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Thermal-Fluid Coupling Simulation and Recast Layer Formation Mechanism

Analysis of Molten Material Evolution in Fast EDM Drilling

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Abstract

Fast electrical discharge machining (EDM) drilling is widely used for manufacturing precision inner holes in aerospace components due to its high efficiency, accuracy, and cost-effectiveness. However, the recast layer generated during the process remains a critical issue, as it may induce microcrack initiation and adversely affect the service performance of components. In this study, dynamic observation experiments are first conducted to investigate the discharge distribution characteristics at different machining locations and to track the evolution trajectories of molten material and machining debris. Subsequently, a two-dimensional axisymmetric thermal–fluid coupling simulation model is established to reveal the evolution behavior of molten material and the underlying mechanisms governing recast layer formation under coupled thermal and hydrodynamic effects. The phase indicator, temperature field, velocity field, and pressure field are systematically analyzed to characterize the generation, migration, and solidification processes of molten material. Furthermore, a continuous discharge simulation model is developed to investigate the cumulative formation characteristics of recast layers under multiple pulse discharges. The results demonstrate that electrode-end discharges account for approximately 57.9% of total discharges, whereas sidewall discharges and secondary

sidewall discharges contribute 11.39% and 30.71%, respectively. The formation and distribution of recast layers on the hole wall are primarily governed by sidewall and secondary sidewall discharges. The pressure differential within the inter-electrode flow field dominates the detachment of molten material from the molten pool, while the combined effects of pressure differential and hydrodynamic impact determine the subsequent migration trajectory of machining debris. The recast layer thickness on the hole sidewall exhibits a gradual increase from the bottom to the top, which is attributed to the accumulation effect of repeated discharges, upward migration of molten material, and secondary discharges induced by debris movement. This study provides a comprehensive understanding of recast layer formation mechanisms in fast EDM drilling and offers theoretical guidance for process optimization and recast layer control.

Key words: fast EDM drilling, molten material, recast layer, thermal-fluid coupling simulation, sidewall discharge.

1. Introduction

Fast electrical discharge machining (EDM) drilling has become an important technology for fabricating precision inner holes with complex geometries. Owing to its advantages of high machining efficiency, excellent dimensional accuracy, and low processing cost, it has been extensively applied in the manufacturing of film cooling holes on aero-engine turbine blades and other critical aerospace components [1,2]. However, the formation of a recast layer during EDM processing remains an unavoidable issue. The recast layer contains defects such as microcracks and metallurgical deterioration, which may propagate under severe service conditions and consequently reduce the reliability and fatigue performance of aerospace components [3].

To address the adverse effects associated with recast layers, numerous studies have focused on developing effective suppression and removal strategies. Hybrid machining techniques such as EDM-electrochemical composite machining [4-8], grinding and polishing assisted machining [9,10], ultrasonic assisted machining [11-13] and abrasive flow machining[14] are the most common methods. The method of regulating the movement mode of electrodes has also been adopted to suppress the recast layer [15-18]. Despite this, research focusing on the formation mechanism of recast layers is still insufficient. Yue employed molecular dynamics simulation to reveal the evolution of microstructures inside the deteriorated layer on the workpiece surface during discharge, treating the recast layer and heat-affected layer as an integral part [19,20]. Tang applied the multi-physical field coupling method to simulate the material removal process of conventional EDM, which identified the boundary of the recast layer under single-pulse discharge via the Level-Set method [21,22]. Chu conducted observation experiments on molten material and simulations on recast layer formation under single-pulse conditions for fast EDM drilling [23].

It can be concluded that the research on the formation mechanism of recast layers in fast EDM drilling is still inadequate. Under the instantaneous high temperature of discharge plasma, molten material is generated and subjected to the combined effects of heat transfer, high-pressure flushing, electrode rotation and feeding in the gap flow field [24]. The mechanism for molten material to form recast layers under the thermal-mechanical coupling of multi-physical fields remains unclear. Moreover, as a special type of EDM, fast EDM drilling operates under unique process conditions [25], and its recast layer differs significantly from that formed in conventional EDM. Clarifying the formation mechanism of recast layers is of great significance for filling the theoretical gaps of fast EDM drilling and proposing targeted recast layer control strategies.

Therefore, this study aims to elucidate the formation mechanism of recast layers in fast EDM drilling through a combination of dynamic observation experiments and thermal–fluid coupling simulations. Considering the practical machining characteristics of turbine blade film cooling holes, a dedicated two-dimensional axisymmetric thermal–fluid coupling model is established to simulate the complete evolution process of molten material, including melting, migration, cooling, and solidification. The influences of temperature, velocity, and pressure fields on molten material behavior are systematically analyzed. Furthermore, a continuous discharge simulation model is developed by incorporating experimentally obtained discharge distribution characteristics to investigate the cumulative formation behavior of recast layers under multiple pulse discharges. The findings provide theoretical insights into recast layer formation mechanisms and offer guidance for process optimization and recast layer control in fast EDM drilling.

2. Observation Experiments on fast EDM drilling

Dynamic observation experiments are conducted to investigate the behavior of molten material during fast EDM drilling. Multiple test groups are implemented to clarify the generation mechanism and distribution patters of discharges at different positions.

Table 1 Statistics of discharge ratios at different positions

Test No.	Electrode End Discharge Ratio	Sidewall Discharge Ratio	Secondary Sidewall Discharge Ratio
1	58.14%	11.63%	30.23%
2	60%	11.43%	28.57%
3	55.56%	11.11%	33.33%

Experimental results indicate that during the initial contact stage, no distinct sidewall is formed on the machined hole. And discharges are concentrated at the end part of the electrode. In the formal

drilling stage, sidewall discharges begin to occur continuously. Statistical analysis reveals that electrode end discharge dominate the machining process, accounting for approximately 60% of total discharges. Secondary sidewall discharge constitutes the primary component of sidewall discharge, representing about 30% of all discharges.

Trajectory tracking and marking experiments are performed on molten material generated by discharges at different positions to evaluate their respective contribution to the recast layer formation. Fig. 2-1 illustrates the trajectory tracking of molten material during electrode end discharges, specifically presenting results from single-pulse discharges during the intervals of 650 μs –670 μs and 1050 μs –1070 μs . The areas enclosed in red boxes denote molten material detached from the molten pool.

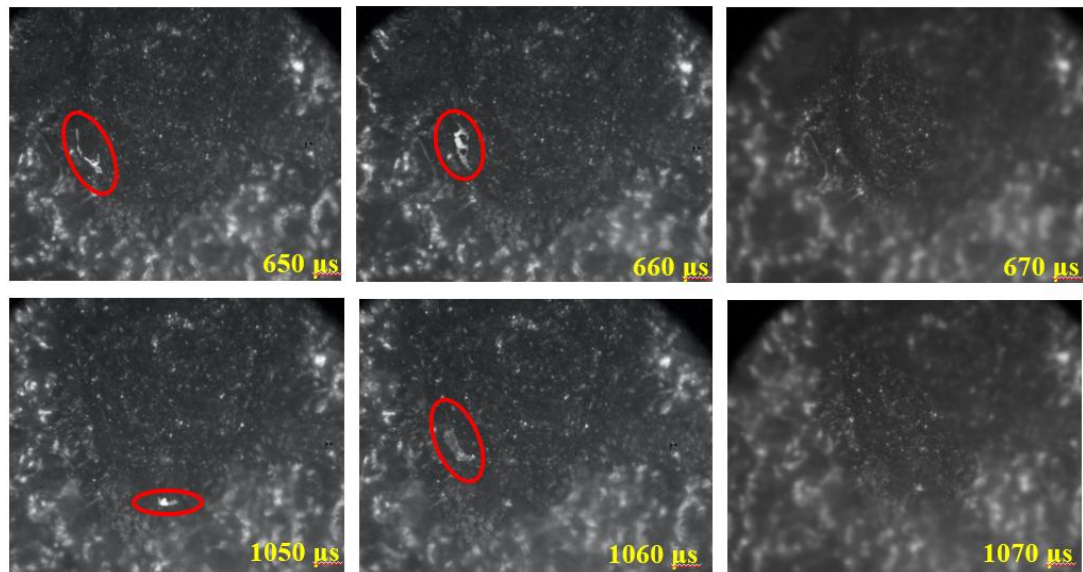


Fig. 2-1 Trajectory tracking of molten material during single-pulse electrode end discharge

Fig. 2-2 displays the trajectory tracking of molten material during sidewall discharge, showing the molten material and machining debris generated during the intervals of 2050 μs –2070 μs and 6530 μs –6550 μs . The regions marked with red boxes indicate molten material and detached machining debris produced by a discharge.

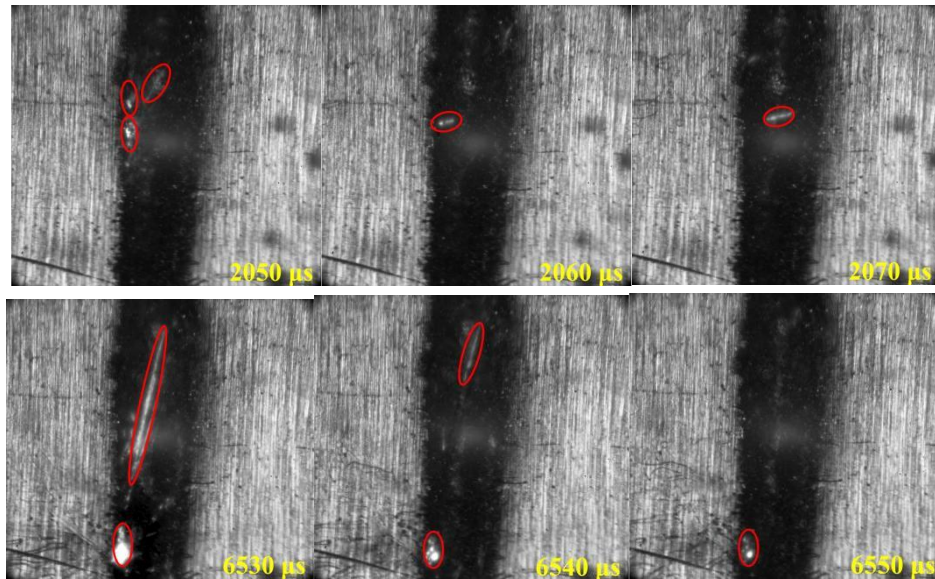


Fig. 2-2 Trajectory tracking of molten material during sidewall discharge

The primary conclusions drawn from observation experiments are as follows:

(1) Molten material generated by electrode end discharges is significantly constrained by the high-pressure flushing fluid. Consequently, it does not splash radially within the inter-electrode gap. The majority of the molten material remains in the molten pool and solidifies to form recast layers. However, these recast layers are subsequently removed by later discharges as machining proceeds.

(2) Sidewall discharges generate a substantial amount of debris that separates from the molten pool. This debris either adheres to the electrode surface to form an adhesion layer or is expelled vertically from the machining area along the flow field. The volume of molten material retained in the pool following a sidewall discharge is relatively small.

(3) Secondary sidewall discharge, a specific form of sidewall activity, occurs at positions determined by the real-time movement of machining debris.

The probability of repeated discharge at a specific sidewall location is extremely low. Therefore, most recast layers formed by sidewall discharges persist until the completion of machining,

constituting the final recast layer on the hole wall. It is confirmed that sidewall discharges and high-pressure flushing fluid play decisive roles in the distribution of recast layers on hole walls.

Dynamic parameters, including the motion trajectory and velocity of molten material and debris at the micro-scale, are obtained via dynamic observation of recast layer formation. However, due to limitations in the frame rate and field of view of observation experiments, the identification of molten material evolution inside the molten pool remains insufficiently clear. Consequently, numerical simulation is further employed to acquire detailed physical parameters of molten material within the molten pool at various time steps.

3. Geometric Model and Main Parameters for Thermal-Fluid Coupling Simulation

Unlike conventional EDM, fast EDM drilling employs hollow tubular electrodes, through which high-pressure working fluid is injected to facilitate inner-electrode cooling and chip removal. Additionally, the electrode rotates at high speed around its axis during the drilling process [25]. Traditional EDM simulation models fail to capture the unique characteristics of fast EDM drilling. Therefore, their calculation results and conclusions are inapplicable to the analysis of recast layers of film cooling holes. To address this, a dedicated geometric model for fast EDM drilling is established in this section.

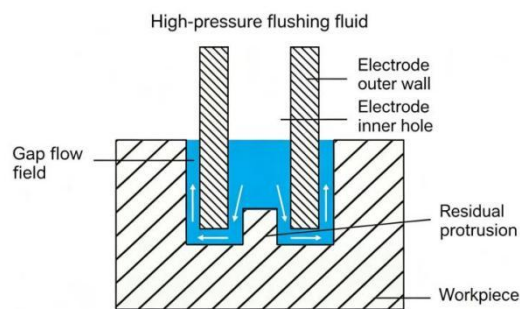


Fig. 3-1 The model of fast EDM drilling

The structural model is simplified to retain only the rotating electrode, the workpiece, and the inter-electrode flow field. Given the axisymmetric nature of the physical system, a two-dimensional axisymmetric model is adopted to reduce computational cost.

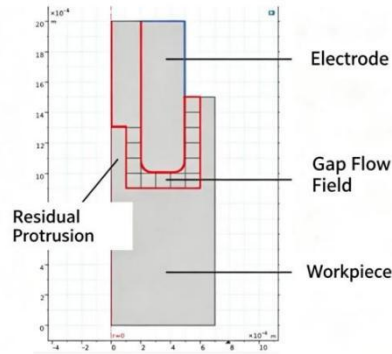


Fig. 3-2 Geometric structure of 2D axisymmetric model for small hole fast EDM drilling

Boundary conditions consistent with practical machining are applied to ensure the validity of the simulation results. The discharge parameters are set identical to those in the observation experiments to verify model accuracy by comparing simulation results with experimental data. Based on experimental findings, sidewall discharge is identified as the primary factor influencing the final thickness and distribution of recast layers. Therefore, this simulation focuses specifically on sidewall discharge. The flow field inlet is defined with a fluid velocity of 15 m/s and a pressure of 0.7 MPa, while the outlet is set to a temperature of 293.15 K and a pressure of 0.1 MPa. The symmetry axis and relevant solid boundaries are defined as adiabatic (thermally insulated) boundaries with a constant temperature of 293.15 K.

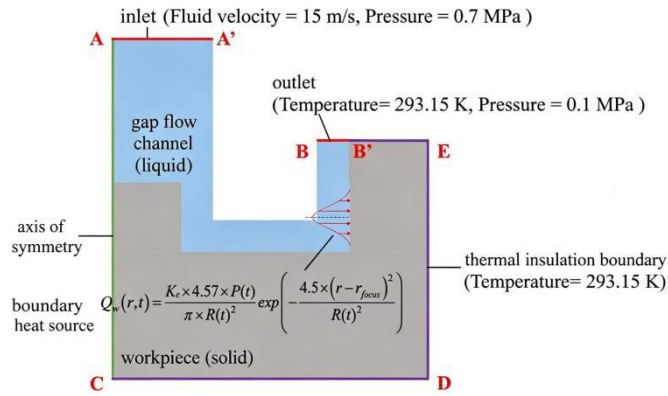


Fig. 3-3 Schematic diagram of boundary conditions for the thermal-fluid coupling model

4. Results and Analysis of Thermal-Fluid Coupling Simulation on Molten material Evolution

4.1 Analysis of Phase Indicator Simulation Results

In fast EDM drilling, the solid high-temperature alloy workpiece is melted into molten material under the instantaneous high temperature of pulse discharges. The molten material interacts with working fluid within the inter-electrode flow field, moving under the influence of complex hydrodynamic forces. As the temperature drops below the melting point, the molten material solidifies to form recast layers. Therefore, tracking the entire lifecycle of the molten material from generation to solidification is the core of thermal-fluid coupling simulation.

In the simulation model, the electrodes and workpieces are defined as solid phases, while molten material and working fluid are treated as liquid phases. A Gaussian heat source is applied on the workpiece sidewall to simulate sidewall discharge. And a phase change module is incorporated to model the transition from solid workpiece to liquid molten material. A phase indicator is employed to characterize the distribution of different phases within the flow field, where the value of 0 represents working fluid and 1 represents molten material.

Fig. 4-1 depicts the evolution of the molten material phase during the pulse-on period of a single sidewall discharge. Detachment from the molten pool into the gap flow field begins at 10 μs , with the volume of entrained material increasing over time. The molten material is primarily distributed on both sides of the pool, exhibiting a larger volume above the pool than below, and shows a slight upward migration along the hole wall.

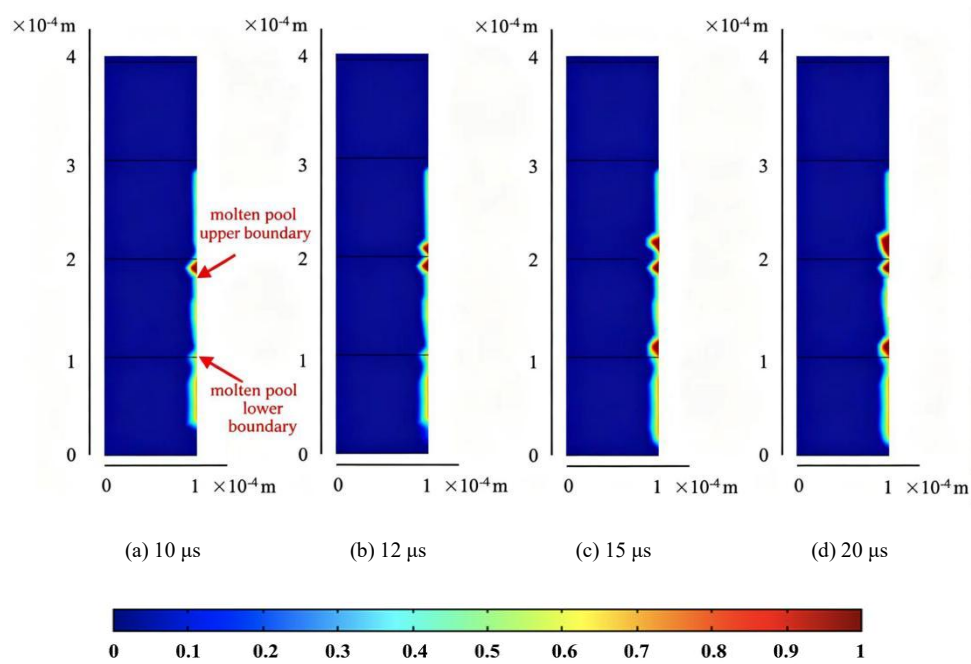


Fig. 4-1 Molten material phase status at sidewall Ton discharge stage

Fig. 4-2 presents the phase indicator results during the pulse-off stage. At 30 μs , machining debris separates from the main molten pool and moves toward the electrode. The generated debris volume is small, consistent with experimental observations, and its calculated velocity of 21 m/s closely matches the experimentally measured horizontal velocity. By 34 μs , the debris disappears from the gap flow field, signifying solidification and adhesion to the electrode surface. The high-pressure flushing fluid has little effect on the debris' horizontal movement, and its vertical displacement is negligible.

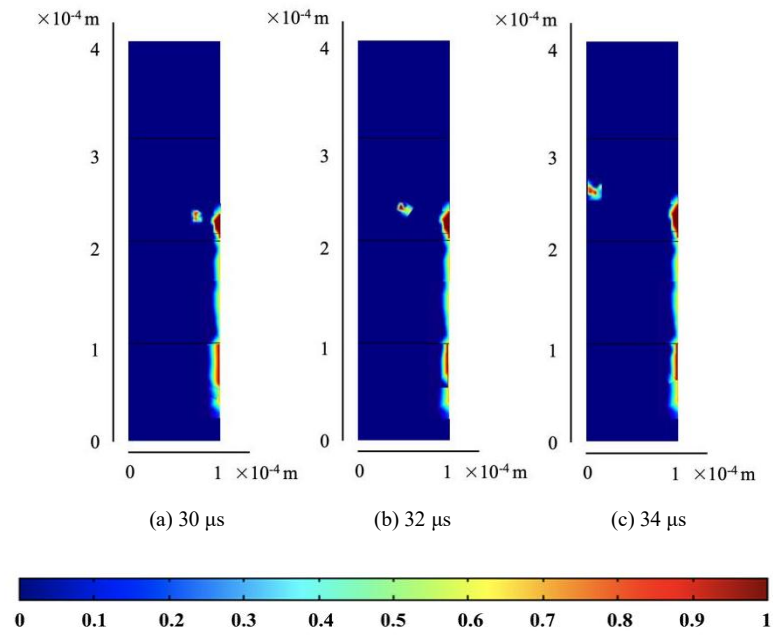


Fig. 4-2 Molten material phase status at sidewall Toff discharge stage

Table 2 Comparison between simulation and observation results

Dynamic characteristics of molten metal	Simulation Result	Observation Result
Generation time	Within 0-10 μ s	Within 0-10 μ s
Molten material inside molten pool	Splashing on both sides of molten pool	Obvious splashing phenomenon
Motion trajectory of debris	Moving towards electrode	Moving towards electrode and discharging vertically upward
Movement velocity of debris	21 m/s	23 m/s

As shown in Table 3-5, the simulation results for generation time, movement velocity, and evolution trend align closely with experimental data, verifying the reliability of the proposed thermal-fluid coupling model. The phase indicator accurately captures the position and volume of the molten material, while the combined temperature, velocity, and pressure fields reveal the intrinsic mechanisms of its evolution.

4.2 Analysis of Temperature Field Simulation Results

Temperature is the dominant factor governing the generation and solidification of molten material. The heat transfer induced by pulse discharge and the cooling effect of the high-pressure flushing fluid jointly determine the duration of molten material movement and the distribution of recast layers.

The temperature field simulation encompasses both the heating process during discharge and the cooling process following discharge. The latent heat of phase change is incorporated based on the material properties of high-temperature alloys, and regions with temperatures exceeding the melting point are defined as molten zones.

Fig. 4-3 illustrates the temperature evolution following the initiation of discharge. At 1 μ s after discharge ignition, the temperature in the central area of the workpiece rises sharply, generating a small amount of molten material. As the discharge continues, the molten zone expands in both the depth and radial directions.

Fig. 4-4 presents the temperature field simulation results at the intermediate stage of discharge. When the pulse-on period ends, the maximum temperature of the workpiece reaches 3300 K. During the pulse-off period, the overall temperature gradually decreases. However, the generation of new molten material can persist until the temperature of the gap flow field drops below the alloy's melting point.

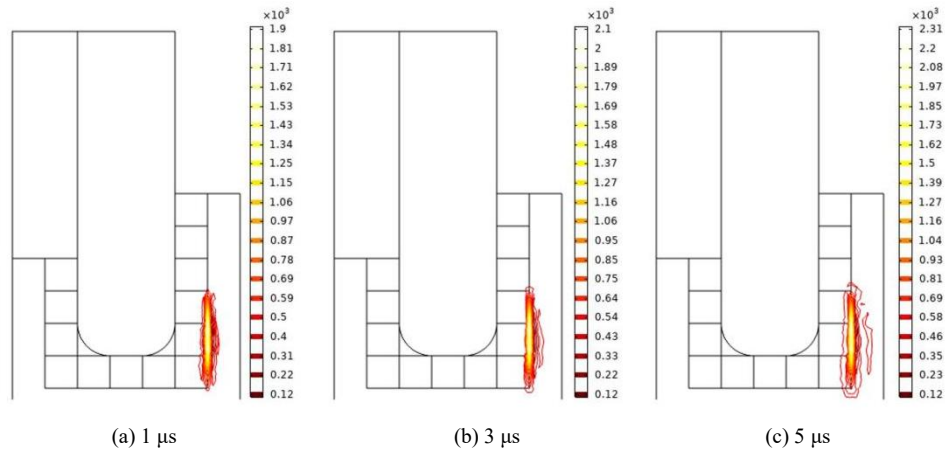


Fig. 4-3 Temperature distribution of workpiece at the initial discharge stage

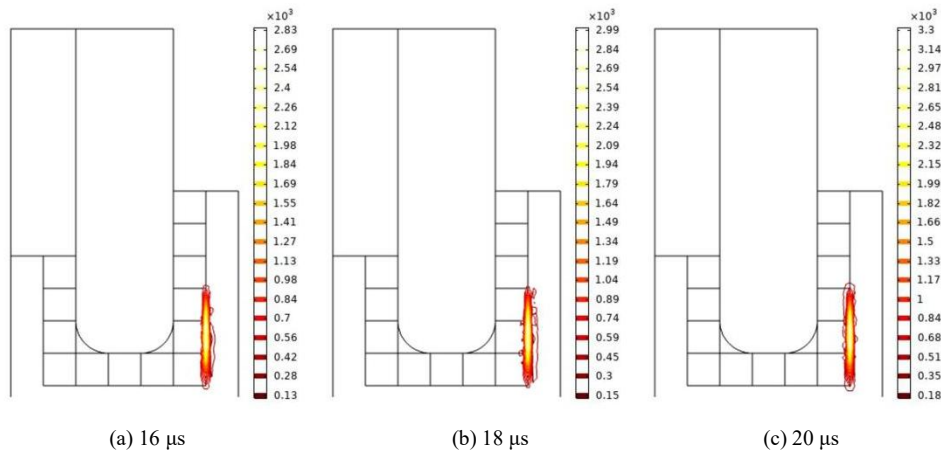


Fig. 4-4 Temperature distribution of workpiece at the middle discharge stage

Fig. 4-5 illustrates the temperature field simulation results during the late stage of a single pulse discharge. Under the cooling effect of the low-temperature water-based working fluid (293.15 K), the high-temperature molten zone continuously contracts, with the majority of the molten material solidifying to form recast layers on the sidewall. However, a small central area maintains a temperature above the melting point, continuously generating minute amounts of molten material. The maximum extent of the molten zone is $103 \mu\text{m} \times 25 \mu\text{m}$, which occurs at 29 μs .

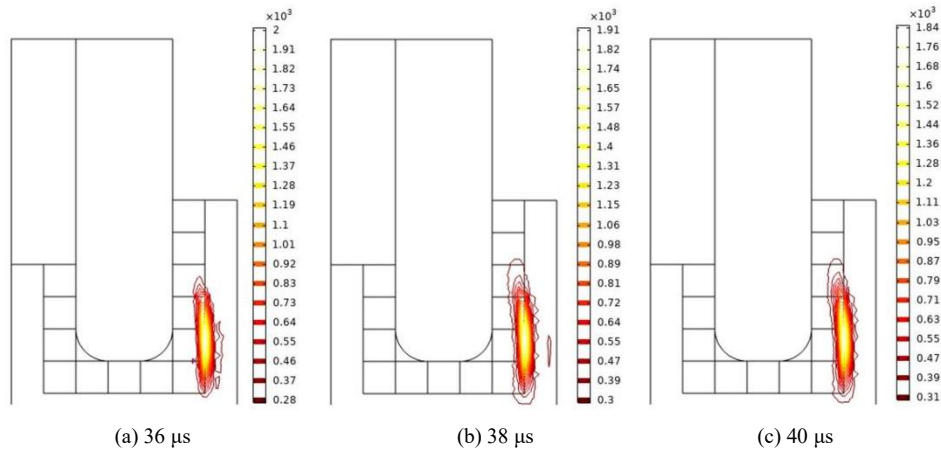
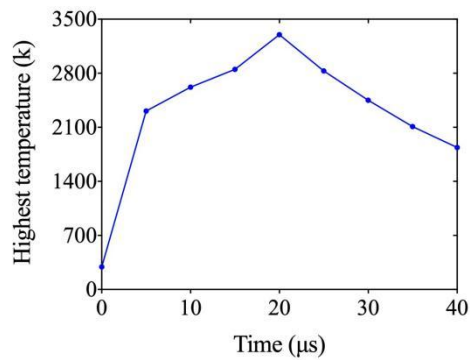
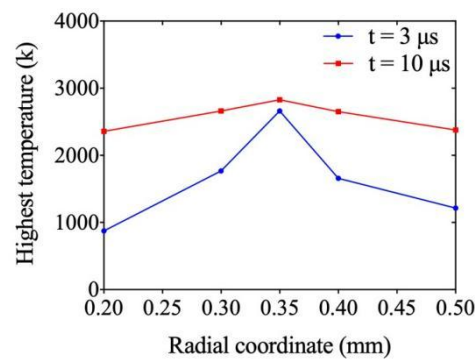


Fig. 4-5 Temperature distribution of workpiece at the late discharge stage

As shown in Fig. 4-6, the temporal evolution of the maximum temperature and the radial temperature distribution at typical moments both exhibit characteristics of an approximate Gaussian distribution.



(a) Curve of the highest temperature versus time



(b) Radial temperature distribution at different times

Fig. 4-6 Variation and distribution rules of temperature field

4.3 Analysis of Velocity Field Simulation Results

The temperature field characterizes the generation time, solidification time, and geometric dimensions of the molten material, while the velocity field is employed to analyze the dynamic movement of the molten material and debris within the gap flow field. Fig. 4-7 presents the numerical simulation results of the velocity field at various instants during the thermal-fluid coupling simulation.

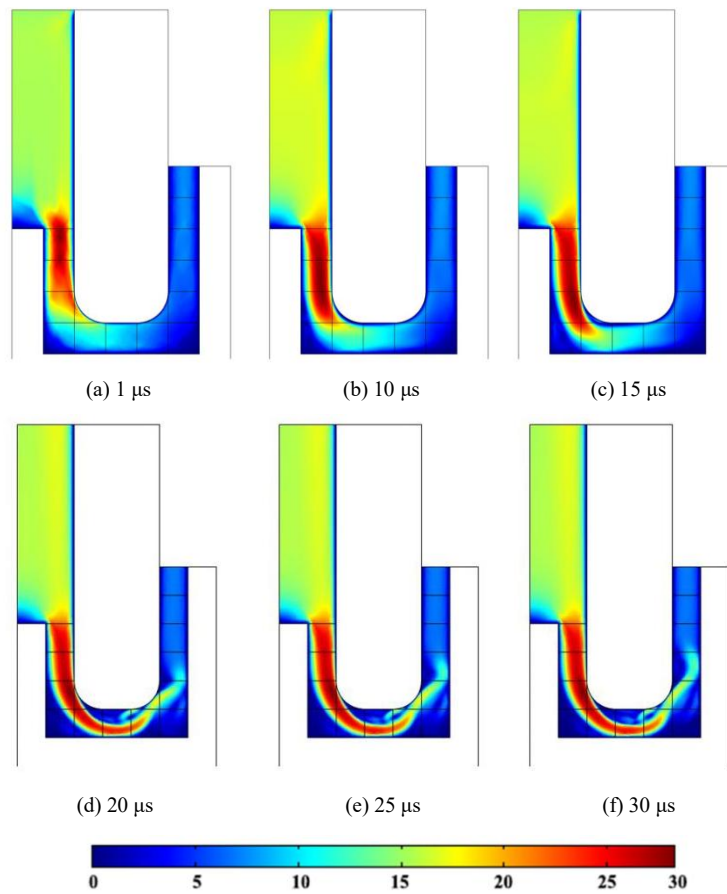


Fig. 4-7 Velocity distribution of gap flow field

The hollow electrode injects high-pressure working fluid. Due to residual protrusions on the workpiece, the flow channel undergoes a sudden constriction. The flow velocity remains approximately 15 m/s prior to the constriction but increases significantly upon entering the narrow channel, peaking at over 30 m/s at the first corner of the electrode. The flow velocity subsequently decreases at the following corners of the electrode tip

In the gap flow field near the electrode end discharge area, regions with flow velocities exceeding 15 m/s are located close to the workpiece surface, generating a strong hydrodynamic impact that drives the molten material outward.

A pronounced velocity gradient exists in the gap flow field of the sidewall discharge area, where the flow velocity is higher in the middle of the gap. Consequently, the vertical movement velocity of the debris exceeds its horizontal velocity. Furthermore, the working fluid velocity is significantly lower than the measured debris velocity, indicating that the high initial velocity of the debris is driven by the explosive force of the discharge rather than the hydrodynamic force of the working fluid.

4.4 Analysis of Pressure Field Simulation Results

The motion state of molten material is determined by the forces acting within the gap flow field. Therefore, the pressure field results are essential for force analysis. Fig. 4-8 shows the pressure simulation results.

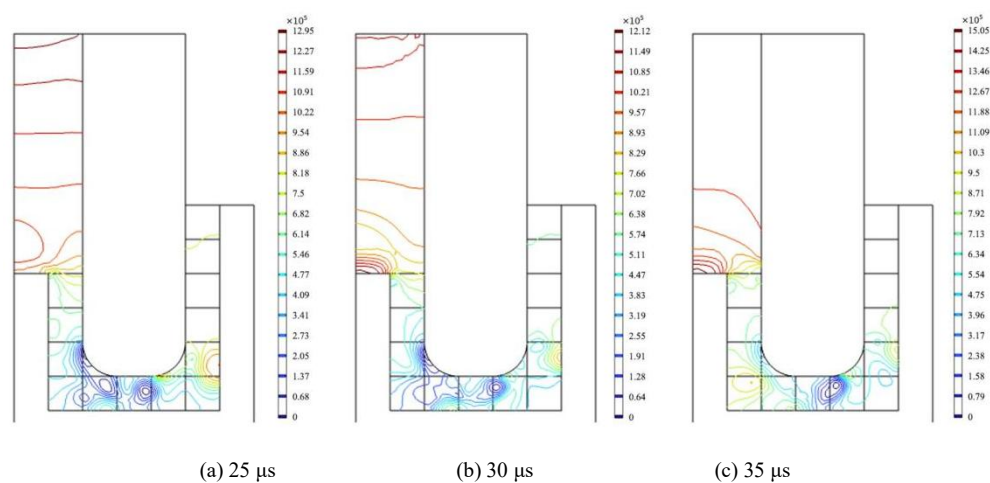


Fig. 4-8 Pressure distribution of gap flow field

The simulation indicates that the gap flow channel undergoes abrupt constriction due to residual protrusions on the workpiece. Consequently, the maximum pressure concentrates at the junction

between the uneroded region and the gap flow field, peaking at 1.505 MPa. Upon entering the gap flow field of the machined region, a low-pressure zone forms at the corner of the electrode tip. This is attributed to the continuous corners in the flow channel, which impede rapid fluid motion near the center of the electrode tip, resulting in relatively low flow velocity. Consequently, a stable, slow-moving flow region emerges within the high-velocity field. Influenced by the surrounding high-speed flow, the pressure in this quiescent region decreases, creating a low-pressure concentration zone between the electrode tip and the workpiece. Simulation results reveal that the pressure differential between this low-pressure zone and the workpiece erosion region reaches 0.45 MPa, exceeding the pressure differential relative to atmospheric pressure (approximately 0.1 MPa).

At the sidewall discharge position, the pressure difference is stably maintained between 0.238 MPa and 0.272 MPa, directed radially from the workpiece sidewall toward the electrode. This pressure gradient serves as the primary driving force for the molten material to detach from the main workpiece and form debris.

After detaching from the workpiece, the debris is subjected to the combined effects of the pressure differential and hydrodynamic impact. This results in a trajectory that approaches the electrode and moves upward along the gap flow field.

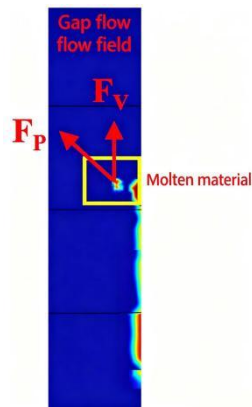


Fig. 4-9 Main forces acting on molten material in inter-electrode flow field

4.5 Comprehensive Analysis of Simulation Results

Based on the multi-physics simulation results, the formation mechanism of recast layers is summarized as follows:

(1) The maximum volume and complete solidification time of the molten material within the molten pool are determined by the discharge power. The majority of the molten material remains at the original discharge position, gradually solidifying to form recast layers.

(2) A small fraction of the molten material detaches from the molten pool to form debris. The pressure differential within the gap flow field serves as the dominant force driving this separation. The subsequent trajectory of the debris is jointly governed by the pressure differential and the hydrodynamic impact force.

Drawing on the single-pulse observation experiments in Section 2 and the sidewall discharge simulation analysis in Section 4, key physical quantities associated with the formation and distribution of recast layers during molten material evolution are extracted. The discharge results at different positions are statistically analyzed and summarized, with detailed results presented in Table 3.

Table 3 Physical field parameters related to recast layers after a single discharge

Discharge Position	Physical Parameter	Result
End discharge	Size of recast layer on hole wall	103 μm $\times$ 25 μm
Sidewall discharge	Size of recast layer on hole wall	10 μm $\times$ 150 μm
Sidewall discharge	Size of vertically moving debris	20 μm $\times$ 20 μm
Sidewall discharge	Velocity of vertically moving debris	50 m/s
Secondary sidewall discharge	Discharge position	Workpiece sidewall, same Z-coordinate as debris

The thermal-fluid coupling model enables micro-scale analysis of recast layers in film cooling holes, providing valuable guidance for practical machining analysis and process parameter optimization.

5. Thermal-Fluid Coupling Model for Continuous Discharge and Influence on Recast Layer Distribution

5.1 Establishment of Continuous Discharge Thermal-Fluid Coupling Model

Actual fast EDM drilling is realized by continuous multiple pulse discharges. And the final distribution of recast layers is the cumulative effect of numerous single discharges. Therefore, a continuous discharge simulation model is established to explore the distribution rule of recast layers.

5.1.1 Distribution of Continuous Discharge Positions

Discharges occur randomly at the electrode end and sidewall in machining process. According to the average value of experimental statistical data, the proportion of electrode end discharge, sidewall discharge and secondary sidewall discharge is 57.9%, 11.39% and 30.71% respectively. The simulation area is divided into an end discharge zone, a sidewall discharge zone and a secondary discharge zone.

A random distribution function $\text{rand}(r,z,t)$ is set for the center coordinate of the Gaussian heat source. This function changes periodically with each discharge cycle, with distributing heat sources randomly in corresponding zones according to discharge proportion. Different from ordinary discharges, the position of secondary sidewall discharge is dependent on the real-time position of undischarged debris. If debris exists in the secondary discharge zone when secondary discharge occurs, the Z-coordinate of debris is set as the center position of secondary discharge.

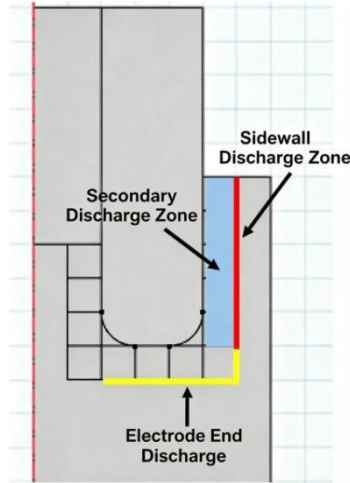


Fig. 5-1 Regional division of different discharge positions

5.1.2 Encapsulation of Physical Parameters for Single Discharge

The evolution of molten material exhibits relative independence between adjacent pulses. To reduce the computational load, the physical field parameters at the end of each single pulse are captured and directly transferred to the next discharge cycle, thereby avoiding the need to repeat a full-process simulation for every individual pulse. The recast layer-related parameters listed in Table 3 are adopted as the baseline parameters for single discharge.

5.1.3 Numerical Calculation of Continuous Discharge Simulation

The thermal-fluid coupling model adopts the same basic geometric structure and discharge parameters as described in Section 3. The initial bottom surface of the workpiece is positioned 10 mm downstream from the flow field inlet. To simulate the actual drilling process, the electrode end discharge position moves downward synchronously as continuous discharges proceed. A random function, $\text{rand}(r,z,t)$, is incorporated to determine the center position of the Gaussian heat source. The pulse cycle is set to 40 μs with a time step of 10 μs , and the total simulation duration is 1 s. Upon

completion of the simulation, the workpiece bottom is fully eroded, and only the sidewall recast layer is retained for subsequent analysis.

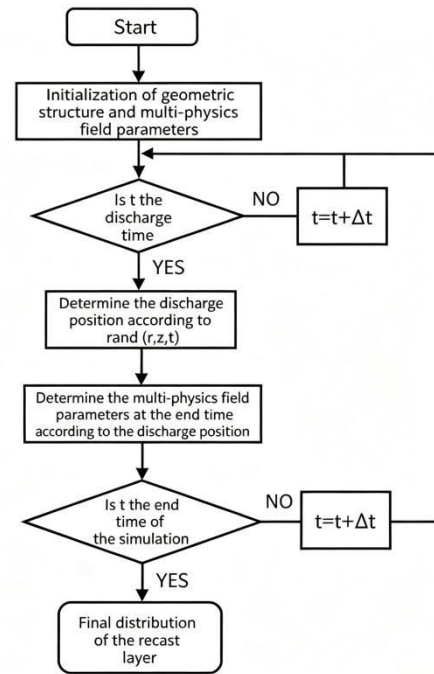


Fig. 5-2 Flowchart of numerical calculation for continuous discharge simulation

5.2 Results and Analysis of Continuous Discharge Simulation

The distribution of recast layers on the hole wall is obtained through continuous discharge simulation. Prior to full hole penetration, the thickness of the recast layers at the hole bottom ranges from $12.5\ \mu\text{m}$ to $20\ \mu\text{m}$. Subsequently, these recast layers are completely removed by subsequent discharges after the hole is penetrated.

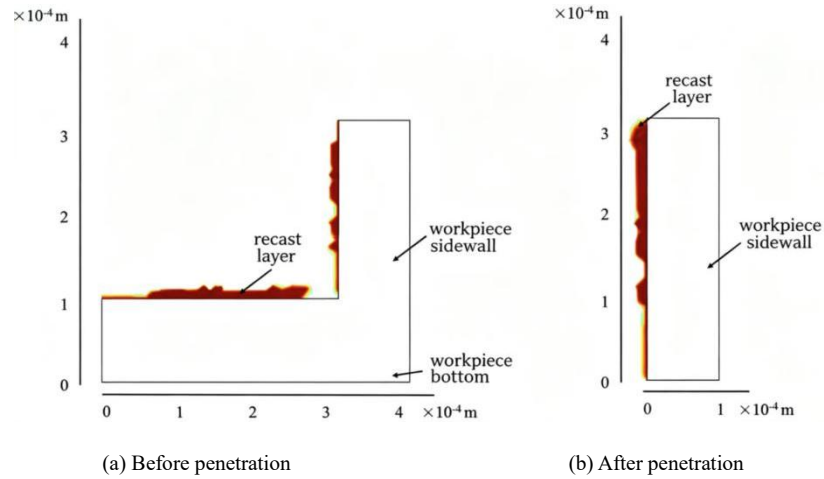


Fig. 5-3 Numerical calculation for continuous discharge simulation

Compared to the readily eroded recast layer at the electrode end, the recast layer on the sidewall is significantly thicker, reaching a maximum of 25.7 μm . This can be attributed to two factors: the sidewall area is substantially larger than the end area, and the proportion of discharges occurring on the sidewall is lower. Consequently, the probability of discharges striking the solidified recast layer on the sidewall is much lower than at the electrode end, rendering the sidewall recast layer less susceptible to erosion by subsequent discharges.

The thickness of sidewall recast layers increases gradually from bottom to top. Firstly, the upper part of the sidewall is formed earlier and retains for a longer time, accumulating more recast layers under repeated discharge actions. Secondly, part of molten material generated by sidewall discharge moves upward and solidifies on the upper sidewall. Thirdly, upward moving debris easily induces secondary discharge in the upper gap, further increasing the thickness of recast layers on the upper part.

An actual hole section observation experiment verifies the simulation conclusion. The measured thickness of recast layers decreases from 23.6 μm at the upper sidewall to 9.1 μm at the lower sidewall, which is consistent with the simulation results.

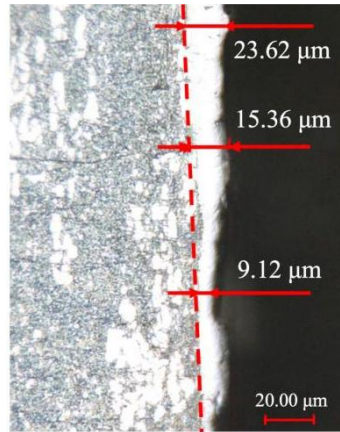


Fig. 5-4 Cross-sectional view of the machined hole after fast EDM drilling

6. Conclusions

In this study, the formation mechanism of recast layers in fast EDM drilling is investigated through dynamic observation experiments and thermal–fluid coupling simulations. A dedicated multi-physical field simulation framework is established to describe the evolution behavior of molten material under continuous interactions among discharge energy, fluid flow, and phase transformation. The main conclusions are summarized as follows.

(1) A dedicated thermal-fluid coupling simulation model is established to analyze recast layers in fast EDM drilling. This model accurately predicts the formation time and thickness of recast layers generated by discharges at various positions. Furthermore, it elucidates the distribution patterns of molten material and the motion trajectories of debris, thereby revealing the intrinsic formation mechanism of recast layers.

(2) The formation mechanism of recast layers is revealed through comprehensive analysis of phase, temperature, velocity, and pressure fields. The temperature field determines the generation and solidification characteristics of molten material, while the pressure differential within the inter-electrode flow field provides the dominant driving force for molten material separation from the

molten pool. After detachment, the migration trajectory of debris is governed by the combined effects of pressure-driven flow and hydrodynamic impact.

(3) A continuous discharge thermal–fluid coupling model is developed by incorporating experimentally measured discharge position distributions and characteristic parameters obtained from single-discharge simulations. The simulation results reveal that the hole-wall recast layer exhibits a non-uniform thickness distribution, gradually increasing from the bottom toward the top of the hole. This behavior is attributed to the combined effects of longer accumulation time in the upper region, upward migration of molten material, and secondary sidewall discharges induced by debris movement.

The findings of this study provide a deeper understanding of recast layer formation mechanisms in fast EDM drilling and provide theoretical guidance for future process optimization and recast layer control strategies.

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Declarations

Ethical Approval Not applicable

Consent to Participate Not applicable

Consent to Publish Not applicable

Authors Contributions Haoyu Chu: Methodology, Conceptualization , Software, Validation, Formal analysis, Writing - Original Draft and Editing. Jian Wang: Formal analysis, Software, Validation. Xuecheng Xi: Funding acquisition, Supervision, Writing - Reviewing and Editing. Wansheng Zhao: Funding acquisition, Supervision, Writing - Reviewing and Editing.

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Competing Interests No conflict of interest exists in the submission of this manuscript, and manuscript is approved by all authors for publication.

Availability of data and materials The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Code availability This paper uses proprietary software and will be not available.

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