Sustainable and Efficient Processing of Gh4169 Superalloy With Rotating Short Arc Milling Method

Jin Zhang
Tsinghua University
Fuzhu Han (hanfuzhu@mail.tsinghua.edu.cn)
Tsinghua University

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Sustainable and efficient processing of GH4169 superalloy with rotating short arc milling method

Jin Zhang[a,b], Fuzhu Han[a,b,*]
[a]Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China
[b]Beijing Key Lab of Precision/Ultra-precision Manufacturing Equipments and Control, Beijing 100084, China
[*]Corresponding author at: Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China.
E-mail address: hanfuzhu@mail.tsinghua.edu.cn.

Abstract

High processing efficiency and low environmental pollution have been recognized as important goals of sustainable electrical discharge machining (EDM). This paper proposed a sustainable and efficient EDM method called rotating short arc milling. In order to improve the processing efficiency and reduce pollutant emissions, the principles of this method to achieve high material removal rate (MRR), low tool electrode wear rate (TEWR) and environmentally friendly dielectric are described separately. The rotating short arcs generated by the compound field can improve the machining efficiency. The action of the magnetic field and the internal high-pressure dielectric can quickly remove the debris avoiding irregular discharge, thereby improving the machining quality. Due to the attraction effect of the magnetic field on the debris, several debris adhere to the processing end of the tool electrode to form a protective layer and participates in the processing as a part of the tool electrode, which can reduce the tool electrode wear. Tap water is used as the working fluid to reduce pollutants generated during processing. Then, a series of experiments are conducted to study the influence of process parameters on the processing of GH4169 superalloy. The results show that the machining voltage, machining depth and magnetic field strength are the three most important factors that affect the efficiency and sustainability of rotating short arc milling. Furthermore, the optimal process parameters are obtained by using gray relational analysis method to optimize the machining process in terms of high efficiency and environmental protection.

Keywords: Rotating short arcs; EDM milling; Composite field; Dielectric.

1. Introduction.

Titanium alloys and superalloys have been widely used in medical, marine, aerospace, automobile sectors and chemical processing recent years due to their excellent properties. However, since titanium alloys and superalloys are typical difficult-to-cut materials, there are many difficulties in machining using traditional processing method. This is manifested in higher tool wear, longer processing time and the inability to obtain certain complex/complex shapes through traditional processing methods.

Electrical discharge machining (EDM) relies on the thermal effect between the tool electrode and the workpiece to remove material. The process of EDM is to convert electrical energy into heat and transfer it to the surface of the workpiece by discharging between the tool electrode and the workpiece. Then, the surface of the workpiece gradually melts and vaporizes, corroding the workpiece in this process, so as to achieve the processing. EDM can process various materials irrespective of its hardness and toughness, as long as the material is conductive, especially suitable for processing difficult-to-cut materials. However, compared with traditional processing method, EDM has lower processing efficiency and higher energy consumption. In addition, EDM uses kerosene as dielectric, which not only poses fire hazards, but also releases a variety of toxic substances during the processing, polluting the environment and endangering the health of the operators. Therefore, traditional EDM does not meet the concept of sustainable manufacturing practices. It is essential to use sustainability standards to reform/innovate traditional EDM to improve processing efficiency and reduce environmental pollution.

As mentioned before, traditional EDM uses oil-based dielectric which pollutes the environment, and is harmful to the health of operators. The type of dielectric, composition and viscosity will affect the fumes and gases produced during EDM processing. Researchers have conducted a lot of researches on using gas, vegetable oil or water-based working fluid as EDM dielectric. They hoped to achieve the goal of environmental protection and sustainable processing by using environmentally friendly dielectric instead of oil-based dielectric. Kunleda et al. (2003) tried to use the water and oxygen gas mixture as dielectric in EDM. It was found that the discharged craters were enlarged and the discharge occurred more frequently, so the MRR was increased. A lot of research has also been done on using water-based working fluid as EDM dielectric. Zhang et al. (2011) had found that the amount of retained austenite phase and the strength of microcracks within the white layer were greatly reduced when using deionized water as dielectric. Besides, the surface processed in deionized water oxidized after heat treatment and no crack propagation occurred which was quite different from that processed in kerosene. Valaki et al. (2016) had found that compared with processing in kerosene or deionized water, water-in-oil emulsion as a dielectric can form a recast layer with higher hardness. Researches on the use of vegetable oil as EDM dielectric have found that the use of vegetable oil-based fluids for industrial applications has a higher sustainability index than hydrocarbon-based and synthetic-based fluids. Valaki et al. (2016) had evaluated the operational feasibility of Jatropha curcas oil-based bio dielectric (Jatropha BD) fluid as EDM dielectric. The results obtained indicate that vegetable oil-based fluids can lead to higher MRR, lower surface roughness (SR) and higher surface hardness (SH) than kerosene.

The low processing efficiency and high energy consumption limit the promotion and application of traditional EDM, and it not in line with the concept of sustainable development. It is generally believed that the following two reasons cause the low processing efficiency of traditional EDM. On the one hand, in order to avoid arc discharge and workpiece damage caused by repeated discharge at the same place, there must be a deionization time to make the previous discharge position become electrically neutral, during which time no workpiece material is removed. On the other hand, because the tool electrode and workpiece are immersed in oil-based dielectric in traditional EDM, debris removal mainly depends on the jump operation (up and down electrode movement during the EDM process to increase and decrease the discharge gap) of tool electrode. Jump operation of tool electrode can enhance machining gap flushing which is beneficial to promote debris removal. However, the jump operation of the tool electrode wastes energy and makes the EDM process discontinuous. In order to improve the EDM processing efficiency and energy consumption, researchers have conducted research on the development of new power sources and new processing methods. Wu et al. (2020) has developed a new type of power supply that combines a pulse generator and a DC power source which are isolated from each other. When EDM uses this power supply to process titanium alloys, the MRR was as high as 21494mm^3/min, while the relative tool electrode wear rate (R-TEWR) was only 1.7%, and the energy utilization rate of the new pulse power supply was increased to 200%. Zhao et al. (2013) proposed a novel processing method namely the Blasting Erosion Arc Machining (BEAM), which can achieve the MRR of Inconel 718 as high as 11300 mm^3/min, while the R-TEWR is only 1%. Kou et al. (2019) developed a novel machining method of high-speed EDM milling with moving electric arcs. He used a DC power supply instead of a pulse power supply to achieve continuous output of energy during the machining process. This new method increased the MRR of titanium alloy to five times that of traditional EDM and reduced the TEWR because a protective layer of titanium alloy is formed on the bottom of the tool electrode during processing.

In addition to studying dielectrics, developing new power sources and new machining methods, some scholars have also combined EDM with ultrasonic, magnetic fields, etc., to make up for the shortcomings of EDM by introducing other processing methods. Among them, magnetic field-assisted EDM (MF-EDM) has been proved to greatly improve the processing performance of EDM. MF-EDM can accentuate and focus the plasma chromatography column, which can obtain deeper and more precise sparks. Besides, Ming et al. (2019) had found that MF-EDM can optimize the debris removal to prevent deposition near the processing surface, and quickly restore the dielectric to achieve the optimal discharge state. Previous researches have proved that the discharge channel of MF-EDM becomes more dispersive, uniform and stable than that of traditional EDM and the MRR of MF-EDM is increased. Chen et al. (2017) explained that this is due to the condensing effect of the magnetic field on the arc, which attributes to concentrate the energy of the arc, so that more energy is transferred to the workpiece and the energy loss caused by the energy transfer to the environment is reduced. In addition, Beravala et al. (2018) had found that MF-EDM can promote debris removal and avoid the accumulation of debris in the processing area, thereby improving the quality of the processed surface, reducing the frequent discharge rate caused by the accumulation of debris, and indirectly reducing TEWR. The influence of MF-EDM on magnetic and non-magnetic materials has also been studied. Ming et al. (2020) conducted a comparative study to process magnetic and non-magnetic materials. It can be found that under similar surface roughness, the influences of the magnetic field on the two different materials contribute to improve the energy efficiency and the MRR.

However, because the Lorentz force promotes the debris removal of magnetic materials, the MRR of magnetic materials (SKD11) is increased more significantly than that of non-magnetic materials (Ti6Al4V). In addition to the above researches, process parameters optimization and energy consumption analysis have also been carried out. Reddy et al. (2018) had employed the Taguchi method and gray relational analysis along with other mathematical models to achieve optimization of the various machining parameters of the EDM process. Ming et al. (2019)established a model to prove that the effect of magnetic field contributes to increasing energy utilization efficiency by 15.2%, material erosion efficiency by 22.6%, and MRR by 21.9%. These above researches show that the development of MF-EDM has enabled EDM to move towards sustainable development.

Based on the above literature research, it is essential to propose a sustainable and high-speed EDM milling method using rotating short arcs. Due to the use of recyclable water as the dielectric, the proposed method can not only increase the processing efficiency by improving the debris removal, but also contribute to establish a clean and environmentally friendly working environment. At the same time, by forming a composite energy field of magnetic field, electric field and flow field, rotating short arcs are generated in the machining gap, which helps to increase MRR and reduce TWER and SR.

2.Principles

2.1. The high material removal rate.

In this research, the magnetic field is evenly distributed along the circumference of the tool electrode machining end, as shown in Fig.1. By the Lorentz force, the electrical force and the high-speed rotation of the tool electrode, rotating short arcs are generated within the discharge channel. This new method changed the machining process from single-point discharge to continuous arcs milling, as shown in Fig.2. It can be seen that the rotating short arcs are moving all the time instead of discharge at a certain point on the workpiece.

The result proves that the materials can be eroded continuously without intervals in the rotating short arc milling process. In this experiment, the magnetic field can constrain the movement of the charged particles to make the charged particles change from linear motion to rotating motion and shorten the mean free path (λ). Keidar et al. (2018) provided that λ can be expressed as:

$$\lambda = \frac{RT}{2^{0.5}\pi d^2 P N_A} \tag{1}$$

where R is the universal gas constant, T is the temperature of the gas, d is the diameter of a molecule, P is the plasma pressure and N_A is the Avogadro's number.

From Eq.1, the plasma pressure which indicates the probability of collisions between particles increases as the mean free path. It will in turn leads to increased particle ionization and conducive to rapid dielectric breakdown given by Eq.3:

$$\gamma = \frac{1}{\exp(\frac{\alpha \cdot V_B}{E}) - 1} \tag{2}$$

where γ is number of electrons emitted from cathode due to initial ionization and V_B

is the breakdown voltage. The coefficient α depends on the plasma pressure and the electric field, as given by Eq.3:

$$\alpha = P \cdot \mathrm{A} \cdot \exp\left(\frac{-\mathrm{B} \cdot P}{E}\right) \tag{3}$$

where A and B are constants, E is the electric field strength in the inter-electrode gap.

As a consequent of the above, the current density J of the discharge gap and the energy of the plasma increase, as given by Eq.4:

$$J = \pi r_c^2 j_e V_B \tag{4}$$

Where r_c is the radius of a micro-peak on cathode emitting electron.

Therefore, the application of the magnetic field limits the expansion of the plasma and increases the energy transferred to the workpiece, thereby improving the MRR in rotating short arc milling. That is, compared with traditional EDM, rotating short arc EDM milling can greatly improve the processing efficiency.

2.2. The low tool electrode wear rate.

This is mainly due to the influence of the magnetic field and the rotating tool electrode. In EDM discharge channel, the energy distributing between anode and cathode can be shown as Fig.3 and can be expressed as:

$$W_T = \int_0^{T_{on}} U(t)I(t)dt = W_A + W_C + W_D \tag{5}$$

where, W_T is the total energy, W_A is energy obtained by anode, W_C is energy obtained by cathode, W_D is energy obtained by dielectric fluid, debris and so on. In this research, the tool electrode is anode and the workpiece is cathode. $U(t)$ is voltage drop in discharge channel, $I(t)$ is current, T_{on} is the discharge time. During EDM pulse discharge process, Singh and Ghosh (1999) found that most of the energy distributed on cathode and anode, and the energy dissipating in the surrounding medium only accounted for 15% to 40% of the total energy. Zhang et al. (2017) found that no matter how the pulse width changes, the energy obtained by the tool electrode (anode) was always much larger than the workpiece (cathode), and the ratio was about 40% and 25%, respectively, which caused high tool electrode wear rate in traditional EDM. However, during rotating short arc milling, the rotation speed of tool electrode is faster than that of rotating short arcs, so that the average energy per unit length obtained by workpiece is larger than that obtained by tool electrode. This indicates that the tool electrode wear rate is much lower than the material removal rate.

Due to the existence of the deionization process, the traditional EDM is a discontinuous single point discharge, which causes pits on the tool electrode， as shown in Fig.4(b). The pit will become larger and deeper with the increase of pulse discharge current and discharge duration time, resulting in defects and unevenness on the tool electrode machining surface. This in turn aggravates the unevenness of the surface discharge of the tool electrode, accelerates the wear of the tool electrode, and even burns the workpiece due to repeated discharge at a specific point. However, in rotating short arc milling process, the machining process is similar to milling, so the tool electrode machining surface is flatter than that of traditional EDM, as shown in Fig.4(c). Therefore, the uneven discharge and burns of the tool electrode can be effectively alleviated during rotating short arc milling process, thereby avoiding the change of the tool electrode shape. In addition, the rotating short arc moves quickly in the machining gap, so the plasma heat source is dispersed from one point to the entire processing area, avoiding concentrated heat release at a certain point, which also reduces the wear of the tool electrode. As a result, the tool electrode wear can be effectively decreased and controlled during the rotating short arc milling process.

2.3. The environmentally friendly dielectric.

In traditional EDM, kerosene is usually used as working dielectric, and many harmful substances are generated during machining process, include smoke, aerosols, decomposed products of eroded metals, electromagnetic radiations, debris, as shown in Fig.5. In addition, kerosene is easily ignited and may cause fire or even explosion. Due to fire hazards, electromagnetic radiation and the emission of harmful substances during processing, traditional EDM has poor operational safety and endangers the health of operators. These problems are still common in the traditional EDM process and cannot meet the requirements of sustainable processing.

In rotating short arc milling, the dielectric fluid is tap water instead of kerosene. On the one hand, tap water has the advantage of being low in cost and easy to obtain, and can be recycled after being filtered. On the other hand, Koyano et al. (2010) had found that high MRR can be achieved by using water-based dielectric. During discharge process, the hydrogen gas and the oxygen gas are produced by the dissociation of water while the gases produced by the dissociation of oil without the oxygen gas. The workpiece can be burned easily with the oxygen gas, which improves the material removal rate. Compared with kerosene, tap water does not produce toxic substances that endanger the health of workers and pollute the environment during processing. And there are no potential safety hazards such as fire and explosion, so it is more environmentally friendly to use tap water as a dielectric. Fig.6 shows the schematic of the self-devised flushing system used in rotating short arc milling process. After tap water is pressurized by a pressure pump, it enters the discharge channel as a high-pressure liquid, which can quickly cool the workpiece and tool electrode, flush away the debris. Then it is reused again after being filtered. Taking into account the increasingly serious energy and environmental issues, using tap water as a dielectric can reduce energy consumption and pollutant emissions. As a conclusion, the rotating short arc milling is economical, safe and environmentally friendly.

3.Experimental methods.

3.1. Equipment and materials.

The experiments are conducted on a three-axis machining center which was equipped with self-devised rotating short arc EDM system. The equipment is consisted of the rotating short arc EDM system, flushing system, CNC system and two kinds of different DC power supplies for machining and excitation device, respectively, as shown in Fig.7(a). The photograph of self-devised rotating short arcs EDM system is shown in Fig.7)b(. The flushing system is used to provide high-pressure dielectric during machining process, which take away both discharge debris and heat on the tool electrode and workpiece. The entire tool electrode is hollow, so the dielectric can be spray out of it. The tool electrode used in this research is graphite and the workpiece is

GH169 superalloy. **Table 1** shows chemical compositions of workpiece (GH4169 superalloy).

3.2. Experimental design.

Single-factor experiment design--During rotating short arc milling process, machining voltage, flushing pressure, tool electrode rotation speed, machining depth, and magnetic field strength all impact on machining performance. In order to study the influence of various parameters on the MRR, relative tool electrode wear rate(R-TEWR) and surface roughness (SR), a single-factor experiment was carried out in this study, and the experiment was repeated three times for each parameter to ensure the accuracy of the results in the experiment. Table 2 presents the settings of machining parameters.

Experimental design based on Taguchi method--In accordance with our previous studies, four machining parameters, each with four levels, are select to design the experiment based on the Taguchi method. The machining characteristics such as MRR (mm^3/min), R-TEWR (%) and SR (μm) are adopted to assess the effects of machining parameters. Table 3 gives the experimentally machining parameters levels and observed values.

3.3. Experimental measurement.

In this study, the MRR, R-TEWR, SR and surface roughness are investigated, respectively. The workpieces and tool electrodes are weighed before and after each experiment using a digital electronic precision balance with an accuracy of 0.1 mg. The MRR and R-TEWR are obtained by the following equations:

$$MRR = (m_1 - m_2) \times 10^3 / (\rho_{st} \bullet t) \tag{6}$$

$$R - TEWR = TEWR/MRR \tag{7}$$

$$TEWR = (M_1 - M_2) \times 10^3 / (\rho_{cu} \bullet t) \tag{8}$$

where m_1 is the weight of workpiece before experiment and m_2 is the weight of workpiece after experiment. M_1 is the weight of tool electrode before experiment and M_2 is the weight of tool electrode after experiment. Each data is measured for three times and take their average. ρ_{st} and ρ_{cu} indicate the density of workpiece and tool electrode, respectively.

The surface roughness was measured by OLYMPUS optical microscope. Three areas are selected on the machining surface for roughness measurement, as shown in Fig.8. The roughness of three areas was measured three times for each area and taking the average of the three times as the SR value of each area. Finally, calculating the average value of the three areas as the final SR value of the machined surface.

Metallographic specimens of lateral sections are obtained using a wire-cutting machine and etched by reagent to observe the recast layer level. The chemical composition of reagent was 2.5g ferric chloride, 10ml hydrochloric acid, and 50ml anhydrous ethanol. The specimen was suspended in the reagent for 1.5min to 2min and then rinsed with deionized water.

4.Results of performance experiments.

Referring to traditional EDM, MRR, R-TEWR, and SR are important indicators to evaluate machining performance during machining GH4169 through rotating short arc milling method. In order to achieve the better processing performance, the relevant influencing factors are analyzed below.

4.1. Analysis of machining voltage effect on MRR, R-TEWR and SR.

The value of the machining voltage determines the current value in the circuit during processing, thereby determining the energy transmitted to the workpiece by the rotating short arc per unit time. When investigating the influence of machining voltage on rotating short arc milling, the machining voltages are set as 85V, 105V, 125V and 145V, and other machining parameters are set as flushing pressure of 0.5MPa, machining depth of 2.5mm, rotation speed of 500rpm and magnetic field strength of 0.15T.

Fig.9 shows the influence of machining voltage on MRR, R-TEWR and SR. It can be found that as the machining voltage increases, the MRR is greatly improved, the R-TEWR gradually decreases, and the surface roughness gradually increases. As the machining voltage increases, the current increases accordingly, the energy received by the workpiece per unit time increases, and the volume of molten metal increases. In addition, the increase of machining voltage makes the dielectric breakdown easier. The greater the machining voltage, the easier it is to achieve dielectric breakdown and arc generation within a relatively large distance between the tool electrode and the workpiece. The increase of the distance between the tool electrode and workpiece will also make it easier to evacuate the debris from the processing area, thereby effectively improving the material removal efficiency. Although the tool electrode wear increases with the increase of the machining voltage, it is obvious that the MRR increases to a larger degree. Thus, as the machining voltage increases, the R-TEWR gradually decrease in the rotating short arc milling process.

Compared Fig.9 (a) and Fig.9 (c), it can be found that with the increase of the machining voltage, the depth and volume of the micro-pits and micro-grooves increase, the undulations of the processed surface also increase, and the overall quality of the processed surface decreases. With the increase of the machining voltage, the workpiece receives more energy per unit time, the volume of the molten metal also increases, and the size of the micro pits and micro grooves becomes larger. In addition, with the increase of the processing voltage, the explosive force and shock wave generated by the arc discharge become larger, pushing the molten metal to form deeper pits and grooves. The thickness of the recast layer also increases with the increasing of the machining voltage, as shown in Fig.9 (b) and (d). This is mainly because the machining voltage increases and the arc energy increases accordingly. The heat generated by arc discharge not only melts the metal material, but also penetrates deeper into the workpiece matrix, which leads to significant changes in the microstructure of the processed surface and increases the thickness of the recast layer.

4.2. Analysis of rotation speed effect on MRR, R-TEWR and SR.

The rotation speed of the tool electrode affects the generation and fracture of the arc, and also affects the rotation speed of the arc. The higher rotation speed of the tool electrode, the more difficult the dielectric breakdown, which will reduce the continuity of arc discharge to a certain extent. When investigating the influence of rotation speed on rotating short arc milling, the rotation speeds are set as 300rpm, 400rpm, 500rpm and 600rpm, and other machining parameters are set as machining voltage of 145V, flushing pressure of 0.5MPa, machining depth of 2.5mm and magnetic field strength of 0.15T.

Fig.10 shows the influence of rotation speed on the MRR, R-TEWR and SR. It can be found that as the rotation speed of the tool electrode increases, the MRR and R-TEWR increase, while the SR decreases significantly. The main reason is that the increase of the rotation speed increases the difficulty of dielectric breakdown. The higher the rotation speed, the more turbulent of the dielectric between the tool electrode and the workpiece, the more difficult it is for dielectric to be breakdown by discharge and arc formation. Therefore, the effective discharges per unit time decrease, the energy received by workpiece is reduced, so the volume of the melted material is reduced. Thus, the removal efficiency of the workpiece material decreases. However, the high-speed rotation of the tool electrode will increase the speed of the dielectric which helps to remove the molten metal from the discharge gap, thereby reducing the molten metal on the machined surface. This can be verified by comparing Fig.10 (a) and (c). As the rotation speed increases, the fluctuation of the processed surface decreases, and the quality of the processed surface becomes better. Therefore, the quality of machined surface become better with the increase of rotation speed. Another aspect of the increase of rotation speed decreases the recast layer, as shown in Fig.10 (b) and (d). This is mainly because the higher the rotation speed, the greater speed of the rotating arc relative to the surface of the workpiece, and the longer journey of the arc passes in a unit time, which reduces the energy obtained per unit area of the workpiece. This greatly reduces the penetration depth of heat generated by arc discharge into the workpiece matrix per unit time, so that the volume of fully melted and partially melted metal is reduced, and the thickness of the recast layer is reduced.

4.3. Analysis of machining depth effect on MRR, R-TEWR and SR.

The machining depth is an important processing parameter in rotating short arc milling. During rotating short arc milling process, the greater the machining depth, the larger contact area between the tool electrode and the workpiece, and the wider electrical discharge machining area, thus the greater impact on MRR, R-TEWR and SR. When investigating the influence of machining depth on rotating short arc milling, the machining depths are set as 2.0mm, 2.5mm, 3.0mm and 3.5mm, and other machining parameters are set as machining voltage of 145V, flushing pressure of 0.5MPa, tool electrode rotation speed of 500rpm and magnetic field strength of 0.15T.

Fig.11 shows the influence of machining depth on MRR, R-TEWR and SR. It can be found that as the machining depth increases, the MRR, R-TEWR and SR increase accordingly. As the machining depth increases, the area involved in electrical discharge machining per unit time increases, and the workpiece material removed increases. However, as the machining depth increases, the flushing environment in the discharge gap gets worse, resulting in higher pressure and lower flow of the dielectric. A large amount of molten metal cannot be removed in time, so it accumulates and recasts in the processing area. This residual molten metal is agitated by the high-speed rotating tool electrode, which increases the R-TEWR and deteriorates the quality of machined surface. By measuring the thickness of the recast layer, it can be found that as the machining depth increases, the thickness of the recast layer gradually increases, as shown in Fig.11 (b) and (d). This is mainly because increasing the machining depth requires reducing the feed speed of the tool electrode to increase the residence time of the arc at the same position, which leads to repeated discharge and heating at the same position. The heat generated by the arc discharge penetrates into the workpiece matrix, melting the matrix material at high temperatures, and ultimately increase the thickness of the recast layer on the processed surface.

4.4. Analysis of flushing pressure effect on MRR, R-TEWR and SR.

The flushing pressure affects the removal of molten metal in the processing gap and the difficulty of the dielectric breakdown. When investigating the influence of flushing pressure on rotating short arc milling, the flushing pressures are set as 0.3MPa, 0.4MPa, 0.5MPa and 0.6MP, and other machining parameters are set as machining voltage of 145V, machining depth of 2.5mm, tool electrode rotation speed of 500rpm and magnetic field strength of 0.15T.

Fig.12 shows the influence of flushing pressure on MRR, R-TEWR and SR. It can be found that as the flushing pressure increases, MRR gradually increases, R-TEWR and SR gradually decrease. During rotating short arc milling process, a large amount of workpiece material is melted in a short time. Relying on the scouring effect of the high-pressure dielectric, the molten metal materials can be quickly removed from the discharge gap to a certain extent. Therefore, the higher the flushing pressure, the better the debris removal effect, and accordingly, the breakdown of the dielectric becomes more difficult, resulting in a decrease in the number of effective discharges per unit time. Therefore, according to the change of the trend line, it can be found that the increasing trend of MRR is very gentle during the increase of flushing pressure. The analysis of the above results proves that the flushing pressure can effectively improve the MRR within a certain range, but it cannot be increased indefinitely. In addition, as the flushing pressure increases, the debris is easily removed from the discharge gap in time, which reduces the accumulation and re-solidification of molten metal on the machined surface. This helps to decrease the undulation of the machined surface, as shown in Fig. 12 (a) and (c), proving the roughness decreases as the flushing pressure increases.

By observing the thickness of the recast layer, it can be found that as the flushing pressure increases, the thickness of the recast layer gradually decreases, as shown in Fig. 12 (b) and (d). The increase of the flushing pressure can not only prevent the accumulation and recasting of the molten metal in the processing area effectively, but also avoid the heat generated by the discharge transfers into the metal substrate. In addition, the water-based dielectric used in this research has a large specific heat capacity and a strong cooling capacity. The increase of the flushing pressure increases the dielectric flowing through the processing surface per unit time, which effectively improves the cooling capacity of the processing area, and to a certain extent prevents the penetration of heat into the workpiece. Therefore, as the flushing pressure increases, the thickness of the recast layer of the workpiece decreases rapidly.

4.5. Analysis of magnetic field strength effect on MRR, R-TEWR and SR.

In the process of rotating short arc milling, the magnetic field strength has a great influence on the machining performance. When investigating the influence of magnetic field strength on rotating short arc milling, the magnetic field strengths are set as 0, 0.05T, 0.1T and 0.15T, and other machining parameters are set as machining voltage of 145V, machining depth of 2.5mm, tool electrode rotation speed of 500rpm and flushing pressure of 0.5MPa.

Fig.13 shows the influence of magnetic field strength on MRR, R-TEWR and SR. It can be found that as the magnetic field strength increases, MRR increases significantly, R-TEWR and SR gradually decrease. As mentioned earlier, the magnetic field has the effect of converging the arc, so the energy obtained in the unit area of the workpiece increases with the increase of the magnetic field strength, thereby increasing the MRR. In addition, the magnetic field strength can attract the debris and make it easier to be removed from the machining gap, avoiding the accumulation of debris in the processing area. Besides, a part of the debris adheres to the machining end of the tool electrode due to being attracted by the magnetic field. As part of the tool electrode, it participates in the subsequent electrical discharge machining and plays a role in protecting the tool electrode. Compared Fig.13 (a) and (c), as the intensity of the magnetic field increases, the size of the micro craters generated by the arc discharge becomes more and more uniform. The homogenizing effect of the magnetic field strength on the arc makes the arc energy generated by each discharge uniform, so the size of the micro craters becomes uniform. Therefore, as the magnetic field strength increases, the R-TEWR and SR gradually decrease. By observing the thickness of the recast layer, it can be seen that with the increase of the magnetic field strength, the thickness of the recast layer gradually increases, but not large, as shown in Fig.13 (b) and (d). This is because the magnetic field can converge the arc to enhance the discharge energy per unit area, which changes the substrate structure of the workpiece and increases the thickness of the recast layer.

5. Optimization of processing parameters by Grey correlation analysis.

Through the research of the above sections, it can be known that different processing parameters have different effects on rotating short arc milling performance. In the process of rotating short arc milling processing superalloys, it is hoped to achieve lower TEWR and better surface quality under the premise of ensuring machining efficiency. For this reason, it is necessary to determine the optimal machining parameters combination. In order to obtain the optimal combination of processing parameters, the gray correlation method is used to analyze the experimental data obtained by Taguchi method. According to grey correlation analysis method, the gray correlation degree (r) between machining voltage (U), rotation speed (S), flushing pressure (P), machining depth (D) and MRR, R-TEWR, SR is calculated, as shown in the Table 4.

According to the theory of the gray correlation analysis method, the larger the calculated value of the correlation degree, the greater the influence of the corresponding factor on the index. Therefore, by sorting the relevance data in Table 4, it can be seen that the influence of the four factors on MRR is ranked as follows:

$$r_U > r_D > r_P > r_S$$

the influence of the four factors on R-TEWR is ranked as follows:

$$r_P > r_D > r_S > r_U$$

the influence of the four factors on SR is ranked as follows:

$$r_D > r_U > r_S > r_P$$

From the calculated data, it can be known that the machining voltage has the greatest influence on MRR, followed by machining depth, flushing pressure and rotation speed. The flushing pressure has the greatest impact on R-TEWR, followed by machining depth, rotation speed and machining voltage. The machining depth has the greatest impact on SR, followed by machining voltage, rotation speed and flushing pressure.

The processing parameter optimization in the rotating short arc milling GH4169 process is a multi-objective decision-making problem. On this issue, several factors interact and influence each other. It is difficult to make systematic and scientific conclusions based on machining experience alone. Therefore, using multi-objective grey decision theory to conduct systematic and scientific analysis to obtain the optimal combination of processing parameters.

In this study, the processing parameter optimization based on the research of rotating short arc milling is defined as event a, 16 sets of test plans are countermeasure b, and the binary combination $s_j = (a, b_j)$ of event a and countermeasure b_j is called situation, it means using the jth countermeasure (b_j) to deal with the situation of event a. When evaluating the machining quality of rotating short arc milling, it is considered that the higher the MRR, the better the machining performance. Therefore, it is stipulated that the target MRR takes the maximum polarity. The smaller the R-TEWR and SR, the better the processing performance. Therefore, the target 2 and target 3 take the minimum polarity. According to the aforementioned target polarity and the final judgment result, the data is transformed into the effect measurement, and the result is shown in Table 5. Then calculate the unified measure of each situation according to the following equation, and the results are shown in Table 6.

$$r_{ij}^{(\Sigma)} = \frac{1}{l}\sum_{p=1}^{l} a_p r_{ij}^{(p)} \tag{9}$$

where, $a_p (p = 1,2,\ldots,l)$ is the weight value of the situation.

According to the unified measurement results Table 6 and the Eq.10:

$$r_j^{\Sigma *} = \max_j r_j^{\Sigma} = 0.76688 = r_{15}^{\Sigma *} \tag{10}$$

The largest unified measure $r_j^{\Sigma *}$ represents the satisfaction situation s_j^*, which shows that $j^* = 15$, that is:

$$s_j^* = s_{15} = (a, b_{15}) = (Parameter\ \ optimization, scheme\ \ 15) \tag{11}$$

Therefore, in the rotating short arc milling GH4169 process, it is determined that scheme 15 is the optimal scheme which is verified in Table 5. The optimized processing parameters are machining voltage of 140V, tool electrode rotation speed of 500r/min, flushing pressure of 0.4MPa, and machining depth of 2.5mm.

6.Conclusions.

This paper proposed a sustainable and high-efficiency EDM method using rotating short arcs, which has the superiority and potential for improving machining performance and machined surface quality. A series of experiments on GH4169 superalloy are carried out to investigate the machining characteristics of rotating short arcs and solve the low efficiency and environment pollution of conventional EDM. The main conclusions obtained from this paper are as following:

(1) The rotating short arc milling method can achieve high MRR, low R-TEWR and good surface quality. Besides, it uses tap water as dielectric which is environmentally friendly and low cost.

(2) As machining voltage and magnetic field strength increase, MRR greatly increases and R-TEWR decreases. With the increase of electrode rotation speed and flushing pressure, SR and recast layer decrease. When the machining voltage is 145V and the magnetic field strength is 0.15T, MRR is 16.56 g/min, Ra is 17.99μm, and R-TEWR is only 0.59%. Therefore, the rotating short arc milling method can improve the processing efficiency and protect the environment.

(3) To balance the MRR and surface roughness, the optimal process parameters for rotating short arc milling are obtained as follows: machining voltage of 140V, tool electrode rotation speed of 500r/min, flushing pressure of 0.4MPa, machining depth of 2.5mm, and magnetic field strength of 0.15T.

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Author contribution Idea and design of the study: Jin Zhang; Conducting of experiments: Jin Zhang; Analysis of data: Jin Zhang; Drafting the manuscript: Jin Zhang; Approval of the manuscript for publication: Jin Zhang, Fuzhu Han.

Data availability The authors confirm that the data supporting the findings of this study are available within the article.

Declarations

Ethics approval Not applicable.
Consent to participate All authors have willingly participated in this publication.
Consent to publish The authors revised the manuscript critically and provided consent to publish.
Conflict of interest The authors declare no competing interests.

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Figures

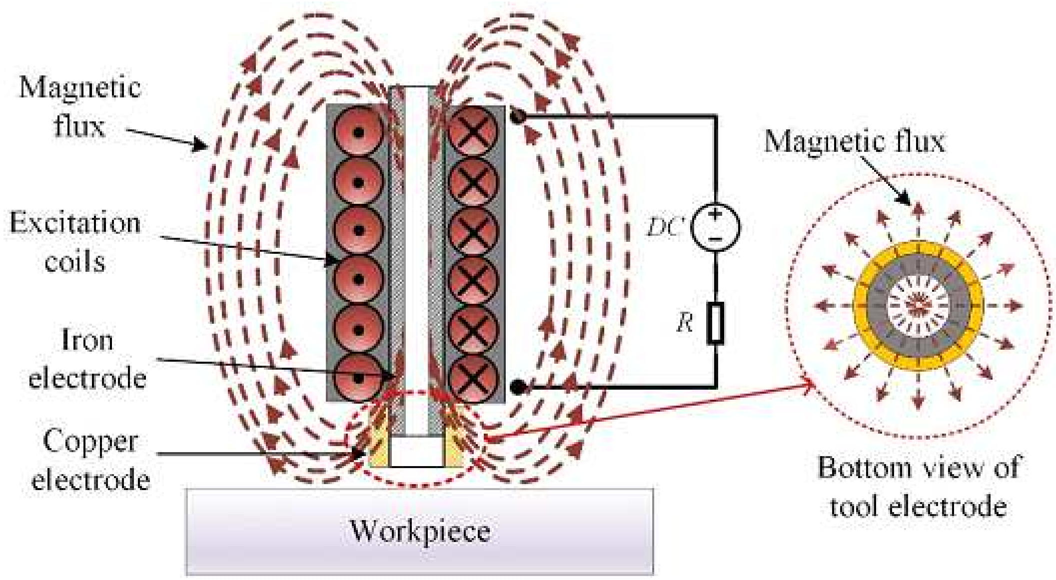

Figure 1

Schematic of the magnetic field generated by excitation device.

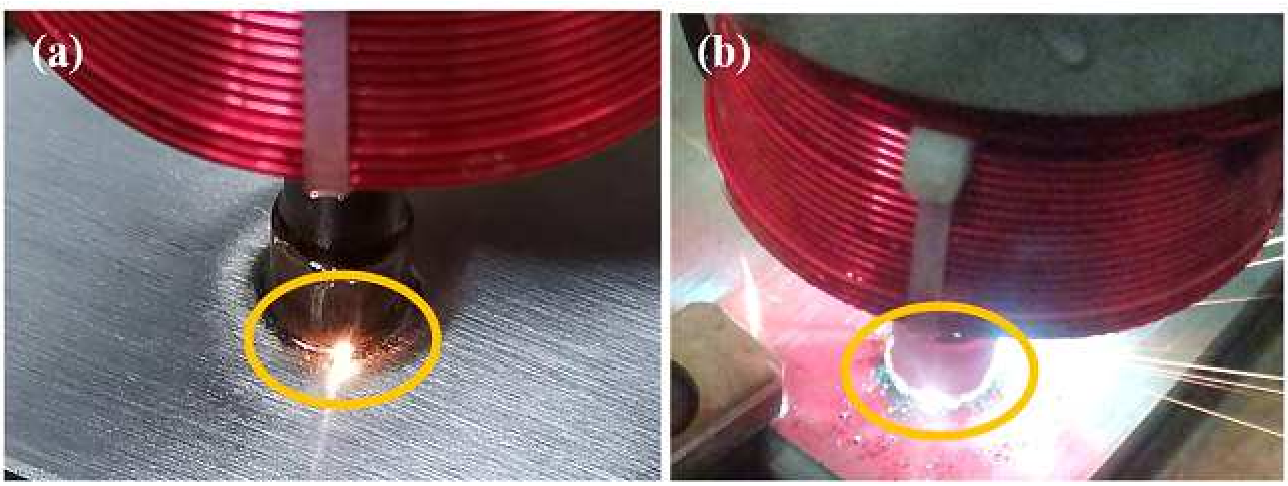

Figure 2

Comparison of stationary arc(a) and rotating short arc(b).

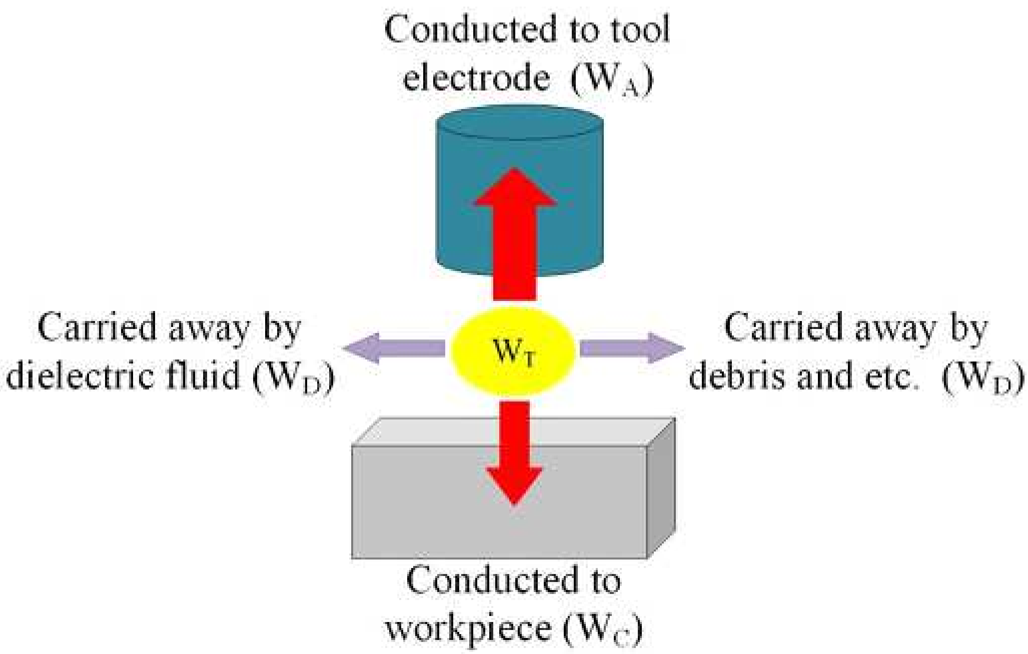

Figure 3

Energy distribution in EDM.

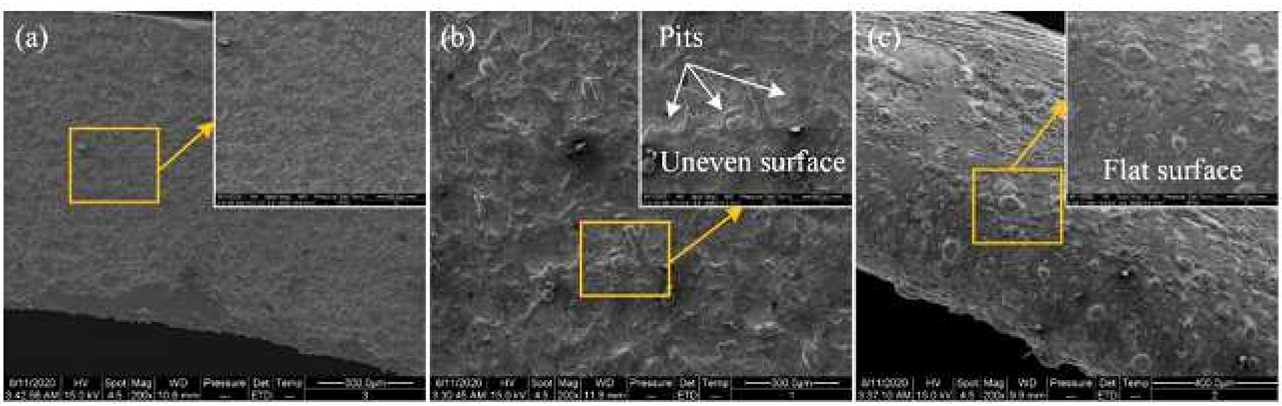

Figure 4

(a) Initial tool electrode, (b) tool electrode used in EDM and (c) tool electrode used in rotating short arc milling.

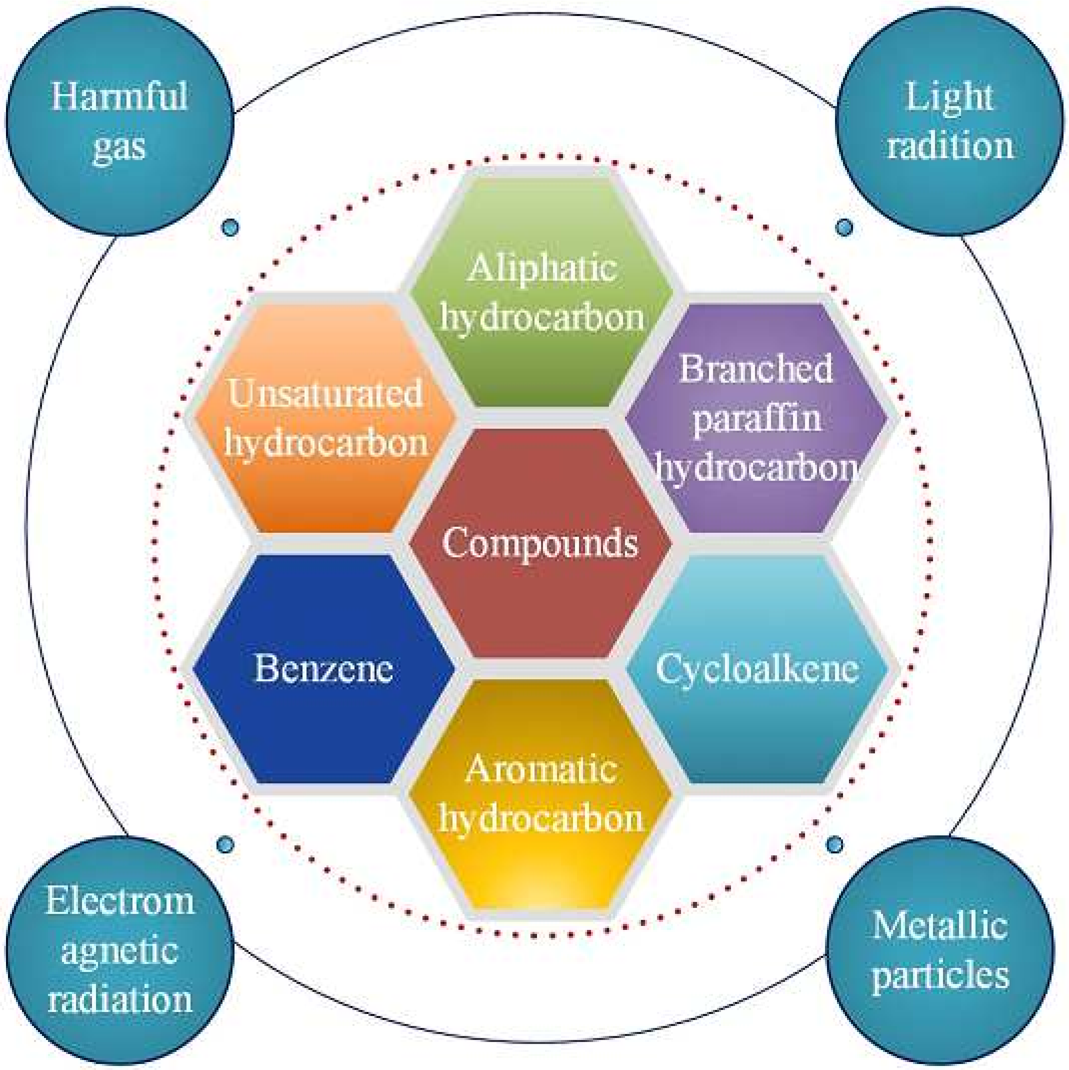

Figure 5

Harmful substances of kerosene in traditional EDM.

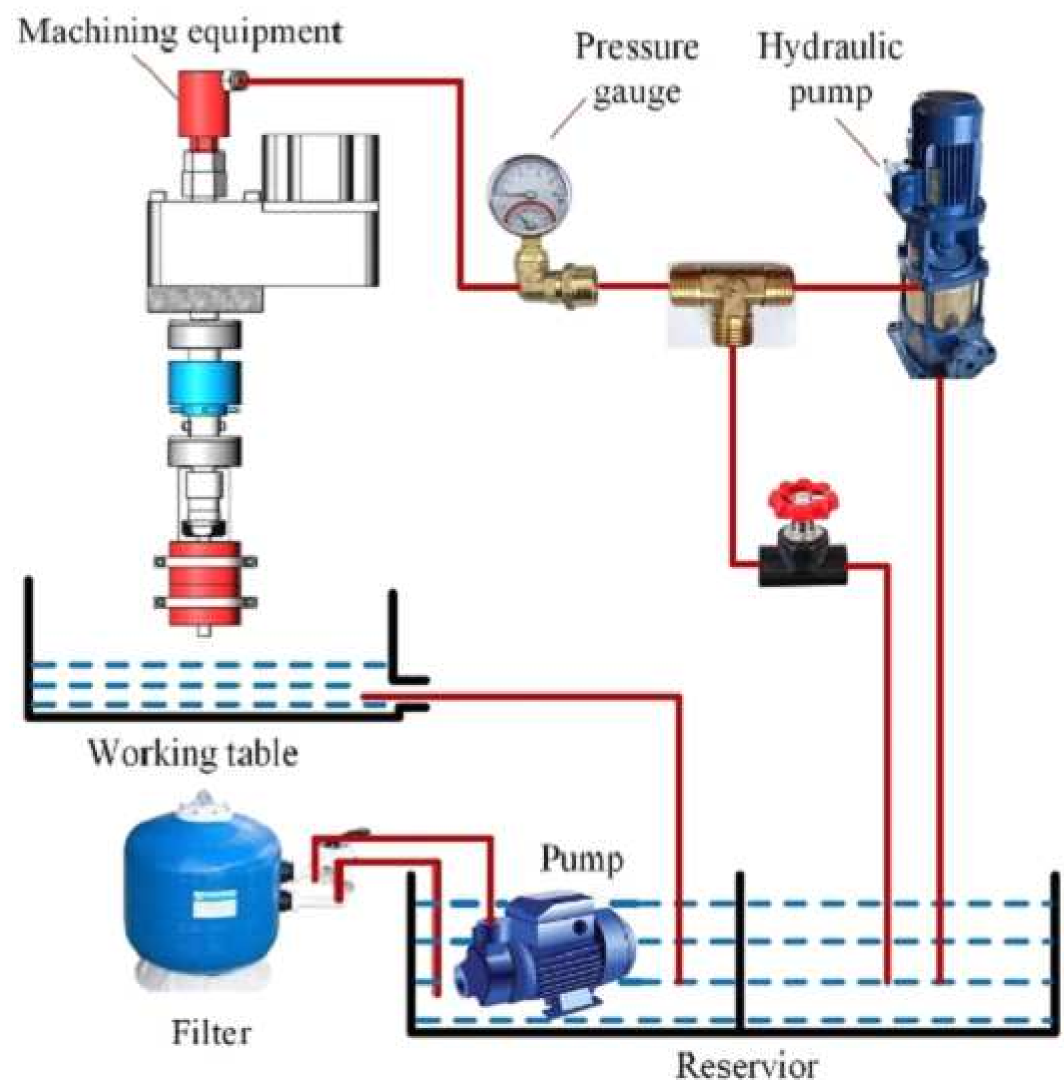

Figure 6

Schematic of self-devised flushing system.

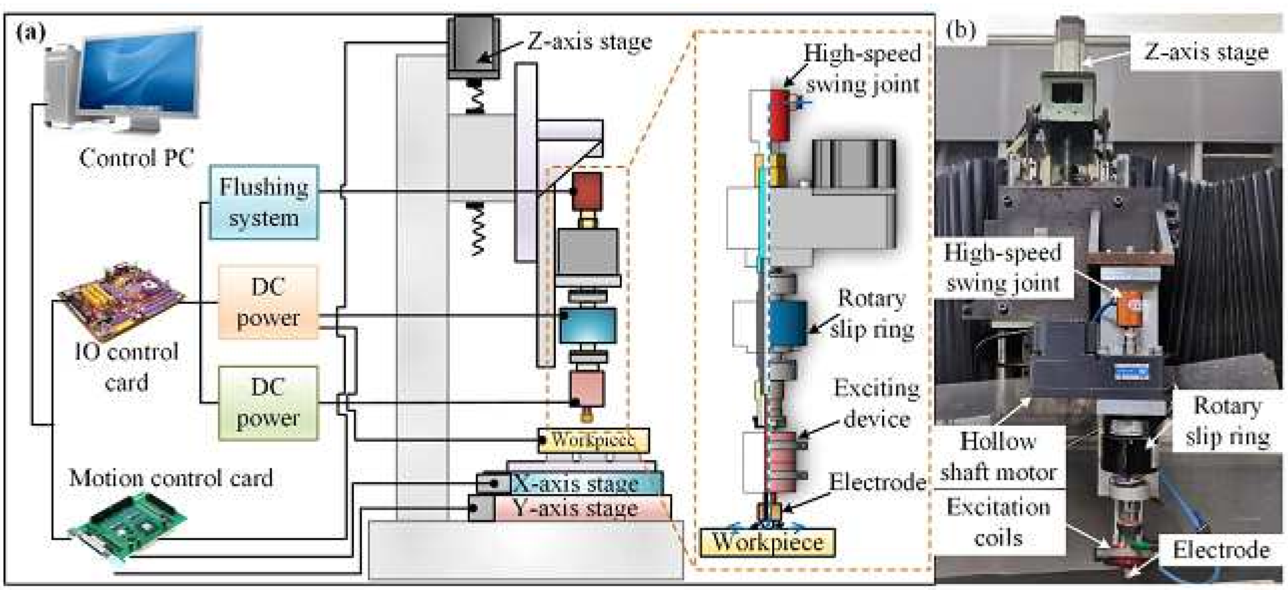

Figure 7

(a) Schematic of machining equipment used to generate rotating short arcs. (b) Photography of self-devised rotating short arc EDM system.

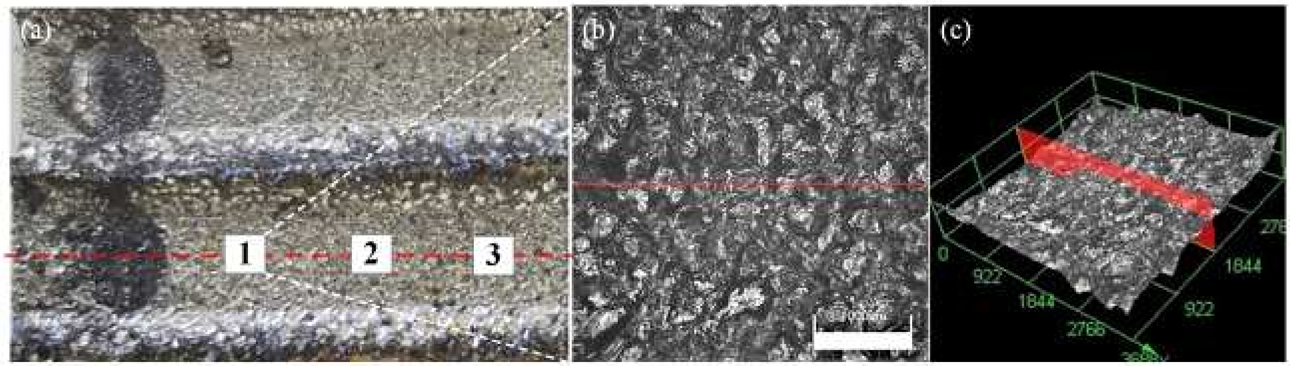

Figure 8

(a) Sampling regions. (b) Plan graph of the sampling region one. (c) 3D graph of the sampling region one.

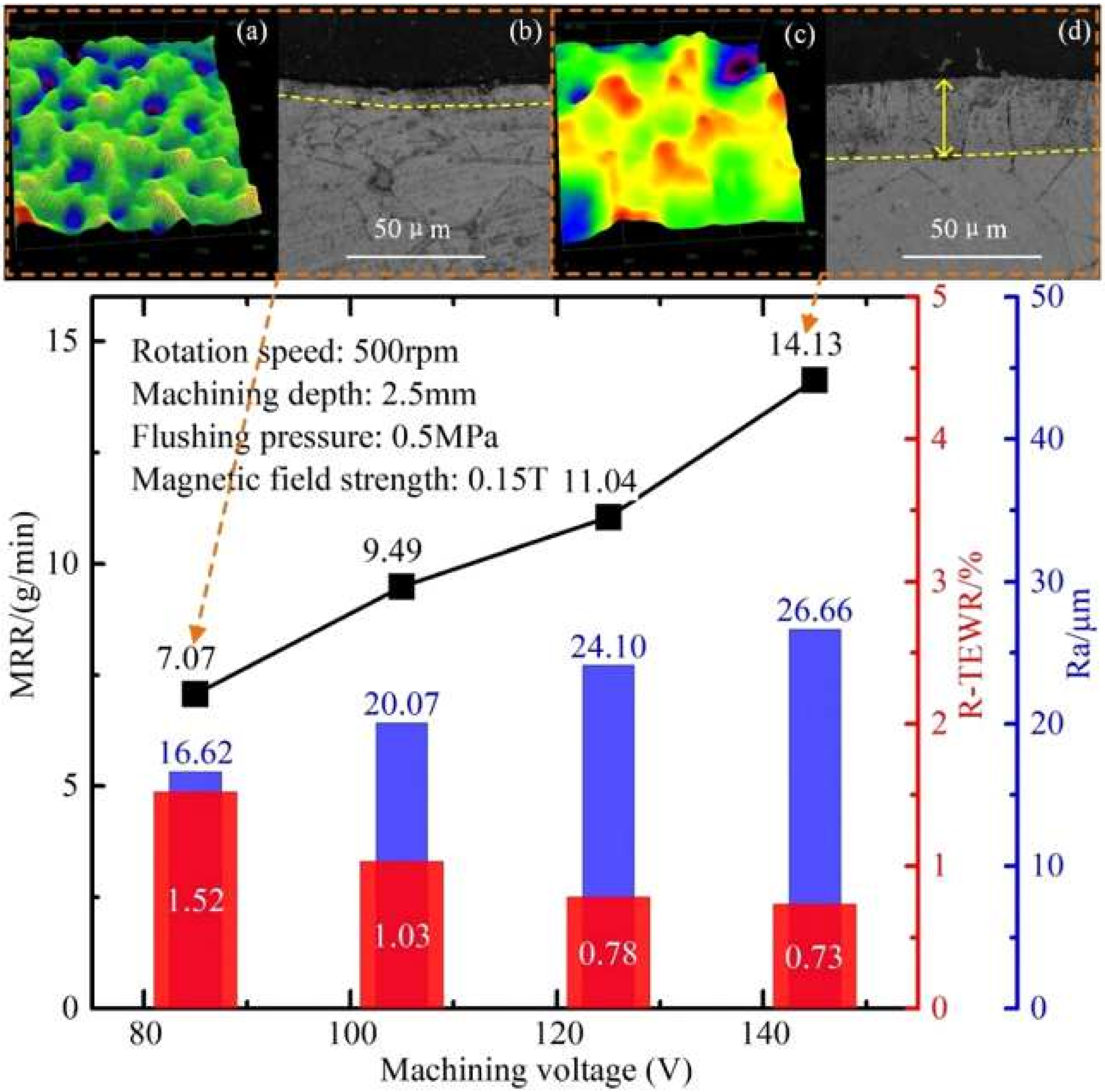

Figure 9

Effect of machining voltage on MRR, R-TEWR and SR.

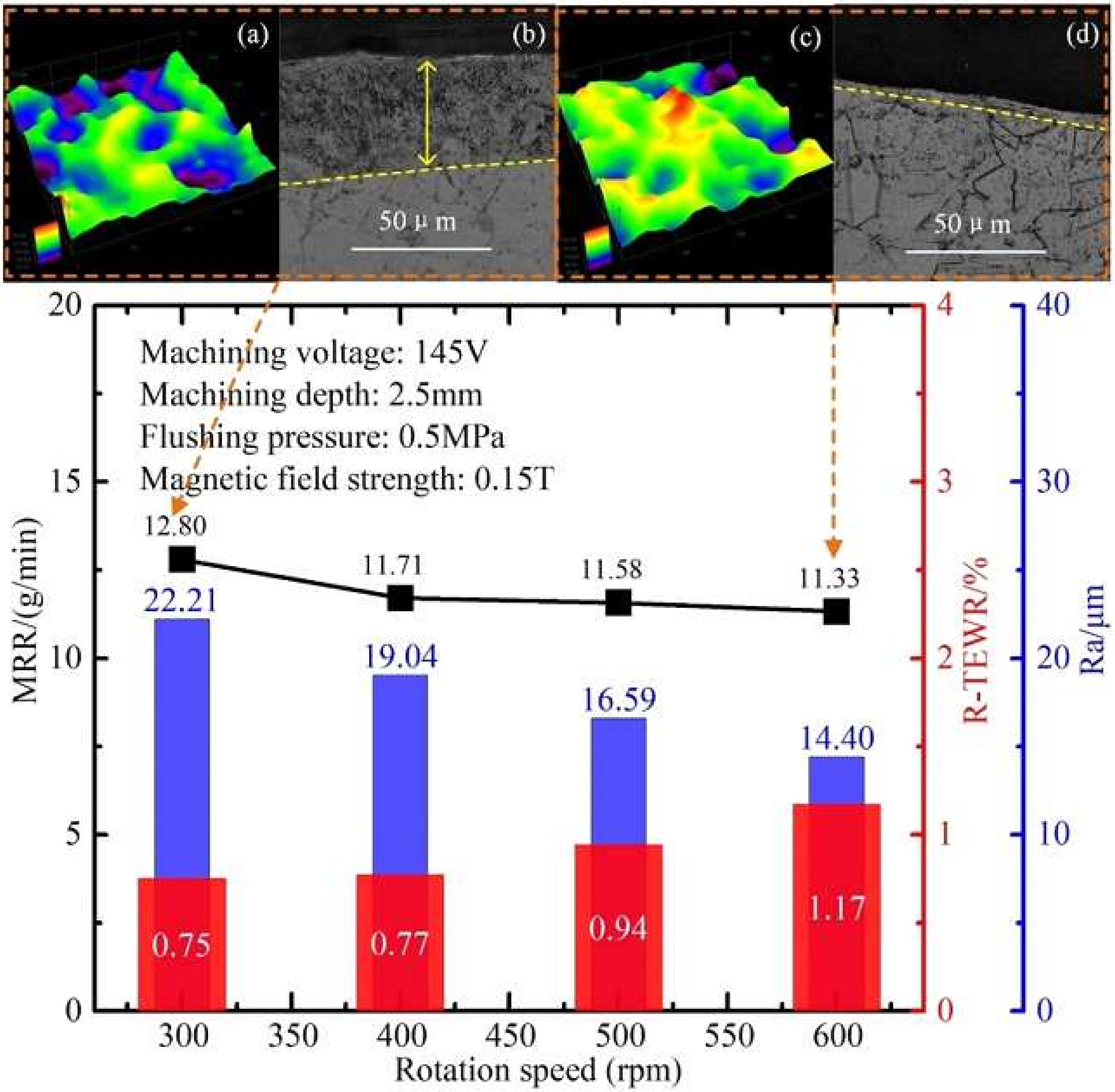

Figure 10

Effect of tool electrode rotation speed on MRR, R-TEWR and SR.

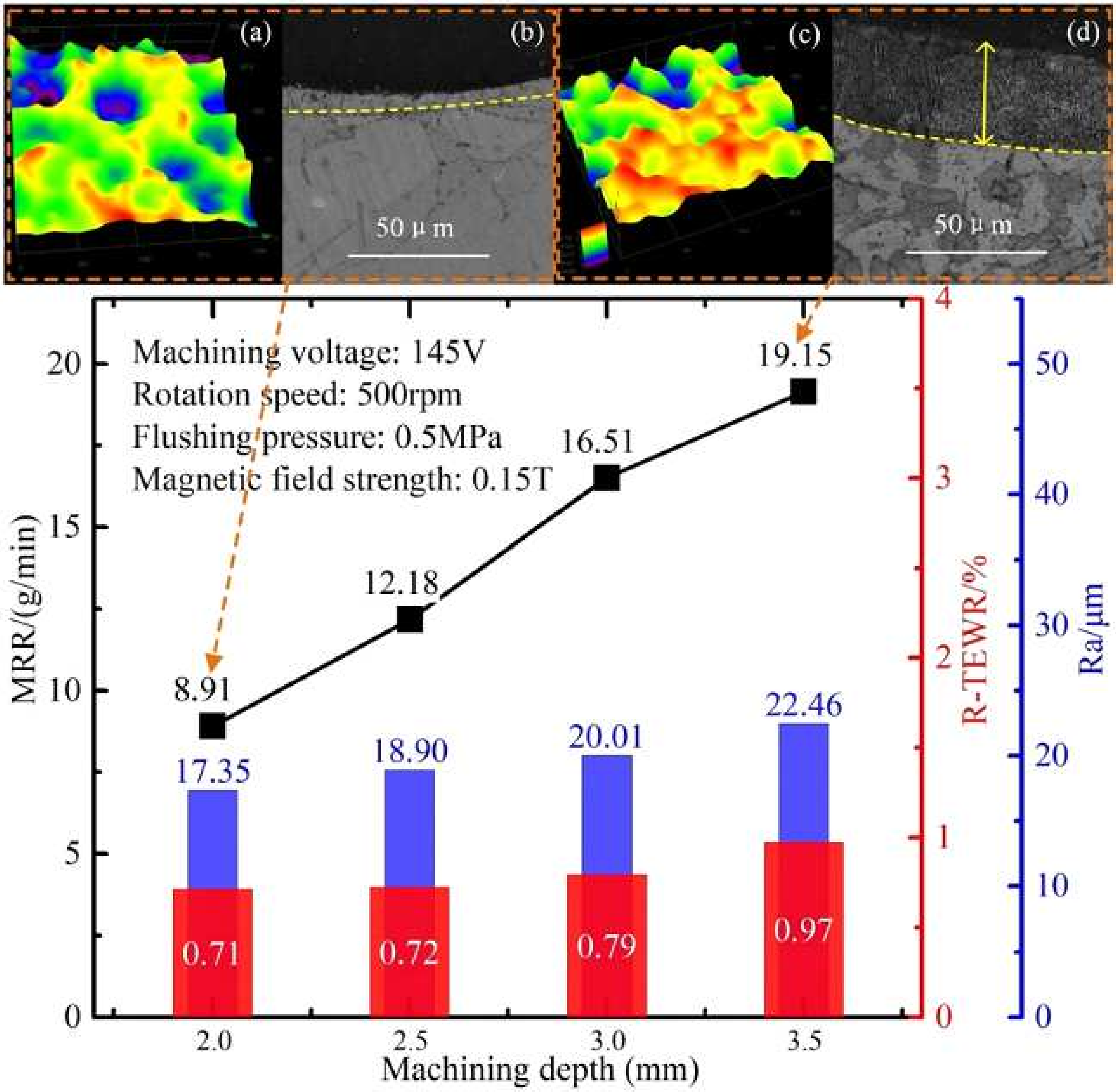

Figure 11

Effect of tool electrode rotation speed on MRR, R-TEWR and SR.

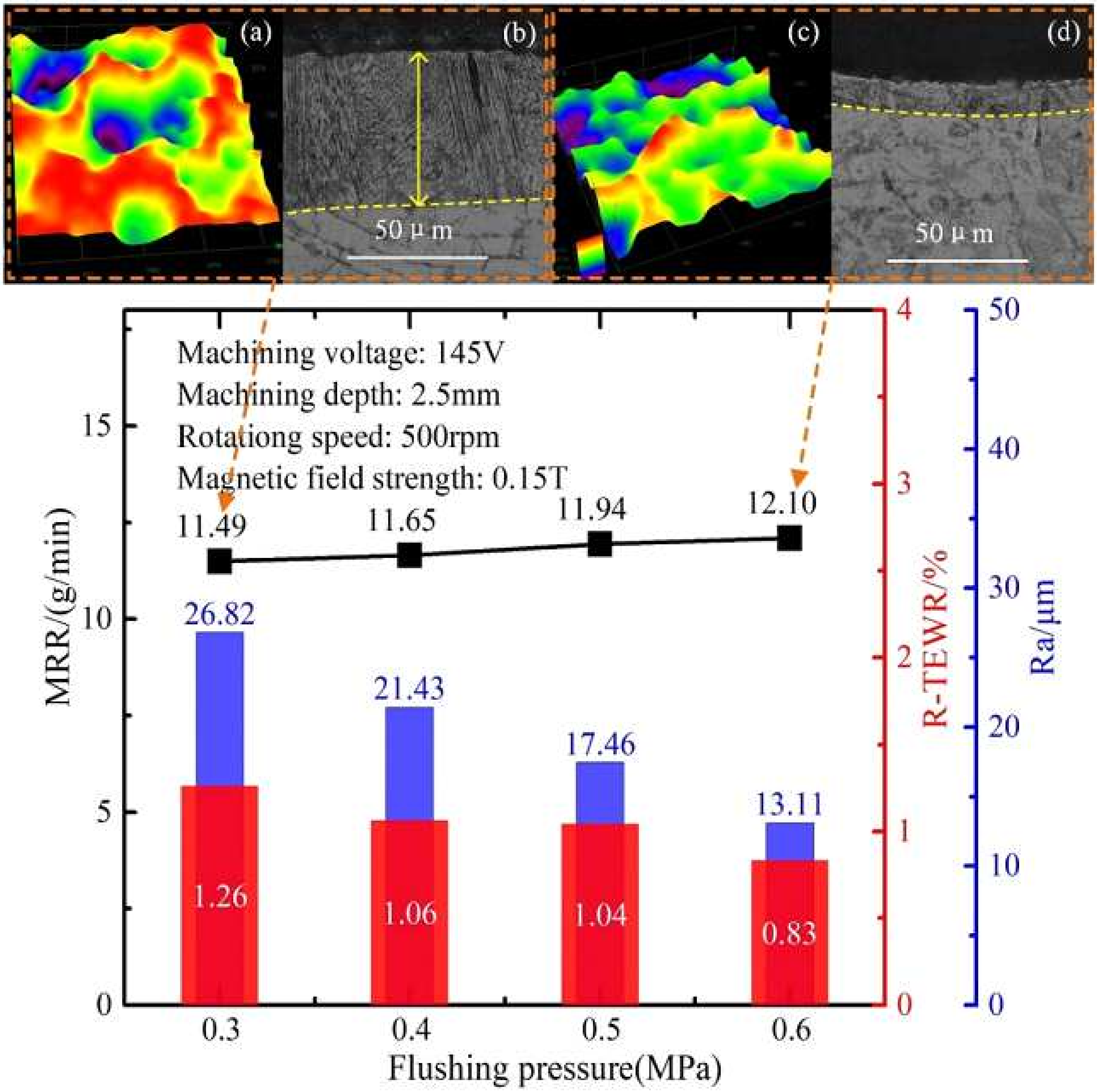

Figure 12

Effect of flushing pressure on MRR, R-TEWR and SR.

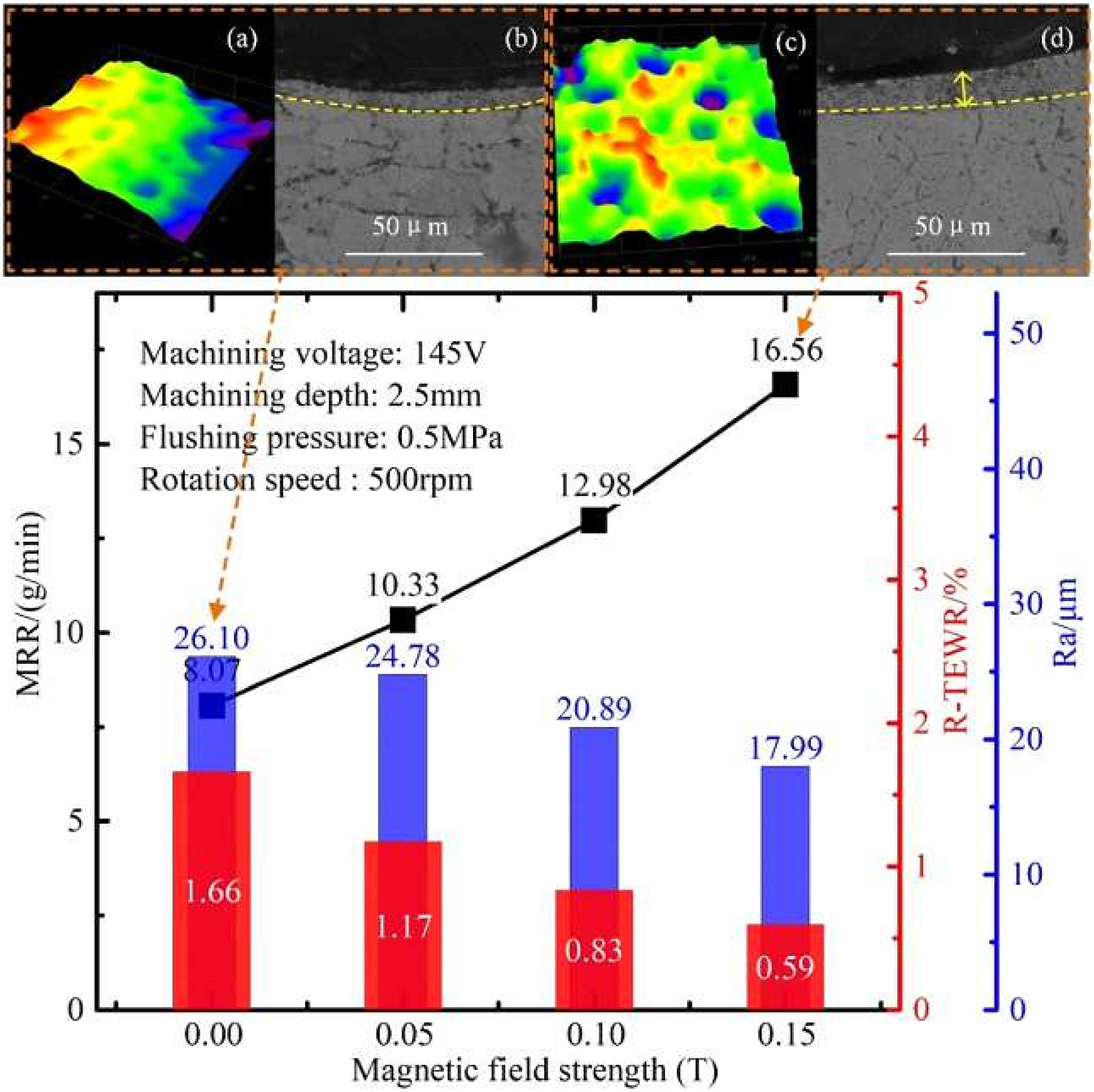

Figure 13

Effect of magnetic field on MRR, R-TEWR and SR.