The research of effect of various parameters on processing performance of compound machining of EDM milling and arc machining

Zhenwei Niu, Yonghong Liu¹, Xinlei Wu, Xuexin Zhang and Zhiwei Ding

College of Mechanical and Electronic Engineering, China University of Petroleum(East China), No. 66, West Changjiang Road, Huangdao District, Qingdao, China

¹E-mail: liuyhupc@163.com

Abstract. As a new processing method for hard-to-cut materials, compound machining of EDM milling and arc machining has the extremely high processing efficiency. The study of machining parameters is indispensable to the research of the process performance. In this paper, a large number of single factor experiments under different processing parameters were carried out by using compound EDM arc milling machining technology. The effects of different peak current, arc pulse duration, arc pulse interval, spindle speed and the external diameter of the electrode on processing efficiency, the surface roughness(SR) and relative electrode wear rate(REWR) were obtained. More importantly, different optimal parameters to get the highest processing efficiency, minimal SR and REWR were also acquired to provide support for future research.

1. Introduction

Electrical Discharge Machining (EDM), also known as Electroerosion Machining, is a method of processing utilizing the electrical corrosion generated during pulse discharge between the two electrodes, which is one of the most essential components of non-traditional machining. As a thermal erosion process, the temperature of the plasma during the discharge process is much higher than the melting point of all materials; therefore, EDM can be used for machining all electrically conductive materials irrespective of their hardness [1]. Nowadays, EDM also has low processing efficiency in processing hard-to-cut materials with high strength and high hardness, and traditional EDM can no longer meet the requirements of processing efficiency in modern industry. In this case, many experts worldwide have done many in-depth researches on the mechanism of EDM and the influence of processing parameters on its performance. Masanori K et al. [2] proposed a new method of EDM machining in a gas environment and achieved a stable EDM machining process. Lin et al. [3] combined EDM with ultrasonic machining to increase the material removal rate (MRR) and to decrease the thickness of the recast layer. Guet et al. [4] designed a new bundled electrode that can achieve an MRR of 150 mm³/min, which was approximately five times the process using a traditional electrode. Goutam Mondal et al. [5] conducted experimental studies on the powder mixed electrical discharge machining (PMEDM) to investigate the effect of process parameters on various responses. Li et al. [6] studied the EDM performance in different working media, and the processing performance was summarized concerning the processing performance in kerosene media. Zhao et al. [7] proposed blasting erosion arc machining employing bundled electrodes, and the MRR of BEAM of Inconel718
could exceed 11,300 mm³/min. Kou et al. [8] presented a processing method of high-speed EDM milling with moving electric arcs to the interruption of the ignition delay and discharge interval. Zhu et al. [9] suggested vibration-assisted Electro-Arc Machining (VEAM) and conducted comparative experiments with different machining parameters.

Wang et al. [10] proposed a compound machining of EDM milling and arc machining, and the compound milling experiments were carried out on the nickel-based superalloy Inconel718. They used the high voltage module to provide the breakdown voltage and DC arc module to provide the high current required for machining. Combined with the tubular electrode and the circulating flushing system, the material removal rate can achieve around 21500mm³/min. The machining performance is affected by various parameters and working medium in the process of compound EDM arc machining. Shen Y. et al. [11, 12] studied the process performance of compound EDM arc milling machining in gas and mist media. Compared with the machining process in the liquid media, the compound machining in the mist media could achieve a higher MRR and get the better surface roughness and narrower over-cut. The main reason behind this effect is the improvement of the dielectric cooling capacity, the growth of the dielectric strength and the aided function of the external flushing system.

During the machining process of compound machining of EDM milling and arc machining, the arc is subject to the erosion of the working solution with considerable pressure and the rotation of the electrode, which causes the break of arc. Besides, the break of the arc and the flushing system will sweep away the molten workpiece material to achieve the rapid removal of the workpiece material. The study of machining parameters is indispensable to the research of the process performance. In this paper, a large number of single factor experiments under different processing parameters were carried out by using compound EDM milling and arc machining technology. The effects of different peak current, arc pulse duration, arc pulse interval, spindle speed and the external diameter of the electrode on processing efficiency, the surface roughness(SR) and relative electrode wear rate(REWR) were obtained. More importantly, the optimal operating parameters to get the maximum processing efficiency, the minimum electrode relative, wear ratio and the optimum surface roughness were obtained to provide support for future research.

1, Inner flushing system. 2, Carbon brush. 3, External flushing system. 4, Electrode. 5, Work piece. 6, Marble table.

**Figure 1.** Schematic diagram of equipment of compound machining of EDM milling and arc machining.
2. Basic principle

2.1. Machine setup
Figure 1 shows the schematic diagram of equipment of compound machining of EDM milling and arc machining. The pulse power is composed of high-voltage DC pulse power module (maximum peak voltage 250V, maximum output current 30A) and high-power pulse DC module (peak voltage 70V, maximum peak current 1000A), and the two modules are isolated from each other with high-power diodes. Besides, the liquid cooling system which consists of internal and external flushing system is mainly used for cooling of electrode and workpiece as well as the removal of debris.

2.2. Experimental conditions
The speed of the spindle is 0-3000r/min, and the electrode used is a tubular graphite electrode with an inner diameter 4mm. The material of workpieces used in this paper is 45# steel. The dielectric fluid was composed of 90 mass% distilled water, and ten mass% emulsified oil (DX-1, Nan-jing Special Oil Factory, China). A precision balance (Sartorus, BS224S) with an accuracy of 0.1mg was used to measure the weight losses of the electrode and the workpiece. A tester for SR (TR300, Beijing Time High Technology Ltd.) was employed to measure this variable.

Other experimental conditions are shown in Table 1. The experiments were carried out with a single-factor variable test method. During the experiments, the layer-by-layer processing method was used which is illustrated as follows. Firstly, the electrode fed towards the workpiece to a certain depth along the Z-axis direction, and then moved a certain distance on the XY plane. After finish it, the electrode continued to step down and followed by the same distance move on the XY plane and then repeated this process. After multiple times of layered processing, the removal amount, surface roughness and the relative electrode wear ratio under different parameters were obtained. Additionally, multiple times of layered processing were performed under the same settings, which avoided accidental circumstances such as inaccurate measurement of electrode wear length and workpiece removal amount after one processing, so that the error was minimized and the accuracy of the experimental results was improved.

| Machining parameter                  | Value          |
|-------------------------------------|----------------|
| Peak voltage of pulse generator(V)  | 250            |
| Peak current(A)                     | 200,300,400,500,600,700,800, 900, 1000 |
| Pulse duration of arc module(ms)    | 1, 2, 3, 4, 5, 6, 7, 8, 9, 10       |
| Pulse interval of arc module(ms)    | 1, 2, 3, 4, 5, 6, 7, 8, 9, 10       |
| Electrode rotation speed(r/min)      | 200, 500, 1000, 1500          |
| Electrode external diameter(mm)     | 8, 10, 12, 16               |

3. Results and discussion

3.1. Effects of processing parameters on processing efficiency
During the process of compound EDM milling and arc machining, the peak current has a significant effect on the processing efficiency. Figure 2 shows the impact of peak current, the pulse duration of the arc module, the pulse interval of the arc module, the electrode rotation speed and the external electrode diameter on the processing efficiency. The processing efficiency increased linearly as the increase of peak current. The energy of each discharge pulse became higher as the increase of peak current, and the amount of material removed would increase, which led to a rise in processing...
efficiency. Given that peak current has the most noticeable effect on the processing efficiency, to achieve higher processing efficiency, increasing peak current should be the priority of consideration.

As shown in Figure 2, the processing efficiency increased linearly with increasing the pulse duration of the arc module. A possible reason is that the processing time of one discharge became longer with the increase of the pulse duration, and after the increase of pulse duration, the processing time of one discharge became longer, and the energy released was more continuous. The processing efficiency decreased with increasing the pulse interval of the arc module. Since the increase of pulse interval led to the smaller duty ratio, and the time of one processing discharge was relatively reduced, resulting in discontinuous discharge and a reduction of processing efficiency.

With the increase of the external electrode diameter, the processing efficiency saw a rise before the decrease. The processing efficiency decreased with increasing the spindle speed, and when the speed exceeded 1000r/min, the processing efficiency did not change significantly. A lower rate than 1000 r/min encouraged the relatively weak suppression, and the discharge was relatively continuous. Therefore, the amount of workpiece material removed by single arc discharge was large. As increasing the rotation speed of the electrode, the suppression of the arc speed of the electrode increased, resulting in an effective arc breaking and a reduction in processing efficiency. When the rotation speed was higher than 1000r/min, the inhibition effect of the rotation speed on the arc was not significant, resulting in a change in processing efficiency.

**Figure 2.** Effects of processing parameters on processing efficiency. a, Current_MRR. b, Pulse duration_MRR. c, Pulse interval_MRR. d, External diameter of electrode_MRR. e, Spindle speed_MRR

**Figure 3.** Effects of processing parameters on REWR. I, Current_REWR. II, Pulse duration_REWR. III, Pulse interval_REWR. IV, External diameter of electrode_REWR. V, Spindle speed_REWR

### 3.2. Effects of processing parameters on REWR

REWR is defined as the ratio of the wear length of the tool electrode to the workpiece removal volume during processing. The effects of peak current, the pulse duration of the arc module, the pulse interval of the arc module, the electrode rotation speed and the external electrode diameter on REWR is illustrated in Figure 3. REWR increased with the increase of the peak current, and REWR was optimal at about 600A. This is because the rise in current significantly increased the material removal volume, and the discharge is more continuous, and the loss of the electrode did not change considerably in this current range so that the REWR decreased with the increase of current.

There are two reasons why REWR decreased with increasing the pulse power. When the peak current was constant, the volume of the workpiece etched by a single pulse during discharge and the depth of the discharge pit increased with the increase of pulse duration, which led to the rise of REWR. Besides, the growth of pulse duration increased the discharge energy transferred to the processing region, and more discharge etching products adhere to the electrode surface, leading to the increase of the compensation for the electrode wear.
When the pulse duration was constant, REWR increased with increasing the pulse interval. When other conditions are constant, the increase of pulse interval caused the amount of material removal per unit time to decrease, increasing REWR. This led to an increase in the relative loss rate of the electrodes. However, there was also a case where REWR reduced (such as the second half of the curve). The reason is that the wear length of the electrode became shorter.

As the diameter of the electrode increased, REWR decreased. This is because while the material removal volume was increased, the electrode wear length decreased with the increase of electrode diameter, eventually resulting in a larger electrode diameter and a smaller REWR. The effect of spindle speed on REWR was not significant. Because the change of the rotational speed has little impact on the material removal volume under the condition of constant current, and the electrode length lost did not change rapidly.

3.3. Effects of processing parameters on SR

SR is a necessary evaluation basis for the quality of processing performance. This paper mainly measured and analyzed the experimental workpiece below 600A, because SR of the workpiece is too bad to measure accurately with high current. Figure 4 shows the effects of peak current, the pulse duration of the arc module, the pulse interval of the arc module, the electrode rotation speed and the external electrode diameter on SR. It can be seen that SR became larger as the peak current increased. One possible reason is that the increase of current caused the rise of single discharge energy, which created the larger discharge pit.

The increase in pulse duration led to a larger SR, and the reason is as same as the current effect. The rise in the pulse width made the energy of the discharge pulse more concentrated, which caused the larger discharge pit. SR decreased slightly with the increase of pulse interval. The main reason is that the increase in the pulse interval caused the discharge energy to be relatively reduced and the discharge was no longer continuous. Besides, the concentrated pulse discharge was weakened, and the discharge pit became smaller.

As the external diameter of the electrode increased, SR became smaller and then became larger. The main reason behind this phenomenon is that the increase of the external diameter of the electrode led to the increase of contact area between the electrode and workpiece, resulting in steady energy distribution, which promoted the surface quality of the workpiece. However, when the diameter of the electrode continued to increase, the debris was not easily discharged, increasing SR. The rotational speed had little effect on SR. The main reason is that the arc was easily broken after increasing the rotation speed, and the pulse discharge energy was slightly concentrated so that the discharge pit changed minimally.

![Figure 4. Effects of processing parameters on SR. (1), Current_REWR. (2), Pulse duration_REWR. (3), Pulse interval_REWR. (4), External diameter of electrode_REWR. (5), Spindle speed_REWR](image)

3.4. Selection of optimal parameters under different processing requirements

The parameters for obtaining the maximum processing efficiency are shown in Table 2. MRR gained by the experiment with this setting was 10126 mm³/min. The workpiece processed and the electrode used is shown in Figure 5. Although the high processing efficiency of the workpiece can be achieved using the parameters, the electrode wear was serious. The setting can be applied in the rough machining of compound machining of EDM milling and arc machining.

The parameters for obtaining the minimum REWR are shown in Table 3. The minimum REWR obtained under the settings was approximately 0.000301mm/mm³. MRR was about 3024mm³/min, and SR of the workpiece is 36.24μm. The workpiece and electrode processed under the parameters are
shown in Figure 6. Using the settings, the processing efficiency was not very high, and REWR was small, and the surface quality of the workpiece was on the general level. It can be used in the semi-finishing process of compound machining of EDM milling and arc machining.

The parameters for obtaining the minimum SR are shown in Table 4. Using the settings, the measured roughness value was 16.97μm, and the processing efficiency was 368mm³/min. The workpiece processed under the parameters is shown in Figure 7. The processing efficiency was lower under the settings, but the surface quality of the workpiece was relatively acceptable. It can be applied in the finishing process of compound machining of EDM milling and arc machining.

Table 2. The parameters for obtaining the maximum processing efficiency.

| Current(A) | Voltage(V) | Pulse duration(ms) | Pulse interval(ms) | Diameter(mm) | speed(r/min) |
|-----------|-----------|--------------------|--------------------|--------------|--------------|
| 1000      | 250       | 10                 | 1                  | 16           | 500          |

Table 3. The parameters for obtaining the minimum REWR.

| Current(A) | Voltage(V) | Pulse duration(ms) | Pulse interval(ms) | Diameter(mm) | speed(r/min) |
|-----------|-----------|--------------------|--------------------|--------------|--------------|
| 600       | 250       | 9                  | 1                  | 12           | 500          |

Table 4. The parameters for obtaining the minimum SR.

| Current(A) | Voltage(V) | Pulse duration(ms) | Pulse interval(ms) | Diameter(mm) | speed(r/min) |
|-----------|-----------|--------------------|--------------------|--------------|--------------|
| 200       | 250       | 2                  | 10                 | 12           | 2500         |

Figure 5. The workpiece processed and the electrode after and before use under the parameters for obtaining the maximum processing efficiency.

Figure 6. The workpiece processed and the electrode after and before use under the parameters for obtaining the minimum REWR.

Figure 7. The workpiece processed under the parameters for obtaining the minimum SR.

4. Conclusions

In this paper, a large number of single-factor experiments under different processing parameters were carried out by using compound machining of EDM milling and arc machining. The effects of different peak currents, arc pulse duration, arc pulse interval, spindle speed and the external diameter of the electrode on machining efficiency, SR and REWR were obtained. Besides, different optimal
parameters to get the highest processing efficiency, minimal SR and REWR were also acquired to provide support for future research.

1) High current and longer pulse duration can dramatically improve the processing efficiency. Conversely, the increase of pulse interval led to the decrease in processing efficiency. The processing efficiency saw a rise before the decreasing trend with the increase of the external electrode diameter. The spindle speed had a slight effect on the processing efficiency, but an appropriately low rate can be selected to improve the processing efficiency. To obtain high processing efficiency, it is ideal to process in the environment with high current, a relatively low spindle speed, longer pulse duration, short pulse interval, and appropriate electrode diameter.

2) REWR decreased with the peak current as a whole, and REWR was the lowest when the peak current was around 600A. The increase of the pulse duration reduced REWR. The rise in the external electrode diameter also caused decrease of REWR. The pulse interval and the spindle speed have little impact on REWR.

3) SR of the workpiece increased significantly with the increase of the peak current. The optimum surface roughness of the workpiece was about 20μm. The increase of the pulse duration and the external diameter of the electrode led to the increase of SR. The increase of the pulse interval and spindle speed led to the decrease of SR, and the effect of pulse interval was more significant.

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