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Using WECM to remove the recast layer and reduce the surface roughness of WEDM surface

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ABSTRACT

When the workpiece is sliced by using wire electrical discharge machining (WEDM), owing to the material removal mechanism of melting and evaporation, numerous overlapping discharge craters and recast layer can be generated on the workpiece surface, leading to the high surface roughness. In this study, a method called WEDCM, which uses wire electrochemical machining (WECM) to remove the recast layer and reduce the WEDM surface roughness, is proposed. An analytical model is developed to identify the appropriate feed rate of the wire electrode during the stage of electrochemical dissolution. The calculation results show that in order to dissolve the recast layer, the wire feed rate should be reduced with the increase of the movement distance. The experiments are carried out on the same machine tool with the same electrolyte (deionized water) to verify the model. The experimental results show that the recast layer on the WEDM surface can be dissolved and the surface roughness can be reduced with WEDCM. Two factors which have great influence on the final surface roughness are also discussed.

1. Introduction

Without contact of tool and the workpiece and no cutting forces during process, electrical discharge machining (EDM) and wire electrical discharge machining (WEDM) are widely used to machine difficult-to-machine materials. When EDM machines the workpiece, dielectric medium is ionized by the pulse power supply applied between the tool and the workpiece providing high frequency pulse voltage. The sparks occur and raise the temperature to 8000-12000℃, which induces a large amount of heat in the processing area, and melts and evaporates the materials (Abbas et al., 2007). Owing to the material removal mechanism of EDM, numerous overlapping discharge craters are generated on the EDM surface, leading to the high surface roughness, even with optimized EDM technology. During the process, some melted materials are cooled down by the electrolyte and recrystallized on the surface, forming a layer called recast layer. Azam et al. (2016) stated that the recast layer is hard, brittle, and totally different from original material structure, and deteriorates properties such as fatigue strength, resistance to corrosion, and life span. Ayesta et al. (2016) reported that since EDM process induces metallurgical changes in the machined material and may reduce fatigue service life of part, the aerospace industry has restricted the use of EDM to the machining of selected components.

In order to fabricate recast layer free surfaces, Wu and Li (2018) proposed a hybrid machine method which combined fixed abrasive wire saw and WEDM to eliminate the recast layer, and the experiments show that wire saw can remove the recast layer and the surface heat affected zone, and reduce the surface roughness. Electrochemical machining (ECM) or wire electrochemical machining (WECM), based on the principle of anodic dissolution of metallic materials, are another widely used methods which can produce smooth and stress-free surface (Sen and Shan, 2005). Meng et al. (2017) used wire electrochemical micro machining to machine Ni-based metallic glasses, and several complex microstructures such as micro gear and micro square helix were machined with different optimized parameters. Qu et al. (2014) studied the integration of pulse ECM and a reciprocated traveling wire electrode to improve the homogeneity of the slit in WECM, and the experimental results show that the combination of pulse ECM and a reciprocated traveling wire electrode can enhance the accuracy of WECM by the timely replenishing of the electrolyte.

Since the material removal mechanism of ECM is based on the Faraday's law, the removal of material is at atomic scale, and it can produce smooth surfaces. However, the dissolution rate of electrochemical reaction is relatively low, especially as short pulses, low voltage and small current are used in ECM to assure required accuracy (Nguyen et al., 2012). Therefore, many researches combine EDM and

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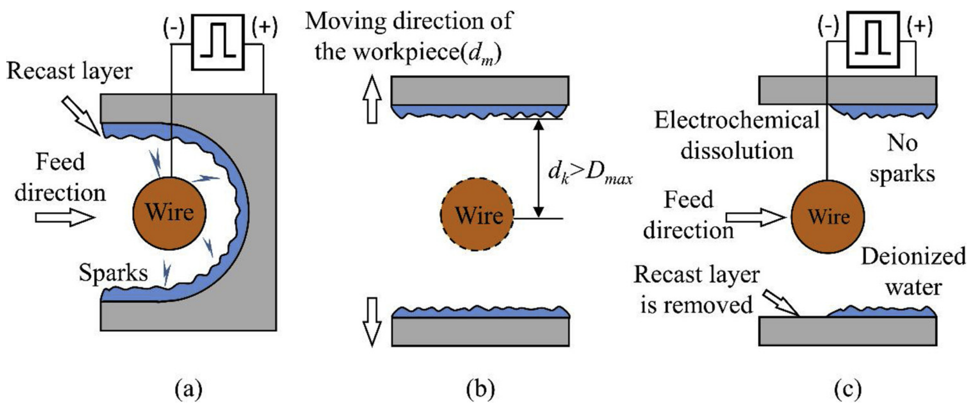

Fig. 1. The principle of WEDCM.

ECM together and introduce ECM to eliminate the recast layer and reduce the EDM surface roughness. Kurita and Hattori (2006) performed ECM finishing after EDM shaping in sequence on the same machine tool in order to get a smooth surface. ECM finishing is carried out by shifting power supply, which is from an EDM to an ECM power supply. The experiments show that the EDM surface roughness is reduced to 0.06 μm by applying ECM lapping. Zeng et al. (2012) carried out the process which consists of EDM shaping and ECM finishing in sequence on the same machine tool with the same electrode but different dielectric medium (i.e. EDM kerosene and ECM electrolyte). The results show that the recast layer and surface defects generated by EDM are removed completely and the surface quality is improved. The mechanical property of the workpiece is better than that machined merely by EDM. Ma et al. (2015) proposed a machining process combining the electrical discharge machining and pulse electrochemical machining (PECM) technique to improve the overall quality of electro discharge machining-drilled holes. The process is carried out in sequence on a machine tool with the electrode unaltered and the electrolyte changed from deionized water to neutral sodium nitrate solution. Tamura (2013) introduced a new process after finishing EDM called surface integrity machining for EDM (SIME) to remove the surface defects. The experiments show that the surface defects generated by EDM could be completely eliminated by incorporating SIME into EDM. However, SIME is conducted using an external power supply.

One of the characteristics of these researches mentioned above is that some equipment, such as power supply, electrolyte, is changed when ECM is used to improve the surface quality after EDM. In recent years, some researches which use ECM to improve EDM surface quality without changing the equipment have been studied. Nguyen et al. (2012) developed a hybrid machining process, called simultaneous micro-EDM and micro-ECM (SEDCM), which combined micro-EDM and micro-ECM in a unique hybrid machining process. The experiments show the process of SEDCM reduces the surface roughness by using the electrochemical reaction to dissolve the recast layer in low-resistivity deionized water. Zhang et al. (2015) and Xu et al. (2018) combined tube electrode high-speed electrochemical discharge drilling (TSECDD) and ECM into a unique machining process using a low-conductivity salt solution to fabricate film cooling holes in hard-to-machine super alloys. The experiments show that when the lateral gap exceeds the maximum discharge gap, ECM can eliminate the recast layer generated by EDM, achieving a remarkable improvement in surface quality.

In this study, a novel method using WECM to remove the recast layer and reduce the surface roughness of WEDM surface is proposed. Since WEDM and WECM are combined together to machine the workpiece, this method is named WEDCM. The analytical model is developed to confirm the appropriate wire feed rate during electrolysis stage. The experiments are carried out on the same machine tool with the same electrolyte to verify the model. Finally, two vital factors which have great influence on the final surface roughness are discussed.

2. The principle of WEDCM

With WEDCM, WEDM and WECM are performed on the same machine tool with the same solution, indicating that the solution exhibits both dielectric and electrolyte characteristics. Therefore, the choice of electrolyte is of importance to WEDCM. On one hand, the solution can be ionized by the voltage applied across the two electrodes and the sparks can be generated to remove the materials; on the other hand, the solution should have slight conductivity and weak electrochemical reaction so that it can dissolve the anode materials. Under these circumstances, deionized water (Chung et al., 2007; Nguyen et al., 2013) and low-conductivity salt solution (Zhang et al., 2016), which is composed of sodium nitrate and deionized water, are often adopted as the bi-characteristic fluid. In view of the characteristic of environmentally friendly, deionized water is employed as the electrolyte in this study.

The WEDCM process divides into three steps and the principle is shown in Fig. 1. Firstly, the workpiece is cut by using WEDM. In this step, although it is the electrochemical dissolution and sparks erosion together to remove the materials, actually the sparks erosion plays the major role. After the workpiece is cut open, the workpiece surface is covered with overlapping discharge craters and recrystallize materials, as shown in Fig. 1(a).

Secondly, the workpiece is moved outwards a certain distance (d_m) driven by the machine tool control system, as shown in Fig. 1(b). After the movement of the workpiece, the gap between the wire and the workpiece (d_k) should be larger than the maximum distance of the spark discharge (*Dmax*) so that the sparks cannot be generated.

Thirdly, the wire electrode is re-fed again along the original route. Owing to the weak electrochemical reaction of the deionize water, electrochemical dissolution plays the predominant role in this step. Thereby, the craters and recrystallized materials are dissolved electrochemically and the surface quality can be improved, as shown in Fig. 1(c).

The main characteristic of WEDCM is that the wire electrode is fed twice: the first feed, the workpiece is cut open by using WEDM; the second feed, the recast layer generated by WEDM is dissolved by using WECM. Between the two feeds of the wire, the workpiece should be moved outwards a certain distance in order to stop the sparks generated during the electrolysis stage.

3. Development of the model to identify the wire feed rate

If the appropriate wire feed rate is adopted to dissolve the recast layer during the third step (electrolysis stage), the recast layer with a thickness d_r can be removed. Therefore, the model will be developed to identify the appropriate wire feed rate in this section.

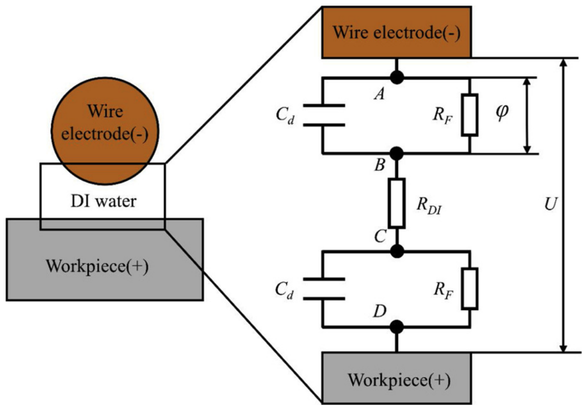

Fig. 2. Equivalent circuit of two electrodes immersed in deionized water.

3.1. The double layer voltage and the Faradic current density

Owing to the slight conductivity of deionized water, which is considered as a weak electrolyte, the gap between the anode workpiece and the cathode wire can be equivalent to an electrochemical cell. When the power supply is applied across the two electrodes, which are immersed in deionized water, an electrochemical reaction occurs owing to the weak electrolysis of deionized water. The ions in the electrolyte move towards electrode surface. At the interface of electrode and electrolyte, two layers of ions with opposing polarity, which act like a two parallel plate capacitor, are formed. Therefore, a double layer model is developed between the electrode and workpiece, as shown in Fig. 2. In this model, φ is the double layer voltage. U is the voltage between the two electrodes. C_d is the capacitance of double layer at the electrode and workpiece interface.

The charging current density iC, which flows through the double layer capacitance C_d, can be expressed as:

$$i_c = C_d{\cdot}d\varphi/dt \tag{1}$$

R_F is the Faradic resistance (or the transfer resistance), and the current density flowing through R_F is the Faradic current density i_F. According to the Butler–Volmer equation (Bard and Faulkner, 2001), the Faradic current density is:

$$i_F = i_0[\exp(\alpha nF\varphi/RT) - \exp(-\alpha nF\varphi/RT)] \tag{2}$$

where i_0 is the exchange current density; α is transfer coefficient; n is the valency number of ions; F is the Faraday constant; R is the gas constant; T is the absolute temperature.

In Eq. (2), the latter term, which represents the cathodic current density, is considered to be quite small compared with the former term, which represents the anodic current density. Thereby, the latter term can be ignored, and the Faradic current density i_F is simplified as:

$$i_F = i_0\exp(\alpha nF\varphi/RT) \tag{3}$$

The current density which flows from node A to node B is:

$$I_{AB} = i_c + i_F = C_d{\cdot}d\varphi/dt + i_0\exp(\alpha nF\varphi/RT) \tag{4}$$

The current density which flows from node B to C is:

$$I_{BC} = (U - U_{AB} - U_{CD})/R_{DI} = (U - 2\varphi)/[\rho(d_i + d_m)] \tag{5}$$

where R_{DI} is the resistance of the electrolyte (deionized water), which is:

$$R_{DI} = \rho d_k = \rho(d_i + d_m) \tag{6}$$

where ρ is the electrolyte resistivity; d_k is the distance between the wire electrode and the workpiece; d_i is the distance between the wire electrode and the workpiece after WEDM, which can be measured in the experiments; d_m is the movement distance after the workpiece is cut by using WEDM in the second step, which is shown in Fig. 1(b).

Since $I_{AB} = I_{BC}$, the following equation can be deduced from Eqs. (4) and (5):

$$\frac{d\varphi}{dt} = \frac{1}{C_d}\left[\frac{U - 2\varphi}{\rho(d_i + d_m)} - i_0\exp(\alpha nF\varphi/RT)\right] \tag{7}$$

The double layer voltage φ can be obtained by solving Eq. (7).

3.2. The volume of material dissolved by WECM

According to the Faraday's first law of electrolysis, the amount of the substance deposited or liberated at the electrode is directly proportional to the quantity of electricity passed through the electrolyte, which is:

$$V = \omega{\cdot}Q = \omega{\cdot}I{\cdot}t \tag{8}$$

where V is the volume of materials dissolved on the anode workpiece surface; ω is volume electrochemical equivalent; Q is the electric quantity passing through the electrolyte; t is the time variable; I is the corresponding electric current, which is:

$$I = i_F{\cdot}S \tag{9}$$

where S is the area of the wire electrode which the current flows through, which is:

$$S = \pi{\cdot}d{\cdot}l \tag{10}$$

where d is the wire diameter and l is the length of the workpiece, as shown in Fig. 3.

Consequently, from Eqs. (8)–(10), in terms of the Faraday's law of electrolysis, the volume of materials dissolved on the anode workpiece by WECM is:

$$V = \omega{\cdot}\pi{\cdot}d{\cdot}l{\cdot}t{\cdot}i_F \tag{11}$$

Since the pulse power supply is used in this study, the volume of materials dissolved during the time Δt is:

$$V_{\Delta t1} = \frac{1}{T_p}{\cdot}\pi{\cdot}\omega{\cdot}d{\cdot}l{\cdot}\Delta t{\cdot}\int_0^{t_{on}} i_F\,dt \tag{12}$$

where t_{on} is the pulse width of the pulse power supply; T_p is the period of the pulse power supply.

3.3. The feed rate of the wire electrode during electrochemical dissolution

As shown in Fig. 4, when the wire electrode moves from position A to position B during the time Δt, the volume of materials dissolved on the workpiece is:

$$V_{\Delta t2} = x_1{\cdot}V_f{\cdot}\Delta t{\cdot}d_r{\cdot}l \tag{13}$$

where V_f is the feed rate of the wire electrode during the electrolysis stage; d_r is the thickness of the recast layer, which can be measured by

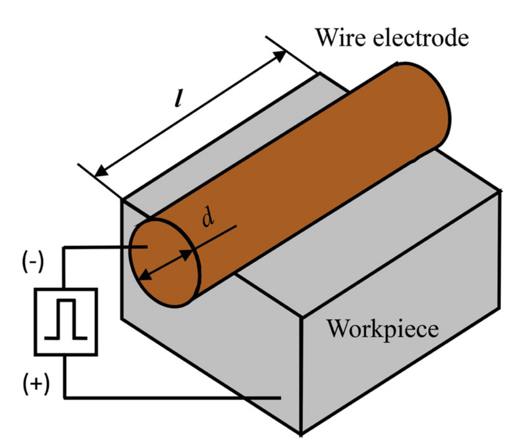

Fig. 3. The wire electrode dissolves the materials.

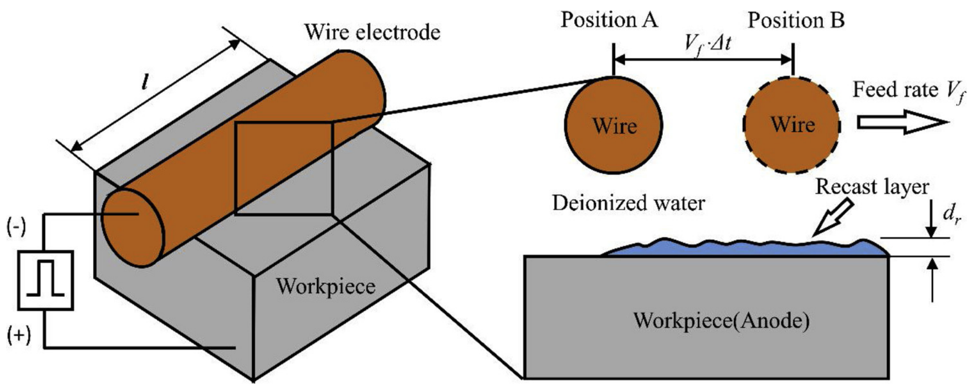

Fig. 4. The movement of the wire electrode during time Δt.

the experiments; x_1 is a coefficient which represents the materials need to be dissolved in the recast layer with a thickness of d_r.

Since $V_{\Delta t1} = V_{\Delta t2}$, the feed rate of the wire electrode V_f can be calculated from Eqs. (12) and (13), which is:

$$V_f = \frac{\pi \omega d}{x_1 T_p d_r} \int_0^{t_{on}} i_F \, dt \tag{14}$$

The calculation process can be summarized in Fig. 5. Firstly, the double layer voltage φ, which is a function of time variable t, is calculated from Eq. (7). Secondly, the Faradic current density i_F can be obtained from Eq. (3), which is still a function of time variable t. Lastly, feed rate of wire electrode V_f during electrolysis stage is obtained by Eq. (14), which is a constant since the definite integral for Faradic current density i_F is calculated. The meaning of the wire feed rate V_f is that with the movement distance of the workpiece during the second step being d_m, if the recast layer with a thickness of d_r needs to be dissolved, the wire feed rate during electrolysis stage should be V_f.

4. Experimental setup

The experiment platform is WEDM cutting machine QT56 produced by Jiangzhou CNC Machine Tool Manufacture Co.,Ltd, as shown in Fig. 6. Stainless steel AISI 304 with a thickness of 2 mm is used as the workpiece, and molybdenum wire with a diameter of 0.18 mm as the wire electrode. Deionized water with resistivity of 1 MΩ cm is employed as electrolyte in the experiments. Scanning electron microscope (SEM) from JEOL (JSM-6390 A) is used to describe the workpiece surface topography. A Leica dual-core DCM 3D measuring microscope from

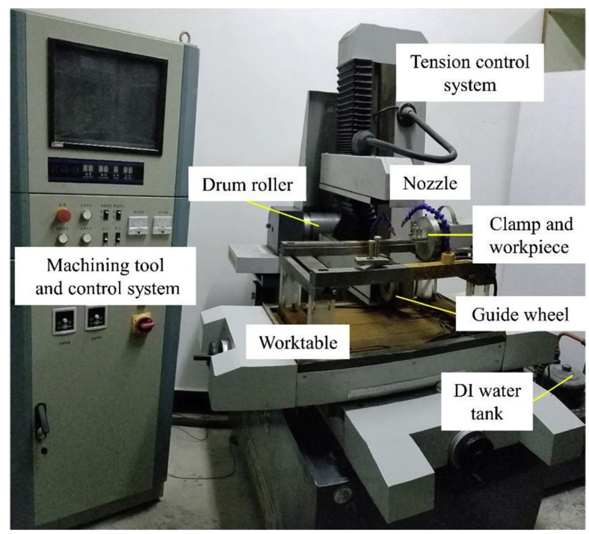

Fig. 6. Experimental platform.

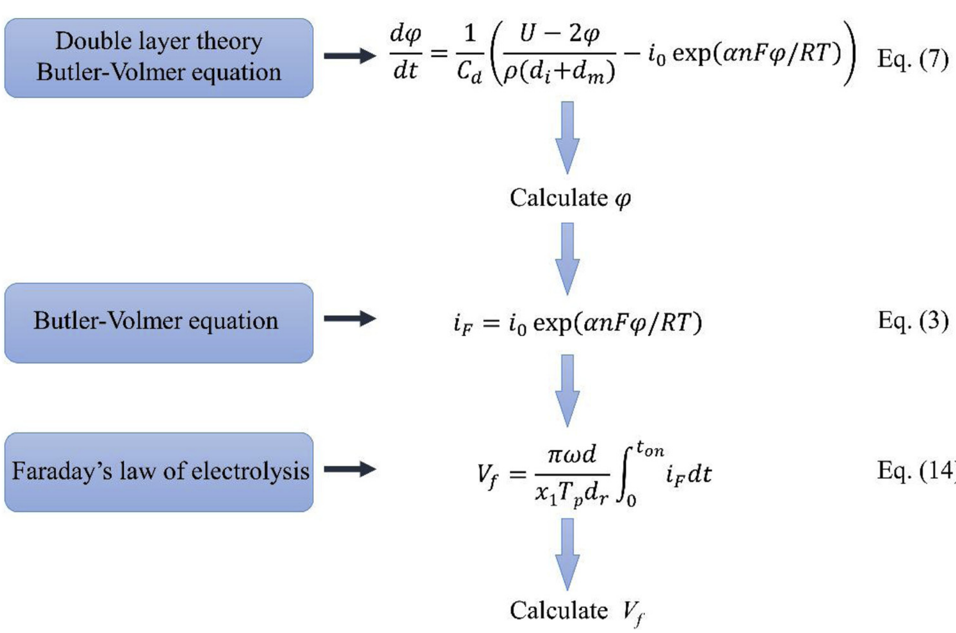

Fig. 5. The calculation process.

Table 1
Machining parameters in the experiments.

Voltage (V)	110
Pulse on time (μs)	14
Pulse period (μs)	56
Feed rate of wire electrode (μm/s)	3
Velocity of the wire electrode (m/s)	2

Sensofar-Tech is used to measure the surface roughness R_a of the workpiece. Four different positions evenly distributed on the workpiece surface are chosen. The surface roughness *Ra* of each position is measured by the equipment. Then the average value is taken as the surface roughness of this workpiece surface. All the surface roughness *Ra* in the manuscript is obtained by using this approach.

The experiments are carried out as follows: Firstly, the workpiece is cut through by WEDM, and the machining parameters are shown in Table 1. Secondly, the workpiece is moved a certain distance d_m under the control system of machine tool. Thirdly, the wire electrode is re-fed with the feed rate V_f to dissolve the recrystallized materials to improve the surface quality, and the other machining parameters are still the ones in Table 1.

5. Results and discussion

5.1. Simulation results and experiments verification

The parameters which are used to calculate are shown in Table 2.

As mentioned in Section 2, the workpiece should move a certain distance d_m between two feeds of the wire electrode. The corresponding wire feed rate V_f can be obtained for each value of movement distance d_m. When the movement distance d_m takes different values, a series of corresponding values of V_f can be obtained. Therefore, the relation between the wire feed rate V_f and movement distance d_m can be plotted, as shown in Fig. 7.

The curve in Fig. 7 presents the appropriate wire feed rate during electrolysis stage, which means that with the feed rate near the curve, the wire can dissolve the recast layer with a thickness d_r. As can be seen in Fig. 7, the wire feed rate V_f decreases with the increase of the movement distance d_m, indicating that when the movement distance increases, the wire feed rate should reduce in order to dissolve the recast layer with the same thickness. This phenomenon can be explained by the Faraday's law. According to the Faraday's law, the material removal rate v can be expressed:

$$v = \eta \cdot \omega \cdot i \qquad (15)$$

where η is current efficiency; ω is the volume electrochemical equivalent; i is the average current density. When the movement distance d_m increases, the distance between the wire and the workpiece d_k also increases. Since the deionize water is used as electrolyte, the resistance between the wire and the workpiece increases as well, leading to the decrease of the average current density i. According to the Eq. (15), the material removal rate v reduces. Therefore, if the recast layer with the same thickness needs to be dissolved, the wire electrode should stay at a certain position on the surface much more time, indicating that the wire feed rate should be slower. Briefly speaking, lower feed rate V_f is required when the movement distance d_m is bigger.

Table 2
Calculation parameters.

Double layer capacitance, C_d (μF/cm^2)	0.5
Exchange current density, i_0 (μA/cm^2)	70
Transfer coefficient, α	0.5
Valency number of ions, n	2
Faraday constant, F (C/mol)	96485
Gas constant, R (J/mol·K)	8.314
Absolute temperature, T (K)	298.15
Volume electrochemical equivalent, ω (cm^3/A·min)	0.0022
Initial gap distance, d_i (μm)	96.5
Resistivity of deionize water, ρ (MΩ.cm)	1
Coefficient, x_1	0.02
The thickness of the recast layer, d_r (μm)	16
Diameter of the wire electrode, d (μm)	180

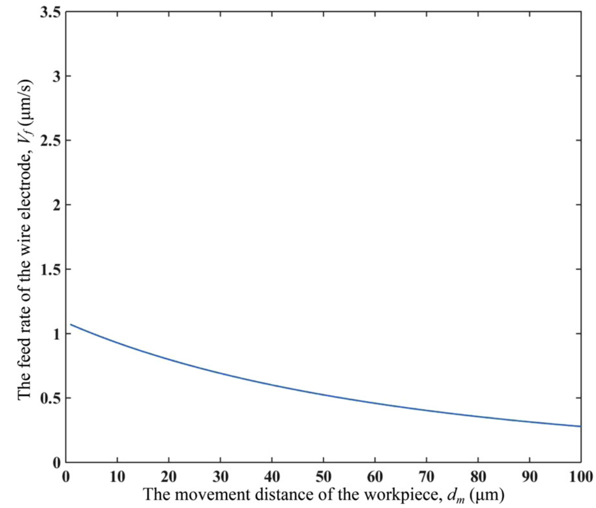

Fig. 7. The calculation results of the wire electrode feed rate.

In order to compare the experimental results with the model, the experiments are carried out with different feed rate V_f and different movement distance d_m, which are superimposed on calculation results, as plotted in Fig. 8. The movement distances d_m of the experiments are 20, 50 and 80 μm respectively. According to the different wire feed rate, the experiments are divided into three types. The first type of the experiments is presented with red triangle and above the curve, the feed rates of which are fast. The second type of the experiments is presented with black rectangle and near the curve, the feed rates of which are appropriate. The third type of the experiments is presented with blue circle and below the curve, the feed rates of which are very slow. The other parameters still use the ones shown in Table 1.

Fig. 9(a) shows the surface cut by using WEDM with the parameters in Table 1. As can be seen, the surface is cover with the recast layer, composed of the craters and recrystallized materials, which has adverse effect on surface quality, leading to the surface roughness R_a 3.14 μm. Fig. 9(b) shows the surface machined by using WEDCM with V_f 0.3 μm/s and d_m 20 μm. Compared with the WEDM surface, almost all craters and recrystallized materials have disappeared and the surface becomes flat, with the surface roughness R_a 0.82 μm.

Fig. 10 shows the surface obtained by WEDCM with different V_f and d_m. Compared with the Fig. 9(a), the craters and the recrystallized materials on the surface are gradually dissolved, surface topography becomes flat, and surface quality is improved in various degrees. The surface roughness declines as well, which will be detailed discussed in Section 5.3.

When the workpiece is sliced with the fast feed rate, such as red triangle in Figs. 8 and 10, some recrystallized materials still can be found on the surface. The reason can be attributed to the characteristic of the electrolysis. If the wire feeds fast, it stays at a certain position on the surface less time, which means that the wire electrode doesn't have enough time to dissolve the recast layer, and as a result, these recrystallized materials are still visible. With the decrease of the wire feed rate, the wire stays at a certain position on the surface much more time. Therefore, more recrystallized materials can be dissolved and the surface quality improved. When the feed rate is reduced to near the curve, such as black rectangle in Figs. 8 and 10, most of the recast layer is dissolved. When the feed rate continues to decrease, such as blue circle in Figs. 8 and 10, no matter what the movement distance d_m is, the wire

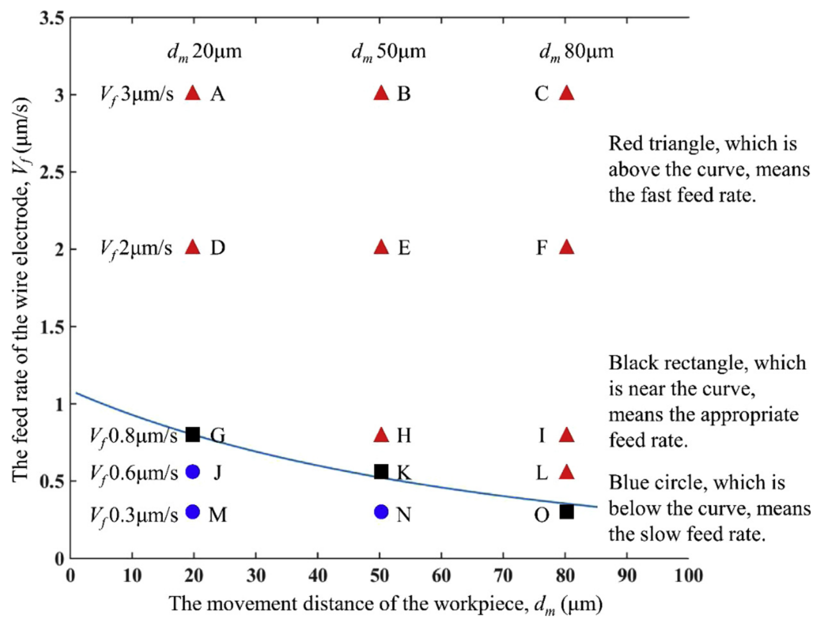

Fig. 8. The design of experimental verification.

has enough time to dissolve the recast layer and most of them are removed.

If the workpiece surface is corroded, grain boundaries can be found on the surface. Since ECM is a corrosion process, after long dissolution time yielded by the low feed rate of the wire, the grain boundaries after corrosion are shown on the surface. Fig. 11 illustrates the grain boundaries on the surface with the wire feed rate V_f 0.3 μm/s and movement distance d_m 50 μm.

5.2. Error analysis of the model

Theoretically, when the workpiece is cut with the parameters near the curve, all the recast layer should be removed. However, as show in Fig. 10(g), (k), and (o), some recrystallized materials are still on the surface, indicating that the recast layer is dissolved incompletely. The reason is attributed to the instability of electrolysis process caused by the wire vibration. In this study, the vibration of the wire is neglected during the model development in order to simplify the calculation. However, as a matter of fact, vibration of the wire electrode always exists during the whole process, and it can be influenced by many factors. For example, even the change of the flow direction of the electrolyte sometimes can cause the wire vibration. Thereby, the entire cutting process is instability, which can lead to the incomplete dissolution of the recast layer, even with the parameters near the curve.

Particularly, the error between the simulation results and experiments is quite obvious when the movement distance is 20 μm. As can be seen in Fig. 10(g), even with the parameters near the curve, the surface is not smooth. One of the characteristics of WEDCM is that the workpiece should be moved a certain distance between the two feeds of the wire, so that the sparks no longer occur during the electrolysis stage. However, after the workpiece is moved 20 μm, the gap between the wire and the workpiece d_k is not big enough. As a result, when the wire feeds second time, owing to the wire vibration, although the sparks greatly reduce during the electrolysis stage, they don't disappear completely and still can be generated from time to time, which means WEDM still plays the role of removing the materials. Therefore, some recrystallized materials are on the surface when the movement distance is 20 μm.

5.3. Analysis of the factors affecting the final surface roughness

After the recast layer is removed, the surface quality is improved, and the surface roughness R_a reduces as well. Fig. 12 shows the surface roughness of WEDCM with different feed rate V_f and movement distance d_m.

5.3.1. The wire feed rate during the electrolysis stage (V_f)

The wire feed rate V_f during the electrolysis stage is one of the most important factors which can affect the final surface roughness. As can be seen in Fig. 12, with the decrease of the wire feed rate, the surface

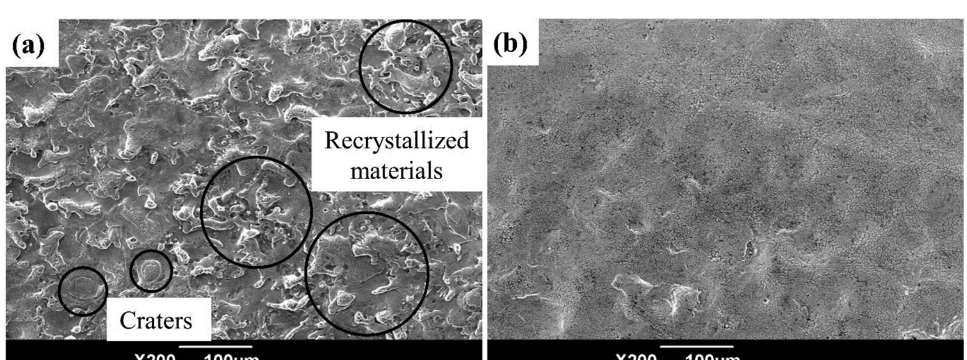

Fig. 9. Surface machined by using (a) WEDM, and (b) WEDCM with V_f 0.3 μm/s and d_m 20 μm.

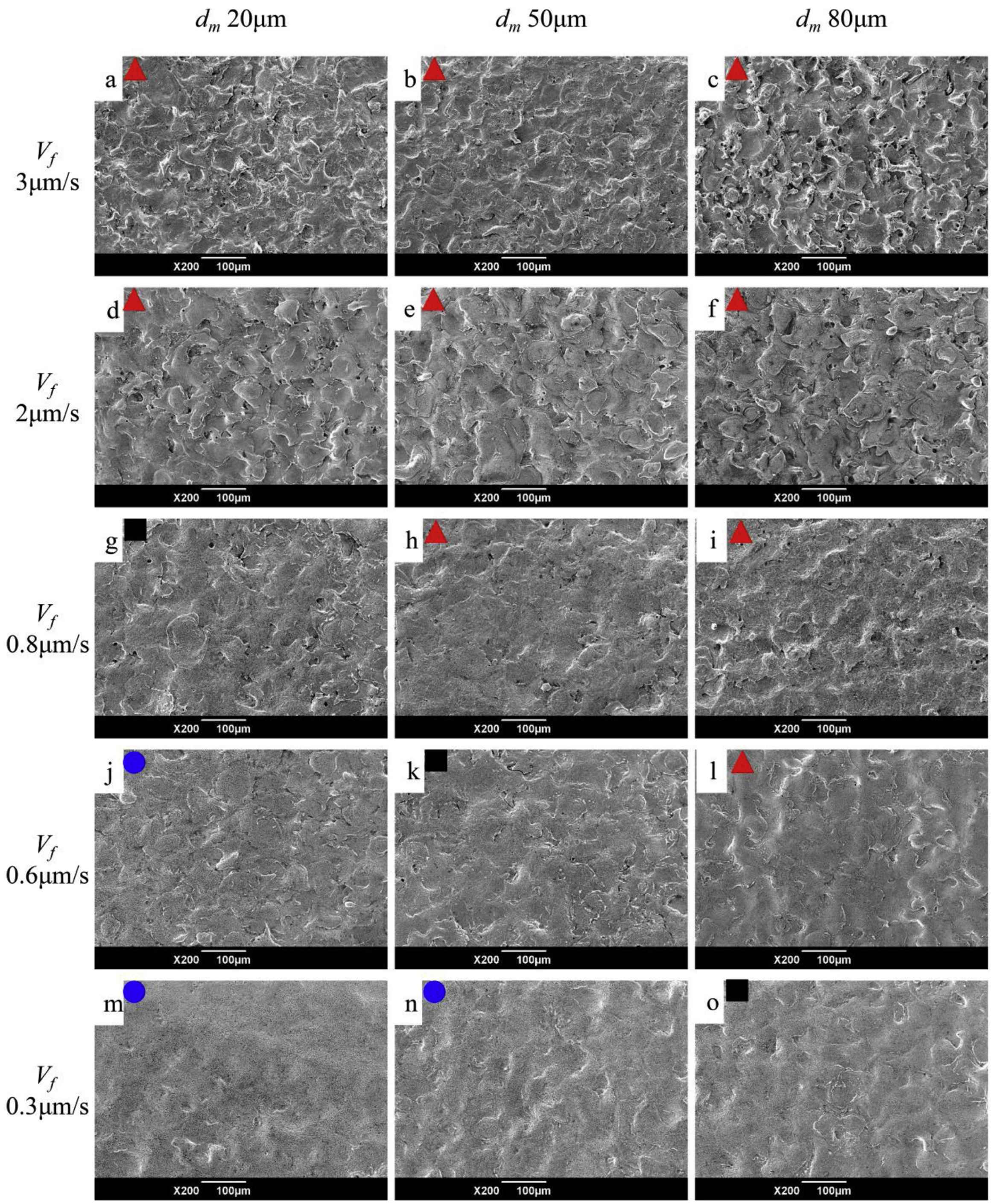

Fig. 10. SEM images of workpiece machined with different feed rate V_f and different movement distance d_m. Red triangle represents the experiments with parameters above the curve; Black rectangle near the curve; Blue circle blow the curve (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

roughness R_a always declines no matter what the movement distance is. The reason is introduced in Section 5.1. If the wire feeds fast, it stays at a certain position on the surface less time, indicating that it doesn't have enough time to dissolve the rough structure, so the surface quality cannot be greatly improved. On the contrary, if the wire feeds slow, which means the wire has much more time for materials dissolution, the surface quality can be improved as a result. Therefore, in order to obtain the good surface quality, the wire electrode should be fed as slow as possible during the electrolysis stage. When the feed rate is 0.3 μm/s and movement distance is 20 μm, the surface roughness R_a significantly reduces to 0.82 μm, decreasing by 74% compared with the WEDM surface roughness, which is 3.14 μm.

5.3.2. The movement distance of the workpiece (d_m)

Aside from the wire feed rate during the electrolysis stage, the movement distance of the workpiece d_m is another factor affecting the final surface roughness.

As can be seen in Fig. 12, when the feed rate is larger than 0.8 μm/s, the movement distance has great influence on the final surface roughness. If the movement distance is 20 μm or 80 μm, the surface roughness is high. However, the reasons of this phenomenon are different. Firstly, if the movement distance is 20 μm, the gap between the wire and the

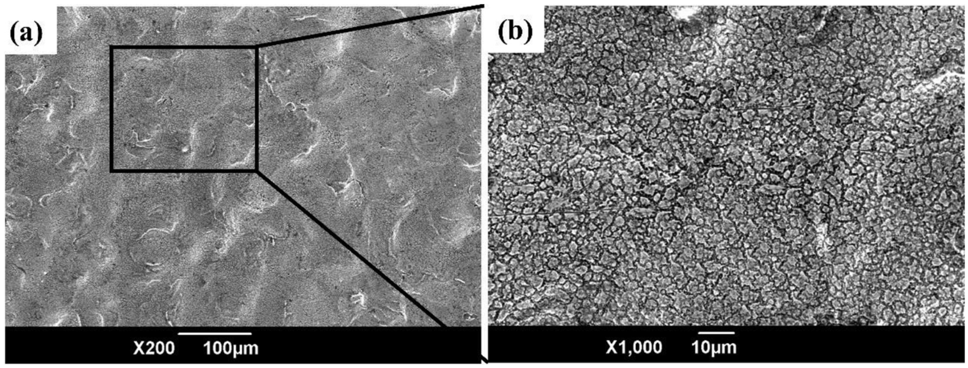

Fig. 11. The grain boundaries on the surface with V_f 0.3 μm/s and d_m 50 μm.

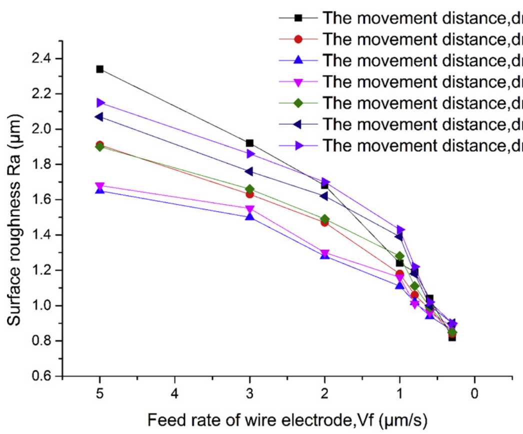

Fig. 12. Surface roughness with different feed rate V_f and movement distance d_m.

workpiece is not big enough. Therefore, owing to the wire vibration, the discharge sparks still can be generated during the electrolysis stage, leading to the high surface roughness. Secondly, if the movement distance is 80 μm, the gap between the wire and the workpiece is big enough so that the sparks don't occur during the electrolysis stage. However, since the gap between the two electrodes is too large, the ability of electrochemical dissolution becomes weak. The recast layer cannot be fully dissolved and the surface roughness is also high. Therefore, in order to obtain the lower surface roughness, the movement distance should be appropriate. After the movement of the workpiece, the gap between the wire and the workpiece should be large enough so that the sparks cannot be generated during the electrolysis stage. At the same time, the gap between the two electrodes must be small enough as well, so that more materials of the recast layer can be dissolved by electrochemical reaction. With the experimental conditions of this study, the suitable movement distance is 40 μm or 50 μm.

When the feed rate is less than 0.8 μm/s, such as 0.6 μm/s or 0.3 μm/s, which is in the red rectangle area in Fig. 13, the influence of movement distance on surface roughness becomes less important. No matter what the gap between two electrodes is, since the wire feeds slowly enough, most of the recast layer can be removed. This phenomenon indicates that if the feed rate V_f decreases to a certain value, its effect on surface quality exceeds that of the movement distance d_m. After these craters and recrystallized materials are dissolved, the surface topography becomes similar, such as Fig. 10(m), (n) and (o), and the values of the surface roughness R_a are relatively close, which are about from 0.82 μm to 0.9 μm with the wire feed rate 0.3 μm/s.

6. Conclusions

In this study, a novel machining method WEDCM, which uses WECM to remove the recast layer and improves the WEDM surface quality, has been proposed and studied. The model based on the double layer model and the Faraday's law of electrolysis has been developed to identify the wire feed rate, and it has been validated by the experiments. The following conclusions can be drawn:

1 Two factors, namely the wire feed rate and the movement distance, have great influence on the final surface quality in WEDCM. Lower wire feed rate is required when higher movement distance is used.
2 If the wire feed rate is high, the movement distance should be appropriate, which means after the workpiece moves a certain distance, the gap between the wire and the workpiece needs large enough to prevent from the sparks occur during the electrolysis stage and small enough so that more materials are dissolved.
3 If the wire feed rate is relative low, no matter what the movement distance is, most of the recast layer is removed. The surface topography becomes similar, and the surface roughness becomes relatively close.

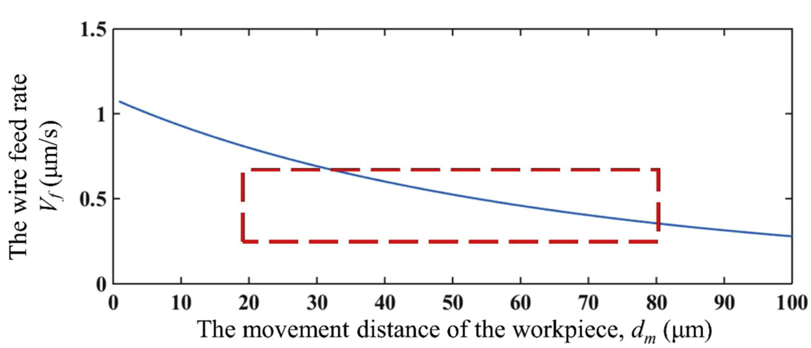

Fig. 13. The recast layer is dissolved with the feed rate less than 0.8 μm/s.

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