Compound machining of silicon carbide ceramics by high speed end electrical discharge milling and mechanical grinding

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A compound process that integrates end electrical discharge (ED) milling and mechanical grinding to machine silicon carbide (SiC) ceramics is developed in this paper. The process employs a turntable with several uniformly-distributed cylindrical copper electrodes and abrasive sticks as the tool, and uses a water-based emulsion as the machining fluid. End electrical discharge milling and mechanical grinding happen alternately and are mutually beneficial, so the process is able to effectively machine a large surface area on SiC ceramic with a good surface quality. The machining principle and characteristics of the technique are introduced. The effects of polarity, pulse duration, pulse interval, open-circuit voltage, discharge current, diamond grit size, emulsion concentration, emulsion flux, milling depth and tool stick number on performance parameters such as the material removal rate, tool wear ratio, and surface roughness have been investigated. In addition, the microstructure of the machined surface under different machining conditions is examined with a scanning electron microscope and an energy dispersive spectrometer. The SiC ceramic was mainly removed by end ED milling during the initial rough machining mode, whereas it is mainly removed by mechanical grinding during the later finer machining mode; moreover, the tool material can transfer to the workpiece surface during the compound process.

electrical discharge machining, silicon carbide ceramics, end electrical discharge milling, mechanical grinding, high speed

Over the last few years, there has been a great upsurge of interest in advanced ceramic materials. As a result of this interest, significant advances in the development and use of ceramic materials have been made, and the world markets for advanced ceramics are growing. Of the various ceramic materials, silicon carbide (SiC) ceramics are the most interested engineering ceramics because of their combination of outstanding mechanical, physical and chemical properties such as low density, high strength, high thermal conductivity, low thermal expansion coefficient and wear and high corrosion resistance even at elevated temperature [1–3]. The broad range of technological applications presently served by SiC ceramics includes cutting tools, automotive engine parts, heat exchangers, high temperature bearings, heavy-duty electric contacts, fixtures, nozzles, turbine blades and many more applications [4–6]. However, the properties that make these materials appealing to use also create a major challenge in traditional diamond grinding or diamond turning, because of their great hardness and brittleness [7,8].

Electrical discharge machining (EDM) is a thermoelectric process, whereby material is removed by a succession of electrical discharges occurring between an electrode and a workpiece which is immersed in a dielectric liquid medium. Unlike traditional cutting and grinding processes, which rely on the force generated by a harder tool or abrasive material to remove the softer work-material, the EDM process utilizes electrical sparks or thermal energy to erode the unwanted material and generate the desired shape. Since no mechanical contact between the electrode and the workpiece is involved during EDM, the process is able to machine any conductive component into accurate and complex shapes irrespective of its high hardness and strength [9–11].

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Since EDM has been shown to be an effective and economical technique for machining difficult-to-machine materials, it is believed that the EDM process will open up an opportunity for the machining of SiC ceramics. However, conventional EDM techniques such as die-sinking electrical discharge machining and wire electrical discharge machining (WEDM) show low efficiency when machining a large surface area on a SiC ceramic [12,13]. Electrical discharge grinding (EDG) integrates electrical discharge machining and mechanical grinding. During this process, the electrical discharge and grinding processes occur simultaneously, so electrically conductive hard materials can be machined with good surface quality, but the material removal rate is low, and the cost is high [14,15]. Recently, some progress has been made to improve efficiency by using EDM milling. The material removal rate can be improved significantly, but it still cannot meet the demand of modern industrial applications, and the machined surface is poor [16–19].

A novel high speed compound machining process that integrates end electrical discharge (ED) milling and mechanical grinding to machine SiC ceramic is proposed in this paper. The process employs a turntable with several uniformly-distributed small cylindrical copper electrodes and abrasive sticks as the tool, and uses a water-based emulsion as the machining fluid. End electrical discharge milling and mechanical grinding happen alternately and are mutually beneficial, so the process is able to effectively machine a large surface area on SiC ceramic with a good surface quality. The effects of polarity, pulse duration, pulse interval, open-circuit voltage, discharge current, diamond grit size, emulsion concentration, emulsion flux, milling depth and tool stick number on the process performance parameters such as the material removal rate (MRR), tool wear ratio (TWR), and surface roughness (SR R_a) have been investigated.

1 Principle and characteristics for end ED milling and mechanical grinding of SiC ceramic

1.1 Principles

The principle of end ED milling and mechanical grinding of SiC ceramic is shown in Figure 1. The tool and the workpiece are connected to the negative and positive poles of the pulse generator, respectively. The tool is a turntable with several uniformly-distributed small cylindrical electrodes and abrasive sticks rotating rapidly around its axis. The tool is mounted onto a rotary spindle, driven by an A.C. motor. The workpiece is SiC ceramic blank and is mounted onto a numerically controlled (NC) table. The machining fluid is a water-based emulsion.

During machining, the tool rotates at a high speed, the machining fluid is flushed into the gap between the tool and the workpiece with several nozzles, and the SiC ceramic
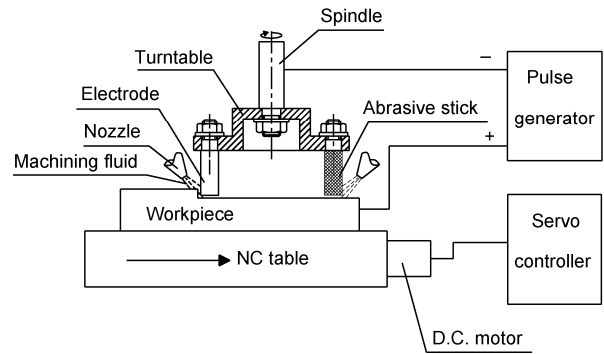

Figure 1 Schematic illustration of end ED milling and mechanical grinding of SiC ceramic.

workpiece is fed towards the tool by the NC table. As the workpiece approaches the tool and the distance between the workpiece and the electrode reaches the discharge gap, electrical discharges are produced. A plasma channel with high temperature and high pressure grows during the pulse duration [20]. The instantaneous high temperature and pressure plasma causes SiC ceramic to be removed by electrical discharge milling, and a modified surface layer is formed on the workpiece surface. The following abrasive stick grinds the modified surface layer. The discharge energy thermally softens the modified surface layer in the grinding zone, and consequently decreases the normal force and the grinding power, allowing the modified surface layer to be removed easily by the abrasive stick, which can also enhance the effectiveness of the subsequent discharge. The combination of these alternating, mutually beneficial processes means that a high material removal rate and good surface quality can be achieved when machining SiC ceramic.

During this compound machining, the discharge gap will match the machining condition, and the abrasive sticks and the electrodes are worn at the same rate. If the wear of the abrasive stick was greater than that of the electrode, the distance between the abrasive stick and the workpiece surface would increase, weakening the mechanical grinding function so that the electrical discharge function becomes stronger; the material on the workpiece surface is then mostly removed by electrical discharges, which will in turn accelerate the electrode wear, to eventually achieve the same wear of the electrodes and the abrasive sticks. If the wear of the electrode was greater than that of the abrasive stick, the distance between the electrode and the workpiece surface would increase, the electrical discharge function become weaker, the mechanical grinding function become stronger, until the material on the workpiece surface was mostly removed by the mechanical grinding function, which would accelerate the abrasive stick wear, until eventually the same wear of the abrasive sticks and the electrodes was obtained.

Comparing with electrical discharge (ED) milling and conventional mechanical grinding, the advantages of the

compound machining process can be explained as follows. During ED milling of SiC ceramic, a modified surface layer will form on the workpiece surface, which makes the subsequent discharge difficult and degrades the workpiece surface quality. During conventional mechanical grinding of SiC ceramic, the grinding force is high because of the high hardness of the workpiece, so the material removal rate is low. During this compound process, mechanical grinding removes the softened material created by the end electrical discharge milling, to produce higher overall machining performance. The comparison experiments have been carried out for positive tool polarity, pulse duration of 50 μs, pulse interval of 2500 μs, discharge current of 15 A, open–circuit voltage of 90 V, diamond grit size of #120 in the abrasive sticks, and diamond concentration of 100% in the abrasive sticks. The experimental results are shown in Figure 2. It can be seen from this figure that a higher MRR, lower TWR and lower SR can be obtained with the compound process in comparison with ED milling alone. Furthermore, although the SR with the compound process is a little higher than that with conventional mechanical grinding, the MRR is far higher and the TWR is far lower with the compound process in comparison to conventional mechanical grinding.

1.2 Characteristics of end ED milling and mechanical grinding of SiC ceramic

The advantages of combined end ED milling and mechanical grinding for SiC ceramic are listed below:

(1) A large diameter turntable with several cylindrical copper electrodes and abrasive sticks is used as the tool (as shown in Figure 3), so a large surface area can be easily machined by the compound process. The process shows high material removal rate and good surface quality. Figure 4 is a photograph of a SiC ceramic workpiece machined by the compound process.

(2) The cylindrical copper electrodes and abrasive sticks used (as shown in Figure 5), can be easily and economically manufactured. Furthermore, the cylindrical copper electrodes and abrasive sticks are easily fixed and replaced, eliminating the need for a high-cost monolithic tool.

(3) The cylindrical electrodes and abrasive sticks are fixed on the turntable alternately and separately; the machining fluid is flushed into the gap, and the chips are flushed away easily. Therefore, the compound process improves the discharge stability and machining efficiency.
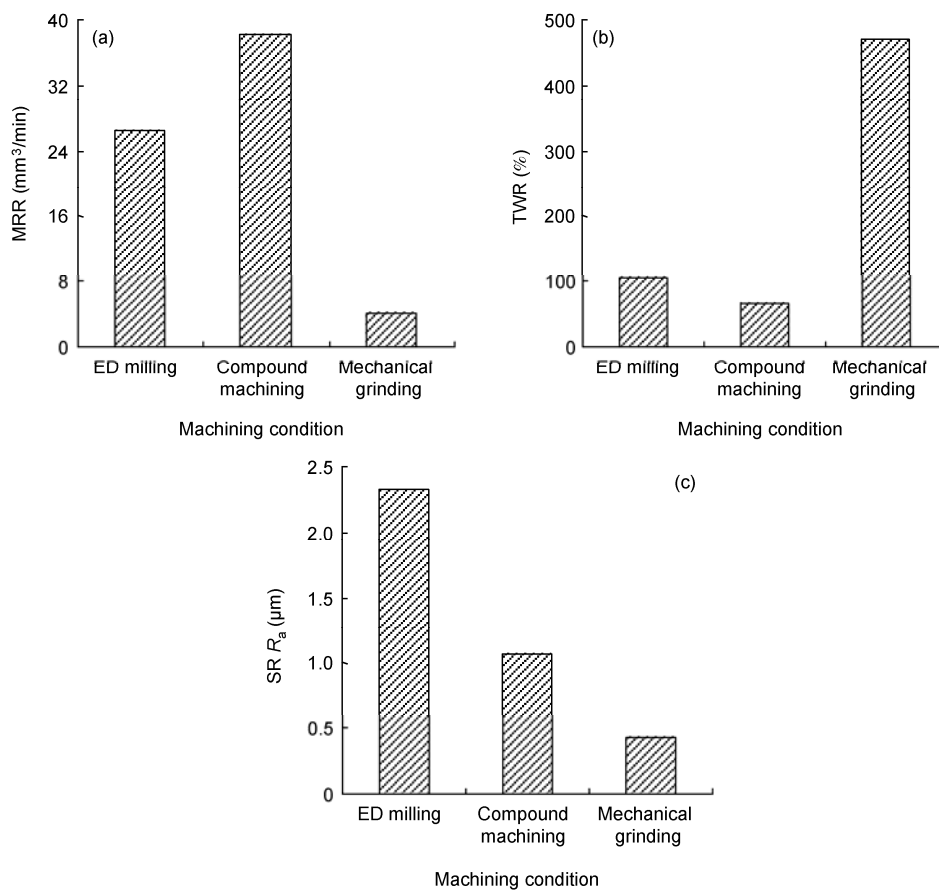
(4) A water-based emulsion is used as the machining

Figure 2 Comparison of experimental results for machining of SiC ceramic with different processes. (a) Effect of machining condition on MRR; (b) effect of machining condition on TWR; (c) effect of machining condition on SR.
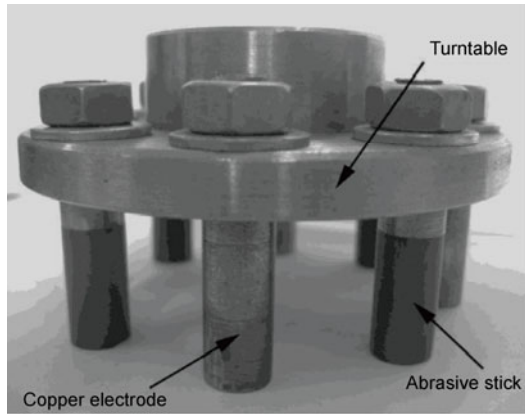
Figure 3 Tool used in the compound process.

Figure 4 Photograph of SiC ceramic workpiece machined by the compound process (130 mm × 60 mm).
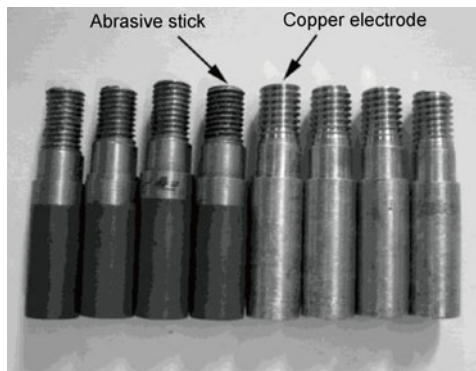

Figure 5 Cylindrical copper electrodes and abrasive sticks used in the compound process.

fluid, so harmful gas is not generated during the compound process, and the equipment is not corroded.

(5) Rough machining, semi-finish machining and finish machining can be obtained on the same machine by adjusting the discharge parameters when a large surface on a SiC ceramic workpiece is machined.

2　Experimental procedures

The experiments were carried out in an electrical discharge milling machine. In the following experiments, the work-

piece material was SiC ceramic, the tool was a turntable with several uniformly-distributed cylindrical copper electrodes and cast iron bonded diamond abrasive sticks around the circumference. The copper electrodes and abrasive sticks were fixed on the turntable alternately (as shown in Figure 3). The diameter of the cylindrical copper electrode was 10 mm, the diameter of the abrasive stick was 10 mm, the diameter of the turntable was 90 mm, the rotational speed of the spindle was 3000 r/min. The machining fluid was a water-based emulsion composed of emulsified oil and distilled water, which were mixed with a constant speed power-driver mixer. The material removal rate (MRR) and tool wear ratio (TWR) were as defined in eqs. (1) and (2), respectively, and were obtained through measuring the dimensions of the workpiece and the tool stick before and after machining with a dial indicator and a vernier caliper. The surface roughness (SR R_a) was measured with a surface roughness tester (TR220, Beijing Time High Technology Ltd., China). The microstructure of the workpiece surface was examined with a scanning electron microscope (JEOL JSM-6380, Japan), equipped with an energy dispersive spectrometer (JEOL JED-2300, Japan). Unless otherwise specified, the following experimental parameters were used: the tool polarity was negative, the pulse duration was 400 μs, the pulse interval was 300 μs, the open-circuit voltage was 150 V, the discharge current was 75 A, the grit size of diamond in the abrasive sticks was #120 (grain size = 124 μm), the concentration of diamond in the abrasive sticks was 100%, the emulsion concentration was 8 mass%, the emulsion flux was 200 mL/s, the milling depth was 0.1 mm, and the number of tool sticks was 8 (four abrasive sticks and four copper electrodes).

$$MRR = \frac{\text{Volume of material removed from workpiece}}{\text{Time of machining}}, \ (1)$$

$$TWR = \frac{\text{Volume of material removed from electrode}}{\text{Volume of material removed from workpiece}} \times 100\%.$$
$$(2)$$

3　Experimental results and discussion

3.1　Effect of tool polarity on the process performance

Tool polarity is a primary factor that affects process performance parameters such as the MRR, the TWR and the SR. The effect of tool polarity on the process performance is shown in Figure 6.

The MRR values obtained with different tool polarities are given in Figure 6(a); under the same conditions, the MRR with negative tool polarity is 1.7 to 1.9 times that with positive tool polarity. The TWR values for different tool polarities are given in Figure 6(b); under the same conditions the TWR for positive tool polarity is 3.5 to 4.5 times higher than that for negative tool polarity. These phenome-

na can be explained as follows. The tool rotates at a high speed during machining, the discharge point transfer velocity between the electrode and workpiece is very high, and the lifetime of the discharge between a particular point of the electrode and a particular point of the workpiece is very short. Because the mass of the electrons is much smaller than that of positive ions, and they can be accelerated quickly over a short time, the bombardment effect by electrons is stronger than that by positive ions; therefore, the MRR is higher in negative tool polarity, and the TWR is higher in positive tool polarity.

Figure 6(c) shows the influence of tool polarity on SR; under the same conditions, the SR with negative tool polarity is 1.1 to 1.3 times higher than that with positive tool polarity. Because the bombardment by positive ions is weaker than that by electrons, the craters on the workpiece surface produced by positive ions are shallow; therefore, the SR is lower when the tool polarity is positive.

3.2 Effect of pulse duration on the process performance

The effect of pulse duration on the process performance is given in Figure 7. As shown in Figure 7(a), the MRR in-

creases gradually with increasing pulse duration. This is because the discharge energy delivered into the machining zone within a single pulse increases with increasing pulse duration. Thermal erosion effects, such as vaporization and melting of the machined surface, are enhanced, and thus the MRR increases.

Figure 7(b) shows the influence of pulse duration on TWR; the TWR decreases with increasing pulse duration. This phenomenon can be explained as follows. During EDM, a layer can be deposited on the electrode surface because of the decomposition of the dielectric fluid and workpiece material attached to the tool electrode surface, and the tool wear can be prevented by the protective effects of this deposited layer [21,22]. As the pulse duration increases, the discharge energy delivered to the machining gap increases; the dielectric and workpiece are heated for more time, the carbon released as a result of decomposition of the dielectric is easily attached to the copper electrode surface, resulting in increased deposition on the electrode. Moreover, the thickness of the modified surface layer formed by electrical discharge milling increases with increasing pulse duration; thus the grinding force decreases and the abrasive stick wear is low—therefore the TWR decreases.
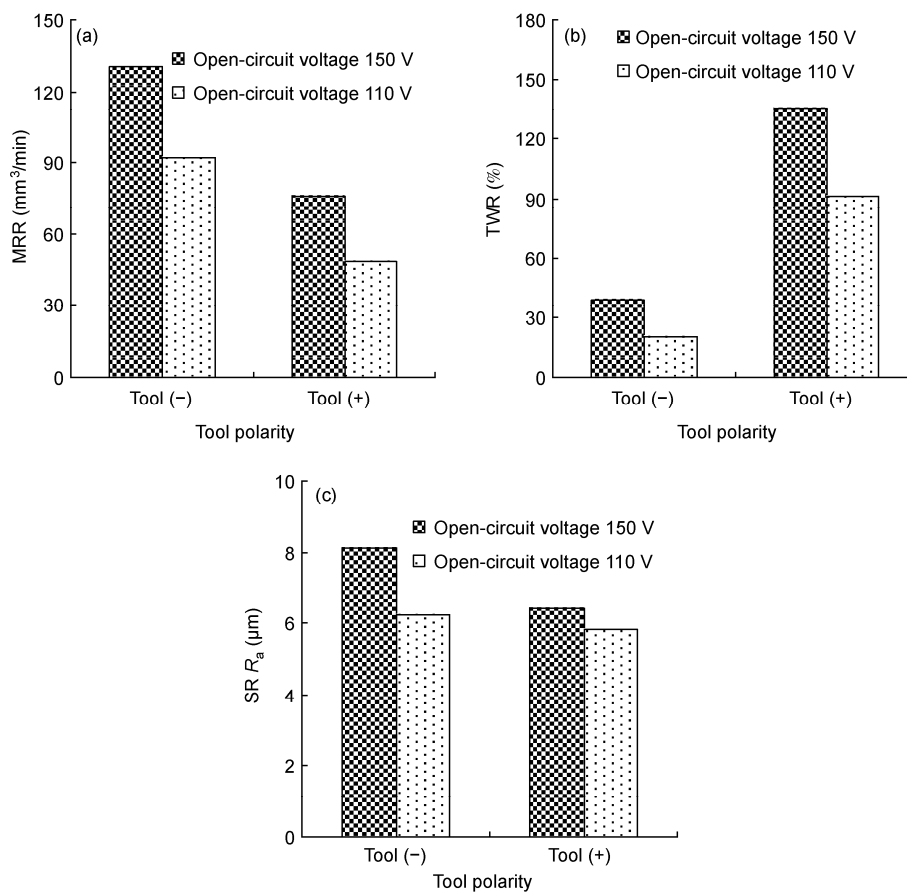
The effect of pulse duration on SR is shown in Figure

Figure 6 Effect of tool polarity on the process performance. (a) Effect of tool polarity on MRR; (b) effect of tool polarity on TWR; (c) effect of tool polarity on SR.
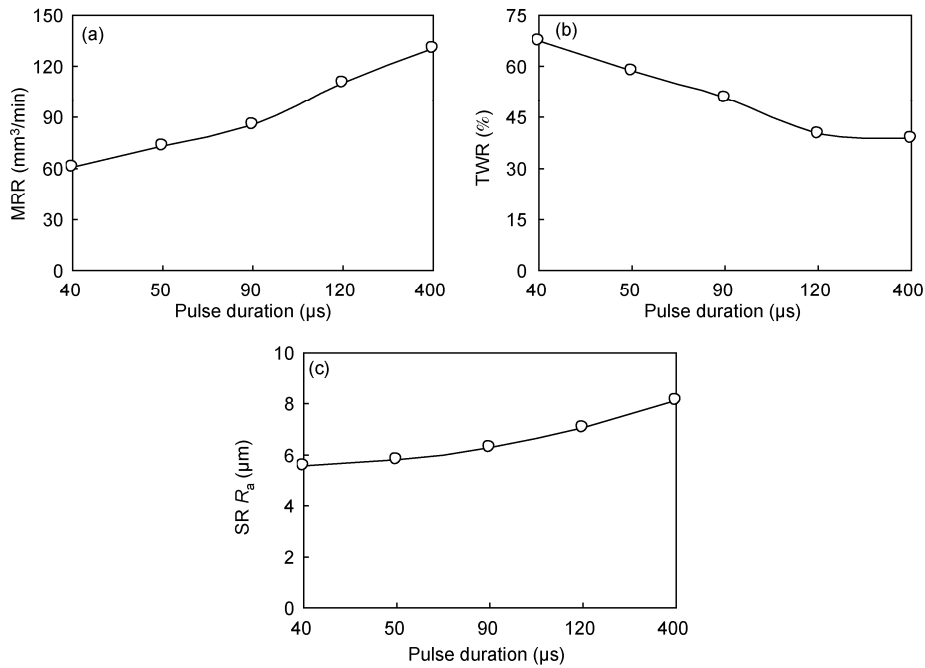
Figure 7   Effect of pulse duration on the process performance. (a) Effect of pulse duration on MRR; (b) effect of pulse duration on TWR; (c) effect of pulse duration on SR.

7(c); the SR increases with increasing pulse duration. This is because the crater size generated by a single pulse becomes larger as the energy of that single pulse increases with the increase in pulse duration.

3.3   Effect of pulse interval on the process performance

The effects of pulse interval on MRR, TWR and SR are illustrated in Figure 8(a), (b), (c), respectively. Figure 8(a) shows that the MRR decreases with increasing pulse interval. The reason for this is that the electrical discharge frequency and the discharge energy delivered to the machining gap decrease as the pulse interval increases, thus decreasing the MRR.

As shown in Figure 8(b), the TWR increases with increasing pulse interval. This phenomenon can be explained as follows. The time for deionization of the dielectric increases with increasing pulse interval; the discharge energy delivered to the machining gap per unit time decreases and thus the amount carbon released via decomposition of the dielectric decreases, weakening the deposition effect and increasing the grinding force on the abrasive sticks. This results in high abrasive stick wear and therefore the TWR increases.

The effect of pulse interval on SR is shown in Figure 8(c); the SR initially increases with increasing pulse interval and then decreases with further increase of pulse interval. There are many reasons behind this phenomenon. A longer pulse interval means more time for deionization of the dielectric, which increases the breakdown voltage and the discharge

explosion force; the crater size generated by a single pulse becomes larger and deeper and therefore, the SR increases with increasing pulse interval. However, once the pulse interval is larger than 1200 μs, the breakdown voltage and the discharge explosion force do not increase any further, and the crater amount generated by electrical discharge decreases, moreover, there is more time to grind the modified surface layer from the workpiece and clear the disintegrated particles from the gap between the tool and the workpiece; therefore, the SR decreases with further increase of pulse interval.

3.4   Effect of open-circuit voltage on the process performance

The effect of open-circuit voltage on the process performance is illustrated in Figure 9. Figure 9(a), (b) shows that the MRR and the TWR increase with increasing open-circuit voltage. The phenomena can be explained as follows. The single pulse energy, thermal energy density and discharge explosive force all increase with increasing open-circuit voltage, which enhances the removal of material from both the workpiece and the tool, resulting in increased MRR and TWR.

Figure 9(c) shows the influence of open-circuit voltage on SR. SR increases with increasing open-circuit voltage. The reason for this is that the material removed by a single pulse increases as the open-circuit voltage increases; the discharge crater becomes larger and deeper, resulting in increased SR.
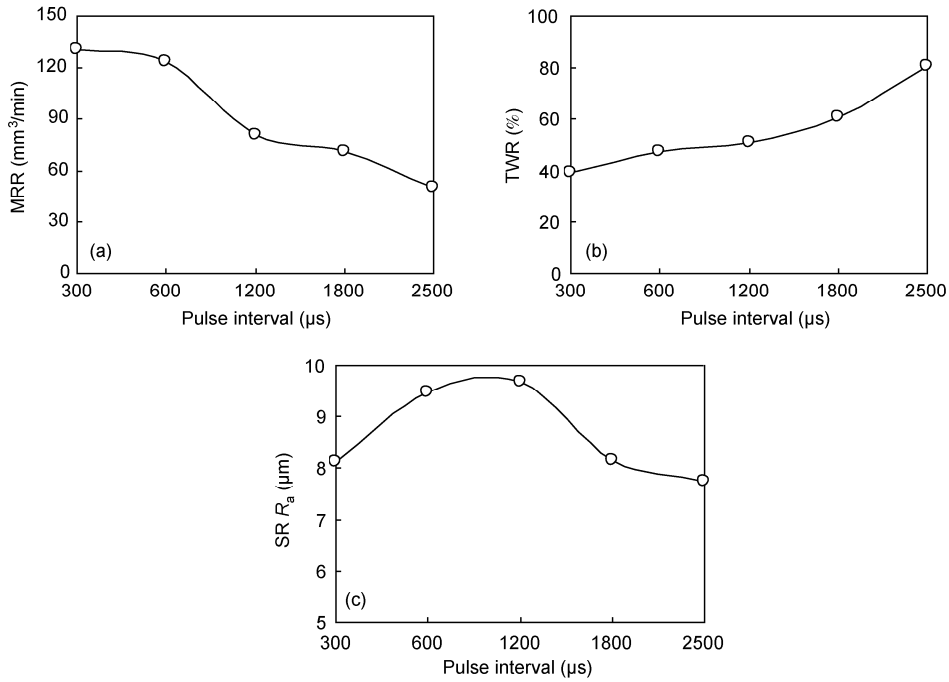
Figure 8   Effect of pulse interval on the process performance. (a) Effect of pulse interval on MRR; (b) effect of pulse interval on TWR; (c) effect of pulse interval on SR.
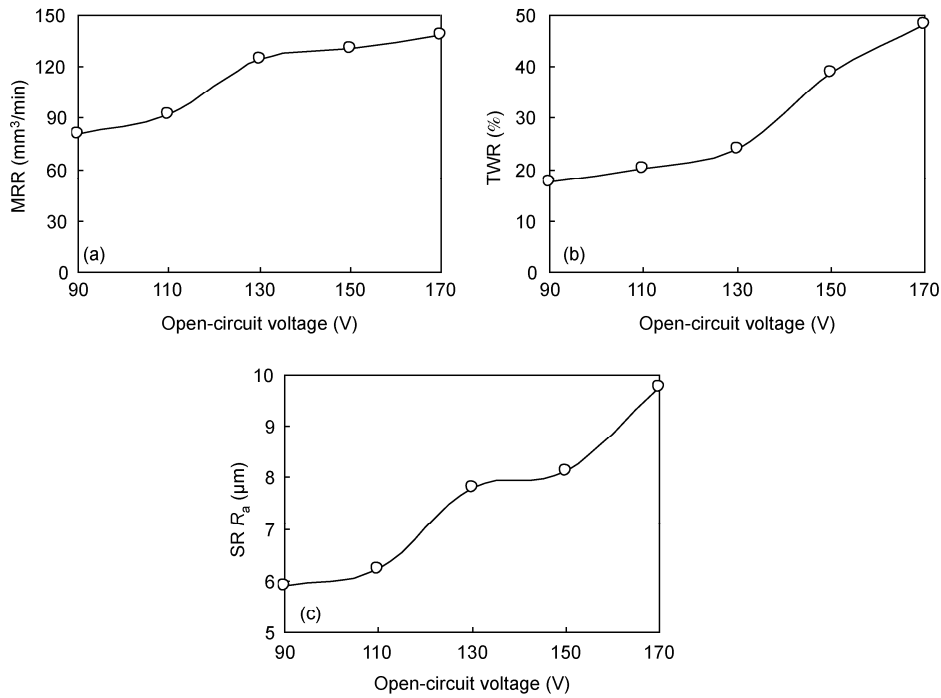

Figure 9   Effect of open-circuit voltage on the process performance. (a) Effect of open-circuit voltage on MRR; (b) effect of open-circuit voltage on TWR; (c) effect of open-circuit voltage on SR.

3.5   Effect of discharge current on the process performance

The effects of discharge current on MRR, TWR and SR are illustrated in Figure 10(a), (b), (c), respectively. Figure 10(a) shows that the MRR increases with increasing discharge current. The phenomenon can be explained by the relationship between the material removed by a single pulse and discharge current as follows [23]:

$$W_0 = k_{W0} T_i I_p , \qquad (3)$$

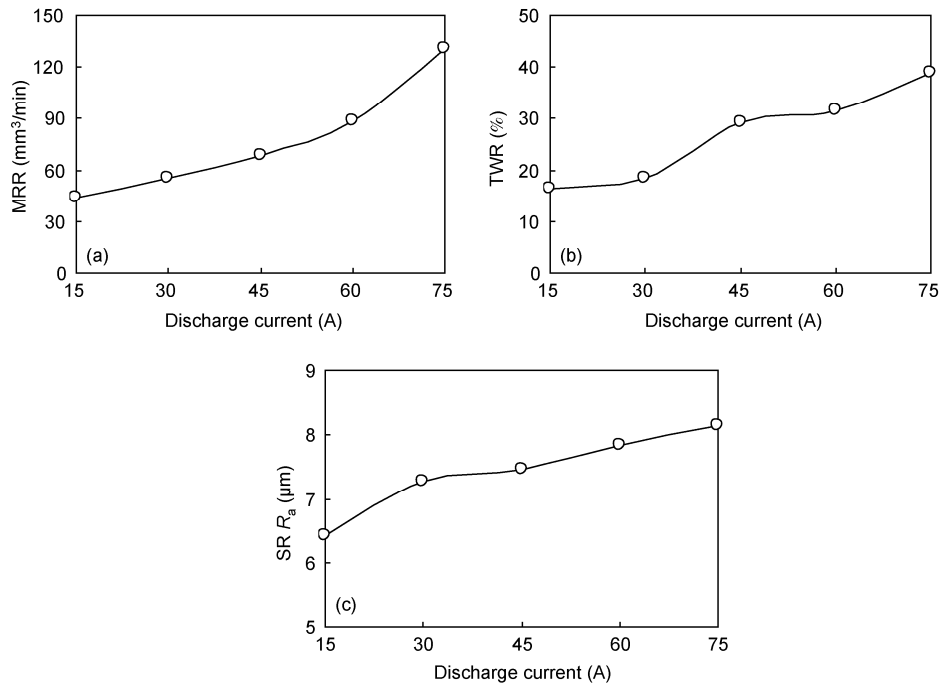where W_0 is the theoretical material removal by a single

Figure 10 Effect of discharge current on the process performance. (a) Effect of discharge current on MRR; (b) effect of discharge current on TWR; (c) effect of discharge current on SR.

pulse (mm^3/pulse), K_{W0} is a constant, T_i is the pulse duration (μs), and I_p is the discharge current (A). Eq. (3) implies that under constant pulse duration, the material removed by a single pulse increases with increasing discharge current; therefore the MRR increases.

The effect of discharge current on TWR is shown in Figure 10(b); the TWR increases with increasing discharge current. This is because the single pulse energy, thermal energy density and discharge explosive force all increase with increasing discharge current; this enhances the material removal from the tool, so the TWR increases.

As shown in Figure 10(c), the SR increases gradually with an increase in discharge current. This is because the crater size generated by a single pulse becomes larger with an increase in single pulse energy. Single pulse energy increases with increasing discharge current; therefore the SR also increases.

3.6 Effect of diamond grit size on the process performance

The effect of diamond grit size on the process performance is illustrated in Figure 11. The MRR with different diamond grit sizes is given in Figure 11(a); under the same conditions, the MRR for #60 diamond grit size is 1.0 to 1.1 times that with #120 diamond grit size. The TWR with different diamond grit sizes is given in Figure 11(b); under the same conditions the TWR for #60 diamond grit size is 1.2 to 1.3 times higher than that with #120 diamond grit size. The explanation for this is that as the diamond grit size decreas-

es, the diamond grain size increases, so the grinding force of the abrasive sticks increases, and the removal of the modified surface layer and the removal of the tool sticks are both enhanced. Therefore, the MRR and TWR increase. As shown in Figure 11(c), the SR with #60 diamond grit size is 1.0 to 1.1 times higher than that with #120 diamond grit size. The reason for this is that as the grinding force increases with the decrease of diamond grit size, the grinding trace becomes more evident and the SR increases.

3.7 Effect of emulsion concentration on the process performance

The effect of emulsion concentration on the process performance is illustrated in Figure 12. As shown in Figure 12(a), the MRR initially increases with increasing emulsion concentration and then decreases with further increase in emulsion concentration. This is a complex phenomenon. The dielectric strength, washing capability, density and viscosity of the machining fluid increase as the emulsion concentration increases, thus enhancing the pinch-effect and energy density of the discharge channel, and increasing the ejection effect of the eroded material; therefore the MRR rises. However, once the viscosity of the machining fluid becomes very high, the eroded materials are difficult to flush away; the stability of electrical discharges becomes unsatisfactory, and hence the MRR falls.

Figure 12(b) shows the influence of emulsion concentration on TWR; the TWR initially decreases with increasing emulsion concentration and then increases with further
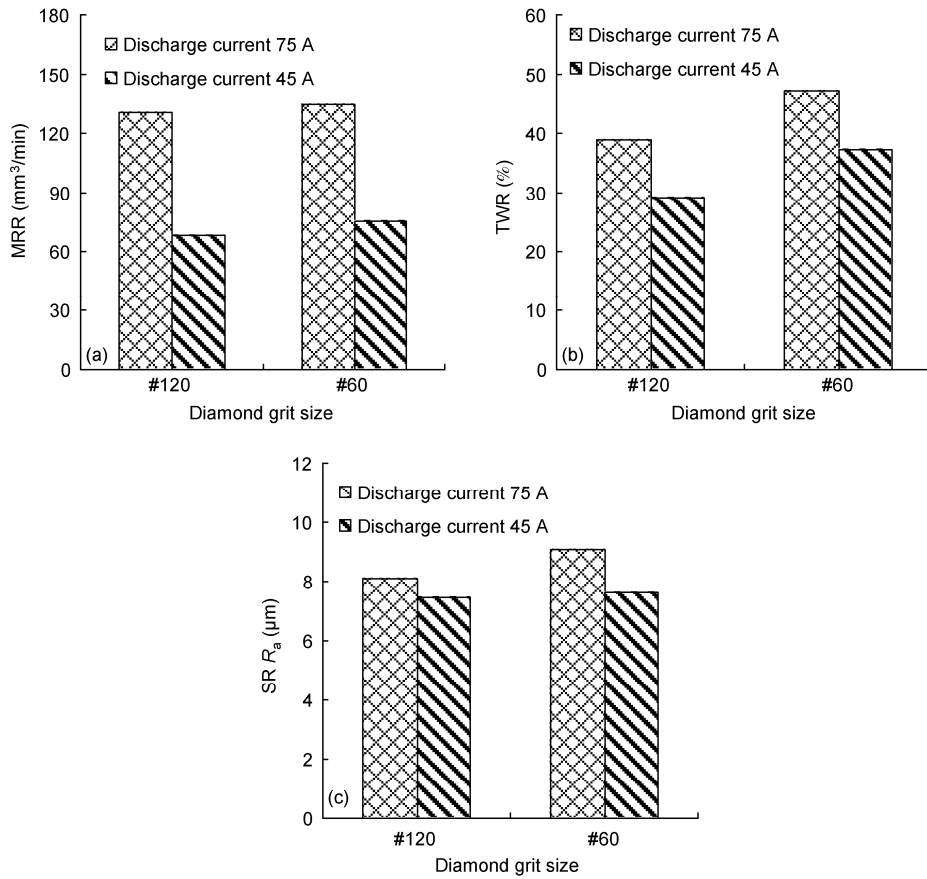
Figure 11   Effect of diamond grit size on the process performance. (a) Effect of diamond grit size on MRR; (b) effect of diamond grit size on TWR; (c) effect of diamond grit size on SR.
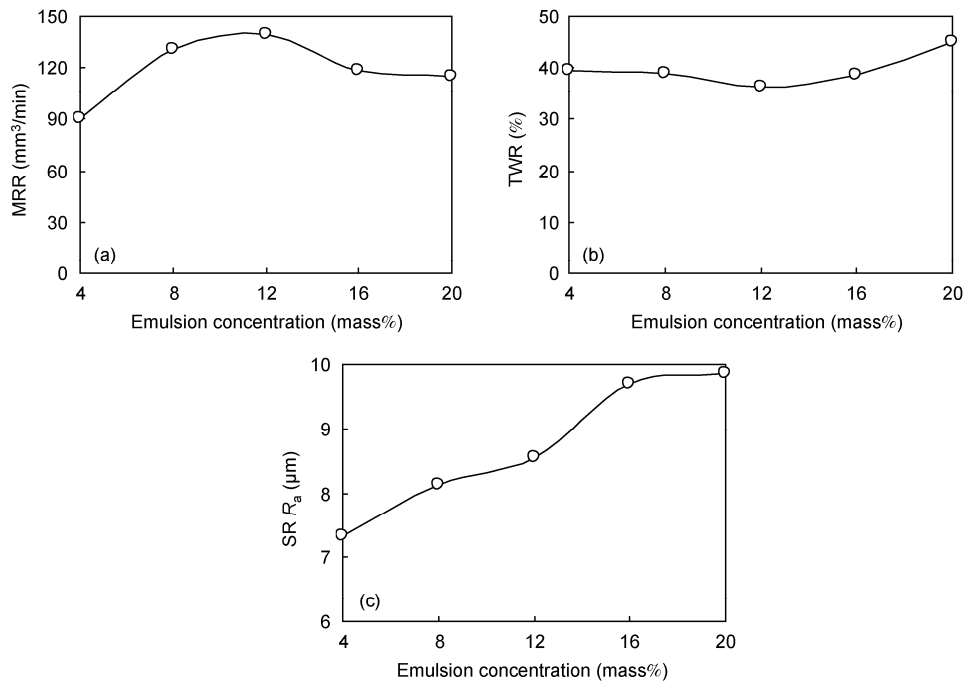

Figure 12   Effect of emulsion concentration on the process performance. (a) Effect of emulsion concentration on MRR; (b) effect of emulsion concentration on TWR; (c) effect of emulsion concentration on SR.

increase in emulsion concentration. The phenomenon can be explained as follows. There are hydrocarbons in the emulsion, and a layer deposits on the electrode surface because of the decomposition of these hydrocarbons during electrical discharges; this layer can prevent the tool wear. As the emulsion concentration increases, the hydrocarbon content in the dielectric increases, the decomposition of the hydrocarbon and the formation of deposits on the electrode surface are enhanced; therefore, the TWR decreases. However, once the emulsion concentration exceeds 12%, the viscosity of the machining fluid increases substantially. The eroded materials become difficult to flush away, and they are gathered in the machining zone. The electrical discharge energy supplied to the machining zone repeatedly strikes the un-expelled eroded materials that are concentrated on the machined surface, causing unnecessary electrode wear; therefore, the TWR is high.

The effect of emulsion concentration on SR is shown in Figure 12(c); SR increases with increasing emulsion concentration. This is because the energy density of the discharge channel increases with increasing emulsion concentration; the crater size generated by a single pulse becomes larger and deeper, therefore the SR increases.

3.8   Effect of emulsion flux on the process performance

The effects of emulsion flux on MRR, TWR and SR are illustrated in Figure 13(a), (b), (c), respectively. It can be seen from Figure 13(a) that the MRR increases with increasing emulsion flux. This phenomenon can be explained as follows. A high emulsion flux results in better cooling of the electrode, and better removal of the eroded materials. Under these conditions, the electrical discharges become strong and stable and therefore the MRR increases.

Figure 13(b) shows the influence of emulsion flux on TWR; TWR increases with increasing emulsion flux. Again, this is because of better cooling of the electrode and better removal of the eroded materials. The deposit formation on the electrode surface decreases and the mechanical grinding function is enhanced; therefore, the TWR increases.

As shown in Figure 13(c), the SR decreases with increasing emulsion flux. This phenomenon can be explained as follows. The high emulsion flux enhances electrode cooling and removal of the eroded materials; the craters generated by the electrical discharges are shallow and uniformly distributed on the workpiece surface, and the mechanical grinding function is enhanced, so the SR decreases with increasing emulsion flux.

3.9   Effect of milling depth on the process performance

The effect of milling depth on the process performance is illustrated in Figure 14. As shown in Figure 14(a), the MRR initially increases with increasing milling depth and then decreases with further increase of milling depth. This is also a complicated phenomenon. A shallower milling depth leads to higher discharge current density, and thus the thermal energy density of the discharge channel is very high. At this time, the material is removed by vaporization. As the heat consumed by vaporization is high, the MRR is low.
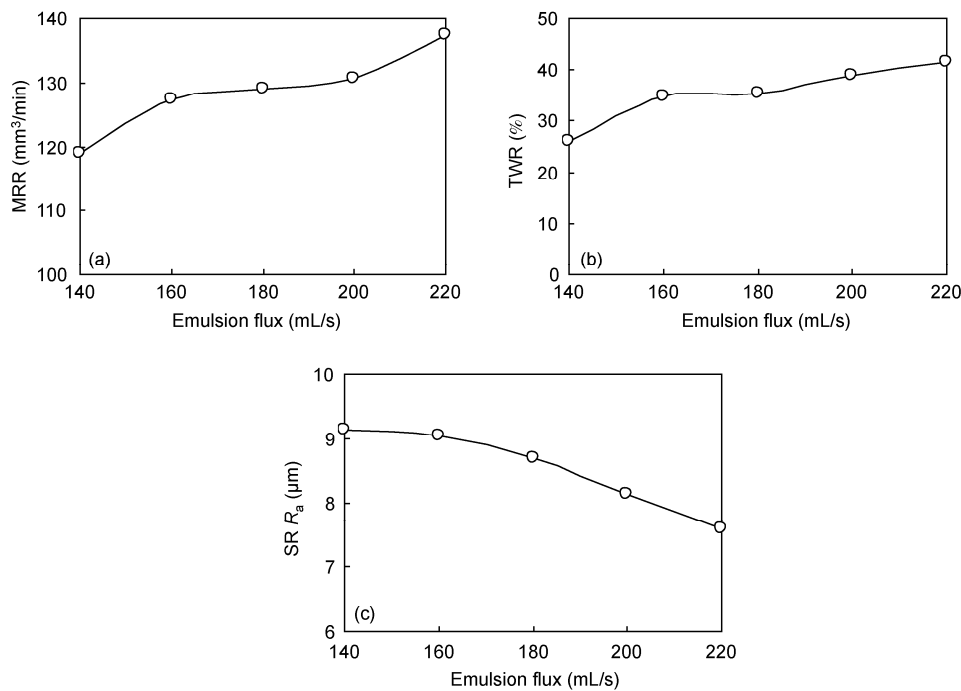

Figure 13   Effect of emulsion flux on the process performance. (a) Effect of emulsion flux on MRR; (b) effect of emulsion flux on TWR; (c) effect of emulsion flux on SR.
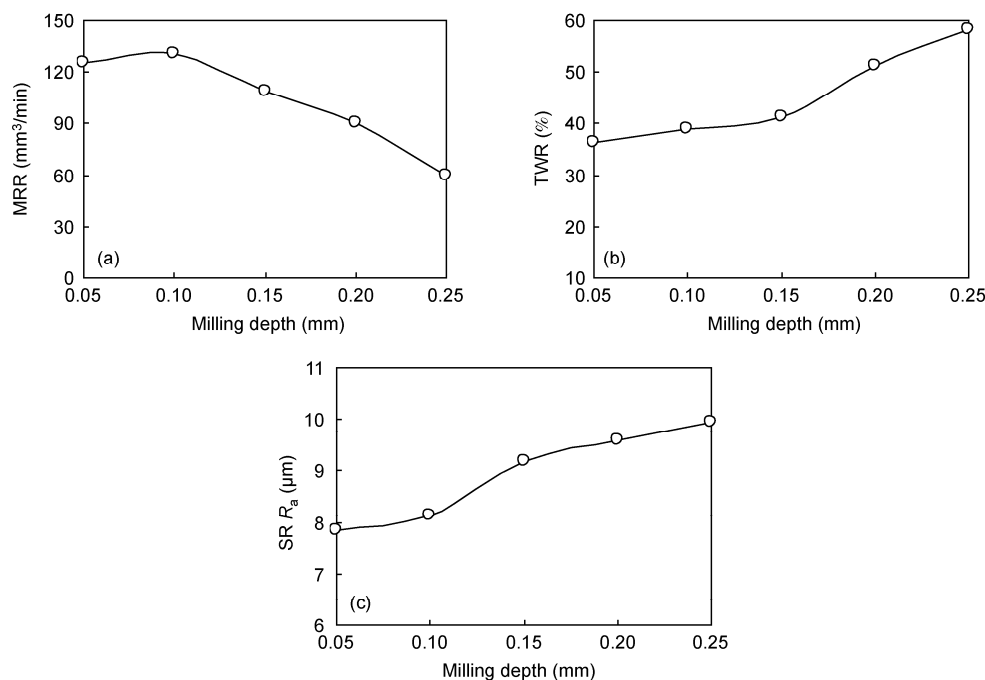
Figure 14 Effect of milling depth on the process performance. (a) Effect of milling depth on MRR; (b) effect of milling depth on TWR; (c) effect of milling depth on SR.

However, at a very deep milling depth, the discharge current density is low, which makes it difficult for the SiC ceramic to be removed, and the electrical discharge becomes unstable; therefore, once the milling depth is above 0.1 mm, the MRR decreases with further increase in milling depth.

Figure 14(b), (c) shows that the TWR and SR increase with increasing milling depth. The phenomenon can be explained as follows. The discharge current density decreases with increasing milling depth. The electrical discharge becomes unstable and arcs are easily generated, causing unnecessary tool stick wear and deteriorating the machined surface; therefore, the TWR and SR increase.

3.10   Effect of tool stick number on the process performance

The effects of tool stick number on MRR, TWR and SR are illustrated in Figure 15(a), (b), (c), respectively. It can be seen from Figure 15(a), (c) that the MRR increases with increasing tool stick number, while the SR decreases. The phenomena can be explained as follows. Since the tool stick diameter and the turntable diameter are constant, as the tool stick number increases, the total electrical discharge time per unit time increases, and the mechanical grinding function is enhanced; therefore, the MRR increases, and the SR decreases.

The effect of tool stick number on TWR is shown in Figure 15(b); the TWR decreases with increasing tool stick number. This phenomenon can be explained as follows. The total electrical discharge time per unit time increases with increasing of tool stick number, and the discharge energy

delivered to the machining gap increases. This means that the dielectric and workpiece are heated for more time, and since the carbon released by decomposition from the hydrocarbon in the emulsion is easily attached to the copper electrode surface, the deposition effect is enhanced; moreover, the thickness of the modified surface layer formed by electrical discharge milling increases with increasing tool stick number, hence the grinding force decreases, and the abrasive stick wear is low; therefore the TWR decreases.

3.11   Microstructures of SiC ceramic surfaces machined by end ED milling and mechanical grinding

The scanning electron microscope (SEM) images of SiC ceramic surfaces machined by the compound process using different machining conditions are given in Figure 16. Figure 16(a) shows that the surface after rough machining is covered with craters, globules of debris, micropores and microcracks. A possible mechanism for the formation of the craters on the machined surface is that sparks are formed on the SiC ceramic during the electrical discharge milling. The discharged energy produces very high temperatures at the point of the spark, causing a minute part of the workpiece to melt and vaporize. Some of the molten material cools rapidly under the effects of the dielectric fluid, forming globules of debris on the surface. The formation of micropores is ascribed to the ejection of gases that escape from the solidified material. The microcracks are formed as a result of the exceedingly high thermal stresses prevailing at the machined surface as the latter is cooled at a fast rate after the discharge. The microcracks on the surface may be responsible for the
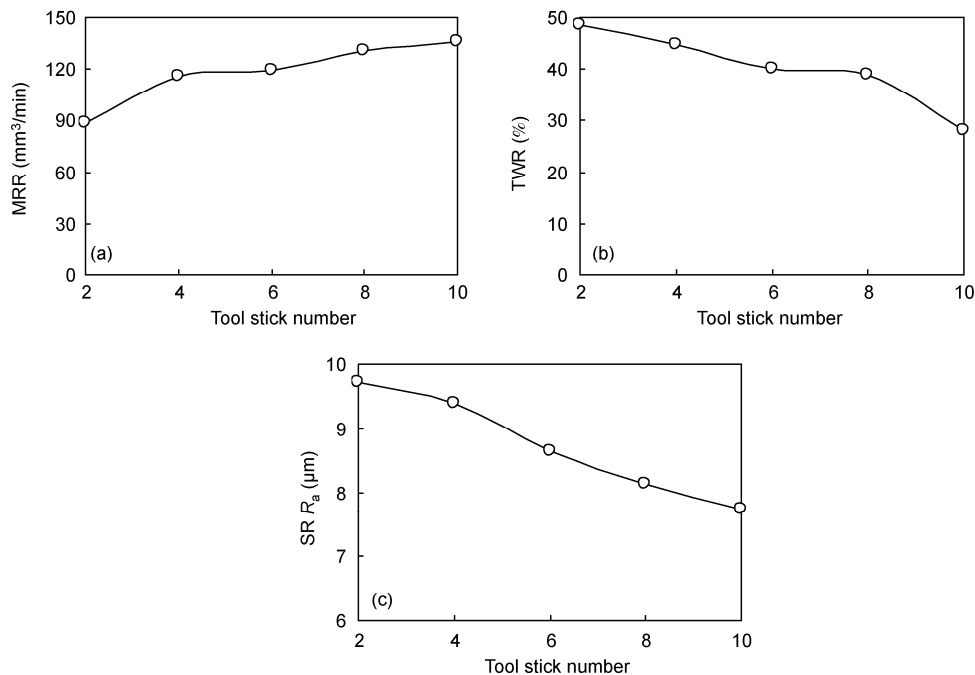
Figure 15 Effect of tool stick number on the process performance. (a) Effect of tool stick number on MRR; (b) effect of tool stick number on TWR; (c) effect of tool stick number on SR.
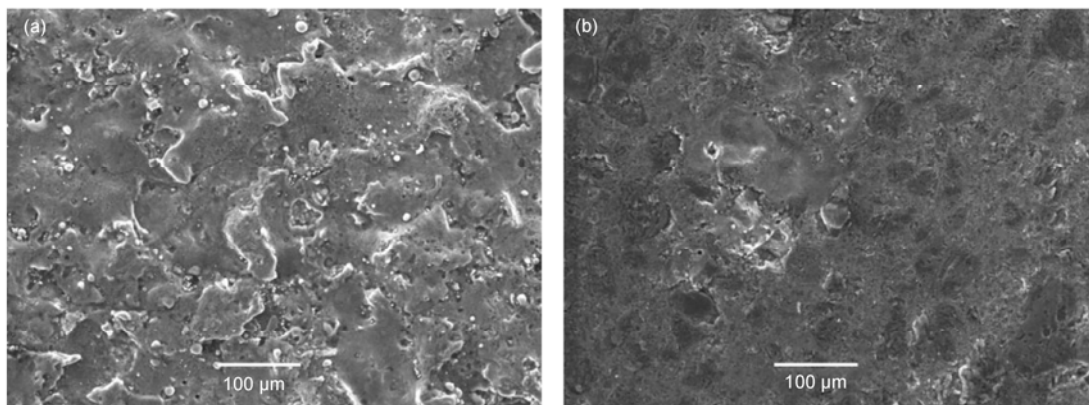

Figure 16 SEM micrographs of SiC ceramic surfaces machined by the compound process with different machining conditions: (a) pulse duration, 50 μs; pulse interval, 300 μs; open-circuit voltage, 150 V; discharge current, 75 A; tool(−)/workpiece(+); (b) pulse duration, 40 μs; pulse interval, 2500 μs; open-circuit voltage, 90 V; discharge current, 15 A; tool(−)/workpiece(+). (a) Rough machining; (b) finish machining.

separation of small volumes of material in the form of flake detachment from the base material. Therefore, the material removal mechanisms in the compound process during rough machining mode are that most material is removed by melting and evaporation, and a smaller amount of material is removed by thermal spalling.

Figure 16(b) shows that the machined surface is smooth after finish machining, with fewer, smaller, craters and pockmarks. Some grinding traces are seen on the machined surface, showing the important role of mechanical grinding. It can be concluded from Figure 16 that the SiC ceramic material is mainly removed by end ED milling during rough machining and by mechanical grinding during finish machining.

During electric discharge machining, the material can be transferred between the electrode and workpiece in the solid, molten or gaseous states simultaneously [24,25]. Figures 17–19 represent the EDS spectral analyses of the unprocessed surface and the machined surface at different machining conditions. Cu and Fe are found on the machined surface, regardless of the machining condition, whereas they are not detected on the unprocessed surface. This can be explained by the melting and resolidification of the copper electrodes and cast iron bonded abrasive sticks during the compound process. It implies that some tool material transfers to the workpiece surface during machining. Figures 18, 19 also show that the copper and iron content on the machined surface increases as the pulse duration, open-
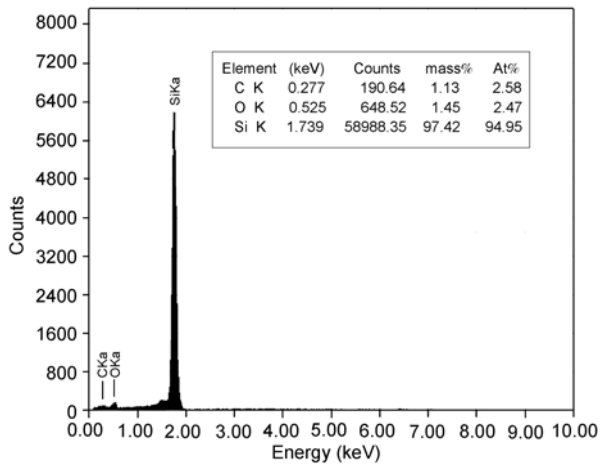
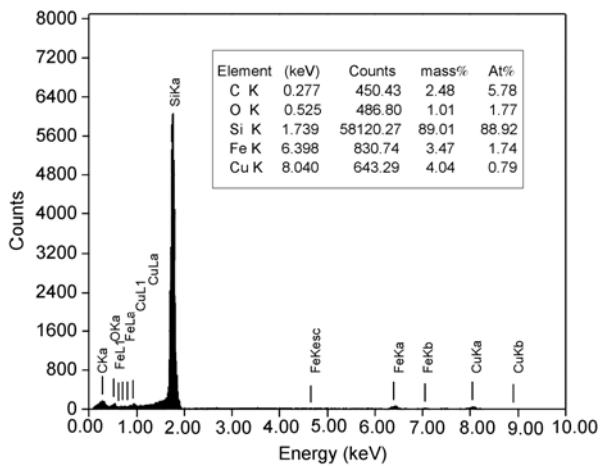**Figure 17**   EDS analysis of unprocessed SiC ceramic surface.

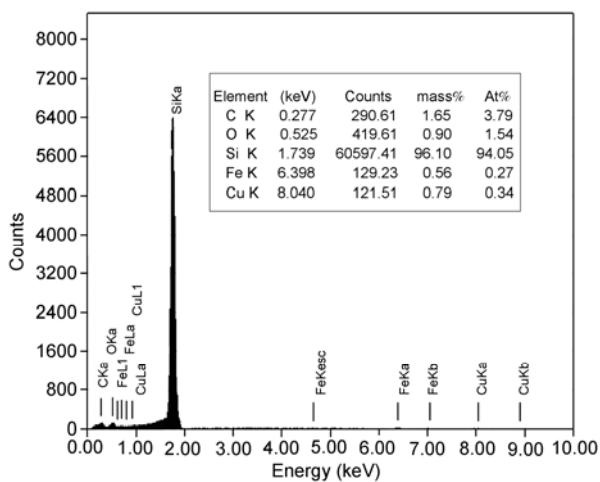**Figure 18**   EDS analysis of SiC ceramic surface after rough machining.

Figure 19   EDS analysis of SiC ceramic surface after machining in finish mode.

circuit voltage, and discharge current increase. This is because during the compound process, the single pulse energy, thermal energy density and discharge explosive force also

increase with increasing pulse duration, open-circuit voltage, and discharge current; the tool material removal is enhanced, and more tool material can transfer to the workpiece surface.

4   Conclusions

(a) End electrical discharge milling and mechanical grinding happen alternately and are mutually beneficial, so the compound process is able to effectively machine a large surface area of SiC ceramic with a good surface quality. The process also shows very good working environmental practice.

(b) Higher MRR, lower TWR, and higher SR can be obtained with negative tool polarity and long pulse duration; the MRR, TWR, and SR increase with increasing open-circuit voltage and discharge current; the MRR, TWR, and SR decrease with increasing diamond grit size; and the MRR and TWR increase, but the SR decreases with increasing emulsion flux. Overall, the pulse interval of 300 μs, emulsion concentration of 12 mass%, milling depth of 0.1 mm, and 10 tool sticks were suitable for the compound machining of SiC ceramic.

(c) In the process developed, the SiC ceramic material is mainly removed by end ED milling during rough machining mode, and by mechanical grinding during finish machining mode. In addition, the tool material can transfer to the workpiece surface during machining.

This paper provides a new machining method for difficult-to-machine materials. The research findings will provide effective guidelines for selecting parameter settings to achieve the desired MRR, TWR and SR during the compound machining of SiC ceramic.

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