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ORIGINAL ARTICLE

Surface modification using semi-sintered electrodes on electrical discharge machining

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Abstract This study investigates how machining characteristics and surface modifications affect low-carbon steel (S15C) during electrical discharge machining (EDM) processes with semi-sintered electrodes. Among the machining characteristics determined, the material removal rate (MRR), surface deposit rate (SDR), and electrode wear rate (EWR) are included. Additionally, exactly how semi-sintered electrodes affect the surface modifications is also evaluated by electron probe microanalyzer (EPMA), micro hardness, and corrosion resistance tests. The experimental results confirmed that the composition of the semi-sintered electrodes is transferred onto the machined surface efficiently and effectively during the EDM process, and that the process is feasible and can easily form a modified layer on the machined surface.

Keywords Electrical discharge machining · Semi-sintered electrodes · Surface modifications · Surface deposit rate

Nomenclature

EDM	Electrical discharge machining
MRR	Material removal rate (g/min)
SDR	Surface deposit rate (g/min)
EWR	Electrode wear rate (g/min)
EPMA	Electron probe microanalyzer
EDA	Electrical discharge alloying
P/M	Powder metallurgy
WDS	Wavelength dispersive spectrometry
I_p	Peak current (A)
τ_p	Pulse duration (μs)
V_0	No-load voltage (V)
DF	Duty factor
WT	Working time (s)

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1 Introduction

Electrical discharge machining (EDM) generates a high temperature within a discharge column from ionization and, therefore, a portion of the substrate ionized within the discharge column can be deposited on the machined surface at the end of electrical discharge interval. Therefore, the machined surface could benefit from surface modification by electrical discharge alloying (EDA) using EDM under appropriate machining conditions. The composition of the electrode easily transfers and deposits onto the machined surface in order to provide a suitable and sufficient surface modification agent when using a semi-sintered electrode in EDM, due to the low bonding strength of the electrode. Thus, using a semi-sintered electrode enhances the effects of surface modification through EDM.

The performance of the machined surface of a machinery component is the most important issue in extending its service life and withstanding environmental corrosion. Thus, surface modifications to improve the machined surface properties is becoming an increasingly important topic. Surface modifications such as ion implantation, laser surface treatment, physical vapor deposition, and chemical vapor deposition have been proposed to reinforce the performance of the machined surfaces [1–7]. However, the cost of surface modifying equipment is high, and the operating procedure for carrying out surface modification processes is complicated. Therefore, mold and tool manufacturers urgently need an effective and simple procedure to modify machined surfaces during the shaping stage.

The EDM machined surface can form an alloying layer during the EDM process to reinforce its performance, as suggested in the literature on EDM [8–10]. The EDM surface modification process has been proposed in several studies. Ogata and Mukoyama [11] investigated the effects of dielectric fluids in EDM, indicating that the machined surface formed a hardened and carbonized layer with kerosene as the dielectric, and a softened and decarbonized layer with distilled water as the dielectric. The machining performance when powder was added into the dielectric has also been explored [12–14]. The investigators found that adding various powders, including silicon, nickel, and chromium, into the dielectric, improved machined surface properties such as corrosion resistance, wear resistance, and hardness. Several researchers studied surface modifications using green compact electrodes in EDM, finding that the electrode elements could be transferred to the machined surface of the workpiece [15–19]. Although surface modifications could be obtained by the EDM process, the effects of the machining parameters on surface modifications have not yet been comprehensively determined. Therefore, adequately selecting the levels of the EDM parameters for surface modification through the EDM process is a critical issue.

EDM requires simpler equipment than other processes. If the electrode compositions can be transferred and deposited on the machined surface during EDM, the machined surface can be modified to fit the special demands of the surface performance with the machinery component by using conventional EDM devices and procedures. Moreover, the electrode composition can be adjusted to satisfy the particular demand of the machinery component. Hence, EDM can be a versatile process for improving the performance of molds and extending the application of EDM. This study investigates how using a semi-sintered electrode affects surface modification through the EDM process. The machining parameters, including peak current, no-load voltage, pulse duration, and elapsed working time, are varied to determine the EDM machining characteristics, such as material removal rate (MRR), surface deposit rate (SDR), and electrode wear rate (EWR). Therefore, the EDM surface modification mechanism can be established and verified though experimental investigation to satisfy machined surface requirements in particular industrial applications.

2 Experimental method

2.1 Mechanism of electrical discharge alloying

Figure 1 depicts schematically the mechanism of electrical discharge alloying (EDA). The experiment was conducted with a semi-sintered electrode consisting of Cu-W powders made through powder metallurgy (P/M) in a dielectric fluid of kerosene using conventional EDM. The metal particles stripped from the semi-sintered electrode were compounded with the pyrolytic carbon released from the kerosene dielectric to form cemented tungsten carbide. Consequently, the compounded product of the cemented tungsten carbide was deposited on the machined surface, resulting in a modified effect during EDM. The advantages of using the conventional EDM process to modify the machined surface are that the equipment investment is reasonably economical, and a modified layer with a rich WC is easily produced on the machined surface through the conventional EDM devices. The modified layer with a rich WC was created quickly on the machined surface, and the mean thickness of the modified layer was regulated easily by varying the EDM machining parameters. Surface modification through EDM was economical. The agent deposited on the machined surface can normally be changed easily and flexibly by varying the composition of the electrode element, enabling EDA to be widely used in surface modification.

2.2 Experimental method

Low-carbon steel (0.15 wt.% C) was utilized as the workpiece material in this work. The specimen dimension was 10×10×20 mm, and they were ground to ensure

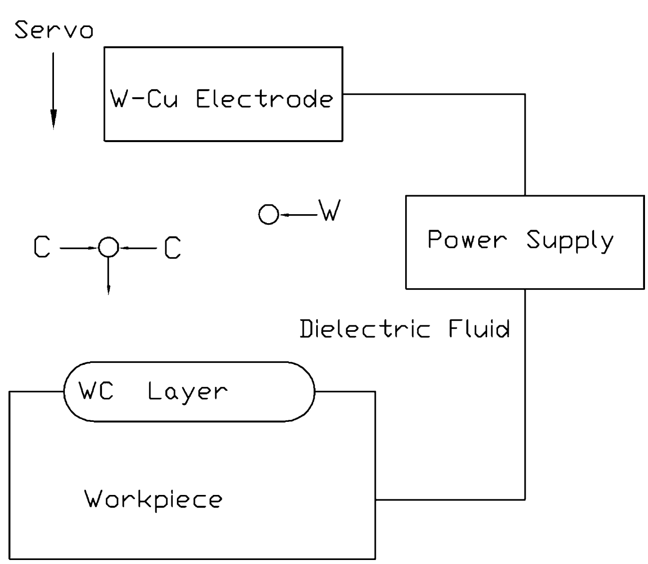


Fig. 1 Mechanism of electrical discharge alloying (EDA)

parallelism before each experiment. The chemical compositions of the workpiece material are listed in Table 1. The electrode material used in the EDM process was a semi-sintered electrode consisting of Cu-W powders formed by P/M. The grain size of the Cu and W powders was less than 45 μm. The P/M powders were blended for 10 h in a cylindrical mixture. Then, 2.8 g of the Cu-W-blended powder were placed in a φ 8×4-mm mold with a compacting pressure of 770 MPa. The green compact of the electrode specimen was slightly sintered at 600°C for 20 min in a furnace. The semi-sintered electrode was soldered to the end face of an electrolytic copper. Consequently, the semi-sintered electrode was utilized to perform a series of experiments to explore the effects of surface modification through EDM. Table 2 shows the fabricated conditions of the semi-sintered electrode. The workpiece and electrode was cleaned in an ultrasonic bath filled with acetone for 5 min before and after each experiment, and then dried with a dryer and weighed in a precise electrical balance with 0.1-mg resolution to calculate the MRR, SDR, and EWR. The MRR and EWR are defined as the weight loss of the workpiece and electrode after the EDM process divided by the elapsed working time. By contrast, the SDR is designated as the increase in workpiece weight divided by the elapsed working time. The micro hardness and corrosion resistance of the machined surface were determined by Vickers micro hardness tester and was immersed in aqua regia solution to evaluate the performance of the modified surface. The EDM conditions are listed in Table 3, and the schematic diagram of the experimental setup is illustrated in Fig. 2. Moreover, the experimental data are the mean values of three measurements in a setting EDM condition to ensure the reliability of the experiment.

3 Results and discussion

3.1 Effect of no-load voltage

Figure 3 shows the effects of the no-load voltage on MRR, SDR, and EWR under particular EDM conditions of peak current, pulse duration, and elapsed working time. The workpiece weight was increased after EDM with the no-load voltage set to 60 V, as shown in the experimental results. This finding is attributed to the semi-sintered electrode used in the EDM process, which not only removed material as in normal EDM, but also deposited onto the machined surface a compound of powder particles stripped from the semi-sintered electrode with pyrolytic carbon released from the dielectric fluid. When the no-load voltage was set to a low level, the electrical discharge energy conducted into the machining zone was very small at the minute peak current and short pulse duration, and the bonding strength of the semi-sintered electrode was very low to withstand the thermal erosion caused by EDM. The use of semi-sintered electrodes could promote the transfer effect of electrode material to the machined surface and obtain an increase in the weight of the workpiece during an EDM process with specific machining conditions. Therefore, the amount of compounded product deposited onto the machined surface was higher than that of the workpiece material removed from the machined surface during EDM. Therefore, the surface of tools and molds can be regulated by depositing a suitable compound onto the machined surface. The amount of workpiece material removed from the machined surface exceeded the deposited layer of the compounded product when the no-load voltage was increased to enlarge the electrical discharge energy within a single pulse. Thus, the material was removed as in the ordinary EDM process. The MRR increased with the no-load voltage, as shown in Fig. 3. Additionally, the EWR substantially rose with the no-load voltage, as the electrical discharge energy conducted into the machining zone increased with the no-load voltage under a given pulse duration.

Table 1 Chemical composition of the workpiece material

Element	C	Si	Mn	P	S	Fe
Wt.%	0.15	0.17	0.53	0.04	≦0.05	Remainder

Table 2 Fabrication conditions of the electrode material

Property	Condition/characteristic
Process	Semi-sintered (P/M)
Powder	Copper, tungsten
Grain size, d	d≦45 μm
Mixing ratio (wt.%)	Copper:tungsten=3:1
Compact pressure	770 MPa
Sintering temperature	600°C
Sintering time	20 min
Dimension	ϕ 8×4 mm

Table 3 Machining conditions of electrical discharge machining (EDM)

Property	Condition/characteristic
Dielectric fluid	Kerosene
Machining polarity	Positive (+)
Peak current, I_p	3, 5, 10, 16 (A)
No-load voltage, V_0	60, 70, 86, 100 (V)
Pulse duration, τ_p	50, 100, 200, 400 (μs)
Duty factor, DF	0.5
Working time, WT	300, 600, 900 (s)

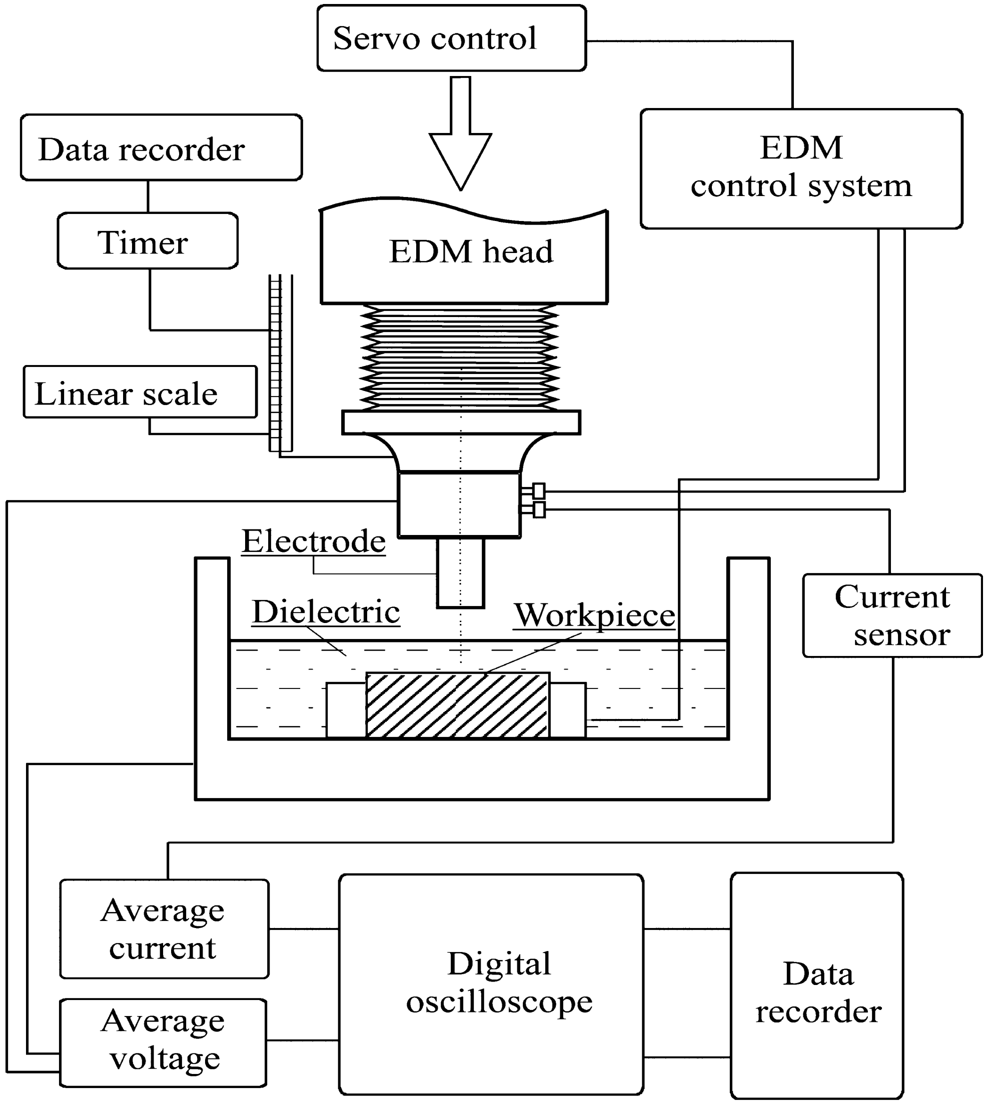


Fig. 2 Schematic diagram of the experimental setup

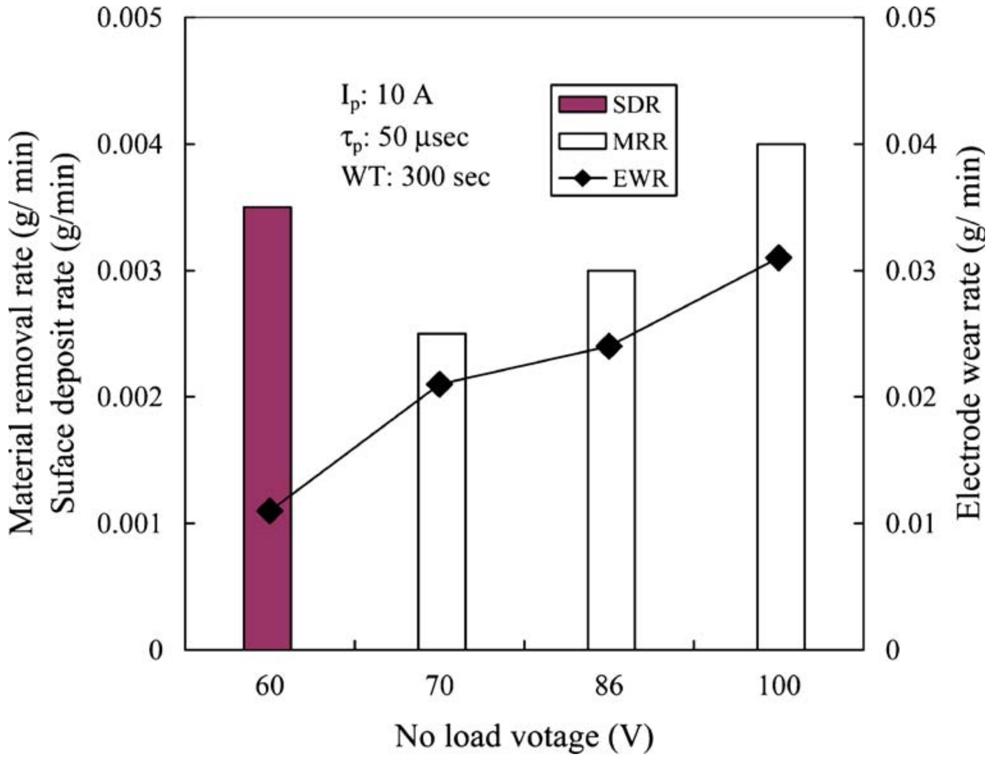
3.2 Effect of peak current

Figure 4 depicts the effects of the peak current on the MRR, SDR, and EWR under identical EDM conditions of no-load voltage, pulse duration, and elapsed working time. The experimental results show that the machined surface exhibited a deposited effect as the peak current was set to a low level (3 A, 5 A), causing a small electrical discharge energy to be conducted into the machining zone. Conversely, the removal of workpiece material from the machining zone was significant only at large peak currents (10 A, 16 A). Furthermore, the MRR increased with the peak current because more electrical discharge energy was conducted into the machining zone. The current density in the electrical discharge spot increased with an increase of peak current at a fixed pulse duration. Therefore, the MRR increased due to a higher material removal efficiency. Additionally, the MRR rose with increasing electrical discharge energy based on the no-load voltage. Moreover, the EWR increased as the peak current rose, since more electrical discharge energy was conducted into the machining zone.

3.3 Effect of pulse duration

The effects of the pulse duration on SDR and EWR under a no-load voltage of 100 V and peak current of 5 A are displayed in Fig. 5. Since the electrical discharge energy conducted into machining zone was low at these EDM conditions, the machined surface presented a deposited effect during the EDM process. Moreover, the experimental findings also demonstrate that the SDR was higher at short pulse durations than that at long pulse durations. The electrical discharge frequency was higher when the pulse duration was short. Generally, the EWR was larger in high-frequency electrical discharges than that at low frequencies

Fig. 3 Effects of the no-load voltage on the material removal rate (MRR), surface deposit rate (SDR), and electrode wear rate (EWR)

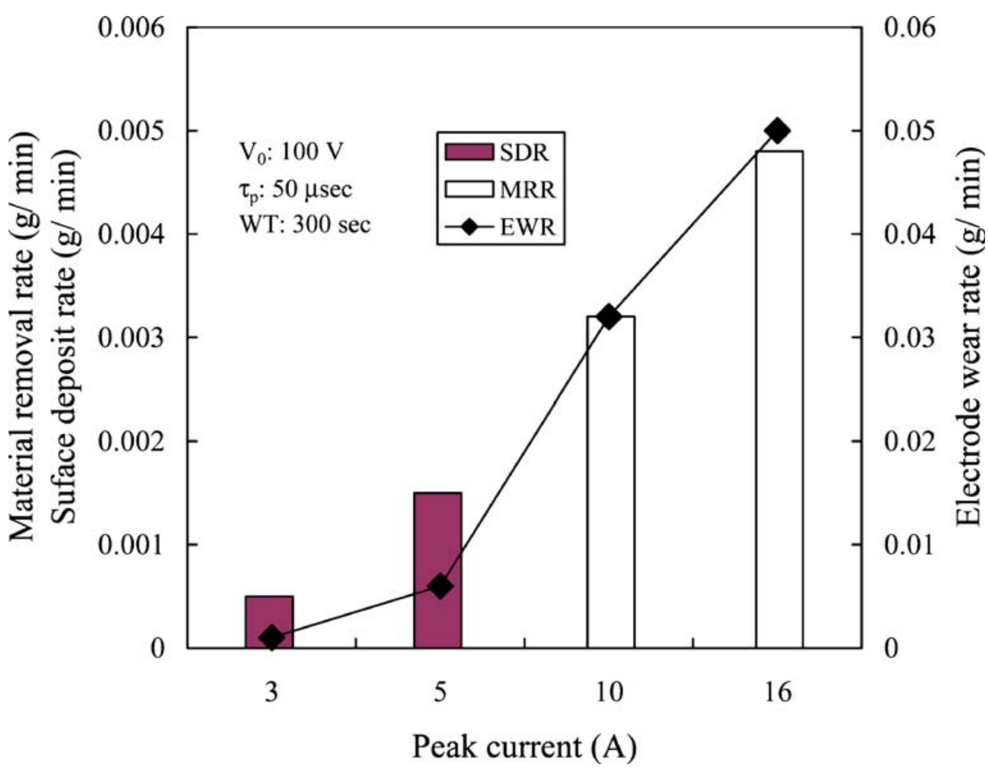


[10]. The SDR was facilitated at high frequencies because the most powder particles of the semi-sintered electrode were stripped and compounded with pyrolytic carbon in EDM processes during high-frequency electrical discharges. Therefore, extending the pulse duration lowered the SDR and EWR.

3.4 Composition analysis of the machined surface

The chemical compositions on the machined surface were qualitatively and quantitatively analyzed by an electron probe microanalyzer (EPMA) to determine the effect of surface modification using semi-sintered electrodes in

Fig. 4 Effects of the peak current on MRR, SDR, and EWR



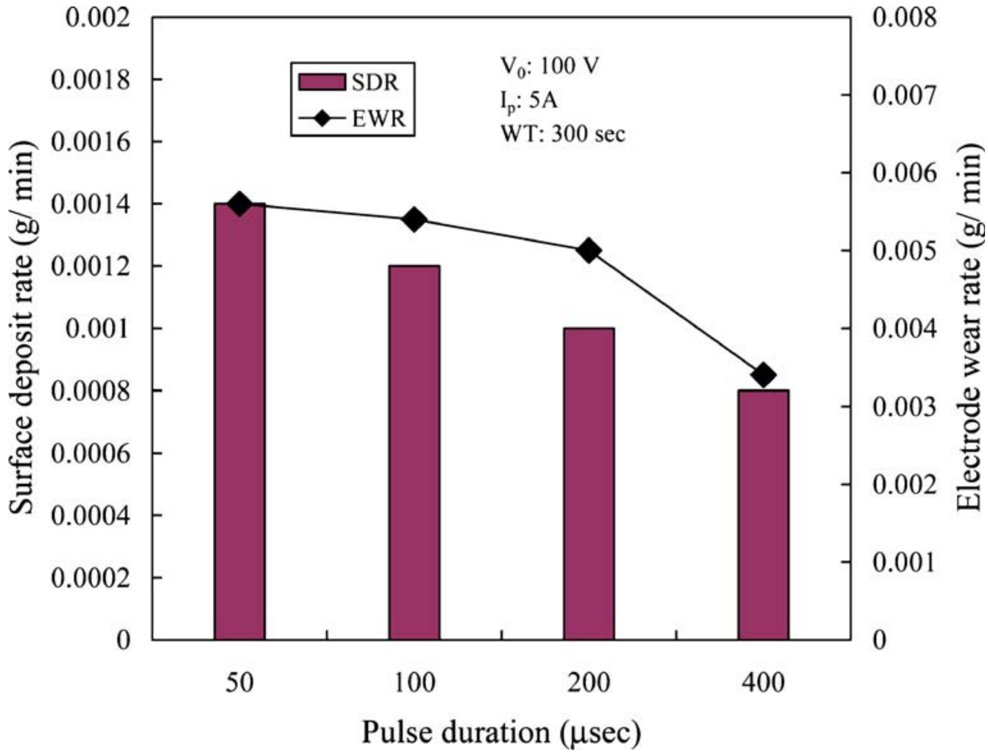


Fig. 5 Effects of the pulse duration on SDR and EWR

EDM. Figures 6 and 7 illustrate the element distributions of C, Fe, and W obtained by EPMA at elapsed working times of 600 s and 900 s, respectively, on the cross-section of the machined surface. The experimental results show that the W element was presented at around 0.2 mm on the machined surface. The compositions of the semi-sintered electrode that transferred and penetrated into the substrate of the workpiece through EDM formed a modified layer on the machined surface. Table 4 lists the experimental results of the quantitative analysis of the chemical composition on the cross-section of the machined surface by wavelength dispersive spectrometry (WDS) at the EDM conditions mentioned in Fig. 6. Two different detected positions that were 120 μm below the machined surface were analyzed by WDS. The atomic ratio of W:C was near 1:1, as listed in Table 4. Therefore, the tungsten carbide, which could be formed through compounding the W powder detached from the semi-sintered electrode with the pyrolytic carbon released from the dielectric fluid, was deposited on the machined surface during the EDM process, generating a high temperature within the discharge column to compound the two elements as a reinforced agent. Hence, the reinforced agent generated a surface modification on the machined surface of EDM.

3.5 Effect of EDM parameters on the surface modification

Semi-sintered electrodes can be used to produce a modified layer on the machined surface through the EDM process. To develop an adaptable EDM application to meet machined surface requirements, the effects of the EDM machining parameters on surface modifications must urgently be understood. Therefore, a series experiments was conducted using EPMA to explore the effects of elapsed working time, no-load voltage, peak current, and pulse duration on the thickness of the modified layer. The typical thickness of the modified layer was obtained from averaging three measurements on different positions of the modified layer for the setting EDM conditions.

3.5.1 Effect of elapsed working time on the modified thickness

Figure 8 displays the relationship between the elapsed working time and thickness of the modified layer on the machined surface obtained by EPMA. The modified layer thickness increased with the elapsed working time, as illustrated in Fig. 8. When the elapsed working time was set to 600 s, the modified layer thickness attained a peak value and maintained it as the elapsed working time extended. This finding indicates that using semi-sintered electrodes through the EDM process is an effective surface modification process, as it only needs a very short operating time to form a certain thickness of modified layer on the machined surface.

3.5.2 Effect of no-load voltage on the modified thickness

The relationship between the no-load voltage and the modified layer thickness on the machined surface obtained

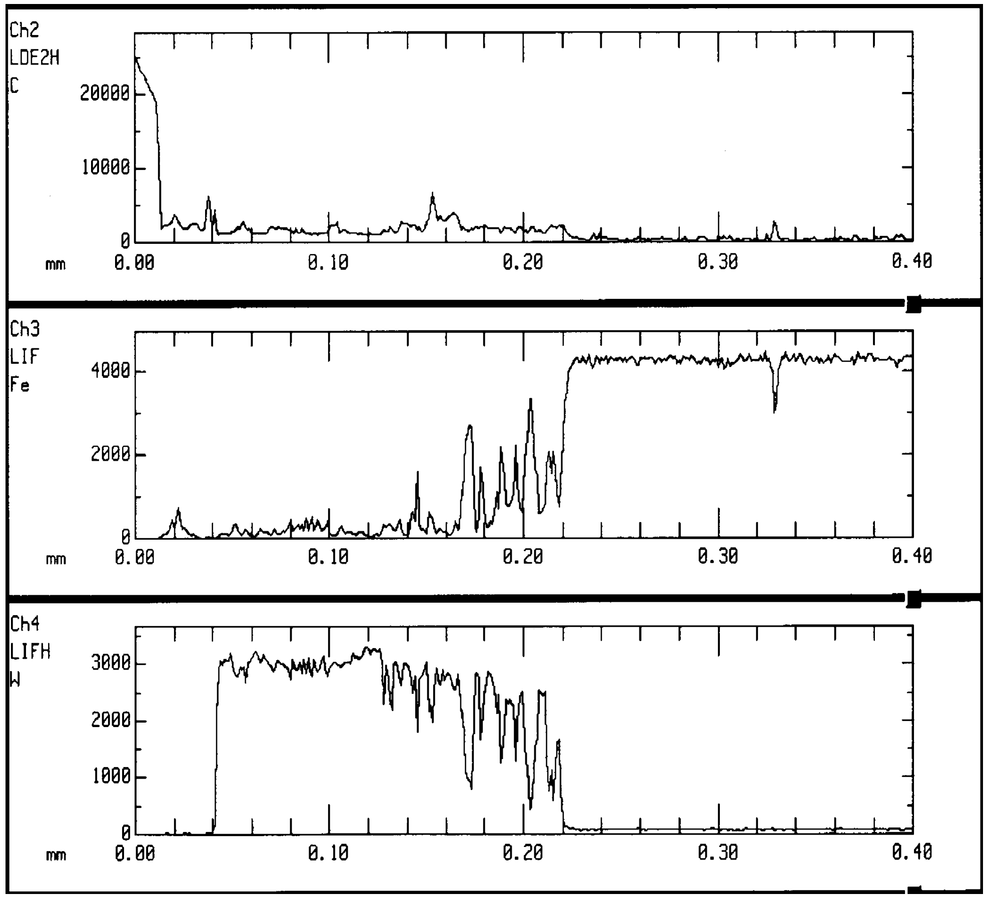


Fig. 6 Element distributions of C, Fe, and W obtained using an electron probe microanalyzer (EPMA) at 600-s elapsed working time (V_0=100 V, I_p=10 A , τ_p=50 μs)

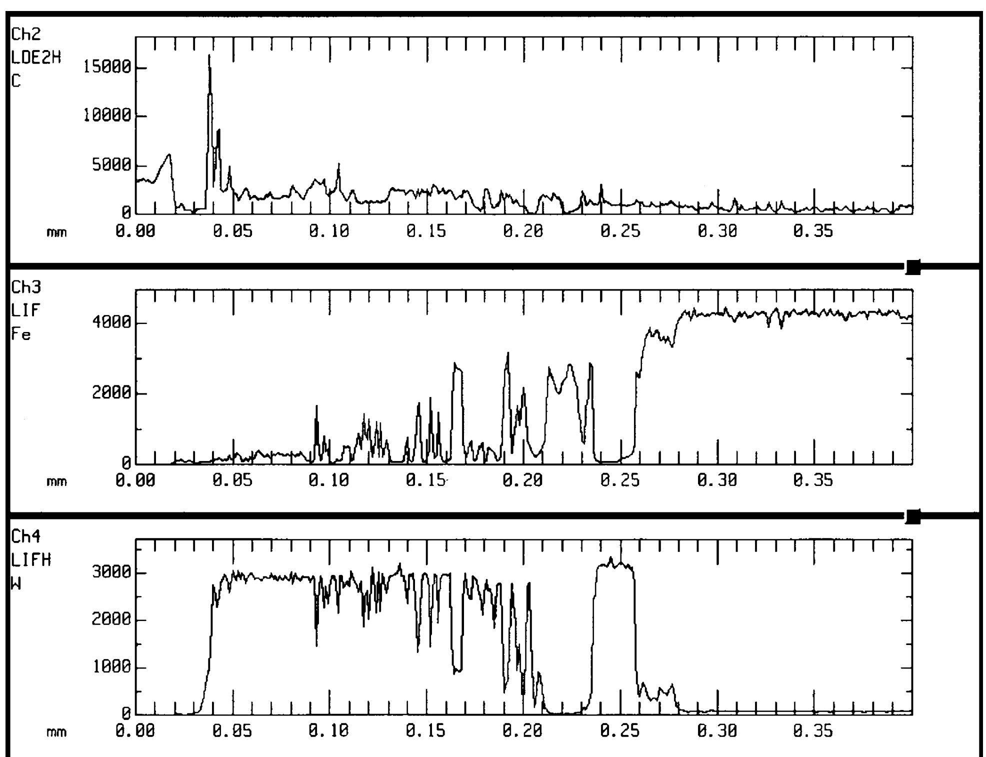


Fig. 7 Element distributions of C, Fe, and W obtained using EPMA at 900-s elapsed working time (V_0=100 V, I_p=10 A, τ_p=50 μs)

Table 4 Element analysis of the modified layer using wavelength dispersive spectrometry (WDS) (V_0=100 V, I_p=10 A, τ_p=50 µs, WT=600 s)

Atomic ratio		
Element	Position 1	Position 2
Cu	–	–
C	49.3810	48.5061
Fe	0.1292	0.9023
Mn	–	–
W	50.4898	50.5916
Total	100.0000	100.0000

by EPMA is illustrated in Fig. 9. The thickness of the modified layer was reduced as the no-load voltage increased. Indeed, when the no-load voltage increased, more electrical discharge energy was conducted into machining zone, causing more workpiece material to be removed because of vaporing and melting caused by the EDM process within a pulse of electrical discharge. Therefore, a large quantity of the modified layer deposited on the machined surface during previous electrical discharge pulses was removed. Additionally, when the no-load voltage is set to a high level, the amount of compounded materials deposited on the machined surface decreased, as the discharge gap between the workpiece and electrode was expanded. Hence, the thickness of the modified layer on the machined surface fell as the no-load voltage increased.

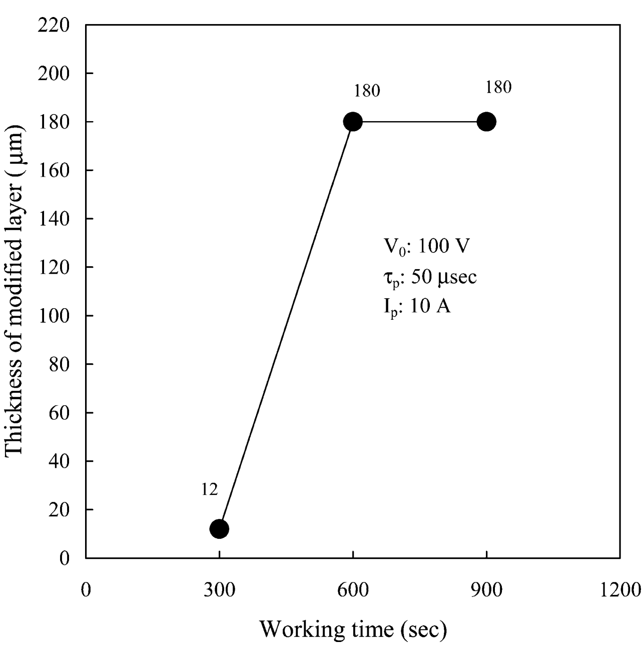


Fig. 8 Influence of working time on the thickness of the modified layer

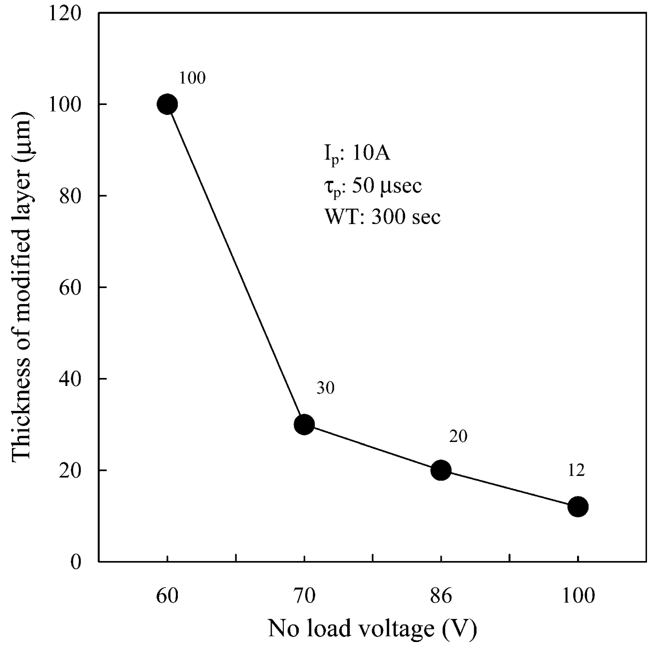


Fig. 9 Influence of no-load voltage on the thickness of the modified layer

3.5.3 *Effect of peak current on the modified thickness*

Figure 10 shows the relationship between the peak current and the modified layer thickness on the machined surface obtained by EPMA. The modified layer was thicker at peak currents of 5 A and 16 A, as shown in Fig. 10. Moreover, the modified layer thickness was the smallest when the

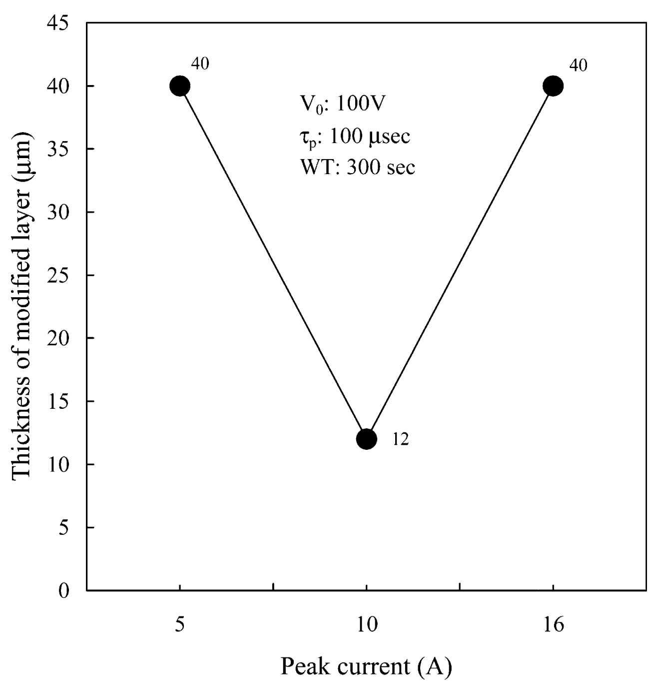


Fig. 10 Influence of peak current on the thickness of the modified layer

peak current was set to 10 A. When the peak current was 5 A, the quantity of workpiece material removed was small due to a small electrical discharge energy. At this EDM condition, the SDR was explicit, increasing the thickness of the modified layer. However, when the peak current increased, the workpiece materials removed in the EDM process were considerable. Generally, more discharge energy was conducted into the machining zone within a pulse duration at a large peak current. The EWR and MRR increased. Indeed, the modified effect increased with the electrical discharge energy [10, 14], so the modified thickness was wealthy at a large electrical discharge energy. Moreover, more powder material was dislodged from the semi-sintered electrode, compounded with the pyrolytic carbon, and deposited on the machined surface when the peak current was set at a high level, such as 16 A. When the peak current was set to 10 A, the quantity of workpiece material removed was larger than that of the compounded material deposited on the machined surface, as mentioned above. Hence, the modified layer was the thinnest at 10-A peak current.

3.5.4 Effect of pulse duration on the modified thickness

Figure 11 shows the relationship between the pulse duration and the modified layer thickness on the machined surface obtained by EPMA. The modified layer thickness increased with the pulse duration, as demonstrated in Fig. 11. The electrical discharge energy conducted into the machining zone rose with increasing pulse duration during a single pulse, so that more electrode material was dislodged from the electrode surface and compounded with the released carbon to form a modified agent. The modified agent was deposited on the machined surface to improve the surface performance. Therefore, the modified layer thickness increased with the pulse duration.

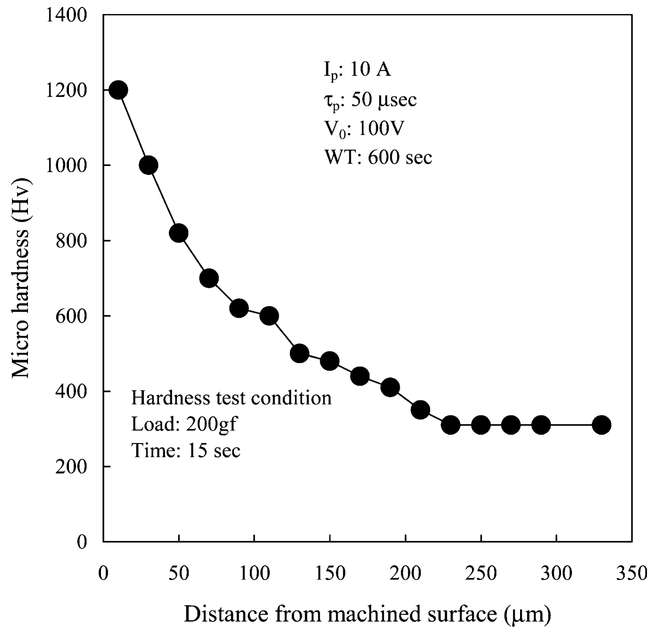


Fig. 12 Variation of micro hardness on a cross-section of the modified layer

3.6 Hardness and corrosion resistance

Figure 12 shows the distribution of the micro hardness on a cross-section of the modified layer. As the experimental

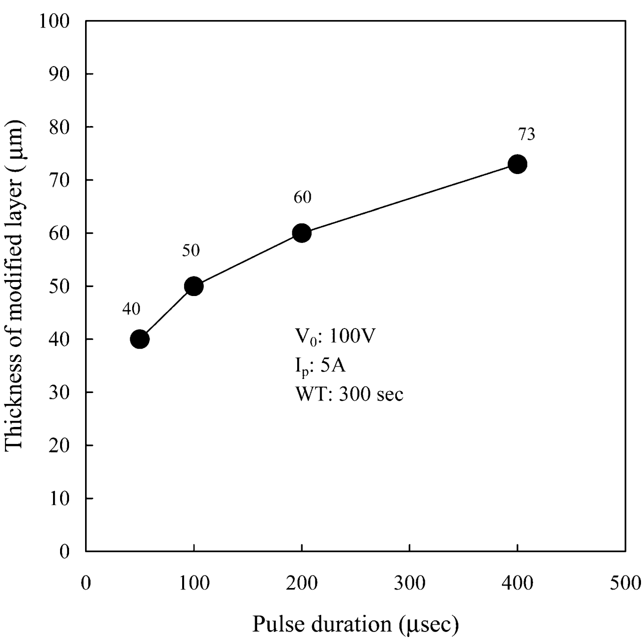


Fig. 11 Influence of pulse duration on the thickness of the modified layer

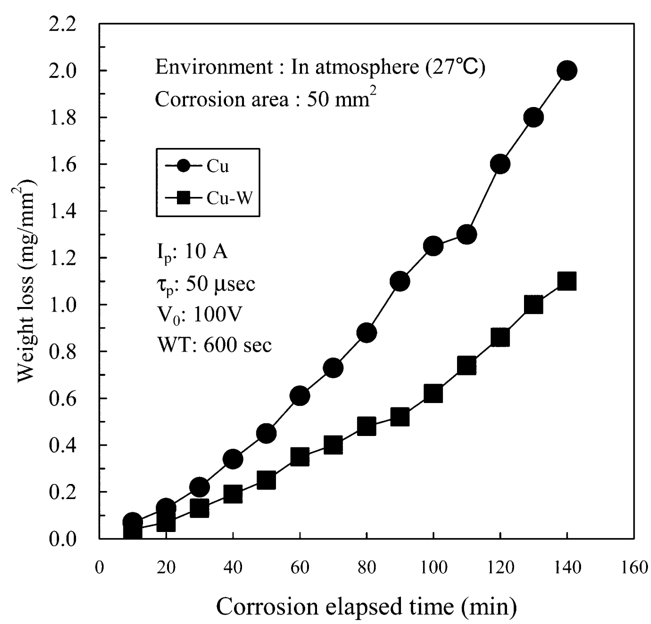


Fig. 13 Relationship between weight loss and corrosion elapsed time with different electrode materials

results show, the micro hardness revealed the highest value adjacent to the machined surface and then declined to a horizontal value as it received more material (310 Hv) near 210 μm from the machined surface. The machined surface could form an alloying layer and a carbide reinforcement on the machined surface during the EDM process. Therefore, the micro hardness of the machined surface was increased due to the modified effects of alloying and particle reinforcement.

Figure 13 displays the relationship between weight loss and the corrosion elapsed time. The specimens that were machined by EDM using green compact electrodes made of pure Cu and Cu-W (mixing ratio 3:1) powders individually were immersed in aqua regia solution to evaluate the corrosion resistance. The P/M procedure of preparing pure Cu electrodes was the same as that of Cu-W green compact electrodes. As the experimental results show, the corrosion resistance of the machined surface using Cu-W as the electrode material was better than that of pure Cu electrodes. Since the penetrated and diffused tungsten element on the machined surface could increase the tungsten content and produce tungsten carbide during the EDM process, the corrosion resistance improved with increasing tungsten content and tungsten carbide generated on the modified surface.

4 Conclusions

This investigation discussed the effects of surface modifications using a semi-sintered electrode in the electrical discharge machining (EDM) process. Based on the results of this study, we conclude the following:

1. The machined surface showed two distinctive results when the EDM conditions were adjusted while using a semi-sintered electrode made of Cu-W powders. When the no-load voltage and peak current were set high, the workpiece material was removed during the EDM process. In contrast, a deposit was formed on the machined surface when the no-load voltage and peak current were set to a low level. The deposited layer could be regarded as a modified agent to improve the machined surface performance.
2. The surface modification through EDM using semi-sintered electrodes was a promising process which could generate an adequate modified thickness (approximately 180–210 μm) in a very short elapsed working time (approximately 600 s). Moreover, the modified agent of the machined surface could be regulated by varying the composition of the semi-sintered powders. Hence, EDM is a flexible surface modification process.
3. The modified thickness could be adjusted by varying the EDM conditions. When the no-load voltage and peak current was set to a small level and the pulse duration was long, the thickness of the modified layer on the machined surface after the EDM process increased.
4. The micro hardness revealed the highest value adjacent to the machined surface and declined to a horizontal value as it received more material (310 Hv) near 210 μm from the machined surface. Moreover, the corrosion resistance improved with increasing tungsten content and tungsten carbide generated on the modified surface.

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References

1. Ando T, Rawles RE, Yamamoto K, Kamo M, Sato Y, Nishitani-Gamo M (1996) Chemical modification of diamond surfaces using a chlorinated surface as an intermediate state. Diamond Relat Mater 5(1):1136–1142
2. Katoh M, Ohte T, Takahashi A, Miyashita K, Ohtani S, Kojima A (1997) Differences between effects of ions in plasma on the edge surface of carbon material and those on the basal surface. Surf Coat Technol 92(3):230–234
3. De Damborenea J (1998) Surface modification of metals by high power lasers. Surf Coat Technol 100–101(1–3):377–382
4. Dong H, Bell T (1999) State-of-the-art overview: ion beam surface modification of polymers towards improving tribological properties. Surf Coat Technol 111(1):29–40
5. Takahashi K, Iwaki M (2000) Electrochemical characterization for ion-implanted materials surface. Colloids Surf B Biointerfaces 19(3):281–290
6. Khan TI, Rizvi SA, Matsuura K (2000) The effect on wear behaviour of H13 tool steel surfaces modified using a tungsten arc heat source. Wear 244(1):154–164
7. Yan BH, Tsai HC, Huang FY (2005) The effect in EDM of a dielectric of a urea solution in water on modifying the surface of titanium. Int J Mach Tools Manufact 45(2):194–200
8. Tsunekawa Y, Okumiya M, Mohri N, Takahashi I (1994) Surface modification of aluminum by electrical discharge alloying. Mater Sci Eng A 174(2):193–198
9. Kruth J-P, Stevens L, Froyen L, Lauwers B (1995) Study of the white layer of a surface machined by die sinking electro discharge machining. Ann CIRP 44(1):169–172
10. Lin YC, Yan BH, Huang FY (2001) Surface modification of Al-Zn-Mg aluminum alloy using the combined process of EDM with USM. J Mater Process Technol 115(3):359–366
11. Ogata I, Mukoyama Y (1993) Carburizing and decarburizing phenomena in EDM'd surface. Int J Jap Soc Precis Eng 27 (3):197–202
12. Ming QY, He LY (1995) Powder-suspension dielectric fluid for EDM. J Mater Process Technol 52(1):44–54
13. Wong YS, Lim LC, Rahuman I, Tee WM (1998) Near-mirror-finish phenomenon in EDM using powder-mixed dielectric. J Mater Process Technol 79(1):30–40

14. Yan BH, Lin YC, Huang FY, Wang CH (2001) Surface modification of SKD 61 during EDM with metal powder in the dielectric. Mater Trans JIM 42(12):2597–2604
15. Mohri N, Saito N, Tsunekawa Y (1993) Metal surface modification by electrical discharge machining with composite electrode. Ann CIRP 42(1):219–222
16. Tsunekawa Y, Okumiya M, Mohri N, Kuribe E (1997) Formation of composite layer containing TiC precipitates by electrical discharge alloying. Mater Trans JIM 38(7):630–635
17. Shunmugam MS, Philip PK (1994) Improvement of wear resistance by EDM with tungsten carbide P/M electrode. Wear 171(1–2):1–5
18. Samuel MP, Philip PK (1997) Power metallurgy tool electrodes for electrical discharge machining. Int J Mach Tools Manufact 37 (11):1625–1633
19. Tsai HC, Yan BH, Huang FY (2003) EDM performance of Cr/Cu-based composite electrodes. Int J Mach Tools Manufact 43(3):245–252