Study of the thermal erosion, ejection and solidification processes of electrode materials during EDM

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ABSTRACT

Due to the complexity of electrical discharge machining (EDM), there is no perfect theory to explain the mechanisms of material erosion, ejection and solidification during the machining process. Therefore, this paper analyzed the micro-process of a single-pulse discharge during EDM and studied the thermal erosion, ejection and solidification processes of the electrode materials. A thermal-fluid simulation model that considered melting-solidification was established. A mathematical model of vapor flow considering the impact pressure was developed, and it was compiled and loaded as a material ejection force in simulations with a user defined function (UDF). The changes in the material ejection, crater formation and material solidification processes at different discharge times were studied. Finally, the simulation results were verified by single-pulse material discharge experiments, which provided a reference for additional understanding of the micro material discharge processes during EDM.

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EDM; material erosion; debris ejection; recast layer solidification; vapor flow

1. Introduction

EDM relies on a large amount of heat that is generated by a pulsed spark discharge between the electrodes to melt and even vaporize the material to remove it from the workpiece. EDM is a kind of non-contact machining process and does not produce a mechanical cutting force; therefore, it is not limited by the strength, hardness and other mechanical properties of the material characteristics and can be used for machining high strength, high hardness and conductive materials. Since the micro-process of EDM is very complicated and accompanied by randomness, the discharge mechanism is not very clear. So far, scholars have not fully understood the material erosion, material ejection, crater formation and solidification process during EDM machining.

In the EDM field, many scholars have studied the discharge erosion process of EDM. Tang et al. developed a novel thermo-hydraulic coupling model to investigate the crater formation process during a single-pulse discharge and conducted experiments to verify the simulations (Tang & Yang, 2017). Tao et al. presented a numerical model and experimental validation of the anode crater formation during the EDM process (Tao, Ni, & Shih, 2012). Yang et al. performed temperature field finite element simulation on the established mathematical physics model based on ANSYS software. The model predicted the crater depth and radius change at different peak currents and pulse widths well (Yang, Lin, Chang, & Yang, 2008). Lasagni et al. measured and compared the electrode erosion due to sparking in several pure materials with existing theories for electrode erosion and with the properties of the materials. The crater shape was related to the surface tension of the molten material (Lasagni, Soldera, & Mücklich, 2004). Macedo et al. studied plasmas and craters generated by single electrical discharges. The results show that gas discharges triggered by streamers have higher plasma expansions than sparks generated from vacuum breakdown mechanisms (Macedo, Wiessner, Hollenstein, Kuster, & Wegener, 2016). Giridharan et al. used FEM to simulate the crater for different plasma flushing efficiencies and validated the model by experiments (Giridharan & Samuel, 2015). Assarzadeh et al. simulated the mechanism of crater formation due to a single discharge. The simulation results show that the temperature of the workpiece decreases as the discharge time increases while the volume of melted and evaporated material increases. Then, an experiment was conducted to validate the model (Assarzadeh & Ghoreishi, 2017). Yadava et al. developed a finite element method based on a mathematical model to simulate...
the hybrid machining process of grinding and electrical discharge machining to calculate the temperature distribution. Experiments were conducted to verify the simulations (Yadava, Jain, & Dixit, 2002). Tohie et al. studied the process reaction force that is generated in EDM using the Hopkinson bar method and obtained the correct waveform for the process reaction force (Tohi, 2002). Shabgard et al. simulated the temperature distribution on the surface of the workpiece and tool during a single discharge during the electrical discharge machining process. The efficiency of the plasma channel in removing the molten material was also analyzed (Shabgard, Ahmadi, Seyedzavvar, & Oliaei, 2013).

As seen from previous studies, the force of the EDM material ejection process is affected by a variety of factors, and its mechanism is very complex. At present, most scholars have not conducted analyses and research on the complete process of material erosion, nor have they established a relatively complete theory. In this paper, CFD is used to model the whole process, and it is a method to simulate various fluid flows (Ghalandari, Koohshahi, Mohamadian, Shamshirband, & Chau, 2019; Ramezanizadeh, Nazari, Ahmadi, & Chau, 2019). A mathematical model of vapor flow for the material ejection force during machining was developed. The mathematical model was compiled and loaded in Fluent, and a model considering melting-solidification was established. The erosion, ejection and solidification processes of EDM materials were simulated, and the change law with time was analyzed. Finally, the single-pulse discharge experiment was carried out on a self-built EDM machine to verify the simulation results. The simulation results reflected the material erosion and solidification processes during EDM.

### 2. Analysis of material melting and solidification processes

The formation of a molten crater on the surface of the workpiece material is primarily the effect of a surface heat source whose energy is transferred from the discharge channel to the surface of the workpiece. Two stages of dielectric breakdown and channel formation, energy distribution and transfer occur. Due to the effect of a heat source with a Gaussian distribution, a phase change phenomenon occurs after a part of the material around the discharge point reaches the melting point. A molten region is formed, and the interior of the regions becomes a molten liquid metal, as shown in Figure 1.

In the energy released by a single-pulse discharge during EDM, the electrical energy is converted into heat, kinetic energy, and magnetic energy. The release of energy is absorbed by the electrode or working fluid in the form of heat conduction, heat convection, and heat radiation. The energy distribution equation between the two electrodes is as follows:

\[
W_t = \int_0^T U(t)I(t)dt = W + W_c + W_a
\]

where \(W_t\) is the total discharge energy; \(W\) is the energy distributed to the discharge channel; \(W_a\) is the energy distributed to the anode; \(W_c\) is the energy distributed to the cathode; \(U(t)\) is the inter-electrode discharge voltage, and the unit is V; and \(I(t)\) is the inter-electrode discharge current, and the unit is A. If one discharge period is \(T\), the energy distributed on the anode in a single-pulse discharge is as follows:

\[
W_a = \eta W_t
\]

where \(\eta\) is the energy distribution coefficient of the anode workpiece. The total energy delivered to the anode workpiece during a single-pulse discharge can be divided into four parts:

\[
W_a = W_a^e + W_a^u + W_a^r + W_a^v
\]

where \(W_a^e\) is the energy transmitted by the electron bombardment to the anode surface, \(W_a^u\) is the energy transmitted by the heat radiation to the anode surface, \(W_a^r\) is the energy transmitted by impact of gas medium in the discharge channel on the anode surface, and \(W_a^v\) is the energy transmitted by the vapor flow from the cathode surface to the anode surface during discharge. According to the reference (Li, 1989), tungsten vapor flow accounts for 40% of the total energy transferred among all the methods of energy transfer, such as electron bombardment and heat radiation, so the vapor flow is the main way of transferring energy.

The impact of this vapor flow causes the material to melt, vaporize and eject from the electrode surface, as shown in Figure 2. The kinetic energy generated in this process is very large, and the molten metal is ejected at
a high temperature, generating a discharge crater on the surface of the electrode. The ejected molten material is cooled by the working fluid and soonsolidified intovery small round particles, namely, debris. However, a small amount of molten metal stays at the bottom of the crater and is solidified under the cooling of the working fluid and forms a recast layer.

### 3. Mathematical model of material erosion and ejection

#### 3.1. Mathematical model of heat flux density

It is generally believed that the thermal model of the EDM process involves a surface heat source, as shown in Figure 3. In the plane with a radius of $R$, the heat flux density conforms to a Gaussian distribution with the maximum heat flow density in the center that is gradually reduced along the radius. Outside the discharge region, the surface of the workpiece is in contact with the working fluid, so there is thermal convection.

According to Figure 3, the heat transfer on the workpiece surface can be expressed as shown in Equation (4):

$$
\frac{\lambda}{\zeta} \frac{dT}{dz} = \begin{cases} q(r), & r < R(t) \\ h(T - T_0), & r > R(t) \end{cases}
$$

where $q(r)$ is the heat flux density of the Gaussian distribution at radius $r$, $h(T - T_0)$ is the heat convection function, and $R(t)$ is the radius of the discharge channel at time $t$, and the unit is m.

In the mathematical model of the heat source during EDM, the heat flux density of the Gaussian distribution at radius $r$ can be expressed as follows (Joshi & Pande, 2009; Liu & Guo, 2016):

$$
q(r) = \frac{k \cdot \eta \cdot U(t) \cdot I(t)}{\pi R^2} \cdot \exp \left( -\frac{k r^2}{R^2(t)} \right)
$$

where $q(r)$ is the heat flux density of the Gaussian distribution at radius $r$, and the unit is J/m².s⁻¹; $U(t)$ is the maintenance voltage, and the unit is V; $I(t)$ is the current, and the unit is A; $R(t)$ is the radius of the heating region as a function of time, and the unit is m; and $k$ is the heat source concentration factor with a value of 4.5.

#### 3.2. Mathematical model of vapor flow

The generation of vapor flow during EDM is caused by the vaporization and explosion of molten liquid metal in a very short time and over a very small space. The vapor is ejected at high speed and releases a very large amount of energy. In this process, strong shock waves are generated and spread to the corresponding electrode surface. Regarding the study of the explosion shock wave, Zingerman deduced the expression of the relationship between the maximum wave front pressure and discharge energy of the shock wave generated during the explosion process in different media (Boyan, Jinquan, Fuqiang, & Xiaozhu, 2006):

$$
P_{\text{max}} = \beta \sqrt{\frac{\rho u(t) i(t)}{t_r t_f}}
$$

where $P_{\text{max}}$ is the maximum wave front pressure of the discharge explosion shock wave, and the unit is Pa; $\beta$ is the coefficient with a value of 0.7; $\rho$ is the density of the working liquid, and the unit is kg/m³; $t_r$ is the rising edge time of the discharge pulse, and the unit is s; and $t_f$ is the pulse on time, and the unit is s.

According to the gas flow theory, the relationship between the maximum outlet pressure of the vapor at the time of ejection and the environmental pressure on the electrode surface can be expressed as follows (Yang, Zhao, & Huang, 2011):

$$
P = (1 + 0.2 M_a^2)^{3.5} \cdot P_0
$$

where $M_a$ is the Mach number, $P_0$ is the environmental pressure, and $P$ is the vapor pressure. Upon substituting Equation (7) into Equation (6), the expression of the
The relationship between the Mach number of vapor outlet airflow and discharge energy can be expressed as follows:

$$Ma = \sqrt{\left( \frac{\beta}{P_0} \right)^{2/7} \left( \frac{\rho \int_0^{t_f} u(t) i(t) \, dt}{t_r t_f l} \right)^{1/7} - 1}$$

(8)

The Mach number is essentially the ratio of the velocity $v$ to the speed of sound $a$ under the current environmental conditions, namely, $Ma = v/a$. Therefore, an equation of the maximum velocity of vapor ejection is finally obtained:

$$v_{\text{max}} = \sqrt{5a \left( \frac{\beta}{P_0} \right)^{2/7} \left( \frac{\rho \int_0^{t_f} u(t) i(t) \, dt}{t_r t_f l} \right)^{1/7} - 1}$$

(9)

Thus, the maximum velocity of the vapor ejection generated under different discharge parameter conditions can be obtained by Equation (9). Since the magnitude of the impact pressure generated by the vaporization explosion of the material is related to the energy released, the amount of energy released is linearly related to the heat absorbed by the material per unit time. It was concluded that the impact pressure generated by the vaporization explosion also satisfies the Boltzmann distribution, and the impact pressure is proportional to the impact velocity.

Therefore, the vapor jet velocity generated at the distance $r$ from any point on the surface of the material to the center of the discharge point can be expressed by Equation (10):

$$v(r) = v_{\text{max}} \cdot \exp \left( -\frac{k r^2}{R^2(t)} \right)$$

(10)

4. Modeling of material melting and ejection and solidification

As shown in Figure 4, the workpiece length and height in the simulation model are set to 700 and 200 μm, respectively. Since the tip electrode can better form a single discharge crater, the tip electrode is used to study the material erosion during EDM. A micro surface of the electrode tip is established above the surface of the workpiece, and the discharge gap is 100 μm (Li, Liu, Ji, & Yu, 2007). The vapor flow is formed and ejected at the tip of the electrode, so the electrode end face is set as the boundary of the vapor flow in the simulation model. The ejection of metal vapor must be generated after vaporization of the electrode material. According to the related literature for the study of the vaporization zone, the vaporization range is set (namely, vapor ejection outlet) to 40 μm (Li, 2015).

As shown in Figure 5, the simulation model is built and meshed in the meshing software. The mesh file is imported into CFD software (Akbarian et al., 2018), the boundary condition is set, and the simulation is calculated. To reduce the calculation time, a 1/2 model is selected for calculation, and the left line is set to be axisymmetric. The simulation is divided into two stages: a material thermal erosion stage and an ejection stage. The secondary development interface module is used to load the heat flux density with a Gaussian distribution on the workpiece surface during the material thermal erosion stage. During the stage of material ejection, the secondary development interface module is also adopted to load the vapor flow, and the velocity outlet is set. In the simulation, the pulse-on time is set to 40 μs, the peak voltage is set to 45 V, the discharge current is set to 20 A, the workpiece is WC cemented carbide, and positive machining is selected as shown in Table 1. The results of the changes in the material temperature, mate-
Table 1. Simulation parameters.

| Description | Parameter |
|-------------|-----------|
| Peak voltage| 45 V      |
| Discharge current | 20 A     |
| Pulse-on    | 40 μs     |
| Workpiece material | WC       |
| Polarity    | Positive  |

5. Simulation results and analysis

5.1. The change process of discharge temperature with time

Figure 6 shows the temperature field of the WC cemented carbide material. It can be seen from the figure that during the discharge period, the heated region on the surface and in the interior of the material gradually increases with increasing discharge time. As shown in Figure 6(a), when the discharge time is 10 μs, the center temperature of the surface of the material reaches approximately 6782 K, which is due to the formation of a discharge channel between the electrode and the workpiece with a small radius and high energy in a very short time. A high-temperature heat source is formed on the workpiece surface. Since the discharge time is short, most of the heat is not able to spread through the heat conduction on the surface and interior of the workpiece, so the energy is concentrated at the discharge point. As shown in Figure 6(b), when the discharge time is 20 μs, the surface temperature of the material decreases to 6059 K. This is mainly because as the discharge time increases, the heat is spread along the radial direction and the depth direction towards the surface and interior of the workpiece in the way of heat conduction, and the center temperature gradually decreases. As shown in Figure 6(c,d), when the discharge time is 30 and 40 μs, the center temperatures are 5780 and 5627 K, respectively. At a discharge time of 40 μs, the radius of the discharge channel expands to its maximum value, and the temperature distribution region reaches its maximum value. In the initial stage of discharge, the temperature drops sharply, and the decline rate tends to stabilize with increasing discharge time. Therefore, the rate of temperature change gradually decreases with increasing discharge time.

Figure 7(a,b) show temperature changes along the radius and depth when the discharge time is 40 μs. The temperature gradually decreases in the direction of radius and depth.

As shown in Figure 7(a), the surface temperature of the workpiece changes along the radial direction when the discharge time is 40 μs. It can be seen from the figure that when the discharge starts, the central temperature reaches 5627.83 K, whereas at a radius of 0.07 μm, the temperature drops slowly, only approximately 300 K. This is because the discharge channel currently forms a high-temperature heat source in this region. The heat flux

![Temperature field distribution at different discharge times.](image_url)
density at the center of the channel is the highest, and the heat flux density of the channel decreases gradually along the radial direction. Since there is no heat flux density in the region outside the discharge channel, the heat is quickly transferred to other regions, and the temperature changes greatly and decreases rapidly. After that, when the temperature is close to 1000 K, the intensity of the temperature change decreases, and the temperature slowly approaches room temperature.

Figure 7(b) shows the surface temperature of the workpiece changes in the depth direction when the discharge time is 40 μs. It can be seen from the figure that when the discharge starts, the center temperature reaches 5627.83 K, and the temperature drops rapidly from the center point of the surface to the depth range of 0.02 μm. This is because only the surface is subjected to the heat flux density, the heating time is extremely short, and the heat cannot be transferred in time along the depth direction. Therefore, the temperature drops rapidly and soon reaches approximately 2700 K. When the depth is greater than 0.02 μm, due to the heat transfer of the workpiece, the temperature drops slowly and finally reaches 300 K at room temperature.

5.2. The changes in the molten pool morphology with time

Figure 8 shows the changes in the WC cemented carbide molten pool. Before discharge occurs, the surface of the workpiece is flat without any distortion. As the discharge progresses, the surface of the workpiece rapidly forms a high-temperature heat source, and an increase in temperature causes thermal erosion of the metal material. When the discharge time is 10 μs, as shown in Figure 8(a), the molten pool region of the material rapidly spreads outward, and the spreading speed in the radial direction is greater than that in the longitudinal direction. The main reason is that the discharge channel is applied to

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**Figure 7.** Temperature along the radius direction and depth direction when the discharge time is 40 μs. (a) Along radius direction, (b) Along depth direction.

**Figure 8.** Surface micro topography of molten pool at different discharge times. (a) t = 10 us, (b) t = 20 us, (c) t = 30 us, (d) t = 40 us.
the surface of the workpiece, so the surface heat expands faster in the radial direction than that in the depth direction. In the following moment, the molten region of the workpiece continues to expand. As shown in Figure 8(b,c), as the discharge time increases, the molten region of the workpiece continues to expand, mainly due to the expansion of the discharge channel causing the surface heat source to spread. As shown in Figure 8(d), when the discharge time is 40 μs and the discharge is finished, the crater is basically formed, and the shape of the molten pool is basically unchanged. In the following stage, the shape change gradually becomes stable. This is due to the gradual decrease in the energy flux density and temperature in the expanding discharge channel. Finally, the surface molten pool of the workpiece during EDM is formed.

5.3. Analysis of material ejection and crater formation processes

Figure 9 shows the workpiece material ejection and crater formation processes at different times. As shown in Figure 9(a), no debris is ejected from the workpiece surface at the time of 0 μs because the molten pool is not formed. As shown in Figure 9(b), at 1 μs, the shock wave is transmitted to the surface of the molten pool and generates an impact on it. The molten material is dented in the middle under the impact force, which makes the molten material splash towards both sides. The molten material flying into the machining gap spreads, forming many liquid droplets. This is mainly because the impact pressure of the vapor flow is the largest at the center of the discharge channel, and the pressure on both sides is low. The molten materials in different positions are affected by different impact forces producing different initial velocities, and the molten materials splash into countless droplets and are ejected away from the crater. As shown in Figure 9(c), at 5 μs, the increasing impact pressure increases the ejection velocity, and additional material is ejected away from the molten pool of the workpiece surface, resulting in a violent bombardment effect. As shown in Figure 9(d), at 10 μs, the material in the molten pool is almost completely ejected. Since the molten droplets have inertia, they continue to flow in the liquid, but their speed decreases, and some of them slowly fall and recast on the surface of the workpiece under the action of gravity, and some of them flow freely in the working fluid and are solidified as debris, which are washed away by the working fluid. Thus, a complete crater is formed under a single-pulse discharge.

Figure 10 shows the curves of the crater radius and depth with time. As shown in Figure 10(a), the crater radius reaches 105.28 μm instantaneously within 1 μs under the impact of the vapor flow. This is mainly because there is a large amount of molten metal liquid in the molten pool, and after impact, most of the metal liquid is ejected away from the crater. Between 1 and 6 μs, the crater radius increases slowly, most of the molten metal has been ejected away from the crater, and the residual molten metal liquid on both sides of the crater is selected by the vapor pressure. The radius of the crater remains the same after 6 μs, mainly because the molten metal liquid on both sides of the crater is solidified by water cooling and is not ejected. The shape of the crater is basically unchanged. As shown in Figure 10(b), the crater depth reaches 14.75 μm within 1 μs under the impact of the vapor flow.

**Figure 9.** Material ejection and crater formation process at different discharge times. (a) t = 0 μs, (b) t = 1 μs, (c) t = 5 μs, (d) t = 10 μs.
flow. Between 1 and 4 μs, the crater grows slowly in the depth direction. At 4 μs, the crater depth does not change, mainly because the crater in the depth direction is smaller than that in the radius direction, so the molten liquid in the depth direction is quickly ejected away, and the crater depth remains unchanged in a short time.

5.4. Analysis of the material solidification process

Figure 11 shows the solidification process of the material ejected at different times in the working fluid. As shown in Figure 11(a), at the moment when the vapor flow stops after 1 μs, the material is ejected. At this time, a small amount of the molten metal material is ejected from both sides of the crater, and the rest of the material is not completely ejected but exists in the crater in liquid form. Since the ejected molten material has just contacted the working fluid and has not been completely cooled, the material is ejected in liquid form. When the vapor flow is stopped after 50 μs, as shown in Figure 11(b), the molten material at the bottom of the crater continues to be ejected to the working fluid, and the molten material that has been ejected is gradually solidified by the cooling of the working fluid and forms debris. Under the effect of inertia, the debris continues to flow in the working fluid, and the accumulated debris begins to scatter. At this time, there is still a small amount of molten metal liquid at the bottom of the crater that has not been completely ejected. Since the vapor flow has stopped at this time, the working liquid flows back to the processing region again, and these high-temperature molten metals that have not been ejected are solidified by the cooling of the working liquid. When the vapor flow stops after 100 μs, as shown in Figure 11(c), the debris still flows in the working fluid at a certain speed under the effect of inertia. A small amount of debris begins to fall on the surface of the workpiece under the action of gravity, and most of the high-temperature molten metal in the
crater has solidified. When vapor flow stops after 500 μs, as shown in Figure 11(d), the amount of flowing debris in the working fluid begins to decrease, and most of the debris is washed away from the machining gap by the working fluid, and the molten metal remaining in the crater has completely solidified, recasting at the bottom.

6. Experiment and analysis of single-pulse discharge material erosion

6.1. Experimental apparatus

To verify the simulation of the thermal erosion, ejection and solidification of material during a single-pulse discharge, single-pulse discharge machining experiments are carried out with a tungsten electrode, and the size of the discharge crater after machining is obtained. A cylindrical electrode with a diameter of 1 mm is used in the experiments. To produce a single discharge and determine the position of the discharge point and crater formation in advance, a machined tip electrode is used to achieve a high success rate in the experiment. Therefore, the cylindrical electrode end face needs to be ground before the experiment to ensure that the cylindrical electrode end face has a sharp angle and can achieve an excellent tip discharge. First, the shape of the electrode end face is ground with an abrasive wheel so that the electrode end face forms a sharp angle. The surface is then polished to reduce the roughness of the electrode tip surface. An electrode with a decreased surface roughness is fabricated, as shown in Figure 12.

In the verification experiment, WC cemented carbide material was used as the workpiece to be processed. The workpiece has dimensions of 20 mm × 20 mm × 4 mm. Before the experiment, the workpiece needs to be pre-treated to ensure that the surface of the workpiece to be processed is flat, and the oxide layer is removed to make it easy to discharge. The working fluid medium is kerosene, and positive polarity machining is selected. The processing parameters and experimental conditions are shown in Table 2.

Figure 13 shows a schematic of a single-pulse discharge experimental apparatus. Figure 13(a) shows a photograph of the single-pulse discharge experiment apparatus. Figure 13(b) shows a schematic diagram of the tip discharge process. During the experiment, the automatic feeding device is first adjusted to make the electrode tip enter the working fluid and maintain a small discharge zone.
gap between the electrode tip and the workpiece surface. Then, the single-pulse discharge power supply is connected so that both electrodes have a voltage output. The feed is adjusted in small increments, and the machine head continues to move down slowly. When the electrode tip reaches a certain discharge gap with the workpiece surface, the medium is broken down, a closed loop is formed, and a discharge is generated. After feedback to the pulse power supply, the power circuit is cut off, the material of both the electrode tip and the workpiece are removed, and the discharge crater is formed. Finally, the surface discharge crater of the workpiece after processing is observed and measured by the digital microscopic imaging system.

### 6.2. Experimental results and analysis

Figure 14 shows the crater from the tungsten electrode that is processing WC cemented carbide with a single-pulse discharge process. Figure 14(a) shows the three-dimensional morphology of the discharge crater, and the edges of the crater are convex. Figure 14(b) shows the crater diameter and depth measurements, with an average diameter of 275.486 μm and an average depth of 22.702 μm. Figure 15 shows the measured values of the crater diameter and depth after simulation. When the vapor flow is removed, the simulation continues until the molten liquid in the crater is completely solidified. A part of the molten material is recast at the edge of the crater and forms a convex edge, which is consistent with the actual crater in the experiment. The diameter and depth of the crater in the simulation are 286.62 and 20.13 μm, respectively. By comparing the simulation values with the experimental values, it can be found that the simulation result is basically consistent with the experimental result with a small error, as shown in Table 3.

### 7. Conclusion

In this paper, a simulated and experimental study of a single-pulse discharge material erosion process was carried out. A simulation model of a single-pulse discharge material erosion process was established. The thermal erosion, ejection and solidification process of materials during single-pulse discharge machining were studied. Based on the simulation method, the surface temperature of the workpiece, the morphology of the molten pool, the crater formation and the solidification of the material with time were analyzed. The model was verified by experiments. The main conclusions were as follows:

1. The temperature of the discharge point in the material increases sharply at first and then decreases slowly. Heat travels faster in the radial direction than that in the depth direction, and the temperature changes along the depth direction are greater than that in the radial direction.
(2) When the vapor flow generated by the electrode is applied to the molten pool, because the central pressure of the crater is greater than that on the edge of the crater, a large amount of molten debris is ejected, and a crater is formed.

(3) When the vapor flow is removed, the molten metal continues to move in the working fluid under the action of inertia. The molten metal with low velocity reaches the surface of the workpiece and is recast under the action of gravity, becoming part of the workpiece. The rest of the molten material is quickly solidified into metal debris under the influence of the low-temperature working liquid and continues to move in the working liquid.

(4) Compared with that for the simulation results for the diameter and depth of the crater on the workpiece surface, the error in the radial direction and depth direction are both small, which proves that the simulation model is reasonable and can accurately predict the thermal erosion, ejection and solidification process of the cemented carbide in EDM.

Due to the limitation of the devices, the ejection process during machining could not be observed. Therefore, the experiment in this paper indirectly verified the simulations. In the future, this topic needs further exploration regarding the residual stress on the crater surface after the solidification process and the formation mechanism of the crater morphology. The crater morphology is also planned to be observed with SEM.

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