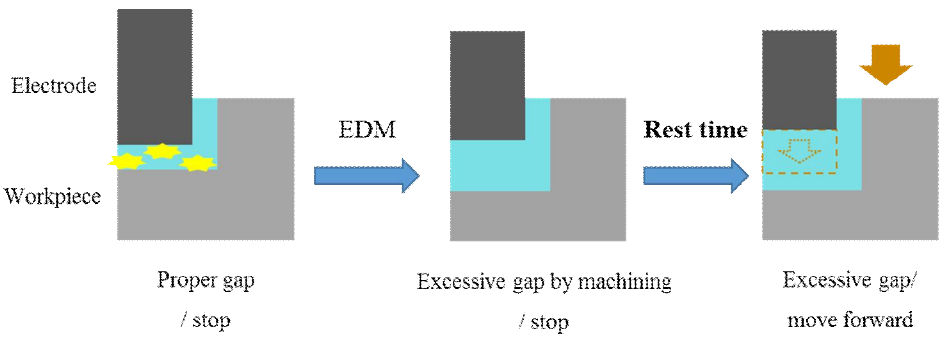


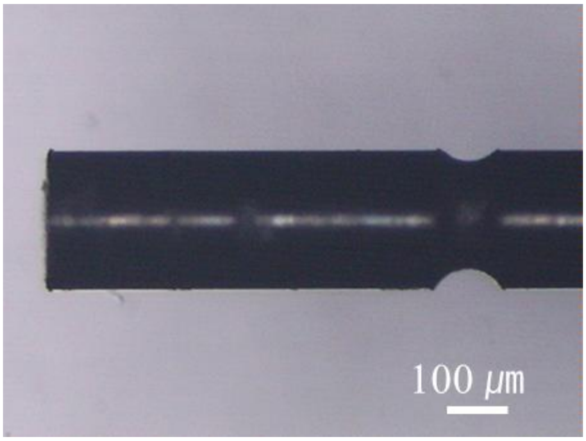
Fig 16. Rest time occurred by excessively long tool pause period

3.4. Optimal design factor selection

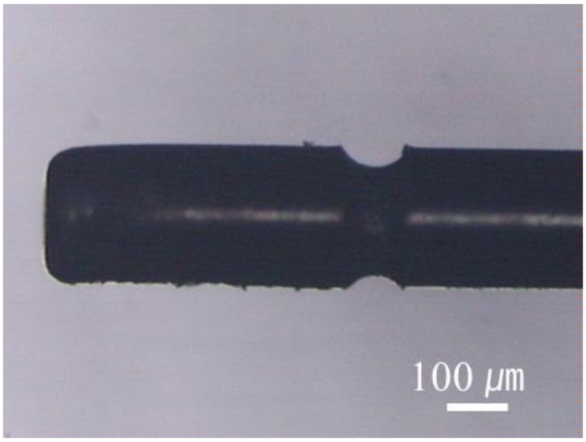
For effective electrical discharge machining, condition that can achieve high MRR, low TWR and machining time should be selected.

Tool pause period only affects to the machining time, and it can decrease as the period get shorter. Already shown in the result of tool feed length experiment, the difference of the pause time does not matter to machining time. And the short feed length(0.25 ~ 1 μm) shows the minimal machining time, high MRR. In terms of the result of the pause period experiod, shorter length of feed shows lower machining time. That is, the shorter both tool pause period and feed length are, the higher MRR and lower machining time can get.

Under the experiment condition of the study, optimal design factor can be selected as 0.5 μm – 0.25 msec. Fig. 17 shows the tool of selected condition. The machining result was; machining time = 230 msec, tool wear length = 200 μm, tool wear volume = 0.0457 mm^3, machining depth = 568 μm, MRR = 198,614 $\mu m^3/sec$, TWR = 61,466 $\mu m^3/sec$, TWRatio = 0.31. Tool volume was calculated as it's diameter is 320 μm.



(a)



(b)

Fig. 17 Tool wear of the optimal design factor (a) Before machining, (b) After machining

Chapter 4.

Conclusion

In this study, machining behavior can be affected by the tool feed length and pause period. As the tool feed length shortens, MRR and TWR increases and machining time and TWRatio decreases. By decreasing the chance to occur insufficient gap state, the number of backward movement tool rapidly decreases. As a result, total machined volume increases and tool wear volume decreases, causing TWRatio lower.

When the tool pause period decreases, MRR and TWR are increased and machining time is decreased. Rapid feedback thanks to the shortened rest time of the tool can decline the machining time. However total machined volume and tool wear volume remains the same, TWRatio gets no difference.

Under the experiment condition of the study, optimal design factor can be selected as 0.5 μm – 0.25 msec.

This study can only shows the relation between design factors in limited condition. Further studies of design factors needs to be conducted in various conditions by changing materials of workpiece, tool and dielectric fluid, application to the transistor discharge pulse generator. With these studies, electrical discharge machining with both good quality and speed can be achieved.

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국문 초록

본 논문은 전극 이송 속도, 전극 이송 거리가 간극 제어가 도입된 미세 방전 드릴링에서 어떠한 가공 결과 변화를 가져다 주는가를 확인하여 각 주요 인자가 미세 방전 가공에 끼치는 영향을 분석하였다. 미세 방전 가공은 절연액 내에서의 전극과 가공물 간의 방전 현상을 이용하는 제거 가공 공정이다. 이는 급증하는 고강도 난삭재의 복잡한 미세 구조 가공에 대한 수요를 충족할 수 있는 가공 공정 중 하나이다. 그러나 미세 방전 가공은 기타 가공 공정보다 가공 속도가 현저히 느리며 전극의 마모는 가공의 정밀성을 떨어뜨리는 원인이다. 이를 해결하여 가공의 품질 향상을 위해 본 연구는 간극 제어의 주요 인자에 초점을 맞추어 미세 방전 드릴링을 개선하였다. 전극의 이송 거리가 짧을수록, 정지 시간이 짧을수록 가공에서의 MRR이 개선되며, 공구의 마모 또한 감소함을 확인하였다.

주요어 : 방전 가공, 간극 제어, 소재제거율, 공구마모율, 가공량 대비 마모량

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