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Micro ED-drilling에서의 TR-iso-pulse generator 성능 평가

Performance of a TR-iso-pulse generator in micro ED-drilling

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서울대학교 대학원

기계항공공학부

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이 논문을 공학석사 학위논문으로 제출함

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Abstract

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This study describes a TR-iso-pulse generator which has better machining performance than an RC-pulse generator in micro-electrical discharge drilling (micro ED-drilling). Although machining with a TR-pulse generator is more efficient compared to when using a RC-pulse generator in macro-scale EDM, an RC-pulse generator is mainly used in micro EDM because it can generate the short discharge pulse necessary to minimize the discharge energy. However, to increase the machining efficiency, it is necessary to develop a TR-iso-pulse generator capable of generating a small amount of uniform discharge energy. In this research, a TR-iso-pulse generator was constructed for micro ED-drilling. For an accurate performance comparison between an RC-pulse generator and a TR-iso-pulse generator, each pulse generator was set up to generate the same discharge energy for a single discharge. Through micro ED-drilling, material removal rate (MRR) and relative wear ratio (RWR) were measured with respect to feed rate, and surface roughness was also measured with a 3D profiler. As a result, MRR increased by 121% and RWR decreased by 39% in the TR−iso−pulse generator compared with the RC−pulse generator. Surface roughness also reduced by 22% in the TR−iso−pulse generator.

Keyword : Micro EDM; TR−iso−pulse generator; RC−pulse generator; ED−drilling

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Chapter 1. Introduction

Electrical discharge machining (EDM) is a thermal process involving the use of the spark energy of a discharge pulse generated by RC or TR circuits. Because an RC−pulse generator creates discharge pulse trains by periodical charging and discharging of a capacitor, the discharge energy is controlled by adjusting the size of the capacitor. On the other hand, given that a TR−pulse generator produces discharge pulse trains through the switching of a FET, the pulse−on time determines the discharge energy [1].

Due to the difference in the principle of discharge generation between RC−pulse and TR−pulse generators, their application areas differ according to merits of each type. An RC−pulse generator can emit a small amount of discharge energy easily given its use of a small capacitor; thus, this type is widely used in micro EDM. However, the machining speed is rather slow because the discharge frequency is very low due to the time required to charge the capacitor. Therefore, machining takes an excessive amount of time. On the other hand, the TR−pulse generator has the advantage of maximizing the machining efficiency because it can secure a high discharge frequency via the on and off signals of a FET. By virtue of this advantage, TR−pulse generators are mainly used in macro EDM, which requires high productivity. However, due to the limitation of the switching speed and the discharge ignition delay time, it is difficult to ensure a short and uniform discharge duration. As a result, the machining accuracy of a TR−pulse generator is lower than that of an RC−pulse generator in micro EDM [2].

There have been various attempts to apply a TR−pulse generator to micro EDM to achieve high machining efficiency, as the switching speed of a FET has become fast enough to be used in micro EDM. Masuzawa et al. reported that it was possible to apply a TR−pulse generator to micro EDM by producing a short pulse−on time of 220 ns [3]. He et al. also developed a nano second order TR−pulse generator, which reduced the pulse−on time to 90 ns using a periodical switching method [4]. In addition to the above two studies, there have been other studies in which TR was applied to micro EDM through periodical switching method [5−7].

Although a short pulse−on time of a TR−pulse generator broadens its applicability to micro−machining, an irregular discharge duration and its open circuit remain as problems. A TR−

pulse generator has a discharge ignition delay time after voltage is applied depending on the insulation status between the tool and the workpiece. Therefore, the unequal ignition delay time, which varies according to the insulation condition, causes an irregular discharge duration and produces a rough surface which is not suitable for micro EDM. An open circuit is one in which a discharge does not occur during the pulse-on time of the FET when the ignition delay time is longer than the pulse-on time [8]. Han et al. reported that when the pulse-on time is less than 100 ns, the ignition delay often becomes longer than the pulse-on time and the discharge does not occur [9]. As the number of open circuit instances increases, the discharge frequency and machining efficiency of a TR-pulse generator can both degrade.

Therefore, it is necessary to apply a TR-pulse generator which produces not only a short but also a uniform discharge duration without an open circuit, i.e., a TR-iso-pulse generator, to micro EDM to achieve high machining efficiency and low surface roughness. Various efforts have been made to apply the TR-iso-pulse generator to micro EDM [10-12]. In these previous studies, the TR-iso-pulse generators could produce short and uniform pulses by monitoring the start of the discharge and switching the pulse−on and pulse−off signals after a pre−set duration. Furthermore, an open circuit does not occur because the pulse−on signal is maintained until the current sensor senses the actual discharge, instead of the periodic switching of the FET. However, most of these previous studies were limited to the WEDM area, and studies of various fields of micro EDM, such as milling, drilling, and die sinking, are too few in number.

In the present study, a TR−iso−pulse generator suitable for micro EDM was constructed and its performance capabilities were compared with those of a RC−pulse generator through micro ED−drilling assessments. For an accurate comparison, we set up the TR−iso−pulse generator to produce discharge energy identical to that of the RC−pulse generator and compared their material removal rates (MRR) with respect to the feed rates. The effect of the TR−iso−pulse generator on the tool wear was also analyzed, a factor which was not covered in previous WEDM studies. For a quantitative analysis of the tool wear, the relative wear ratio (RWR: the tool wear length over the machining depth) was used. Finally, the surface roughness of both generators was compared using a 3D profiler.

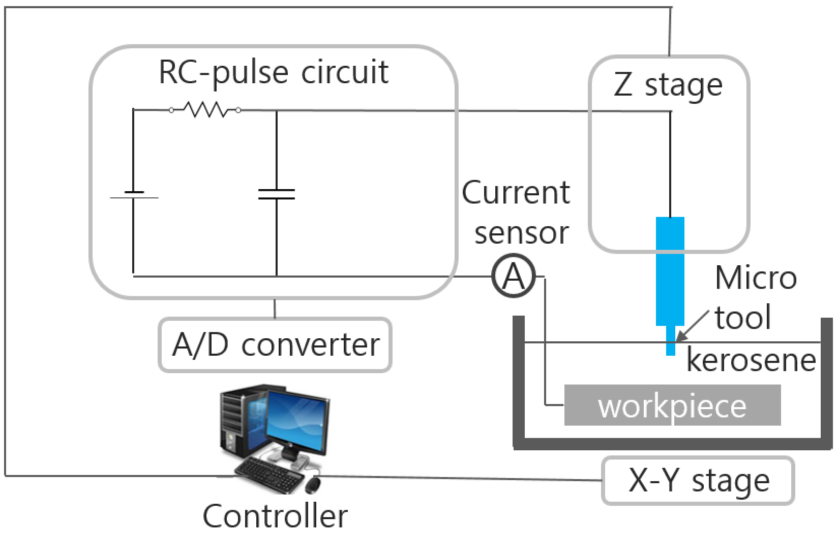
In the following paragraphs, the TR−iso−pulse generator used in this study will be explained in more detail. We will then analyze and discuss the performance differences between the RC−pulse and the TR−iso−pulse generator with respect to the MRR, RWR, and surface roughness.

Chapter 2. Experimental setup

In this section, I describe the experimental setup, the machining conditions and the TR−iso−pulse generator used in this study.

2.1. Experimental setup

Fig. 1 shows a schematic diagram of the micro−EDM system. The custom micro EDM machine consists of a precision three−axis stage (linear resolution: 0.1 μm, Parker, USA), a controller (CEM104, Delta Tau, USA), and a pulse generator. An analog−to−digital converter was used to control the machining gap between the tool and the workpiece. The tool−servo−feed method was applied and the system monitored the tool status. When the tool comes into contact with the workpiece, which is hereafter referred to as a short, the tool moves backward. When the machining gap is within a proper range, which is hereafter referred to as a hold, the tool stops. When the tool is away from the workpiece and discharge does not occur, the tool moves forwards. An oscilloscope was used to observe the current and voltage between the tool and the workpiece. The micro−tool was fabricated using a WEDG system [13]. The machining conditions are listed in Table 1.



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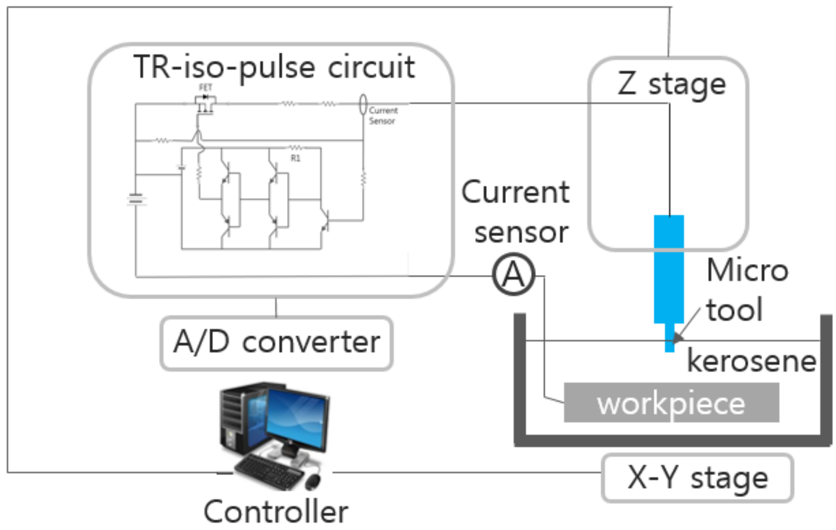


(b)

Fig. 1. Schematic diagram of the micro−EDM system: (a) RC−pulse generator system, and (b) TR−iso−pulse generator system

Table 1. Machining Conditions

Condition	RC-pulse generator	TR-iso-pulse generator
Open voltage [V]	100	
Peak current [A]	4.4	
Pulse on time [ns]	800	
Feed rate [μm/s]	1,2,3,4	
Dielectric	kerosene	
Tool	WC-Co / Φ100 μm	
Work piece	STS304	
Drilling depth	300 μm	

2.2. Introduction of the TR-iso-pulse generator

Fig. 2 shows the RC−pulse generator and the TR−iso−pulse generator used in this study. The TR−iso−pulse generator was originally developed by Han et al. [9], and the specifications of each circuit element were adjusted to generate a pulse with a current and duration identical to those of the RC−pulse generator. As a result, both circuits generated discharge pulses, each of which had a peak current of 4.4 A and a pulse−on time of 800 ns, suitable for micro ED−drilling. However one difference is that reverse current only occurred in the RC−pulse generator. The current sensor (LAH 25−NP, LEM) with a reaction time of up to 500 ns and an n−channel power MOSFET (IRF730) capable of rapid switching were installed.

In addition, NPN and PNP transistors were used to form the internal circuit. Finally, the resistors were appropriately arranged to achieve an identical pulse−on time in both the RC−pulse and TR−iso−pulse generators. The components applied in both generators are listed in Table 2, and the current pulses obtained from each generator are shown in Fig. 3.

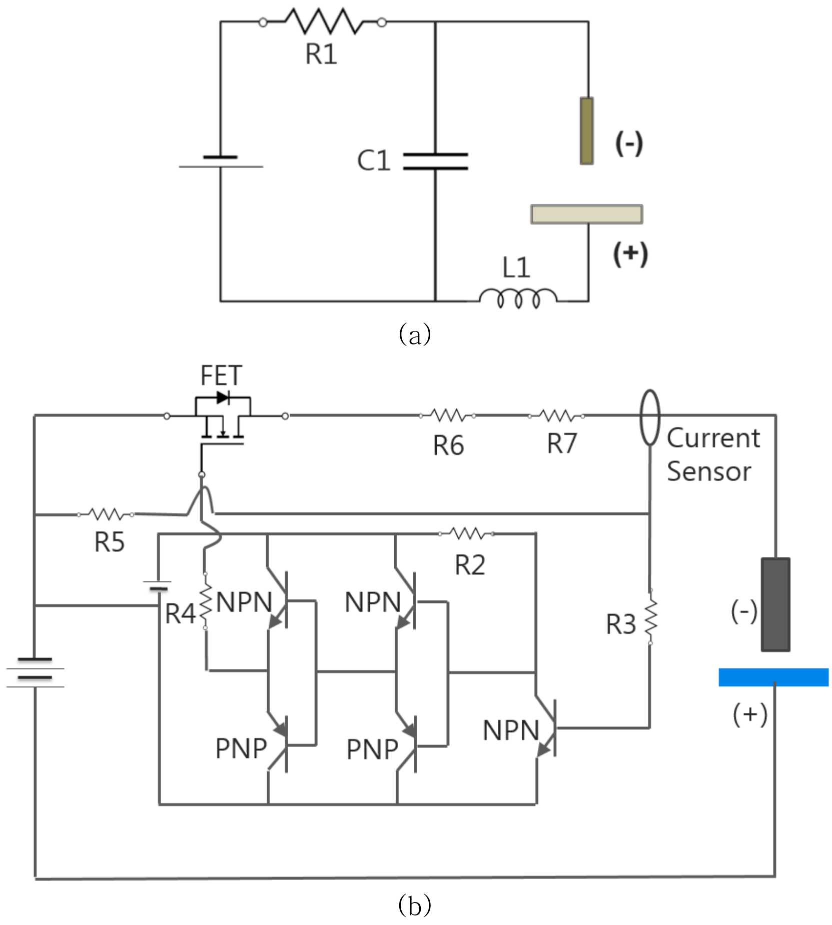
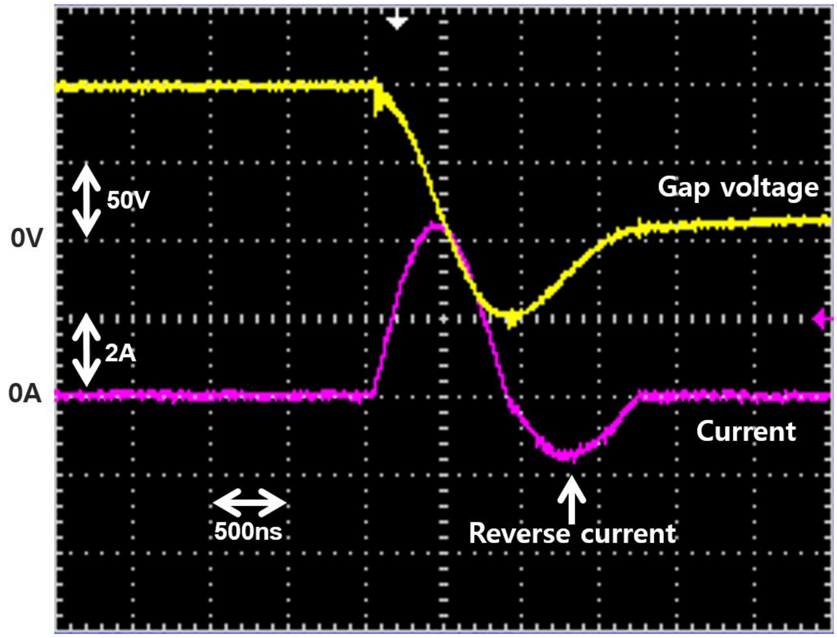


Fig. 2. Pulse generator circuit: (a) RC−pulse generator, and (b) TR−iso−pulse generator

Table 2. Components Lists

Number	Part	Specifications
1	Resistor (R1)	1 KΩ
2	Capacitor (C1)	6 nF
3	Coil (L1)	5.6 μH
4	Current sensor	Step response time to 90% of I_{PN}: <500 ns
5	MOSFET	Turn on time: 25 ns Turn off time: 52 ns
6	NPN	Turn on time: 35 ns Turn off time: 255 ns
7	PNP	Turn on time: 35 ns Turn off time: 255 ns
8	Resistor (R2)	5 KΩ
9	Resistor (R3)	1 KΩ
10	Resistor (R4)	100 Ω
11	Resistor (R5)	430 Ω
12	Resistor (R6)	20 Ω
13	Resistor (R7)	5 Ω



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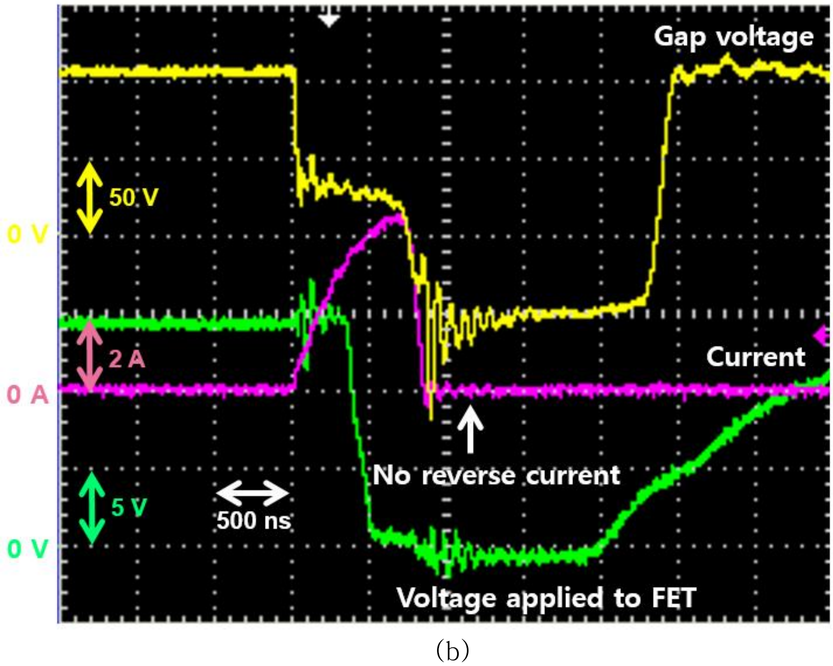


(b)

Fig. 3. Current pulse: (a) RC−pulse generator,

and (b) TR−iso−pulse generator

The circuit of the TR–iso–pulse generator is divided into an internal circuit which controls the iso–duration of the discharge and an external circuit which generates the discharges. The operation sequence is explained in Fig. 4. (1) The FET is turned on by an internal circuit to prepare the discharge in the initial state. (2) When current flows through the external circuit as the micro–tool approaches the workpiece and the discharge occurs, the current sensor recognizes the discharge and transmits a signal to the internal circuit. (3) The internal circuit cuts off the current flow of the external circuit by switching off the FET after a pre–set time elapses. (4) The current sensor detects the current interruption and transmits a signal to the internal circuit. (5) After the pre–set turning–off duration, the FET is turned on again by the internal circuit for the next discharge.

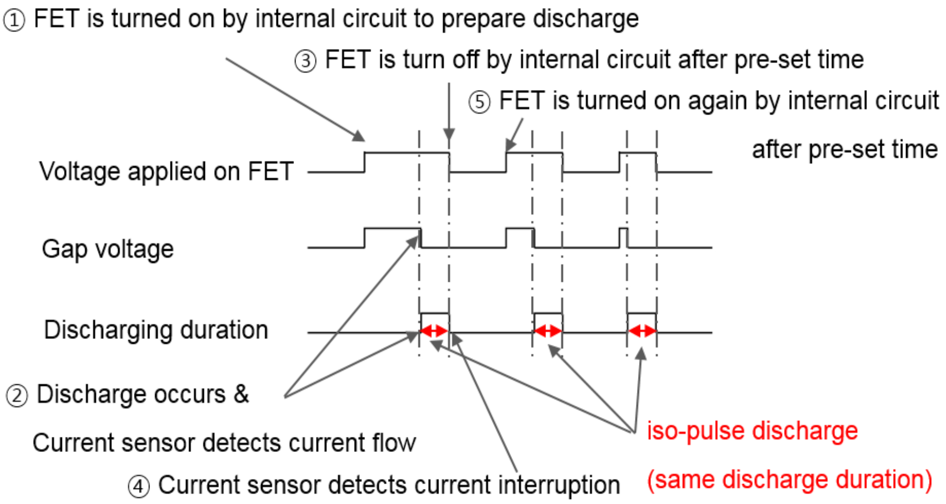


Fig. 4. Operation sequence of the TR–iso–pulse generator

Chapter 3. Result and discussion

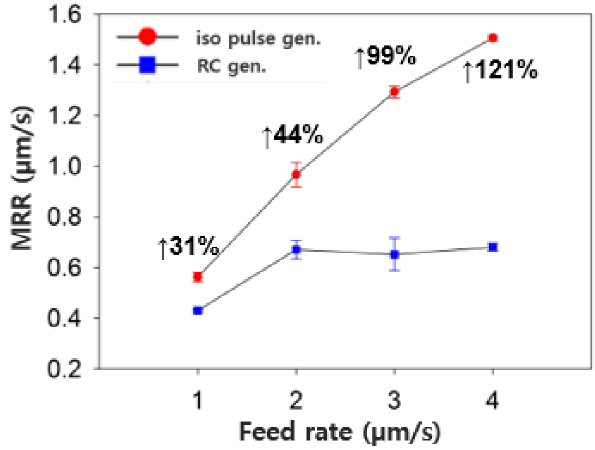
3.1. Material Removal Rate (MRR)

3.1.1. Experimental result

The experiment was carried out under the machining conditions specified in Table 1, and Fig. 5 shows the experimental results of the MRR, the machining depth, and the machining time. The MRR is normally the machining volume over the machining time. However, because the cross−sectional area is constant in ED−drilling, the MRR is defined as the machining depth over the machining time in this research. The TR−iso−pulse generator demonstrated a higher MRR by 121% than the RC−pulse generator at a feed rate of 4 μm/s. While the MRR of the TR−iso−pulse generator increased as the feed rate increased, that of the RC−pulse generator remained constant after 2 μm/s without a further increase.

The test result of the machining depth showed that the machining depth of the TR−iso−pulse generator was 20−25% deeper than that of the RC−pulse generator at all feed rates; however, variations in the machining depth were not observed with respect to the feed rate.

The machining time of the TR-iso-pulse generator decreased gradually with an increase in the feed rate and was 45% shorter than that of the RC-pulse generator at 4 μm/s. On the other hand, the machining time of the RC-pulse generator decreased until 2 μm/s and did not decrease after 2 μm/s.



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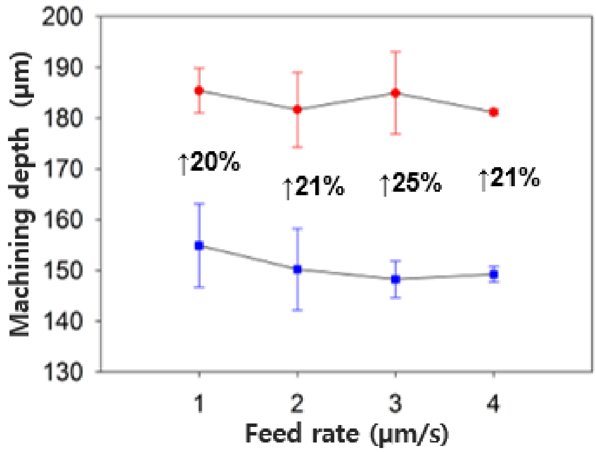

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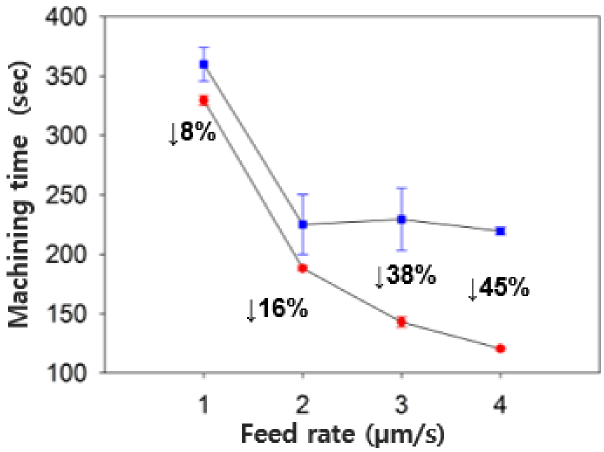


(c)

Fig. 5. Comparison of the experimental results: (a) MRR, (b) machining depth, and (c) machining time according to feed rate

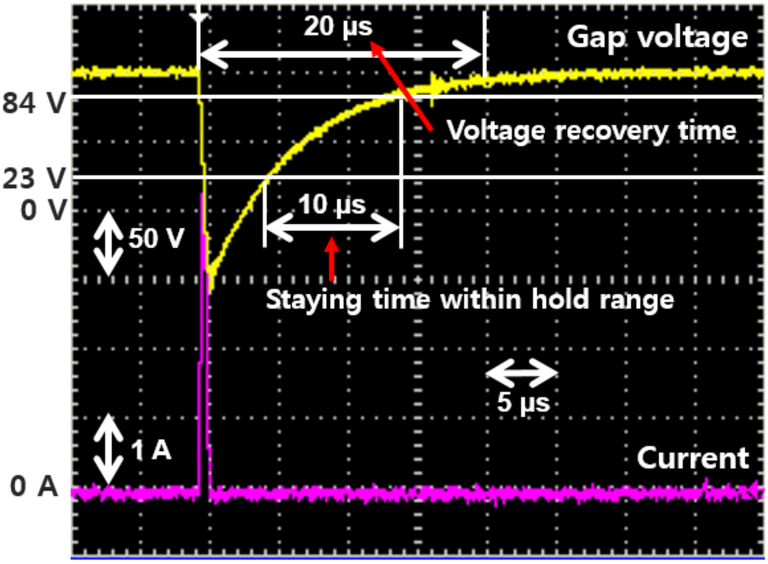
3.1.2. Effect of the machining depth and machining time on the MRR

The TR−iso−pulse generator demonstrated a higher MRR than the RC−pulse generator. This occurred because, regardless of the feed rate, it had a deep machining depth of 20−25% for all feed rates. However, as the feed rate increased, the MRR was affected more by the machining time than by the machining depth. As shown Figs. 5(b) and 5(c), the machining depth of both the RC−pulse generator and the TR−iso−pulse generator showed little change with an increase in the feed rate. On the other hand, the machining time showed a significant difference between the RC−pulse and the TR−iso−pulse generators according to the feed rate. As the feed rate was increased, while the machining time of the TR−iso−pulse generator decreased gradually, that of the RC−pulse generator remained nearly constant after 2 μm/s. Consequently, the TR−iso−pulse generator showed better MRR performance than the RC−pulse generator at a high feed rate due to the reduced machining time by 45%.

3.1.3. Effect of the voltage recovery time on the machining time

As shown in Fig. 6, the voltage recovery time of the TR-iso-pulse generator was remarkably short compared to that of the RC-pulse generator. Due to this quick voltage recovery time, fewer shorts and holds occurred in the TR-iso-pulse generator, which reduced the machining time.

The voltage recovery time of the TR-iso-pulse generator was approximately 2.5 μs while that of the RC-pulse generator was 20 μs. This indicates that the discharge preparation time of the RC-pulse generator for the next discharge is eight times longer than that of the TR-iso-pulse generator. When the tool is transported toward the workpiece according to a set feed rate, if the discharge preparation time is longer than the time required for the tool moves to the workpiece, the tool comes into contact with the workpiece without a discharge. Therefore, an extremely long preparation time of the RC-pulse generator results in many more shorts at a high feed rate. On the other hand, the TR-iso-pulse generator can be ready to discharge before the tool comes into contact with the workpiece due to its short discharge preparation time; therefore, it can finish the machining process with nearly zero shorts even at a high feed rate. This is clear from the experimental test conducted for a comparison, in which the numbers of shorts are shown in Fig. 7.



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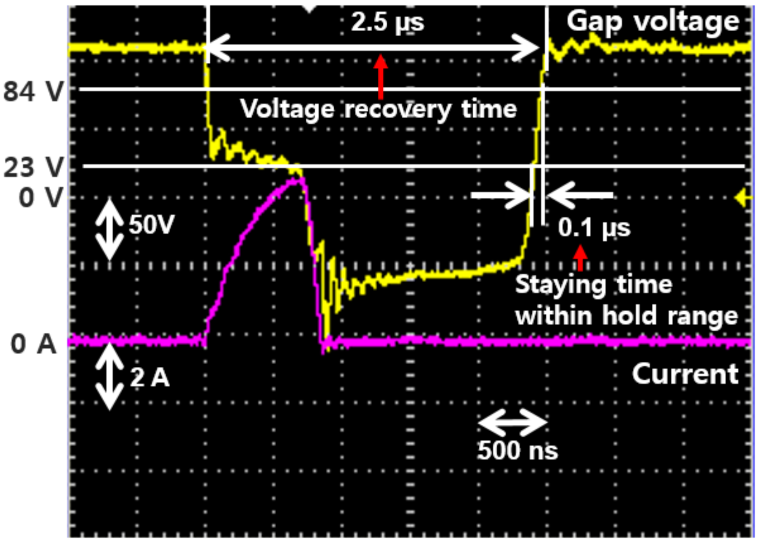
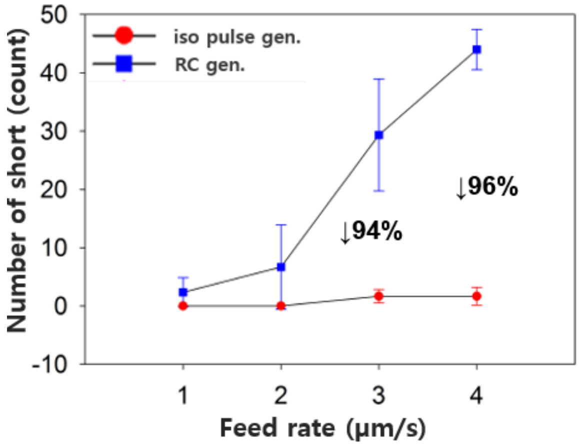


(b)

Fig. 6. Discharge graph: (a) RC−pulse generator, and (b) TR−iso−pulse generator



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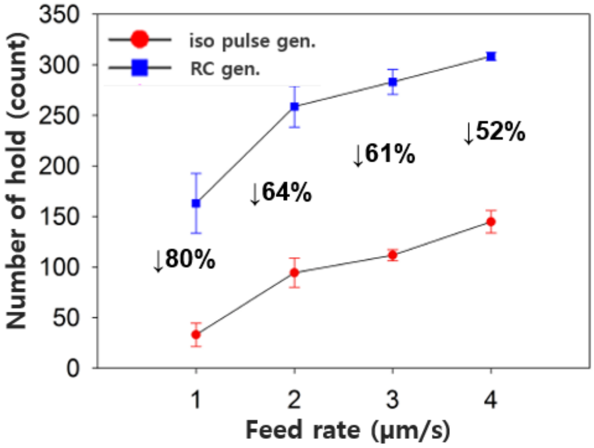


(b)

Fig. 7. Comparison of the experimental results: (a) number of shorts, and (b) number of holds according to feed rate

Fig. 8 shows the gap voltage range set for the servo-feed control. On the servo-control system, when the gap voltage is within the boundaries of the hold range (23V to 84V), the tool holds to secure appropriate clearance with the workpiece and stops feeding for a moment to recover the insulation of the dielectric liquid. Therefore, a long staying time within the hold voltage range results in more holds and a longer machining time. As shown in Figs. 6 and 7, the staying time within the hold range of the RC−pulse generator during one discharge is 10 μs and that of the TR−iso−pulse generator is 0.1 μs. In other words, the RC−pulse generator had in this case a longer staying time by 100 times than the TR−iso−pulse generator during the voltage recovery time. As a result, nearly 150 times more holds were generated in the RC−pulse generator, and the machining time became longer than that in the TR−iso−pulse generator.

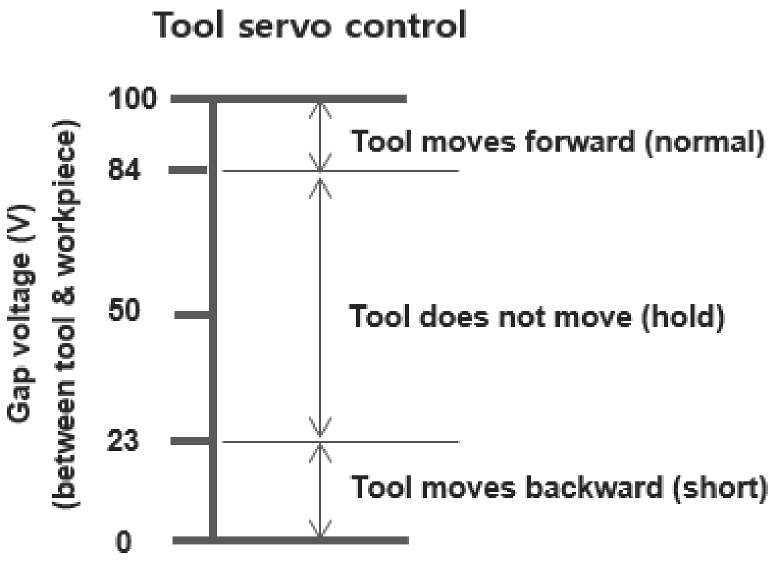


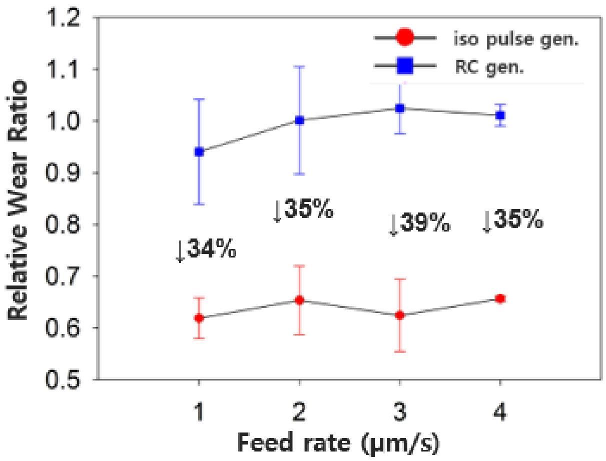
Fig. 8. Servo feed control by gap voltage.

3.2. Relative Wear Ratio (RWR)

3.2.1 Experimental result

Fig. 9 shows experimental results of the relative wear ratio (RWR) and tool wear length. In this study, RWR is the tool wear length over the machining depth; therefore, a low RWR means low tool wear.

The RWR value of the TR–iso–pulse generator was 39% lower than that of the RC–pulse generator at a feed rate of 3 μm/s, and significant variations were not observed according to the feed rate. The tool wear length of the TR–iso–pulse generator was lower at all feed rates compared to that with the RC–pulse generator, and the tool wear length did not show significant changes with an increase in the feed rate.



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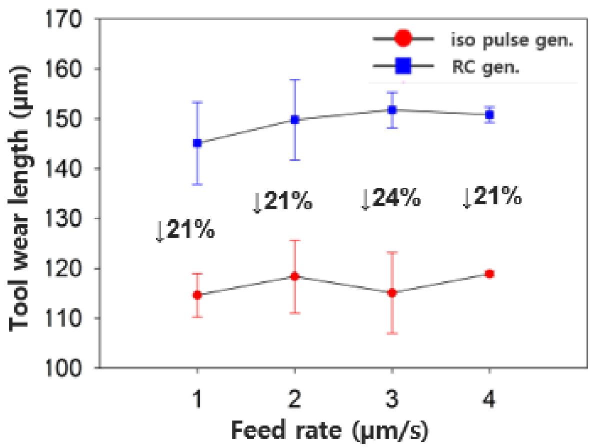

(b)

Fig. 9. Comparison of the experimental results: (a) relative wear ratio, and (b) tool wear length according to feed rate

3.2.1. Effect of reverse current on the tool wear length

Due to the reverse current, additional tool wear occurred in the RC−pulse generator. In micro EDM, the tool is usually charged negatively because electrons are the main factor behind the machining mechanism [14]. When a plasma channel is created through a discharge, negative electrons move rapidly to the anode and collide with the workpiece. As shown in Fig. 3(a), in the case of the RC−pulse generator, the polarity of the tool fluctuated due to stray inductance and reverse current flows. In the duration of reverse current, electrons collide with the tool instead of the workpiece, which could intensify the tool wear. However, in the case of the TR−iso−pulse generator, the FET cuts off the current during the pulse−off time, and thus as we mentioned in experimental setup, reverse current did not occur as shown in Fig. 3. Therefore, additional tool wear due to the reverse current could not occur in the TR−iso−pulse generator.

3.3. Surface roughness

3.3.1. Experimental result

The surface roughness was measured by a 3D profiler, and the average roughness (Ra) of the TR−iso−pulse generator was found to be 22% lower than that of the RC−pulse generator, as shown in Fig. 10.

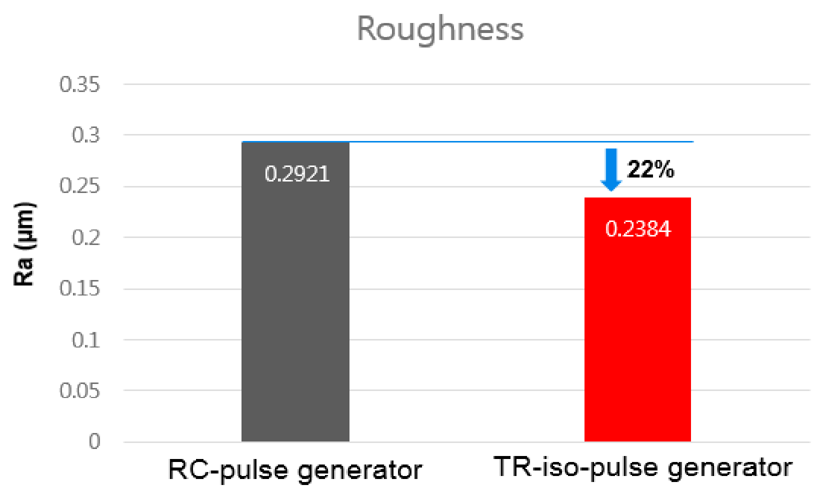

Fig. 10. Comparison of the experimental results of Ra

3.3.2. Effect of the uniform discharge energy

The discharge energy of the TR−iso−pulse generator is uniform for every single discharge. Therefore, the machined surface of the TR−iso−pulse generator is smoother than that of the RC−pulse generator.

Every single discharge of the TR−iso−pulse generator has the same peak current and pulse−on time, as the TR−iso−pulse generator uses a pulse−on−and−off control system in the circuit in which the discharge start and finish times are monitored. However, each discharge. The RC−pulse generator starts charging the capacitor immediately after a discharge. If flushing is insufficient and the insulation recovery of the dielectric liquid is inadequate, an abnormal discharge occurs while charging the capacitor. As a result, the discharge energy will vary depending on the magnitude of the current charged in the capacitor immediately before the discharge, meaning that a uniform discharge will not be generated.

Therefore, the TR−iso−pulse generator, which generates more uniform discharge energy, can produce a smoother surface compared to the RC−pulse generator, and the other study using a TR−iso−pulse generator showed a similar outcome [15].

Chapter 4. Conclusion

This study found that a TR-iso-pulse generator offers better machining performance than a RC-pulse generator. Here, a TR-iso-pulse generator was applied to micro ED-drilling, in which an RC-pulse generator has long been used. Through an extremely rapid pulse-on-and-off control system in the circuit, the TR-iso-pulse generator could generate short and uniform discharge energy without an open circuit, which is not possible with conventional TR-type pulse generators; thus, making it feasible or use in micro ED-drilling applications. In order to evaluate the performance of the TR-iso-pulse generator accurately, each pulse generator was set up to generate an identical level of discharge energy and quantitative comparison tests were carried out. From the results of this study, the following conclusions were drawn with regard to micro ED-drilling:

a. Due to the quick voltage recovery time, TR-iso-pulse generator was able to perform machining much more quickly than the RC-pulse generator with nearly zero shorts and fewer holds at a high feed rate. Therefore, the TR-iso-pulse generator could achieve a higher MRR by 121% at a feed rate of 4 μm/s.

b. Reverse current did not occur in the TR−iso−pulse generator because the FET blocks the reverse current flow at the pulse−off time. Therefore, additional tool wear due to the reverse current did not occur in the TR−iso−pulse generator. As a result, the RWR was decreased by 39% at a feed rate of 3 μm/s.

c. The TR−iso−pulse generator could generate short and uniform discharge energy during every single discharge. Consequently, the constant discharge energy of the TR−iso−pulse generator reduced the Ra by as much as 22%.

This study covered the issue of tool wear, which was not included in previous studies, and it was found that the tool wear could be reduced by using a TR−iso−pulse generator. Therefore, TR−iso−pulse generators are expected to be used even in other applications of micro EDM where low tool wear is required, especially in micro ED−milling where geometric errors stemming from tool wear represent a critical problem.

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국문초록

본 연구는 미세 방전 드릴링에서의 TR-iso-pulse generator의 성능 평가를 통해, TR-iso-pulse generator가 RC-pulse generator 대비 하여, 보다 우수한 가공 성능을 갖는 다는 것을 기술한다. 일반적으로 macro-scale EDM 에서는 TR-pulse generator가 RC-pulse generator에 비해, 보다 높은 가공 효율을 가지고 있는 것으로 알려져 있다. 하지만 micro-scale EDM에서는, 낮은 가공 효율에도 불구 하고, 여전히 RC-pulse generator가 주로 사용이 되고 있다. 왜냐하면 RC-pulse generator는 용량이 작은 capacitor 적용을 통해, micro 가공에 적합한 작은 방전 에너지를 손쉽게 만들어 낼 수 있기 때문이다. 그러나 micro EDM에서 높은 가공 효율을 확보하기 위해서는, TR-pulse generator 적용이 필수적이다. 따라서 본 연구에서는 작고 균일한 방전 에너지를 생성할 수 있는, TR—iso-pulse generator를 제작하여 성능 평가를 실시 하였다. RC-pulse generator와 TR-iso-pulse generator간의 정확한 성능 비교 평가를 위하여, 각 pulse generator는 단발 방전당 같은 크기의 방전 에너지를 발생하도록 설정 하였고, Micro ED-drilling을 수행하여, feed rate에 따른 material removal rate (MRR) 과 relative wear ratio (RWR)을 측정 하였다, 그리고, 3D profiler를 통해 표면 거칠기 또한 측정 하였다. 그 결과, TR-iso-pulse generator에서 MRR은 121% 향상되고, RWR은 39% 감소 되었으며, 표면 거칠기 또한 22% 줄어 들었다.

주요어 : 미세방전가공, 방전 드릴링, TR-pulse generator, RC-pulse generator

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