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ORIGINAL ARTICLE

Experiment investigation of using wire electrochemical machining in deionized water to reduce the wire electrical discharge machining surface roughness

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Abstract
When the workpiece is sliced by using wire electrical discharge machining (WEDM), the materials are removed by melting and evaporation. Owing to the material removal mechanism, the surface of the workpiece after WEDM is composed of recast layer and numerous discharge craters, leading to the low surface roughness. In this study, wire electrochemical machining (WECM) is introduced to eliminate the recast layer and improve the surface quality of the workpiece cut by using WEDM. Two methods, which are based on electrochemical dissolution reactions, are proposed to dissolve the recast layer and craters on the WEDM surface. The processes are conducted on the same machine tool with the same electrolyte (deionized water) and the same machining parameters. Two factors, which have a great influence on the surface roughness, namely the feed rate of the wire electrode and the movement distance of the workpiece, are analyzed. Experiment results show that the recast layer and craters on the WEDM surface can be dissolved owing to the anodic dissolution of WECM, and the surface quality can be improved. In order to obtain the good surface roughness, the wire electrode should be fed as slow as possible during the electrolysis, and the movement distance of the workpiece should be appropriate.

Keywords Wire electrical discharge machining (WEDM) · Wire electrochemical machining (WECM) · Anodic dissolution · Surface roughness · Recast layer

1 Introduction

Electrical discharge machining (EDM), a common non-traditional machining, has been widely used to fabricate difficult-to-machine materials due to the fact that it is a noncontact electro-thermal machining method, which has no cutting forces during machining.

When the pulse power supply applied between the electrode and the workpiece ionizes the dielectric fluid, a series of electrical discharges are generated, which remove the materials by melting and evaporation [1]. Owing to the characteristic, multitudinous overlapping craters, which are generated by the spark discharge, can be found on the surface after the workpiece is processed by using EDM [2]. During the process, the un-expelled materials are re-solidified on the surface to form a layer called recast layer, which is hard, brittle, and totally different from its base metal material. Owing to the existence of the craters and recast layer, the EDM surface has high surface roughness. It is hard to acquire a surface with low roughness even with optimized EDM technology [3]. Moreover, the recast layer can deteriorate some properties such as fatigue strength, resistance to corrosion, and service life [4]. For this reason, the aerospace industry has restricted the use of EDM to manufacture the selected components [5].

In order to reduce the surface roughness of EDM, some other processing methods have been introduced to remove the craters and recast layer. Wu et al. [6] combined fixed

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abrasive wire saw and WEDM to improve the surface quality. The experiments show that the hybrid machine can reduce the surface roughness and kerf width compared with WEDM. The recast layer and the surface heat-affected zone can also be eliminated.

Besides the wire saw method, where tools are in contact with the workpiece, electrochemical machining (ECM), which is based on the principle of anodic dissolution of metallic materials, is another method which is employed to obtain better surface quality. When the voltage is applied between the anode workpiece and the cathode tool, a current passes through them since the electrolyte acts as a current carrier, and the anode workpiece is dissolved in term of Faraday's law [7]. Owing to the fact that it can dissolve the conductive materials at atomic sizes regardless of their hardness and the toughness of the workpiece, ECM can produce smooth and stress-free surfaces [8]. Therefore, many researches have been made to improve the EDM surface using ECM.

Minh Dang Nguyen et al. [9–11] combined micro-EDM and micro-ECM in a hybrid machining process to achieve improved performance in both surface finish and machining accuracy by using low-resistivity deionized water. Xu et al. [12] studied a hybrid electrochemical discharge drilling method to machine holes. The recast layer generated by electrical discharge at the side gap is removed electrochemically, and the 4-mm-deep hole of 0.5-mm diameter is machined with low tool wear and almost no recast layer. Tsuneo Kurita et al. [13] investigated EDM shaping and ECM finishing technology. These two processes are carried out in sequence on the same machine tool with the same electrode and the same electrolyte. The EDM surface of 1 μm R_a is improved to 0.2 μm R_a by using ECM. Ramasawmy et al. [3] investigated the parameters of electrochemical polishing which affect the 3D surface texture of EDM surfaces, and a high influence of the interactive effect of current density and electrode gap was also observed. Chung et al. [14] investigated machining characteristics of electrochemical finishing process after micro-EDM in deionized water. The research shows that craters generated by electrical discharge are removed and smooth surfaces are obtained after about 40 s finishing time. Hung et al. [15] proposed a process of using micro-EDM combined with electropolishing to reduce the surface roughness of micro-holes and low surface roughness of the hole wall can be achieved by applying a proper electrolytic voltage and a suitable concentration of solution. The maximum surface roughness reduces from 2.11 to 0.69 μm after electropolishing.

When the wire electrical discharge machining (WEDM) is used to cut the materials, the workpiece surface has the same problems. The craters, cracks, and recast layer on the surface seriously deteriorate the surface quality. This paper proposes two methods to eliminate the recast layer and reduce the WEDM surface roughness. The first method, which combines WEDM and WECM in sequence, named as WEDCM, is introduced and investigated by the experiments. The impacts of two vital factors, namely the wire feed rate during electrolysis and movement distance of the workpiece, are analyzed. The second method, which simultaneously combines WEDM and WECM in a hybrid machining process, named as SWEDCM, is also discussed. The experiments are conducted to validate the proposed methods.

2 The principle of WEDCM and SWEDCM

In this study, WEDM and WECM are performed with the same electrolyte, which means that the electrolyte have the characteristics of both dielectric and electrolyte. On the one hand, the electrolyte can be ionized by the voltage applied across the anode workpiece and cathode wire; on the other hand, the electrolyte should have weak electrochemical reaction so that it can dissolve the anode workpiece during machining. Under these circumstances, the low-conductivity salt solution [16] and low-resistivity deionized water [9, 11] are often used. Given the characteristic of environmentally friendly, deionized water is adopted in this study.

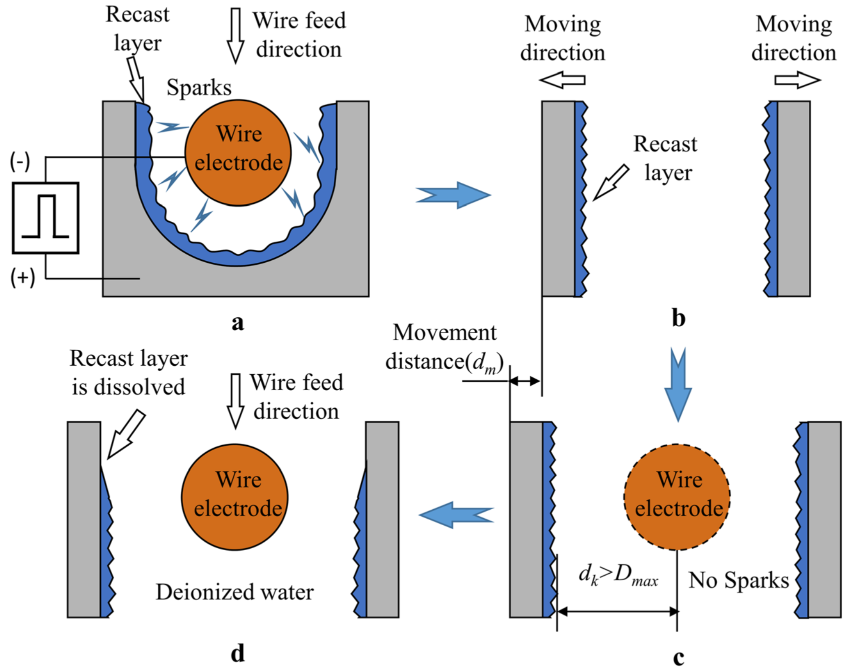
Figure 1 illustrates the WEDCM principle. The machining process is divided into three steps: in the first step, the workpiece is sliced by using WEDM, as shown in Fig. 1a. In this step, the process is also affected by electrochemical dissolution simultaneously, but the sparks erosion still plays the dominant role in material removal. Therefore, the workpiece surface is covered with overlapping discharge craters after the process, and recast layer can also be found, leading to a rough surface, as shown in Fig. 1b. In order to reduce the surface roughness, WECM is introduced.

In the second step, the workpiece is moved outwards under the control of the machine tool control system for a certain distance (d_m). After the movement, the gap between the wire and the workpiece (d_k) should be larger than the maximum distance of the spark discharge (D_{max}), so that the spark can no longer be generated, as shown in Fig. 1c.

The third step is the step of WECM. In this step, the wire electrode is re-fed again. As mentioned above, no sparks can be generated during this step, indicating that WEDM stop working. Since the deionize water has weak electrochemical reaction, electrochemical dissolution plays the predominant role in this step, which means the craters and recast layer begin to be dissolved due to the principle of anodic dissolution, as shown in Fig. 1d.

In this way, WEDM and WECM are performed in sequence on the same machine tool with the same electrolyte (deionized water) and the same machining parameters. The discharge craters and the recast layer generated by electrical discharge can be removed electrochemically, and the surface quality can be improved.

Fig. 1 The principle of WEDCM



The main characteristic of WEDCM is that the wire electrode needs to feed twice: the first feed, WEDM slices the workpiece through, and the second feed, WECM dissolves the recast layer. Moreover, between the two feeds, the workpiece should move outwards for a certain distance.

Based on the same fundamentals, the second method, named SWEDCM, is proposed. In this method, WEDM and WECM can be combined in a single process simultaneously. The wire electrode just needs to feed only once, and the workpiece keep still. The principle of SWEDCM is shown in Fig. 2.

The main characteristic of SWEDCM is that the feed rate of the wire should be slow during the whole process. Firstly, the workpiece is sliced by the wire electrode with slow feed rate, and the sparks remove the materials constantly, as shown in Fig. 2a. Since the feed rate of the wire is less than the rate of the sparks removal materials, the electrode-workpiece gap (d_k) becomes larger and larger as the cutting continues. When the gap between the wire and the workpiece (d_k) is larger than the maximum distance of the spark discharge ($D_{\max}$), the sparks cannot be generated, as shown in Fig. 2b. At this moment, owing to the weak electrochemical reaction of the deionize water, the anodic materials begin to be dissolved, the recast layer is removed and better surface quality can be obtained, as shown in Fig. 2c. As the wire electrode continues to feed, once the gap between the wire and workpiece is close, the sparks reappear to remove the materials. This process is repeated again and again until the workpiece is cut off.

3 Experiment

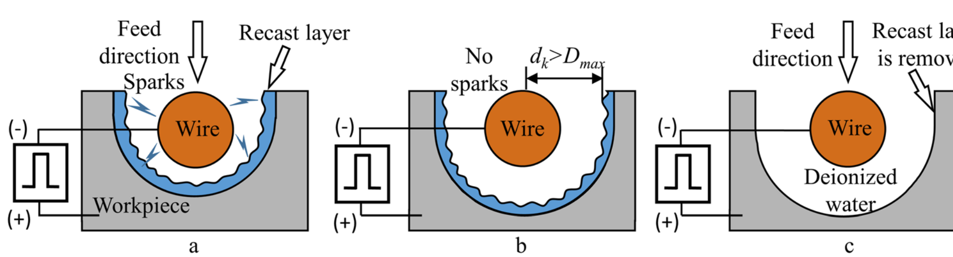
3.1 Experimental set-up

In this study, the experiments are conducted with WEDM cutting machine QT56 produced by Jiangzhou CNC Machine Tool Manufacture Co., Ltd., as shown in Fig. 3. Stainless steel AISI 304 (Chinese standard: 0Cr18Ni9, Japanese standard: SUS304) is employed as workpiece. The other experimental and testing apparatuses are in Table 1.

3.2 Experimental procedure

In the experiments, firstly, the workpiece is cut by using WEDM. The processing parameters are shown in Table 2. Secondly, the workpiece is moved outwards under the control

Fig. 2 **a**–**c** The principle of SWEDCM



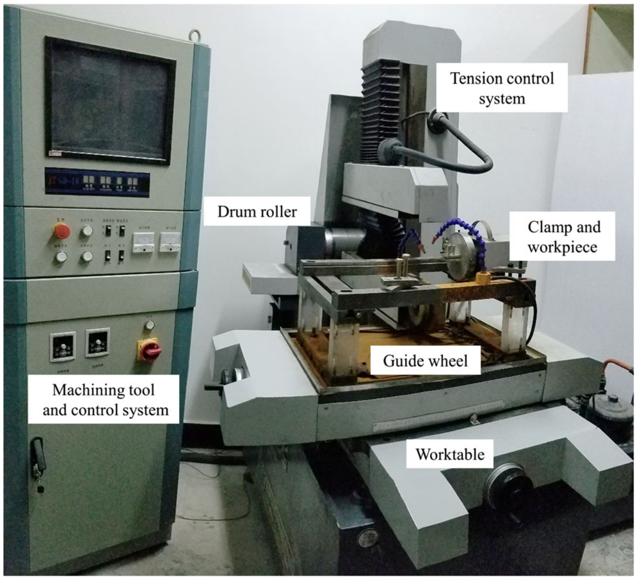


Fig. 3 Experimental platform

system for a certain distance (d_m). Thirdly, the wire electrode is re-fed along the original route and begins to electrochemically dissolve. During the process of electrolysis (the third step), the processing parameters is still the same parameters used in the first step, which are shown in Table 2.

In order to investigate the effect of the movement distance of the workpiece (d_m) in the second step and the feed rate of the wire during the third step on the surface quality, different movement distances and feed rates are adopted in this study, as shown in Table 3.

The surface roughness *Ra* of four different positions, which are evenly distributed on the workpiece surface, are measured, and the average value is calculated as the surface roughness of this workpiece surface. When the kerf width is calculated, the experiments are carried out three times under the same parameters, and the average value is taken, but only representative images are shown.

4 Results and discussion

4.1 Surface topography after WEDM

Figure 4 illustrates the workpiece surface sliced by using WEDM with the parameters in Table 2. As can be seen in Fig. 4a, the surface is covered with numerous craters. Furthermore, the molten metal is cooled by the electrolyte and then recrystallized, forming the recrystallized materials on the surface, as shown in Fig. 4b. The surface quality is not good, and surface roughness R_a is 3.14 µm.

After the workpiece is cut off by using WEDM, the workpiece is moved 50 µm outwards, and the wire electrode is re-fed to dissolve the anode materials with the different feed rates

Table 1 Experimental and testing apparatuses

Power supply	Pulsed DC power supply
Workpiece (anode)	Stainless steel 304 with a thickness of 2 mm
Tool (cathode)	Molybdenum wire with a diameter of 0.18 mm
Electrolyte	Deionized water with resistivity of 1 MΩ cm
Surface roughness *Ra* test	Sensofar-Tech, S. L, Leica DCM3D
SEM measurement	JEOL, JSM-6390A

respectively, namely, 3 µm/s, 1 µm/s, and 0.8 µm/s. The SEM images after WECM are shown in Fig. 5b–d.

As can be seen in Fig. 5, after the anode materials are dissolved by the wire electrode during the second feed, although the wire feed rate is different, the surface quality of the workpiece is improved to varying degrees. Owing to the action of electrochemical dissolution, the recrystallized materials are dissolved; the craters on the workpiece surface also disappear; the surface topography becomes smooth; thereby the surface quality is improved.

When the wire feed rate declines to 0.8 µm/s, the grain boundaries of the workpiece after corrosion is found on the surface. Figure 6 shows the grain boundaries on the surface after machining with the movement distance 30 µm and the feed rate 0.8 µm/s. Grain boundaries are seen on the workpiece surface, only after the workpiece surface is corroded. Since ECM is a corrosion process, the fact that grain boundaries is found on the surface after machining indicates that the materials remove mechanism is ECM, rather than sparks discharge.

Figure 7a illustrates the element composition on the surface after WEDM. Figure 7b, c shows the element composition after WECM with the same movement distance 50 µm but the different wire feed rate. The average value of the surface elements after WECM with the different feed rate is calculated, and it is compared with the element composition after WEDM, as shown in Fig. 7d. As can be seen, the carbon element after WEDM is increased. The possible reason may be result from the re-deposition of debris particles on the machined surface [10]. In the process of WECM, the wire is not in contact with the workpiece, and the anode workpiece is dissolved in deionized water, so the elements composition on the surface are almost unchanged after electrolysis.

Table 2 Processing parameters

Voltage (V)	110
Pulse on time (µs)	14
Pulse off time (µs)	42
Feed rate of wire electrode (µm/s)	3
Velocity of the wire electrode (m/s)	2

Table 3 Movement distances of workpiece and wire feed rates during the third step

Movement distance of workpiece, d_m (μm)	20, 30, 40, 50, 60, 70, and 80
Feed rate of wire electrode during electrolysis (μm/s)	5, 3, 1, and 0.8

4.2 Effect of the feed rate of the wire electrode on the surface quality

Different movement distances in the second step and different feed rates in the third step, which are shown in Table 3, are used to machine the workpiece. The SEM images after process are shown in Fig. 8, and the surface roughness R_a is shown in Fig. 9. As can be seen, these two factors, namely movement distance of the workpiece and feed rate of the wire electrode, significantly affect the surface quality after processing.

As can be seen in Figs. 5, 8, and 9, no matter what the wire feed rate is, the surface quality can always be improved. Furthermore, the lower the feed rate is, the better surface quality can be obtained.

When the feed rate is 3 μm/s, some recrystallized materials on the surface are still visible, which are not fully dissolved. When the feed rate decreases to 1 μm/s and 0.8 μm/s, most recrystallized materials are gradually dissolved or even disappear, and the surfaces become flat. The same conclusions can be made from Fig. 9. As can be seen, whatever the movement distance is, with the decrease of the wire feed rate, the surface roughness is always reduced. When the movement distance is 50 μm and the wire feed rate is 0.8 μm/s, the surface roughness is significantly reduced to 1.01 μm, which decrease by 68% compare with the WEDM surface roughness.

This is a consequence of the electrolysis. In the stage of electrolysis, if the wire electrode is fed slow, the wire stays at a certain position on the surface much more time. Thereby, more materials are dissolved, leading to the better surface quality. On the contrary, if the wire is fed fast, it has not enough time to dissolve the rough structure, so the surface quality is still unsatisfactory. Therefore, in order to obtain the better surface quality, the wire feed rate during the electrolysis should be as slow as possible.

4.3 Effect of the movement distance of the workpiece on the surface quality

Aside from the feed rate of the wire electrode, another factor which can affect the machined surface is the movement distance of the workpiece during the second step (d_m).

Figure 9 shows that no matter what the feed rate is, with the increase of the movement distance, the surface roughness R_a decreases at first, which reduces to the minimum value when the movement distance is 40 μm or 50 μm, and then the surface roughness rises again. The reason lies in two aspects: the vibration of the wire electrode and characteristic of the electrochemical dissolution.

If the movement distance is too small, such as 10 μm, the gap between the wire and the workpiece (d_k) after the movement is still smaller than the maximum distance of the spark discharge (D_{max}), which means that the second feed is still based on EDM removal mechanism. Lots of spark can be seen during the wire second feed in the experiments. Therefore, this small movement distance does not meet the requirement of the method.

As mentioned in Section 2, the movement distance should be big enough so that the electrode-workpiece gap (d_k) is larger than the maximum distance of the spark discharge (D_{max}), which means that the sparks cannot be generated in the electrolysis stage. However, owing to the vibration of the wire and the machine tool, the maximum distance of the spark discharge is not stability.

For example, when the movement distance increases to 20 μm, although the sparks reduce significantly during the wire second feed, the sparks do not disappear completely. With the vibration of the wire and the machine tool, or even the change of the flow direction of the electrolyte, the sparks can be generated from time to time. Consequently, although the surface quality is improved when the movement distance is 20 μm, the improvement is not significant. When the movement

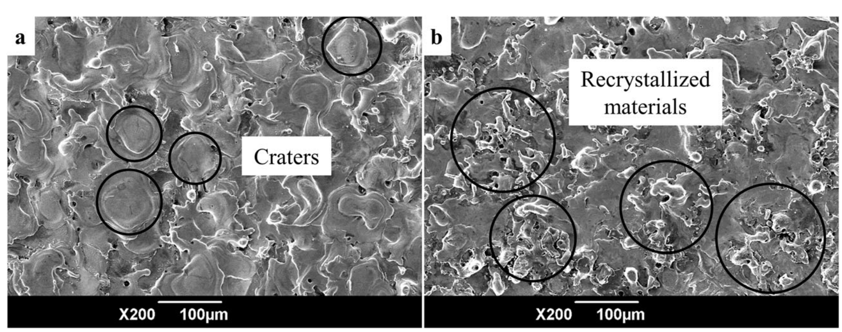


Fig. 4 The characteristics of WEDM surface. **a** Craters. **b** Recrystallized materials

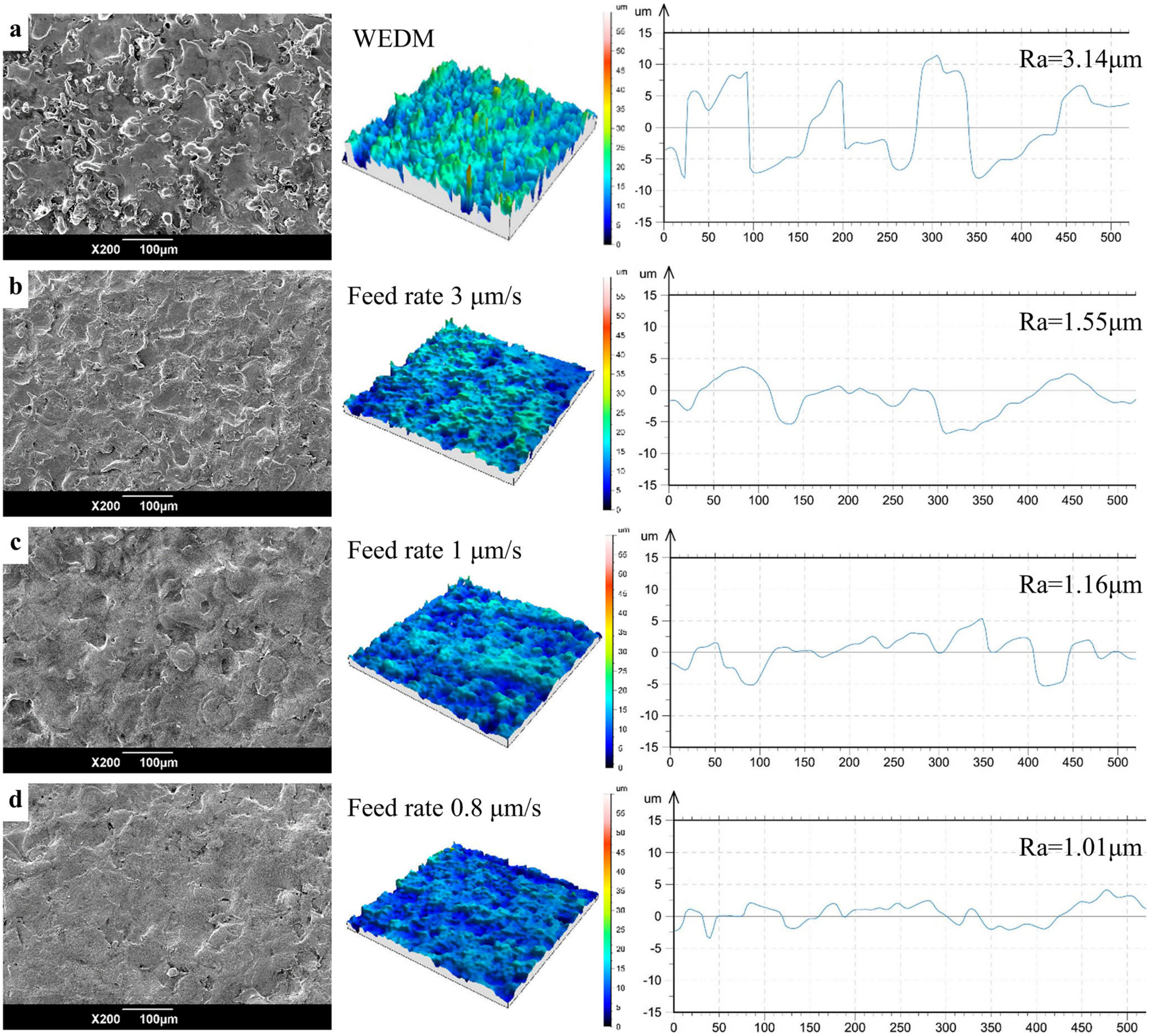
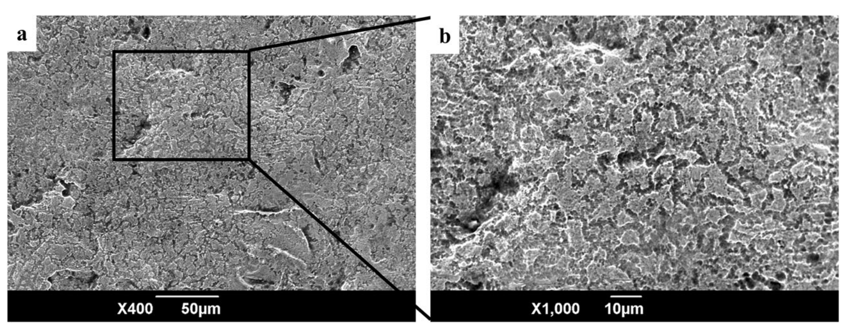


Fig. 5 SEM images of workpiece machined using **a** WEDM and **b**–**d** WECM with the same movement distance (50 μm) but the different wire feed rate

distance is 20 μm and the feed rate is 5 μm/s, the surface roughness R_a is up to 2.34 μm. Even though the feed rate is as slow as 0.8 μm/s, the surface roughness R_a is 1.19 μm.

When the movement distance enhances to 40 μm and 50 μm, the sparks completely disappear during the wire second feed, indicating that the process is totally electrochemical dissolution in the electrolysis stage. As can be

Fig. 6 The grain boundaries on the surface when movement distance 30 μm and the feed rate 0.8 μm/s



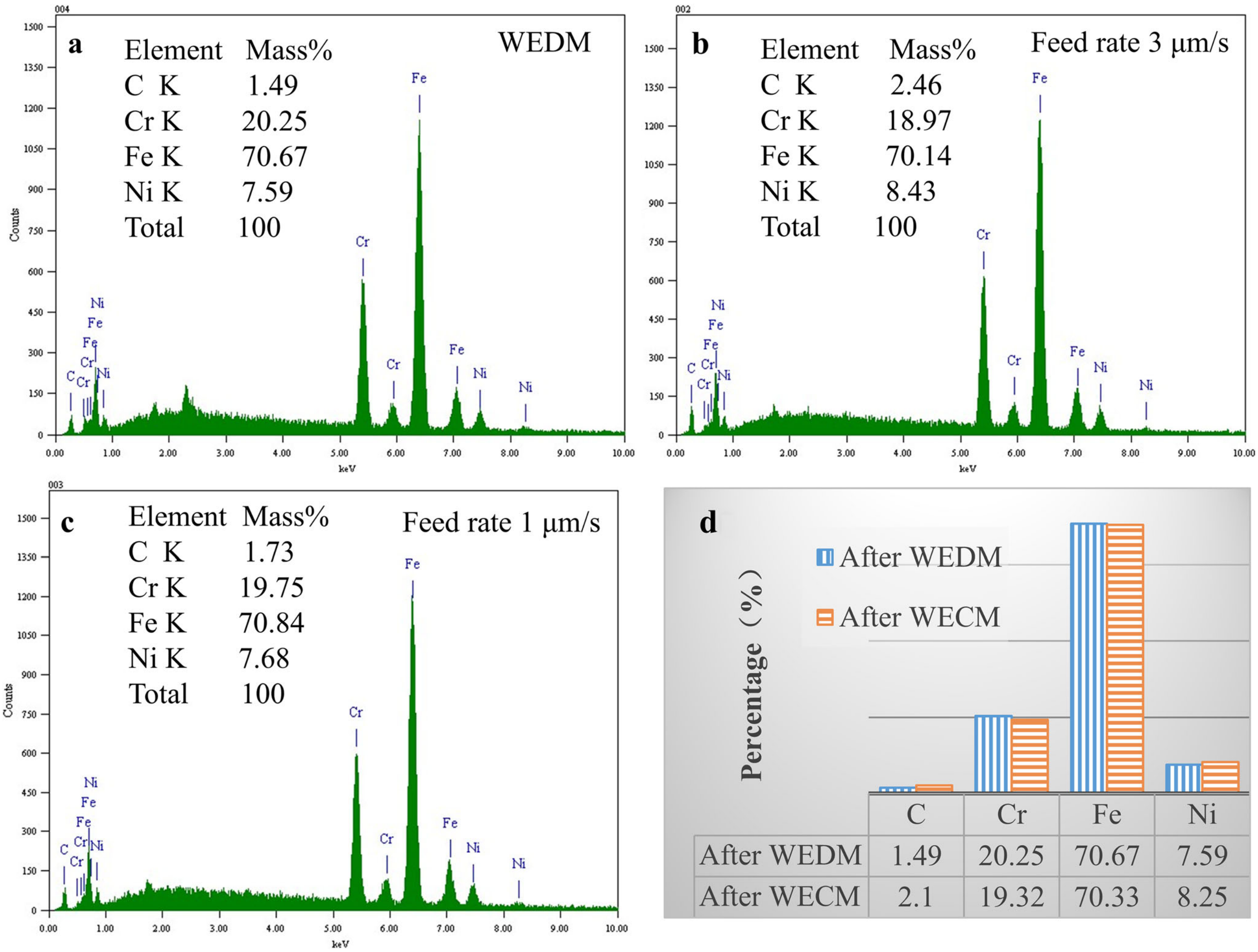


Fig. 7 Elements composition on the surface. **a** After WEDM. **b**, **c** After WECM with the same movement distance (50 μm) but the different wire feed rate. **d** Comparison of elements composition

seen in Fig. 8, more recrystallized materials on the surface have been dissolved, and the surfaces become relatively smooth. Figure 9 shows that no matter what the wire feed rate is, the surface roughness R_a is always the lowest when the movement distance is 40 μm or 50 μm.

However, when the movement distance of the workpiece further increases, such as 70 μm and 80 μm, although there are no sparks at all during the second feed, which means the whole process is electrochemical dissolution, the surface roughness increases again. This phenomenon stems from the decrease of the material removal rate of WECM. According to the Faraday's law, the material removal rate relies on the electrochemical properties of workpiece, properties of electrolyte and the electric current, which is:

$$v = \eta\omega i \tag{1}$$

where η is current efficiency; ω is volume electrochemical equivalent; and i is the average current density.

When the gap between anode workpiece and cathode wire increases, the resistance between them also increases, leading to the decrease of the average current density (i). Therefore, the material removal rate decreases as well. As can be seen in Fig. 8j, when the movement distance is 80 μm and feed rate is 3 μm/s, the surface is covered with the recrystallized materials again, indicating that the materials are not fully dissolved at all. As a result, the surface roughness rises again. With the feed rate 0.8 μm/s, if the movement distance increases from 50 to 80 μm, the surface roughness R_a increases from 1.01 to 1.22 μm.

In summary, in order to obtain the better surface quality, the movement distance should be suitable. On the one hand, after the workpiece is moved, the gap between the wire and the workpiece (d_k) should be far enough so that it can exceed the maximum distance of spark discharge ($D_{\max}$) and guarantee that the sparks cannot be generated. On the other hand, the gap between the wire and the workpiece should be close enough so that the recast layer can be fully dissolved. For

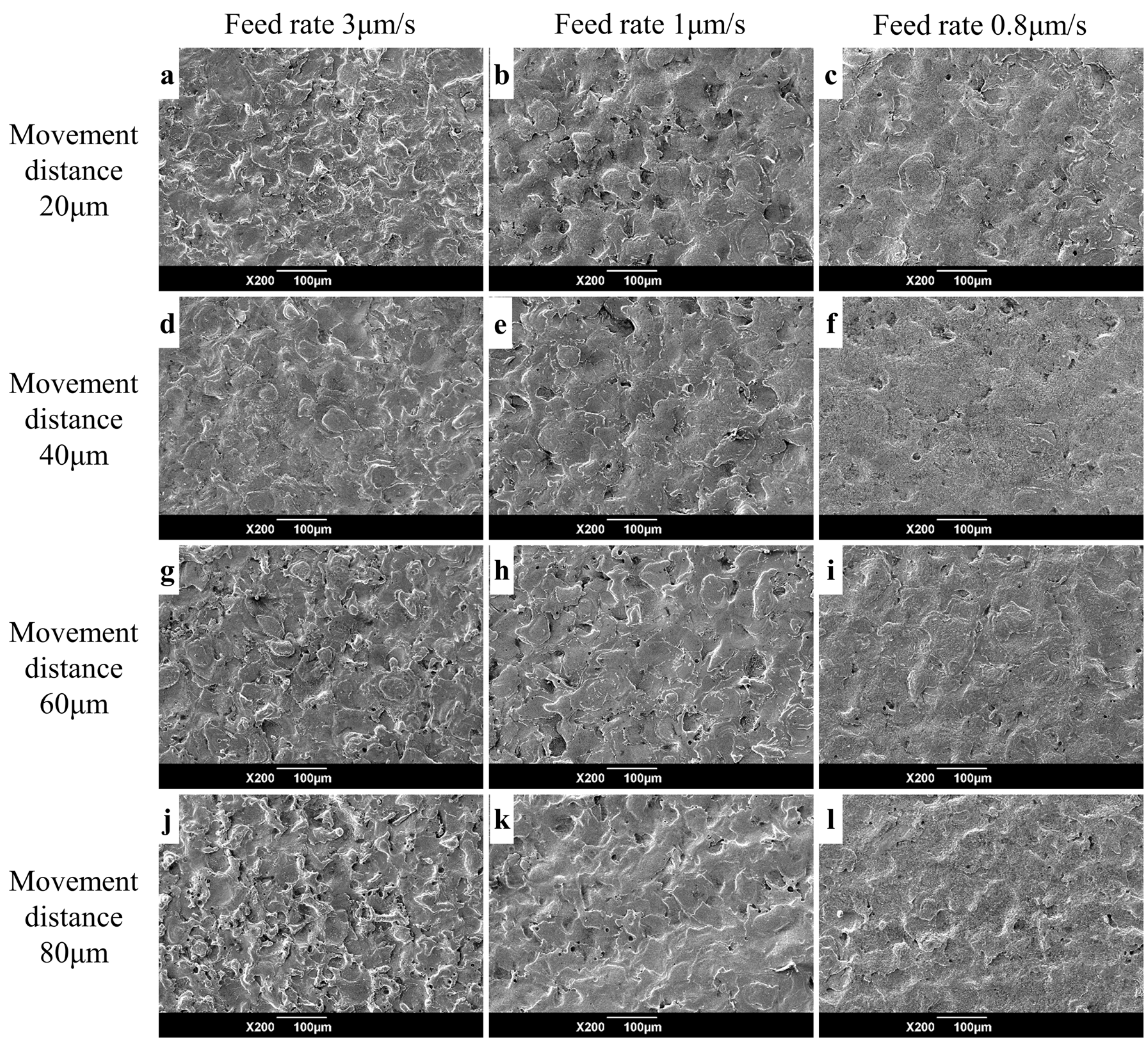


Fig. 8 SEM images of workpiece machined with different movement distances and different feed rates

the experimental conditions of this study, the suitable movement distance is from 40 to 50 μm.

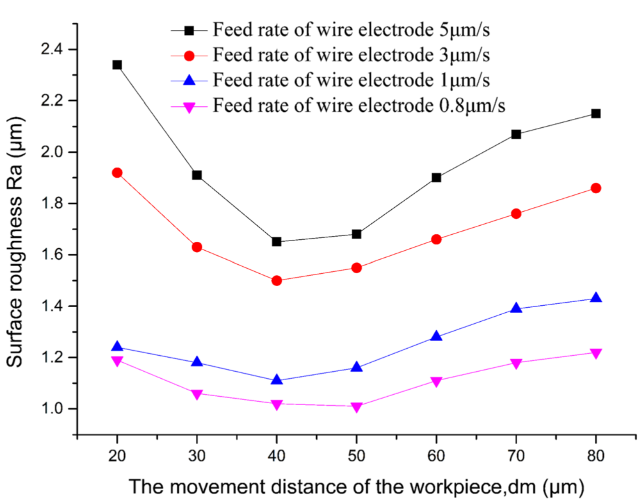


Fig. 9 Surface roughness with the different movement distances and the wire feed rates

4.4 Multiple feeds during electrolysis stage

As mentioned in Section 4.2, in order to dissolve the recast layer and obtain the better surface quality, the wire feed rate during the electrolysis stage should be as slow as possible. The reason is that the recrystallized materials need enough time to be dissolved. Besides reducing the feed rate, increasing the number of wire feed can also provide more time to dissolve the materials. Therefore, multiple feeds during electrolysis stage is another choice to improve the surface quality.

With the parameters of movement distance 60 μm and the feed rate 4 μm/s, the workpieces are sliced with different feed numbers during the electrolysis. The wire is fed once, twice, three times, and four times respectively during WECM, and the SEM images are shown in Fig. 10. As can be seen in Fig. 10, as the feed number increases, the recrystallized materials are dissolved gradually, the surface quality is getting better, and the surface roughness R_a reduces to 1.13 μm after the wire is fed four times.

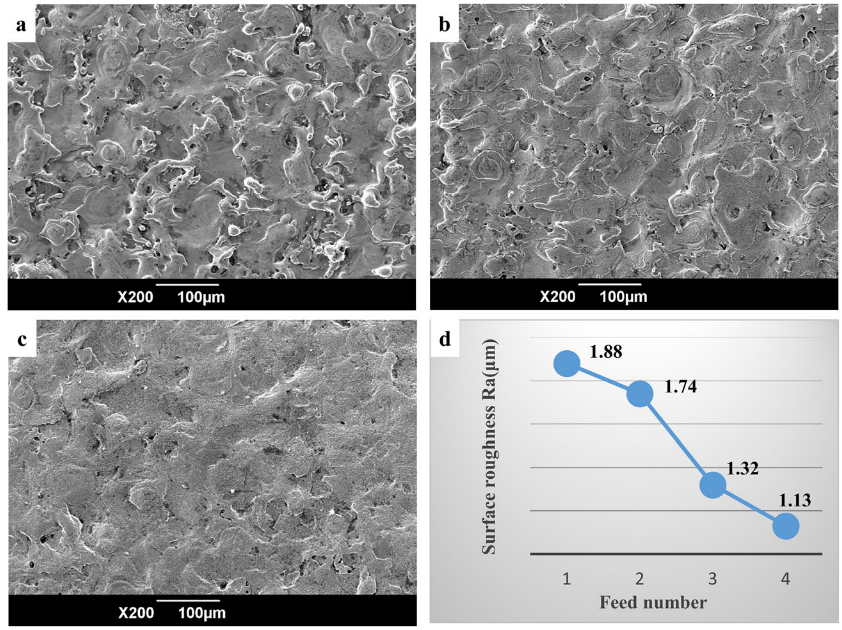


Fig. 10 SEM images of workpiece with different feed numbers during WECM. **a** Once. **b** Twice. **c** Four times. **d** The change of the surface roughness

The experiments provide a possibility method to improve surface quality without sacrificing cutting efficiency. If several wire electrodes are clamped together in a row, the workpiece are sliced in the same position by using these wires one by one. The first wire cut the workpiece by using WEDM, and the following wires dissolve the recast layer with the higher feed rate. Therefore, in this way, the cutting efficiency and surface quality can be both improved.

4.5 Cutting workpiece with SWEDCM

As mentioned in Section 2, if the workpiece is cut with slow feed rate, the better surface quality can also be obtained. Figure 11 exhibits the surface machined with the feed rate 0.5 μm/s, and other parameters are still in Table 2. With this method, the wire is fed just once, and the surface roughness R_a is 1.17 μm.

At the beginning of the process, bright sparks can be seen in the cutting area. Although discharge erosion and electrochemical dissolution occur simultaneously, the WEDM plays a dominant role at this stage. After the cutting lasts for some time, the sparks begin to decrease, which means the feed rate of the wire is less than the materials removal rate of WEDM. At this moment, the gap between wire and workpiece surface is approaching the maximum distance of spark discharge. As the process continues, the sparks gradually disappear, indicating that the gap between wire and workpiece surface is larger than the maximum distance of spark discharge. From this moment, WEDM stop working. Owing to the weak electrolysis of deionize water, WECM begins to work, and the materials on the workpiece surface begin to dissolve. After the disappearance of sparks for a period of time, as the wire continues feeding, the sparks appear again and begin to remove the materials.

It is noteworthy that, in ordinary WEDM, if the feed rate of the wire is slow, the better surface quality is obtained as well, but the material removal mechanism is still the sparks removal, which is different compared with SWEDCM. No matter how slow the wire feeds in WEDM, the materials are removed by melting and evaporation, and the surface is still covered with discharge craters and recast layer. But with SWEDCM, the materials removal mechanism is combining the discharge erosion and electrochemical dissolution together. During the cutting process, the sparks sometimes are bright, sometimes

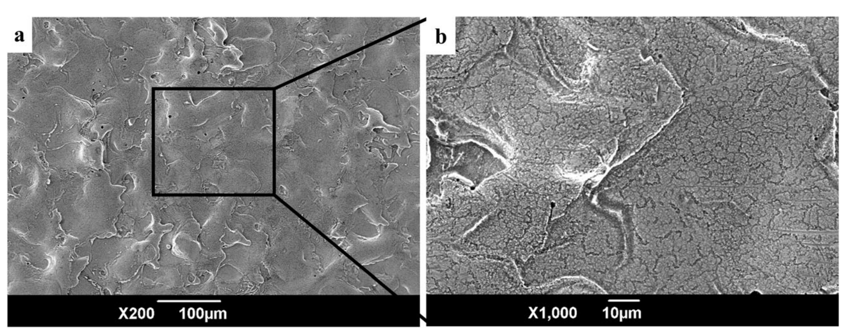


Fig. 11 SEM images of workpiece sliced with the feed rate 0.5 μm/s

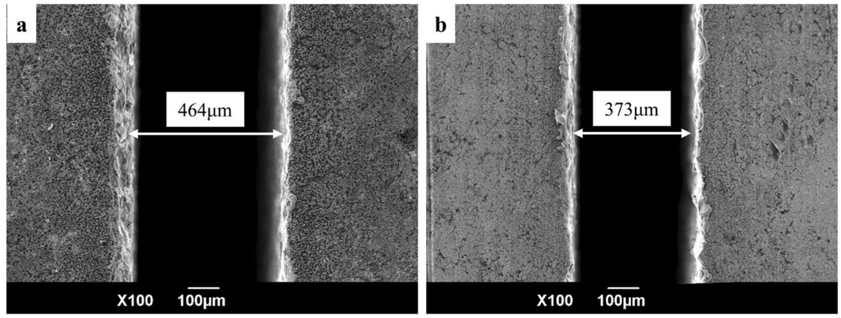


Fig. 12 The kerf width of different feed rate. **a** 0.5 μm/s. **b** 3 μm/s

faint, or even disappear, indicating the materials are removed by WEDM and WECM alternately. At the moment when the sparks disappear, the WECM plays a dominant role to dissolve the recast layer and improve the surface quality. Figure 11b shows the grain boundaries after corrosion by WECM can be found on the surface, indicating that the materials are remove by electrochemical dissolution.

In the method of SWEDCM, the gap between the wire and the workpiece during the process should be larger than the maximum distance of the spark discharge. Therefore, the kerf width of SWEDCM is larger than that of ordinary WEDM. As shown in Fig. 12, when the wire feed rate is 0.5 μm/s, which implies the processing is SWEDCM, the kerf width is 464 μm. When the wire feed rate is 3 μm/s, which indicates the processing is ordinary WEDM, the kerf width is just 373 μm. Figure 13 shows the surface roughness of workpiece cut by SWEDCM and WEDCM with the same feed rate 0.5 μm/s.

In WEDCM, when the feed rate is 0.5 μm/s during the second feed, no matter what the movement distance is, the surface roughness R_a is always lower than the surface roughness of workpiece cut by SWEDCM with the same feed rate. The reason may be attribute that the time for electrochemical dissolution in WEDCM is little longer than that in SWEDCM. In WEDCM, the whole process during the second feed is a process of electrochemical dissolution, and the only role of the wire is to dissolve the recast layer. However, in SWEDCM, the process is a combination of WEDM and WECM. That is to say, during the whole process, only part of the time is used for electrochemical dissolution, and the rest of the time is used for sparks to remove the materials. Thereby, in SWEDCM, materials have no enough time to be dissolved compared with WEDCM, and the surface roughness is little higher.

5 Conclusions

In the study, WECM is introduced to eliminate recast layer and improve the surface quality of the workpiece cut by using WEDM. The experiments are carried out on the same machine tool with the same electrolyte (deionized water) and the same machining parameters. On the basis of theoretical analysis and experimental research, the following conclusions can be made:

1. WECM dissolves the recast layer and craters generated by sparks discharge and improve the WEDM surface quality. In order to obtain the better surface quality, the wire feed rate during the electrolysis stage should be as slow as possible. However, the movement distance of the workpiece should be suitable. After the workpiece is moved, the gap between the wire and the workpiece should be not only far enough so that it can exceed the maximum distance of spark discharge and no sparks can be generated,

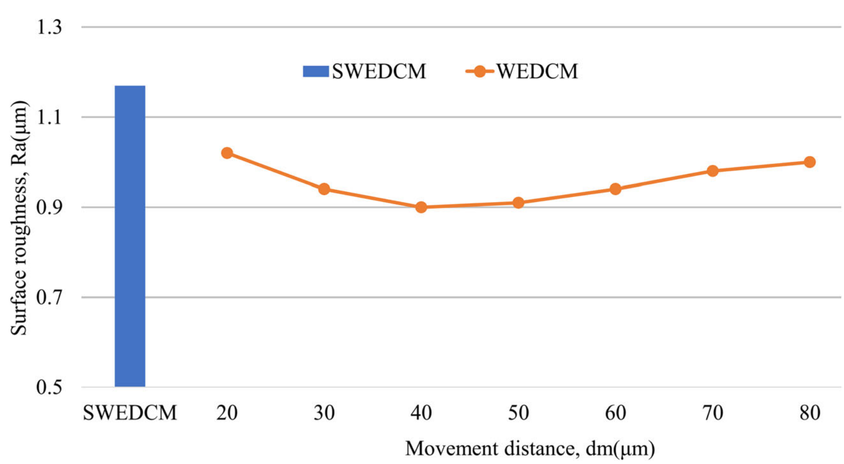


Fig. 13 Surface roughness of workpiece cut by SWEDCM and WEDCM with the same feed rate 0.5 μm/s

but also close enough so that the recast layer can be fully dissolved. The suitable movement distance is from 40 to 50 μm with the experimental conditions in this study.

2. Multiple feeds during WECM can also reduce the surface roughness. The experiments provide a possibility method, with which the cutting efficiency and surface quality can be both improved.
3. When the workpiece is sliced in deionized water, with the slow feed rate such as 0.5 μm/s, the wire is fed only once, WEDM and WECM is combined together simultaneously and the electrochemical dissolution can remove the recast layer generated by sparks and improve the surface quality.

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References

1. Abbas NM, Solomon DG, Bahari MF (2007) A review on current research trends in electrical discharge machining (EDM). Int J Mach Tools Manuf 47(7):1214–1228. https://doi.org/10.1016/j.ijmachtools.2006.08.026
2. Nguyen MD, Rahman M, Wong YS (2012) Enhanced surface integrity and dimensional accuracy by simultaneous micro-ED/EC milling. CIRP Ann Manuf Technol 61(1):191–194. https://doi.org/10.1016/j.cirp.2012.03.011
3. Ramasawmy H, Blunt L (2007) Investigation of the effect of electrochemical polishing on EDM surfaces. Int J Adv Manuf Technol 31(11):1135–1147. https://doi.org/10.1007/s00170-005-0302-8
4. Azam M, Jahanzaib M, Abbasi JA, Abbas M, Wasim A, Hussain S (2016) Parametric analysis of recast layer formation in wire-cut EDM of HSLA steel. Int J Adv Manuf Technol 87(1–4):713–722. https://doi.org/10.1007/s00170-016-8518-3
5. Ayesta I, Izquierdo B, Flaño O, Sánchez JA, Albizuri J, Avilés R (2016) Influence of the WEDM process on the fatigue behavior of Inconel® 718. Int J Fatigue 92:220–233. https://doi.org/10.1016/j.ijfatigue.2016.07.011
6. Wu XY, Li SJ (2018) Experimental investigations of a hybrid machining combining wire electrical discharge machining (WEDM) and fixed abrasive wire saw. Int J Adv Manuf Technol 95(5–8):2613–2623. https://doi.org/10.1007/s00170-017-1357-z
7. Sen M, Shan H (2005) A review of electrochemical macro-to micro-hole drilling processes. Int J Mach Tools Manuf 45(2):137–152. https://doi.org/10.1016/j.ijmachtools.2004.08.005
8. Zeng Y, Yu Q, Fang X, Xu K, Li H, Qu N (2015) Wire electrochemical machining with monodirectional traveling wire. Int J Adv Manuf Technol 78(5–8):1251–1257. https://doi.org/10.1007/s00170-014-6745-z
9. Nguyen MD, Rahman M, San Wong Y (2013) Transitions of micro-EDM/SEDCM/micro-ECM milling in low-resistivity deionized water. Int J Mach Tools Manuf 69:48–56. https://doi.org/10.1016/j.ijmachtools.2013.03.008
10. Nguyen MD, Rahman M, San Wong Y (2012) Simultaneous micro-EDM and micro-ECM in low-resistivity deionized water. Int J Mach Tools Manuf 54:55–65. https://doi.org/10.1016/j.ijmachtools.2011.11.005
11. Nguyen MD, Rahman M, Wong YS (2012) An experimental study on micro-EDM in low-resistivity deionized water using short voltage pulses. Int J Adv Manuf Technol 58(5–8):533–544. https://doi.org/10.1007/s00170-011-3397-0
12. Xu ZY, Zhang Y, Ding F, Wang F (2018) An electrochemical discharge drilling method of small deep holes. Int J Adv Manuf Technol 95(5–8):3037–3044. https://doi.org/10.1007/s00170-017-1355-1
13. Kurita T, Hattori M (2006) A study of EDM and ECM/ECM-lapping complex machining technology. Int J Mach Tool Manu 46(14):1804–1810. https://doi.org/10.1016/j.ijmachtools.2005.11.009
14. Chung DK, Lee KH, Jeong J, Chu CN (2014) Machining characteristics on electrochemical finish combined with micro EDM using deionized water. Int J Precis Eng Manuf 15(9):1785–1791. https://doi.org/10.1007/s12541-014-0530-7
15. Hung J-C, Yan B-H, Liu H-S, Chow H-M (2006) Micro-hole machining using micro-EDM combined with electropolishing. J Micromech Microeng 16(8):1480–1486. https://doi.org/10.1088/0960-1317/16/8/007
16. Zhang Y, Xu Z, Zhu D, Xing J (2015) Tube electrode high-speed electrochemical discharge drilling using low-conductivity salt solution. Int J Mach Tool Manu 92:10–18. https://doi.org/10.1016/j.ijmachtools.2015.02.011