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Short Communication

Design, analysis and experimental study of a high-frequency power supply for finish cut of wire-EDM

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ABSTRACT

This paper presents the development of a high-frequency power supply for surface quality improvement of wire electrical discharge machining (wire-EDM). A novel fixed pulse-width modulation pulse control method is proposed to generate high-frequency and short-duration pulse control signals. A spark gap model using a resistance–capacitance (RC) circuit and a Zener diode is proposed for circuit design and simulation analysis. Tests revealed that the developed power supply using anti-electrolysis circuitry and digital signal processor-based pulse control circuit can provide very low discharge energy pulses with a frequency of 4.4 MHz, discharge duration of 90 ns and a peak current of 1.2 A. Experimental results demonstrate that a pulse duration ratio (defined as a ratio between pulse duration of positive polarity and that of negative polarity) of three can reduce the electrolytic effect of tungsten carbide for the machining conditions of high discharge frequency more than 500 kHz.

1. Introduction

Wire electrical discharge machining (wire-EDM) is a widely accepted non-traditional material removal process in tool and mold industry because of its excellence in precisely produce intricate shapes and varying tapers in all electrically conductive materials irrespective of their hardness and toughness [1]. Since deionized water is used as a dielectric liquid and wire electrode has a negative polarity in wire-EDM, direct current passing through water causes ions to react chemically with the machined part and an electrolytic effect increases the chemical erosion effect of the water dielectric. The occurrence of the recast layer is unavoidable and critical, since surface quality degeneration directly affects fatigue strength, surface roughness, surface integrity and premature failure of the machined part.

In order to reduce the recast layer and the electrolytic and corrosive effect as well as obtain better surface quality, some machine tool builders have been devoting their effort in developing new pulse generators using water dielectrics and anti-electrolysis circuitry [2–5]. Wire-EDM machines equipped with multi-generators have also been presented to supply high energy to the machining gap during roughing and lower energy for finish machining while connecting the wire electrode to the positive pole [6]. A new high-frequency AC power supply using intermittent waveform circuit has been presented to reduce electrostatic force during machining as well as achieve super-fine surface of 0.3–0.5 μm R_z and machining accuracy of 1–2 μm [7]. A study has shown that a discharge current with short pulse duration and high peak value can generate better surface roughness, which cannot be achieved with a discharge current with long pulse duration and low peak value [8].

A transistor-controlled RC-type fine-finish power supply for wire-EDM has been presented to successfully improve surface quality as well as achieve a fine surface finish of 0.22 μm R_a [9]. However, this power supply is unable to provide high-frequency discharge pulses more than 1 MHz and short discharge duration lower than 100 ns, and thus has a limited range in the improvement of surface quality. Therefore, this paper presents a modified anti-electrolysis circuit and a novel high-frequency pulse control method in wire-EDM. The developed power supply can provide high-frequency pulses in the range of 1–5 MHz and short discharge duration in the range of 90–360 ns. A spark gap model using a resistance–capacitance (RC) circuit and a Zener diode is proposed to verify the proper operation of the modified anti-electrolysis circuit. Experimental verification of the developed pulse generator for the improvement of surface quality in wire-EDM is shown.

2. Circuit design and simulation analysis

An anti-electrolysis power supply for micro wire-EDM has been developed by our previous study [9]. In this paper, the anti-electrolysis power supply was modified to provide high-frequency discharge pulses more than 1 MHz and short discharge duration

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lower than 100 ns as shown in Fig. 1. The power supply composed of a full-bridge circuit, two snubber circuits and a pulse control circuit can provide both high-frequency and very low-energy pulses by using transistor-controlled circuitry. The full-bridge circuit uses four MOSFETs M_1 and M_3, and M_2 and M_4 to provide alternating discharge current in the spark gap. When controlled in pairs (M_1 and M_3 and M_2 and M_4), it changes the direction of gap voltage, hence the direction of discharge current. The two snubber circuits driven by MOSFET M_5 and M_6 have the duty to absorb an excessive discharge energy stored in the spark gap for positive polarity and negative polarity discharge circuit, respectively. As shown in Fig. 1, the diodes D_1 and D_2 in serial with MOSFET M_1 and M_4, respectively, serve the purpose of suppressing the excessive discharge energy stored in the sparking gap and thus protecting MOSFET M_1 and M_4 from damage. The current-limiting resistors R_1 and R_2 in serial with the discharge circuit were designed to adjust the peak current. The current-limiting resistor R_3 in serial with the snubber circuits was designed to absorb the excessive discharge energy stored in the sparking gap.

Metal removal process of electrical discharge machining is characterized by nonlinear, stochastic and time-varying characteristics. A mathematical model for the precise description of the complex and stochastic phenomenon of the electrical discharge machining (EDM) process is difficult to obtain. Nevertheless, discharge gap may be viewed as a combination of industrial electronics from the viewpoint of electric circuitry. A gap model that uses a silicon-controlled rectifier and a Zener diode has been proposed to describe the dynamic behavior of the micro EDM process [10]. This gap model is applicable for RC-type pulse generators commonly used in micro EDM process, but it is not suitable for transistor-controlled anti-electrolysis circuitry widely used in wire-EDM process. In order to verify the correct functioning of the developed anti-electrolysis circuit and predict scaling trend, an anti-electrolysis circuit model for SPICE simulation that uses a RC circuit and a Zener diode for modeling discharge gap is shown in Fig. 2. A capacitor C_g is used to represent the capacitance between the workpiece and the wire electrode. A resistor R_g is employed to model the resistivity of dielectric liquid in the spark gap. A series connected Zener diode with a breakdown voltage of 22 V is used to represent a voltage potential required to break down the insulating properties of the dielectric fluid in the spark gap. An inductor L stands for wire inductance in the discharge path. Assume that the capacitor C_g, the resistor R_g and the Zener breakdown voltage are the same for both positive and negative polarity discharge circuit. In the experiments, R_1, R_2, R_3, C_g, R_g and L are experimentally set as 5, 5, 150 Ω, 1.3 μF, 13 Ω and 20 μH, respectively, by using measured values of peak current and discharge duration. For simplicity, stray capacitance that exists between the workpiece and the wire electrode is neglected in this circuit model. Pulse on-time and pulse off-time are set as 1 and 2 μs, respectively. Through circuit simulation analysis from experimental data, electronic components and circuit parameters can be chosen appropriately. A circuit test revealed that power MOSFETs modeled as IRF510 by International Rectifier Corp. are applicable for this anti-electrolysis circuit because of their dominance in high-frequency switching speed.

3. Fixed pulse-width modulation (FPWM) pulse control method

Original fine-finish power supply as presented in our previous study [9] can provide low discharge energy pulses with a frequency of 500 kHz and discharge duration of 120 ns. Once the pulse frequency is more than 1 MHz, there is not enough time to charge the spark gap to an open gap voltage more than 50 V during on-time period and excess energy stored in the discharge

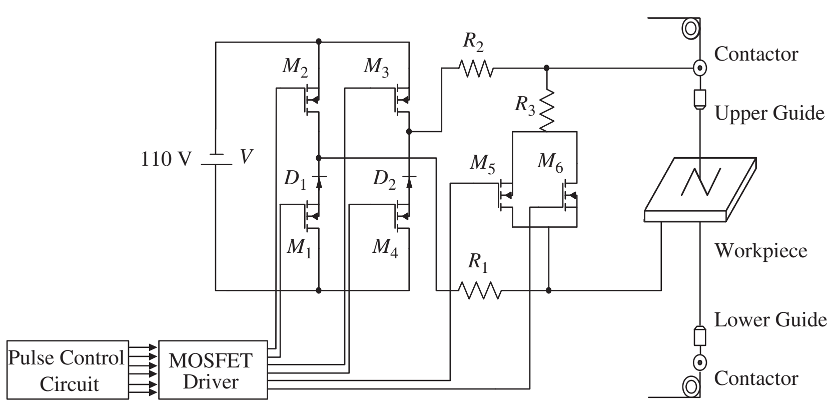

Fig. 1. Circuit diagram of the developed high-frequency power supply for wire-EDM.

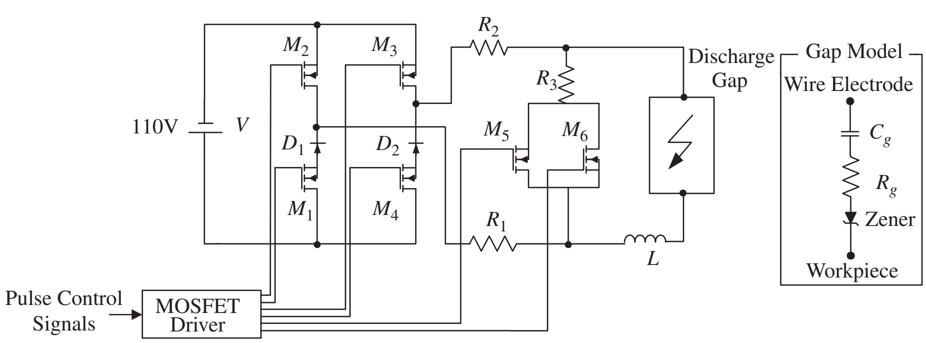

Fig. 2. An anti-electrolysis circuit model for SPICE simulation that uses a RC circuit and a Zener diode for modeling discharge gap.

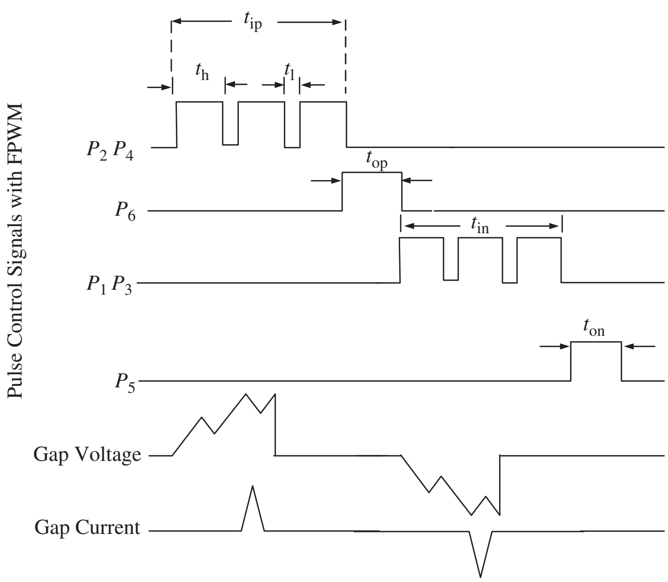

Fig. 3. Timing chart of fixed pulse-width modulated control signals and associated pulse trains of wire-EDM for high-frequency power supply.

gap is absorbed by using two snubber circuits during off-time period. As a result, open gap voltage is too low to produce a spark.

To provide high-frequency and very low-energy pulses, a novel fixed pulse-width modulation pulse control method is proposed in this paper. Fig. 3 illustrates the timing chart of fixed pulse-width modulated pulse control signals and associated pulse trains of wire-EDM for the developed high-frequency power supply. P_1, P_2, P_3, P_4, P_5 and P_6 are the pulse control signals of the MOSFET M_1, M_2, M_3, M_4, M_5 and M_6, respectively. As depicted in Fig. 3, pulse control signals P_2 and P_4 have a fixed pulse duration t_{ip} and their pulse duration is divided into three short-duration pulses with a fixed pulse on-time period t_h and a fixed pulse off-time period t_l. By modulating the pulse on–off time of the pulse width at a high fixed frequency, a desired high-frequency and low-energy pulses can be controlled. When the MOSFET M_2 and M_4 are turned on three times through the pulse control signals P_2 and P_4, respectively, if spark occurs within one of three pulse on-time periods and generating discharge current with very short duration flows from the wire electrode to the workpiece. There are at most three sparks during pulse duration of positive polarity and the discharge duration is expectedly less than the pulse on-time. After each discharge, the MOSFET M_2 and M_4 are turned off, and the MOSFET M_6 is turned on through the pulse control signal of P_6, an excessive discharge energy stored into the spark gap is directed to the resistor R_3. Correspondingly, this pulse control method offers the same function for the negative discharge circuit as shown in Fig. 3. In this paper, a digital signal processor card modeled as VP2812EVM evaluation board by Value Provider International Corp. is employed to generate the pulse control signals for easy modification purpose.

Fig. 4 shows a comparison on current waveforms between the developed high-frequency power supply and original fine-finish power supply. The developed power supply can provide a peak current of 1.2 A and discharge duration of 90 ns compared with a peak current of 4 A and discharge duration of 120 ns for our original fine-finish power supply. Fig. 5 shows the effect of pulse duration ratio (defined as a ratio between pulse duration of positive polarity and that of negative polarity) on surface roughness of tungsten carbide. It can be seen that an increase of discharge frequency results in surface degeneration of tungsten carbide when the pulse duration ratio is one. Surface quality can be improved under high discharge frequency conditions when the pulse duration ratio is three.

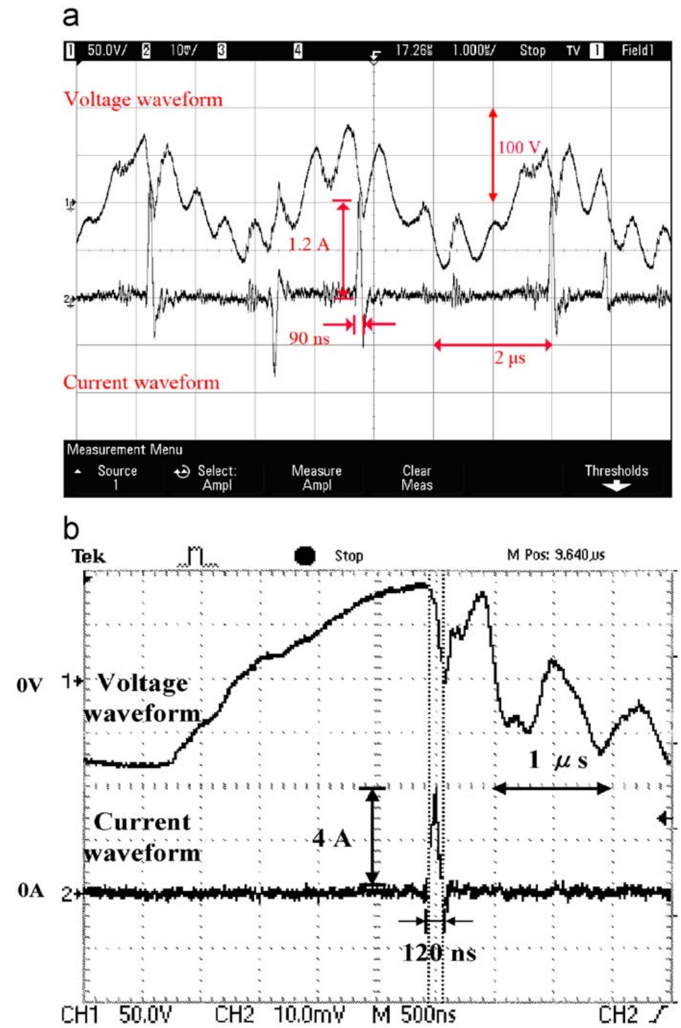

Fig. 4. Pulse waveforms of (a) the developed power supply and (b) original fine-finish power supply.

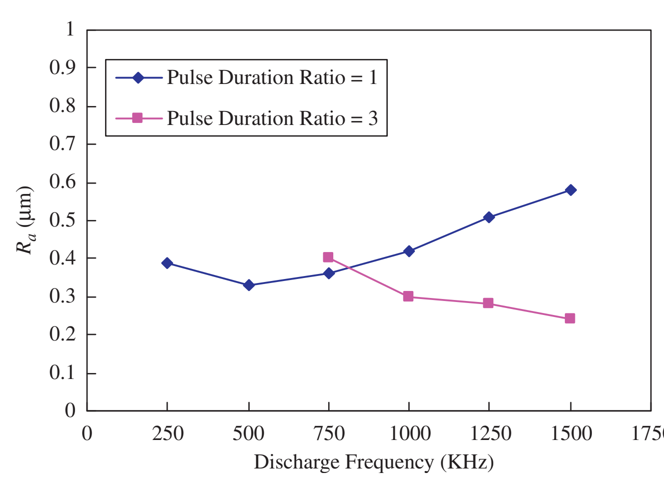

Fig. 5. Effect of discharge frequency on surface roughness of tungsten carbide for different pulse duration ratios. (Brass wire ∅0.25 mm; wire tension: 1700 gf; wire feed: 5 mm/min; water-resistivity: 125 kΩ cm; pulse on-time: 240 ns; pulse off-time: 120 ns.)

4. Conclusion

In this study, a transistor-controlled fine-finish power supply using anti-electrolysis circuitry and DSP-based pulse control circuit for wire-EDM has been developed. SPICE simulation that uses a RC circuit and a Zener diode for modeling discharge gap has verified the proper functioning of the anti-electrolysis circuitry. The proposed fixed pulse-width modulation pulse control method has been proved to be useful in generating high-frequency and short-duration pulses. With the proposed pulse control method, the developed high-frequency power supply can provide very low discharge energy pulses with a frequency as high as 4.4 MHz, discharge duration as short as 90 ns and a peak current as low as 1.2 A. Experimental results demonstrate that surface quality of tungsten carbide can be improved for the machining conditions of high discharge frequency more than 500 kHz by using a pulse duration ratio of three.

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