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Thermal simulation of the continuous pulse discharge for electro-spark deposition diamond wire saw

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Abstract

Due to their excellent physical and mechanical properties, third-generation super-hard semiconductor materials (such as SiC, GaN) are widely used in the field of microelectronics. However, due to its ultra-high hardness, the machining is very difficult, which has become the bottleneck of its development. The electro-spark deposition (ESD) process can deposit electrode materials on the substrate under the condition of low heat input to achieve metallurgical bonding between metal materials. And it can improve the wear resistance, corrosion resistance, and repair the size of the workpiece. It has been widely used in the field of surface modification engineering. It can effectively improve the bonding strength of the abrasive grains, and the sawing ability of the wire saw to make the consolidated diamond wire saw by the ESD process. Due to its thin matrix and poor thermal properties, the saw wire is easy to burning or even breaking in the manufacturing process. At present, the selection of pulse interval time in the ESD process is generally determined by the duty factor. However, the pulse interval time selected according to duty factor is difficult to meet the heat dissipation requirements of electro-spark deposition diamond wire saw (ESDDWS). In this paper, two kinds of motion modes of ESDDWS manufacturing are put forward, according to the manufacturing characteristics of ESDDWS. The boundary conditions of the continuous pulse discharge of ESDDWS are established. The thermal simulations of continuous pulse discharge of ESDDWS under two motion modes are analyzed. According to the simulation results, the basis of the value of pulse interval in the ESDDWS process is put forward. The effect of pulse interval time on the mechanical performance of the wire saw is analyzed experimentally. The results show that the discharge interval time selected base on the simulation results

can ensure the continuous production of the ESDDWS.

Keywords: Diamond wire saw, ESD, Continuous pulse discharge, Thermal analysis

Nomenclature

c	Specific heat capacity
h	Convection heat coefficient
I	Discharge current
k	Thermal conductivity
m	Number of discharge
q_0	Maximum heat flux
R	The radius of the plasma channel
R_j	The radius of the saw wire
r	Coordinates of cylindrical work domain
T	Temperature
T_0	Environment temperature
t	Time
t_{on}	Pulse duration time
t_{off}	Pulse interval time
z	Coordinates of cylindrical work domain
β	The angle between the incident direction of the heat flow and the normal direction at a point on the core wire surface
θ	Coordinates of cylindrical work domain
ρ	Density

1 Introduction

The third-generation semiconductor materials (such as SiC and GaN) have the characteristics of a high breakdown field, great charge carrier saturation, and elevated dissociation temperatures. It can meet the new requirements of modern electronic technology for high temperature, high voltage, high frequency, high power, and radiation resistance [1, 2]. Therefore they have a broad application prospect in the field of microelectronics [3, 4]. From the crystal bar to wafers, crystal machining mainly includes slicing, grinding, and polishing. Slicing is the first machining procedure that directly affects the subsequent processes [5, 6]. However, due to its ultra-high hardness, the machining is very difficult, which has become the bottleneck of its development [7].

Fixed diamond wire saw has become the main tool for slicing hard and brittle materials [8, 9]. At present, fixed diamond wire saw mainly includes resin diamond

wire saw and electroplated diamond wire saw. The diamonds are attached to a core wire by resin or electroplated [10]. Diamonds are less strongly bonded and have shorter service life due to easy drop-off and wear of the abrasive layer [11]. Slicing the super hard crystal is very difficult and inefficient [12]. In order to improve the slicing efficiency, it is necessary to improve the holding strength and wear resistance of the DWS.

ESD is a deposition process in which the electrode material is deposited on the metal substrate by applying a short duration and high current pulse between cathode and anode [13, 14]. It has become the new surface treatment technology that improves the wear resistance and corrosion resistance of workpieces. Many research results show that the substrate can be kept close to room temperature with less heat input, and the mechanical properties of the substrate can be maintained [15]. Obviously, this is only for large-size workpieces. Adam et al. [16] found that the range of the heat-affected zone was 10 to 20μm. At present, the diameter of the DWS matrix is 50 to 450μm, and there is a decreasing trend. Therefore, the thermal effect on the saw wire can not be ignored during the ESDDWS process. It is necessary to research the temperature field in the continuous pulse discharge of the ESDDWS process.

The discharge interval is an important factor in the ESD process. It influences the discharge state and heat diffusion [17]. However, there are little researches on the selection of pulse interval time in the ESD process. And it is determined mainly by the duty factor. Jain et al. [18] considered that the duty factor of ESD could be between 40% and 86%. He has studied the influence of the duty factor on the height and width of the deposition layer through experiments. The results show that the height and width of the deposition layer increase with the increase of the duty factor. Mohri et al. [19] considered that the duty factor of the ESD should be less than 6%. Furutani et al. [20-22] fabricated wire saw in kerosene medium by ESD, and the duty factor was 3%. However, it was found that the wire is broken frequently when the current exceeds a certain range during the fabrication process. Obviously, the ESDDWS process is different from the surface treatment for the large-size workpiece. Because the size of the workpiece is hundreds or even thousands of times larger than the size of the discharge channel, the local temperature of deposition point has little effect on the overall temperature of the substrate, which can make the workpiece almost keep at room temperature. Due to its thin diameter and poor heat dissipation performance, the saw wire is sensitive to the temperature increasing during the ESDDWS process.

In this work, two kinds of motion modes of ESDDWS manufacturing were put

forward, according to the manufacturing characteristics of ESDDWS. The boundary conditions of continuous pulse discharge of ESDDWS were established. The thermal simulations of continuous pulse discharge of ESDDWS under two motion modes were analyzed. According to the simulation results, the basis of determining the pulse interval time in the ESDDWS process was put forward. The effect of pulse interval time on the mechanical performance of the wire saw is analyzed experimentally. The results show that selected the discharge interval time base on the simulation results can ensure the continuous production of ESDDWS.

2 The principle of fabrication of ESDDWS

The principle of fabrication of ESDDWS has been studied [23]. It is not difficult to find the particularities of the ESDDWS process. Generally, the surface modification technology requires a certain thickness of the deposited layer to meet the specific performance requirements, so it needs to be repeated deposition in a certain area. However, the DWS only needs one abrasive layer. Under proper parameters, the requirement of consolidated diamond grains can be satisfied after several pulses or even one pulse of deposition in the ESDDWS process.

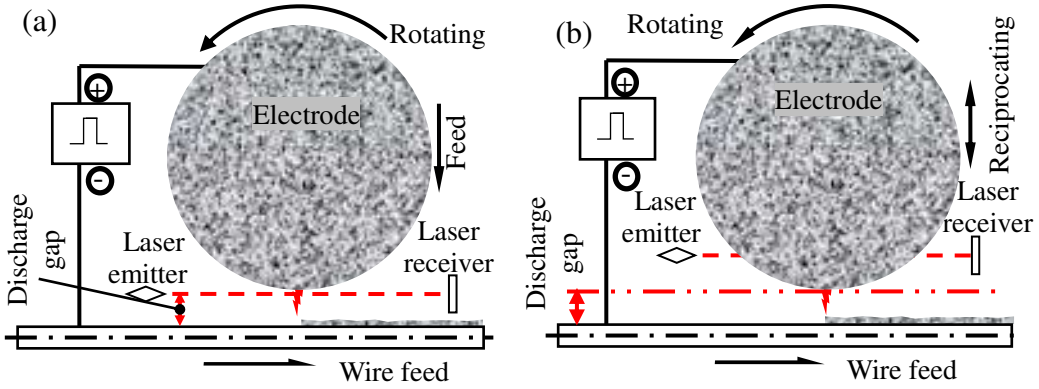


Fig.1 Move model of electrode and wire

According to the characteristics of the ESDDWS process, the movement modes of electrode and wire can be divided into two styles (as shown in Fig.1). (1) During the manufacturing process, the electrode and matrix maintain a fixed gap. The electrodes rotate uniformly and the matrix feeds uniformly. Meanwhile, the circumferential velocity of the electrode is equal to the velocity of the core wire. The feed of the electrode is controlled by a laser limiter. (2) In the manufacturing process, the wire remains stationary during the reciprocating movement of the electrode. When the electrode returns to its original position, the wire moves forward for a distance and the electrodes rotate for an angle. The feed of the electrode is automatically adjusted by reciprocating motion.

In order to simplify the calculation, there are some assumptions made as follows.

(1) In the manufacturing process, the arrangement of the core wire and electrodes makes the electrode column face to the surface of the matrix;

(2) In the process of manufacturing, the discharge is single-channel discharge and normal spark discharge;

(3) The discharge points are at the minimum gap between the core wire and the electrode;

(4) The shape of both electrode and core wire is ideal. It is ignoring the change of electrode material consumption and wire surface material accumulation.

3 Thermal simulation of ESDDWS

3.1 Governing equations of heat conduction

For the transient, non-linear thermal analysis of the ESD process, the governing Fourier heat conduction equation [24, 25] is given by Eq. (1):

$$c\rho\frac{\partial T}{\partial t}=k\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{\partial^2 T}{\partial z^2}\right) \tag{1}$$

Where r and z are the coordinates of the cylindrical work domain; T is temperature; ρ, c, k, and t are mass density, specific heat capacity, thermal conductivity, and time, respectively.

3.2 Boundary conditions

The single discharge surface heat source of the core wire [23] can be given as Eq. (2):

$$q(\theta,r)=q_0\exp(-4.5\frac{r^2}{(a^2\cos^2\theta+b^2\sin^2\theta)})\cos\beta;\ \begin{cases}R(t)<R_j, a=b=R(t)\\ R(t)>R_j, a=R(t), b=R_j\end{cases} \tag{2}$$

Where θ is the coordinates of the cylindrical work domain; β is the angle between the incident direction of the heat flow and the normal direction at a point on the core wire surface, $\beta=\arcsin\frac{r\cos\theta}{R_j}$.

Eq. (2) only consider the heat flux on pulse duration time. The continuous pulse discharge boundary conditions of the core wire can be given as Eq. (3)

$$k\frac{\partial T}{\partial \mathrm{n}}=\begin{cases}q(\varphi,r); & m(T_{on}+T_{off})<t\le m(T_{on}+T_{off})+T_{on}, 0<r\le R\\ h(T-T_0); & m(T_{on}+T_{off})<t\le m(T_{on}+T_{off})+T_{on}, r>R\\ h(T-T_0); & T_{on}+m(T_{on}+T_{off})<t\le (m+1)(T_{on}+T_{off})\end{cases} \tag{3}$$

Where h is the convection heat transfer coefficient; k is the thermal conductivity; R is the radius of the plasma channel; m is the number of discharges. Initial temperatures

of the core wire are assumed to be uniform at environment temperature, $T_0 = 25℃$.

3.3 Meshing

Generally, the thermal analysis model of ANSYS is a closed model. In single pulse analysis, the heat-affected zone of discharge point is smaller because of the short action time and less heat input. Limited models can already meet the requirements of simulation(shown in Fig.2(a)). However, Due to the long action time and the high total heat input, the limited model can not meet the requirements in the continuous pulse discharge deposition process, which increases the saw wire temperature (shown in Fig.2(b)). Based on the element independence analysis (shown in Fig.3), the element size is determined to be 3×2×2μm. Although, increasing the number of elements can alleviate the problem of temperature accumulate without changing the element size. However, increasing the number of elements will result in the calculation time substantial increase.

Based on the physical model of the ESDDWS, we can see that the saw wire is slender, and the heat can be transferred infinitely in the axial direction of the core wire during the deposition process. That is, the boundary of the wire saw on the axis is open. In ANSYS software, the far-field element can solve the problem, which is the infinite boundary of heat transfer. For 3D transient thermal simulation, the infin111 unit should be selected. It should be noted that the far-field elements have only one layer and require an infinite boundary load on the outside. According to the symmetry of the saw wire, the meshing model of continuous pulse discharge thermal simulations of ESDDWS is shown in Fig.4.

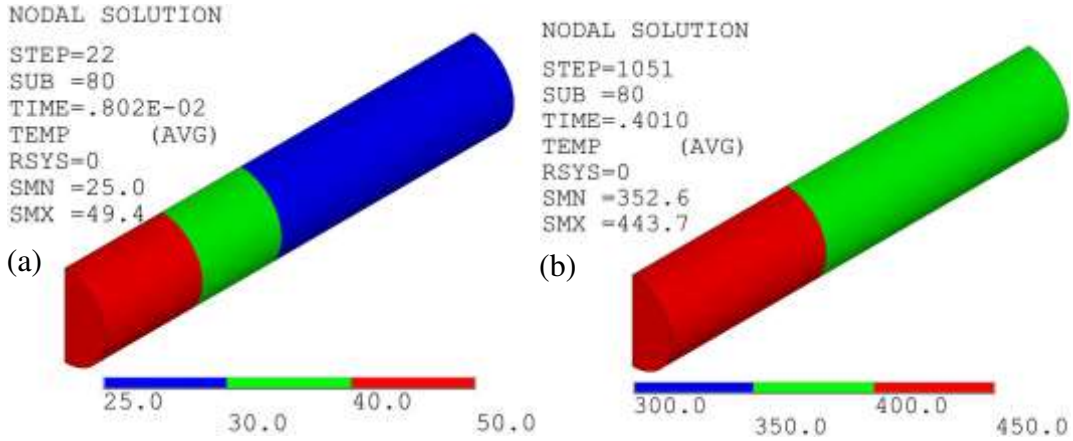
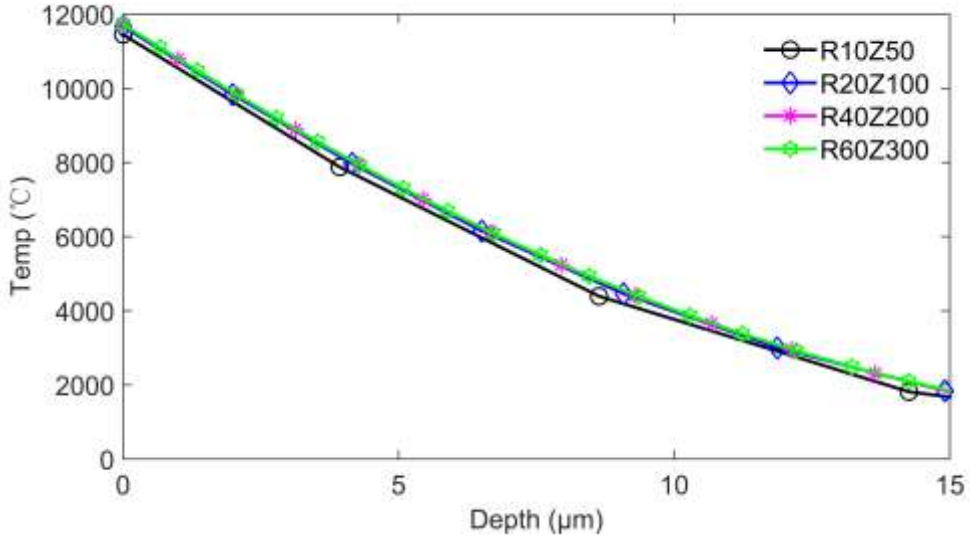


Fig.2 Temperature field of ESDDWS: (a) Single period temperature field; (b) Continuous pulse discharge temperature field without infinite element

(a)



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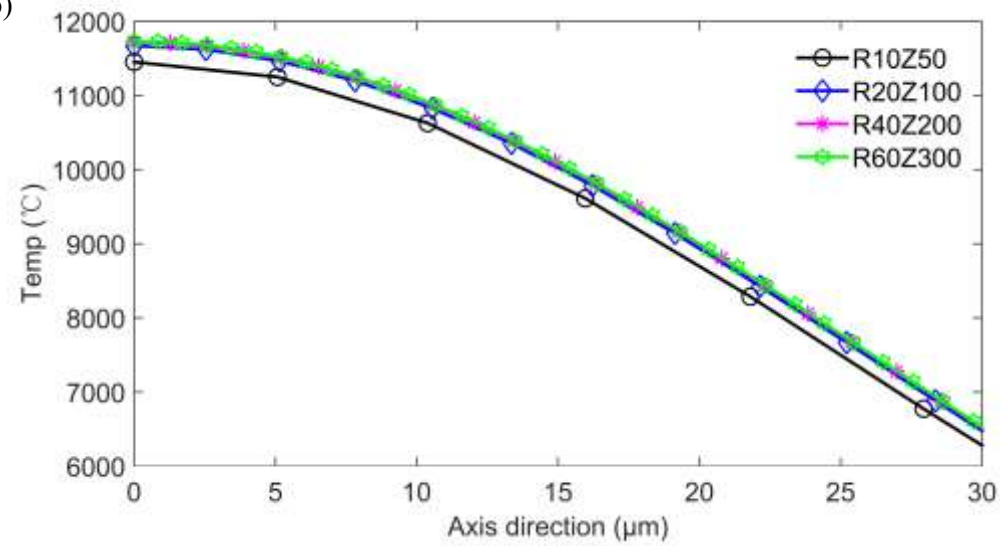
(b)



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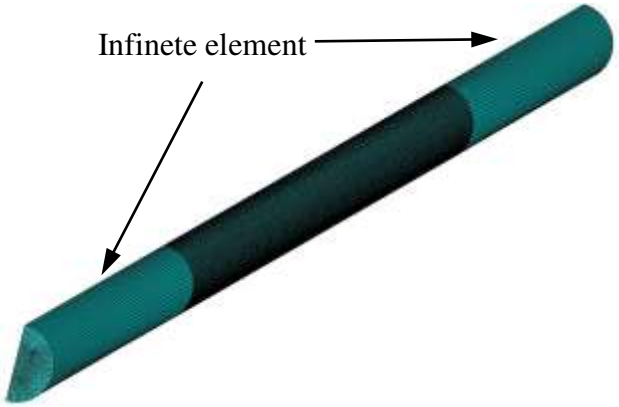
167 Fig.3 The element independence analysis: (a) depth direction; (b) axis direction



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169 Fig.4 Meshing model of saw wire

4 Simulation results and discussion

In this work, the diamond abrasive used W40 Ti coated diamond. The selection of discharge parameters based on the condition, the melting volume of electrode material is the volume of diamond girt's 5, 10, and 15 times. According to the prediction range of the process parameters [23], the discharge parameters determined as follows. The current is 19A, and the pulse duration time is 12μs, 20μs, and 30μs. The thermal simulations of continuous pulse discharge of ESDDWS under two motion modes are analyzed. Under motion mode 1, when the current is 19A, the pulse width is 20μs, the pulse interval is 600μs, and the moving speed is one discharge channel diameter per period. The temperature field of continuous pulse discharge deposition is shown in Fig.5(a). Under motion mode 2, when the current is 19A, the pulse width is 20μs, and the pulse interval time is 8ms. The temperature field of continuous pulse discharge deposition is shown in Fig.5(b).

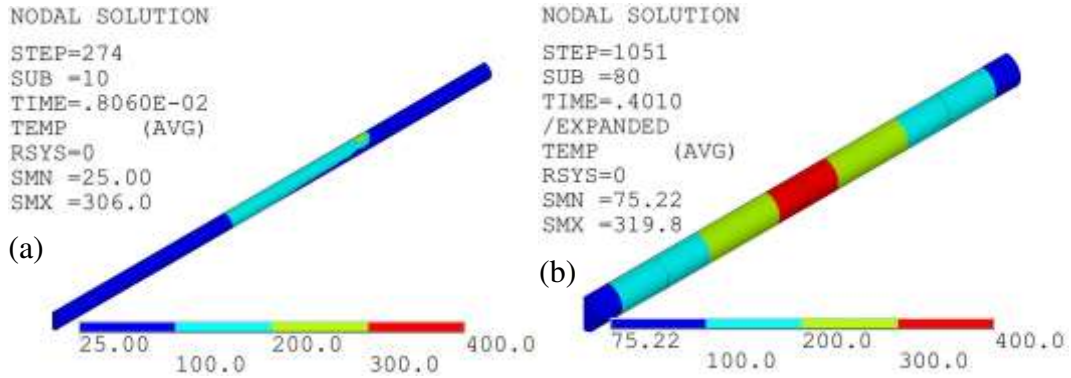
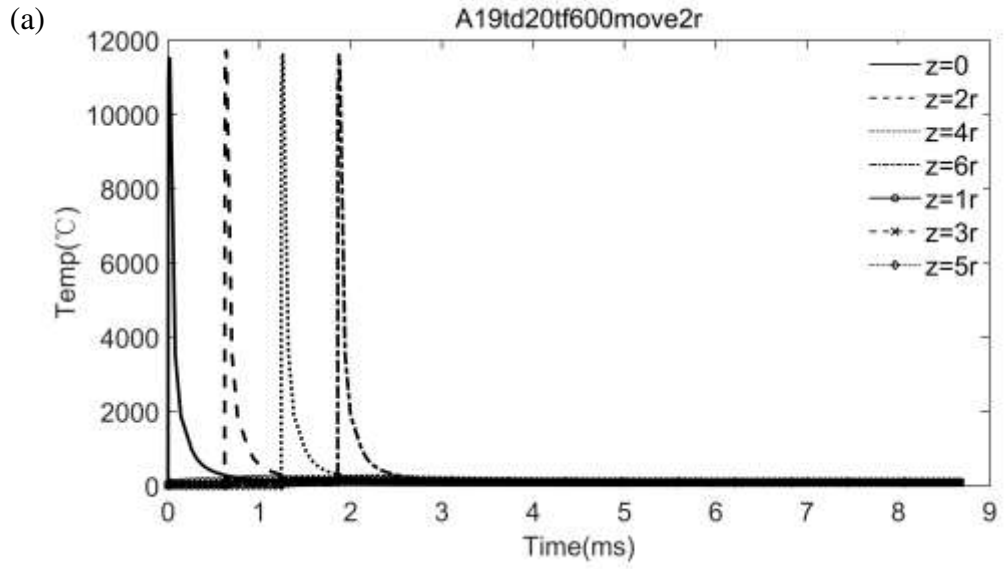
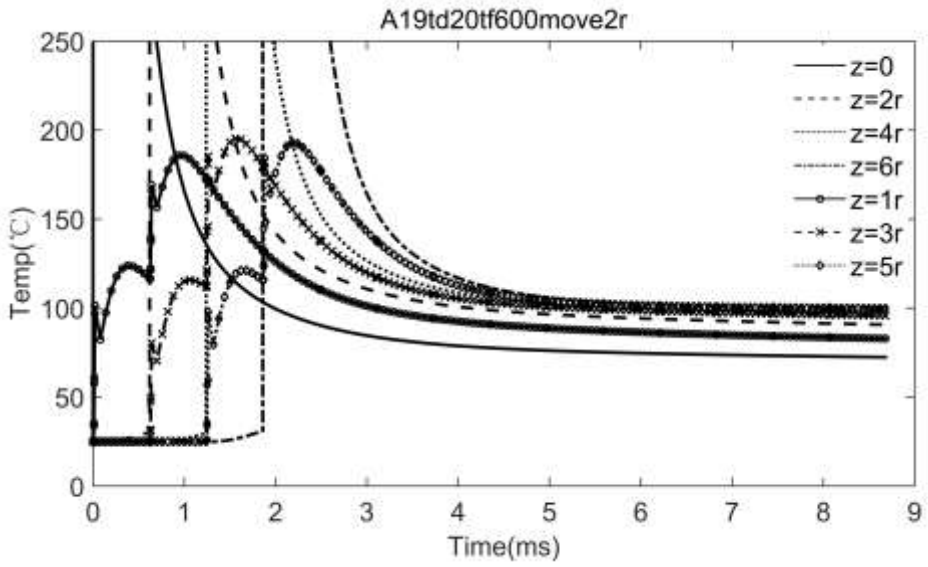


Fig.5 Temperature field of continuous pulse discharge deposition: (a) move motion 1; (b) move motion 2



(b)



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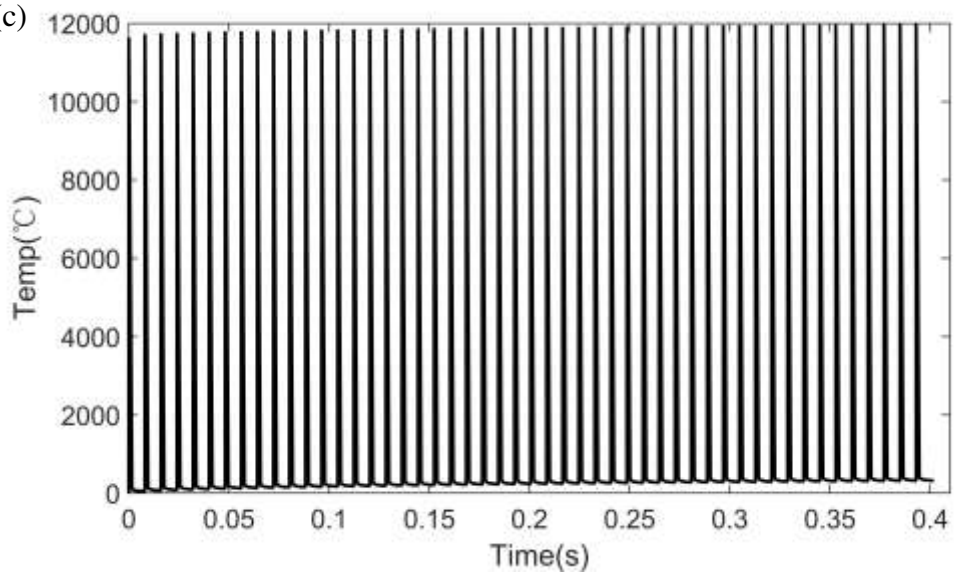
(c)



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(d)

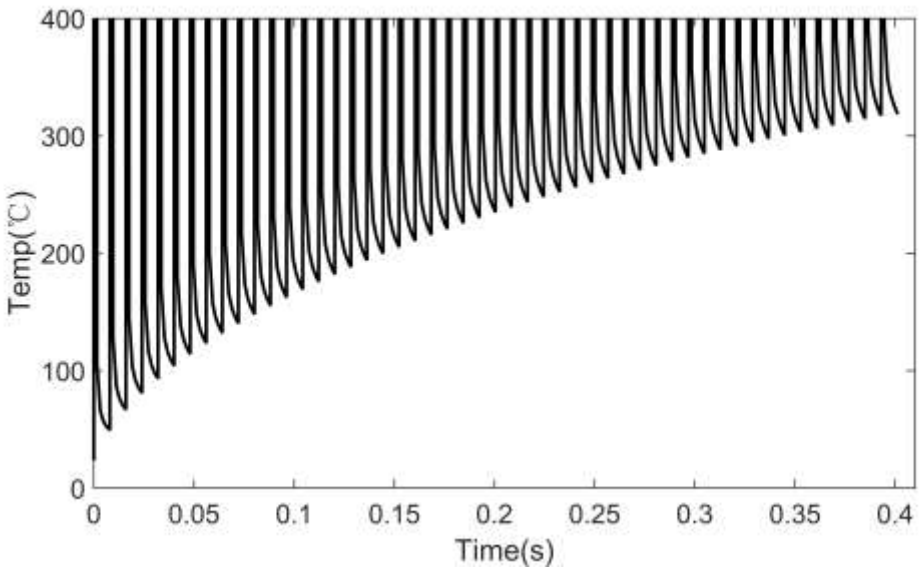

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Fig.6 Temperature curve of the discharge center; (a) move model 1; (b) low-temperature stages of move model 1; (c) move model 2;(d) low-temperature stages of move model 2

From Fig.6(a) and (c), it can be seen that during a discharge period, whatever mode 1 or 2, the core wire's temperature rises rapidly, and then decreases rapidly. At the heating stages, the heating rate can reach 6×10^{9}°C/s. After discharging, the cooling process can be divided into two stages. At the high-temperature stages, the temperature of the core wire decreases rapidly, and the cooling rate is similar to the heating rate. At the low-temperature stages, the cooling rate decreases gradually.

By comparing the temperature curves, it can be seen that there is a big difference between motion modes 1 and 2. In motion mode 1, there is no mutation in the temperature-time curves of adjacent discharge centers such as z=0, z=2r, z=4r, and z=6r. It indicates that the temperature of the next discharge center is not affected by the previous discharge. There are two abrupt mutations in the temperature curve of the edge point of the discharge channel in a period. And there are four mutations in total such as z=r, z=3r, and z=5r. The first mutation is caused by the heat source and then decreases with the end of discharge. The second mutation is due to the diffusion of a large amount of heat from the discharge center. It indicates that the adjacent discharges have an impact on the edge point of the discharge channel. The effect of temperature superposition can be ignored when the distance between two discharge points is greater than three times the discharge channel radius. Finally, the core wire tends to equilibrium temperature. In motion mode 2, the discharge centers are in the same position. During the increase of discharge times, the core wire's temperature increases continuously due to the superposition of energy.

We take the final temperature at the discharge center as the dynamic equilibrium temperature of the core wire. According to the ANSYS simulation results, the relationship between the core wire equilibrium temperature and the pulse interval time in movement model 2 has obtained, as shown in Fig.7.

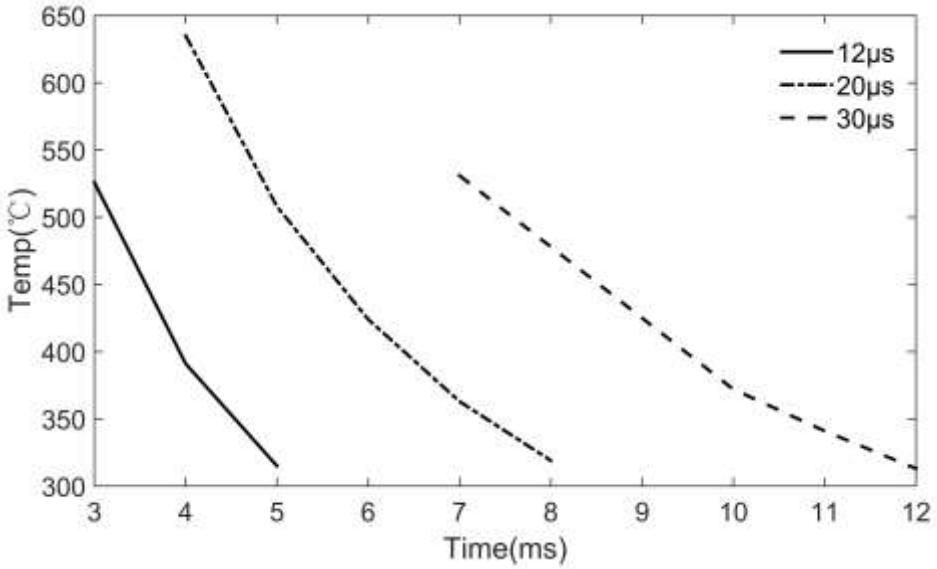


Fig.7 The relationship of balance temperature of wire and pulse interval duration time(move model 2)

5 Experiments

The manufacturing experiment is carried out on a self-made ESD machine, and the saw wire was deposited from one side. The experimental parameters are described in Table 1.

Table. 1 Experiment parameter

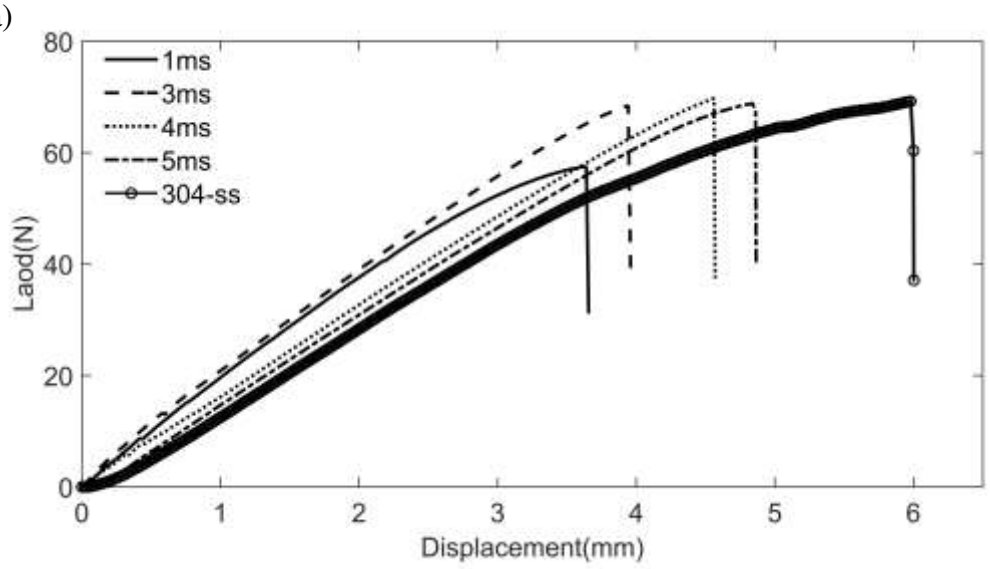
Parameter	Value									
Workpiece (Cathode)	304-ss(ϕ 0.2mm)									
Electrode (Anode)	Cu(10μm):Ni(10μm):Diamond=12:12:1									
Coated diamond	W40									
Current(A)	19									
Pulse duration time(μs)	12					20			30	
Pulse interval time(ms)	1	3	4	5	4	6	8	6	8	10
Working medium	Air									
Movement mode	2									
Discharge time(s)	0.4									

The mechanical properties of the 304-ss wire changed because of the microstructure's transformation. Because it is slender, the change of local structure will affect the overall performance of the core wire. Researchers have reported that the martensitic transformation of 304-ss begins at 300℃ [26]. Therefore, the local equilibrium temperature of the saw wire should maintain at about 300℃ during the ESDDSW process. Therefore, select the pulse interval time should base on the discharge

parameters. In the experiment, when the pulse duration time is 12μs, the pulse interval time is set to 1ms, 3ms, 4ms, and 5ms. When the pulse duration time is 20μs, the pulse interval time is set to 4ms, 6ms, and 8ms. When the pulse duration time is 30μs, the pulse interval time is set to 6ms, 8ms, and 10ms. During the experiment, when the pulse duration time is 12μs and the pulse interval time is 1 ms, the saw wire is broke frequently. And the saw wire deforms obviously after deposition. Under other parameters, the saw wire does not break, and the saw wire keeps its original shape.

Tensile tests have been carried out on the deposited wire saw, and the load-displacement curve is shown in Fig.8. It can be seen that: when the pulse duration time is 12μs and the pulse interval time is 1 ms, the wire breaking force is 10N lower than that of the raw wire. And its ductility is also greatly reduced. Under other parameters, with the decrease of pulse interval time, the broken force of the saw wire does not decrease obviously, but its ductility also decreases gradually. It indicated that the pulse interval would first affect the plasticity of the wire saw. And when it exceeds a certain range, it would affect the tensile strength of the wire saw. Therefore, in order to maintain its mechanical performance, the balance temperature of the wire saw should be around 300℃ during the ESDDWS process.

(a)



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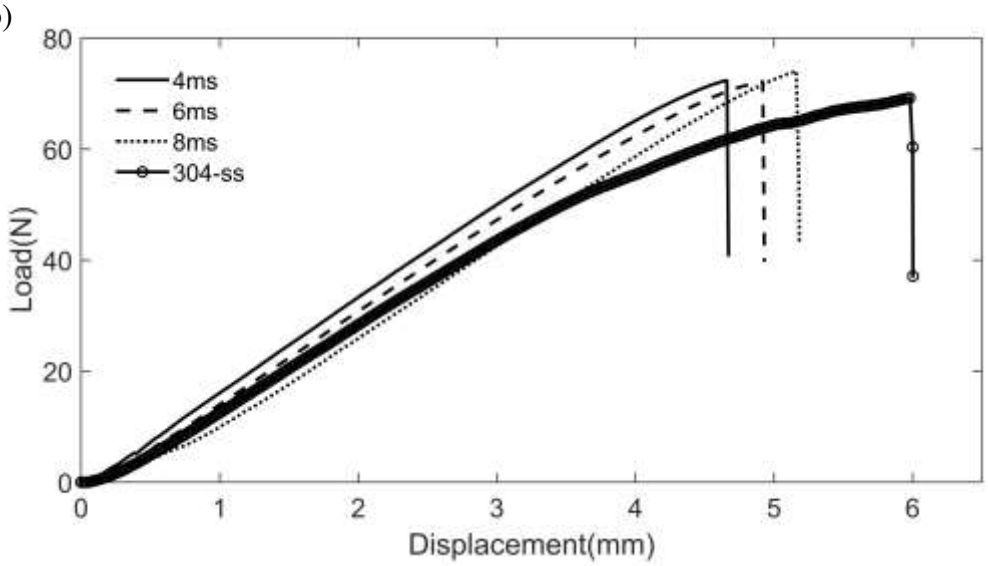

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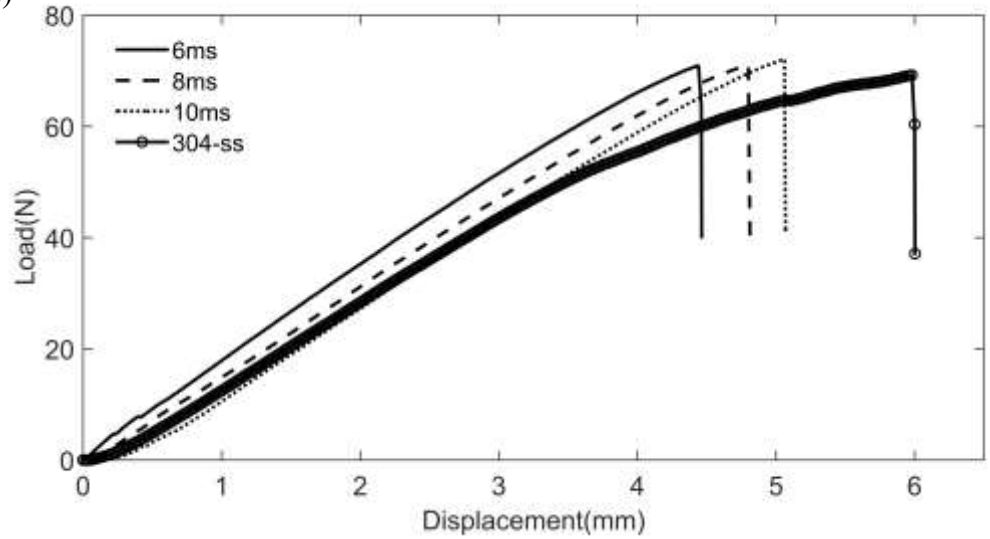

Fig.8 Load and displacement curve of tensile test:(a) 12μs; (b) 20μs; (c) 30μs

6 Conclusion

(1) According to the process characteristics of ESDDWS, two kinds of motion modes of manufacturing are put forward.

(2) According to the characteristics of the saw wire, a simulation model of continuous pulse discharge deposition is established.

(3) According to the two different motion modes of electrode and core wire, the thermal simulations of continuous pulse discharge of ESDDWS were analyzed.

(4) The simulation results show that: in movement mode 1, the temperature of adjacent discharge points has the superposition effect. The effect of temperature superposition can be ignored when the distance between two discharge points is

greater than three times the discharge channel radius. The wire saw's temperature tends to balance finally. In motion mode 2, the discharge centers are in the same position. During the increase of discharge times, the core wire's temperature increases continuously due to the superposition of energy.

(5) The pulse interval would first affect the plasticity of the wire saw. And when it exceeds a certain range, it would affect the tensile strength of the wire saw. In order to maintain its mechanical performance, the balance temperature of the wire saw should be around 300℃ during the ESDDWS process.

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Declarations

Ethical approval

Not applicable

Consent to participate

Not applicable

Consent to publish

The authors declare that this work has not been submitted elsewhere for publication, in whole or in part.

Authors contributions

Chengyun Li is the executor of article writing and experiment operation.

Peiqi Ge contributed to the conception of the work.

Wenbo Bi contributed to the experiment preparation.

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Competing interests

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work. We have no competing financial interests.

Code availability

Not applicable.

Data availability

The data and materials supporting the results of this article are included within the article.

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Figures

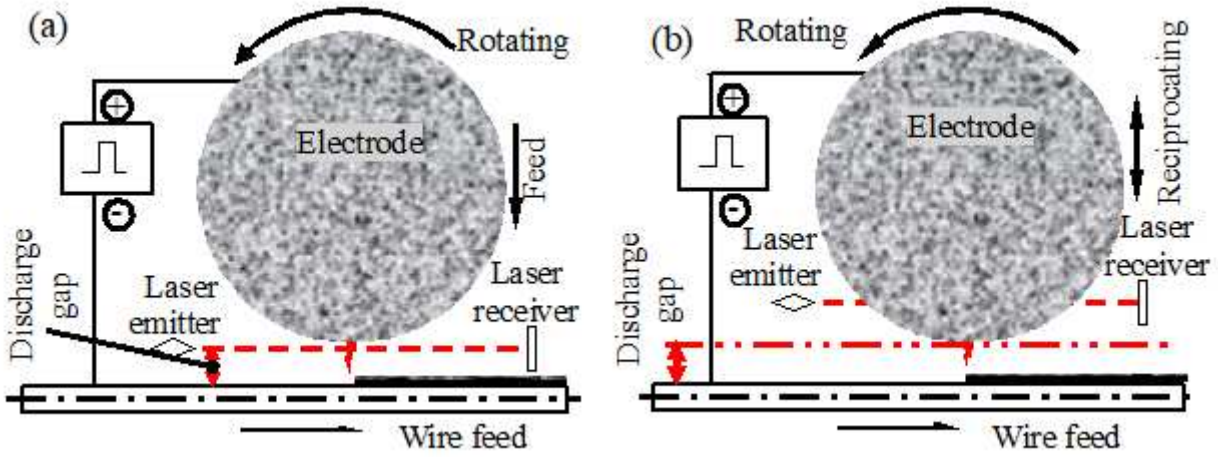

Figure 1

Move model of electrode and wire

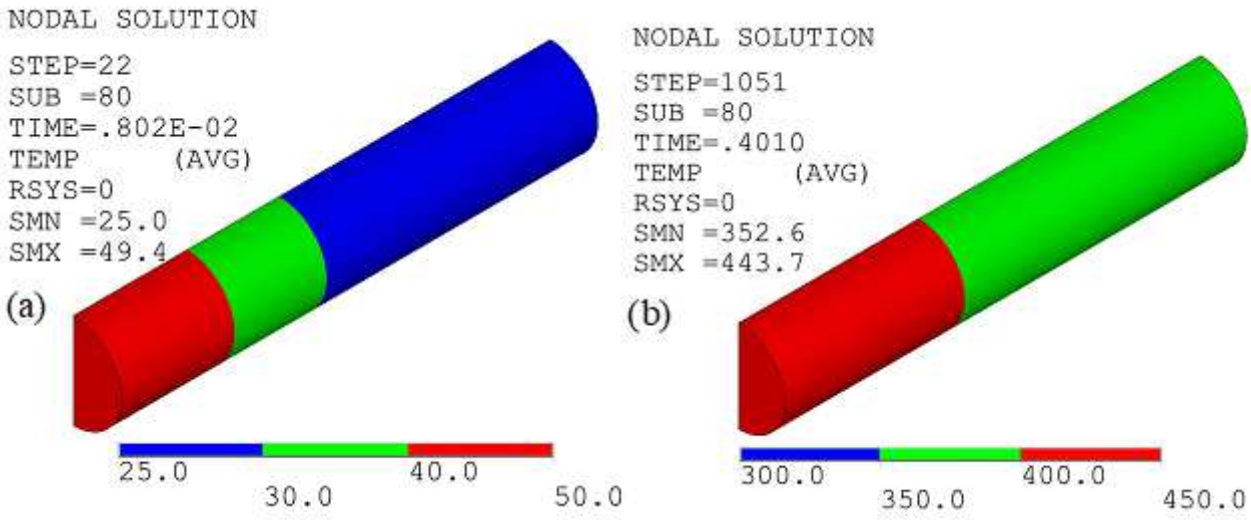

Figure 2

Temperature field of ESDDWS: (a) Single period temperature field; (b) Continuous pulse discharge temperature field without infinite element

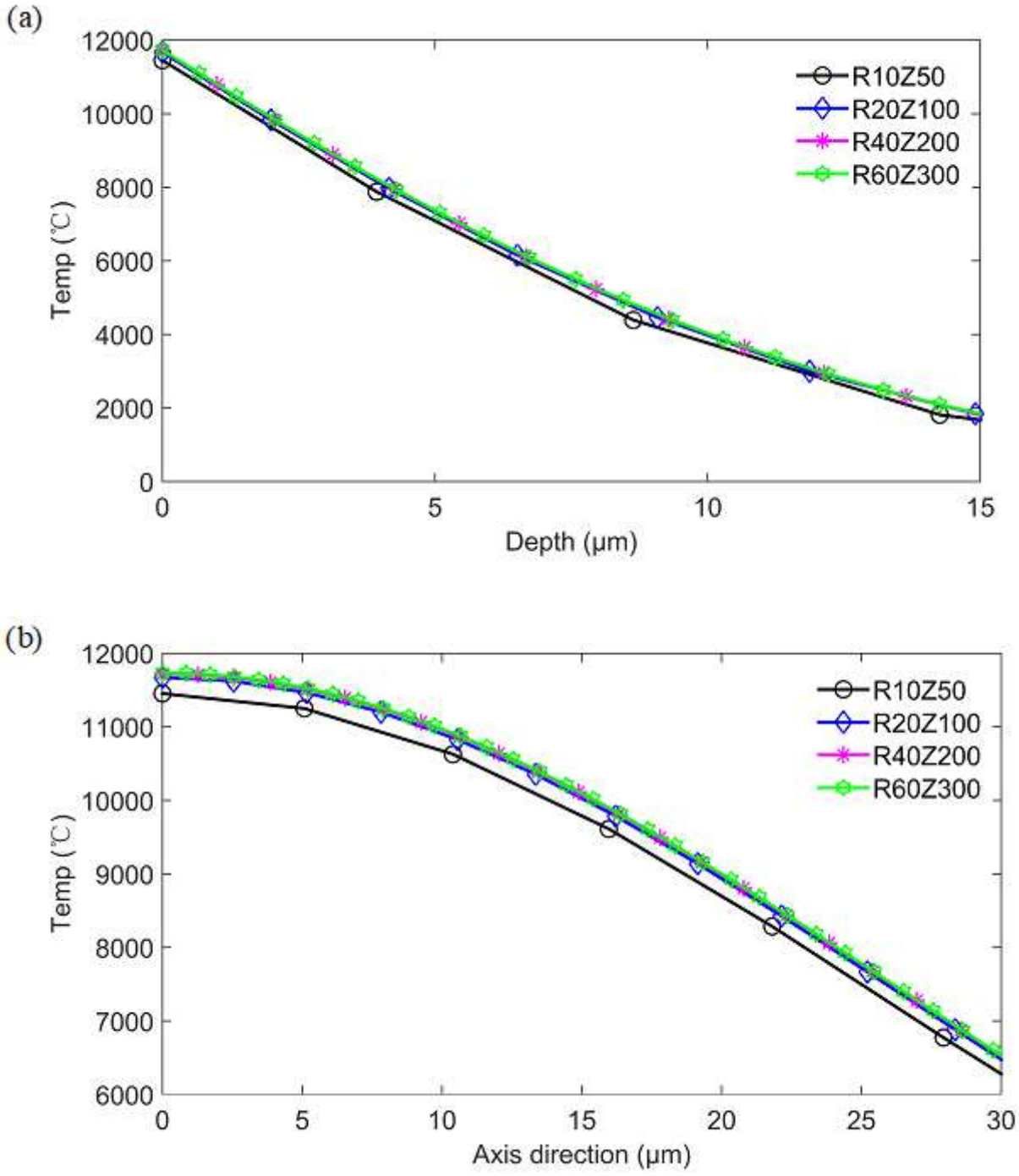

Figure 3

The element independence analysis: (a) depth direction; (b) axis direction

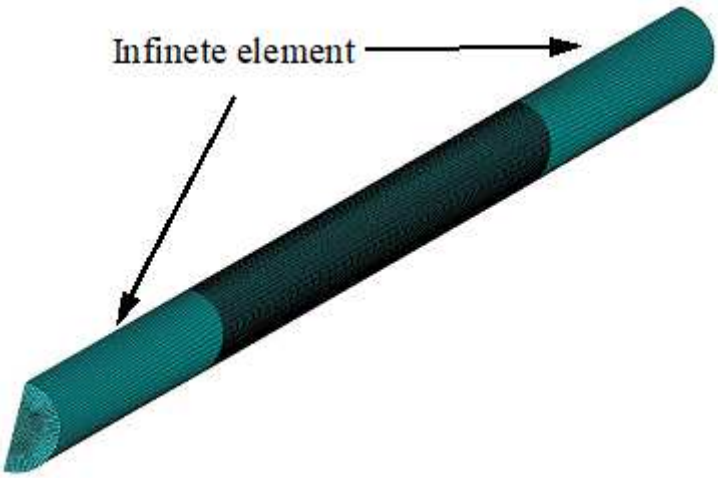

Figure 4

Meshing model of saw wire

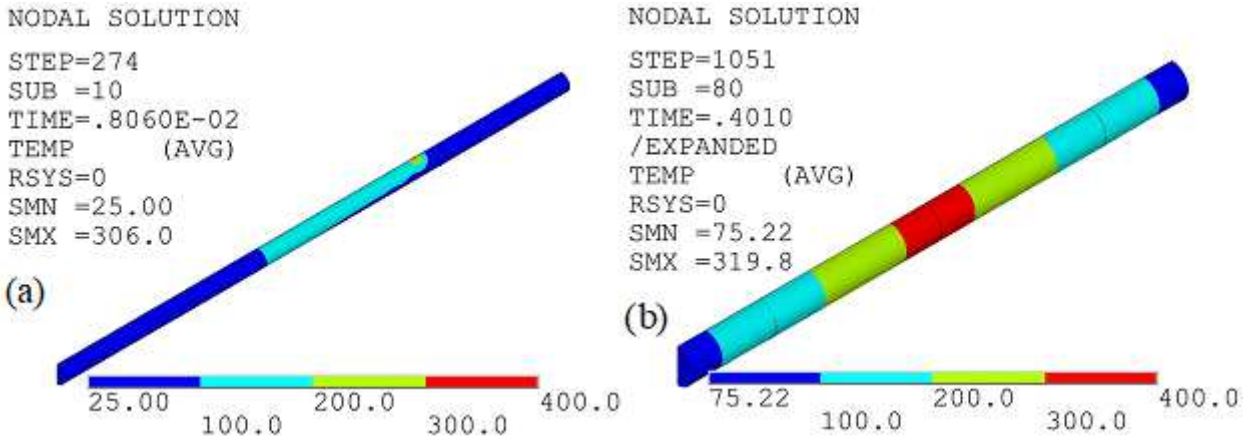

Figure 5

Temperature field of continuous pulse discharge deposition: (a) move motion 1; (b) move motion 2

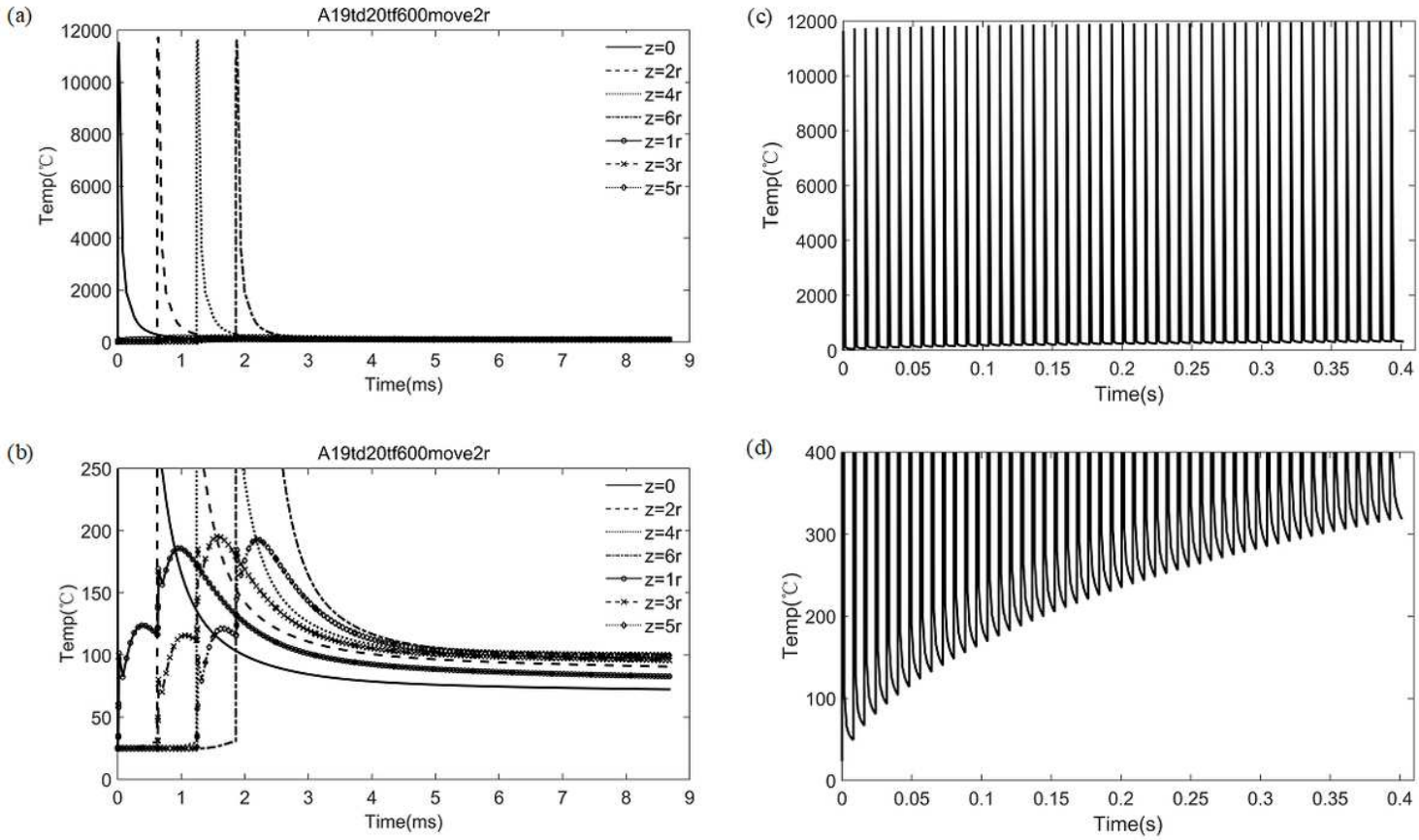

Figure 6

Temperature curve of the discharge center; (a) move model 1; (b) low-temperature stages of move model 1; (c) move model 2;(d) low-temperature stages of move model 2

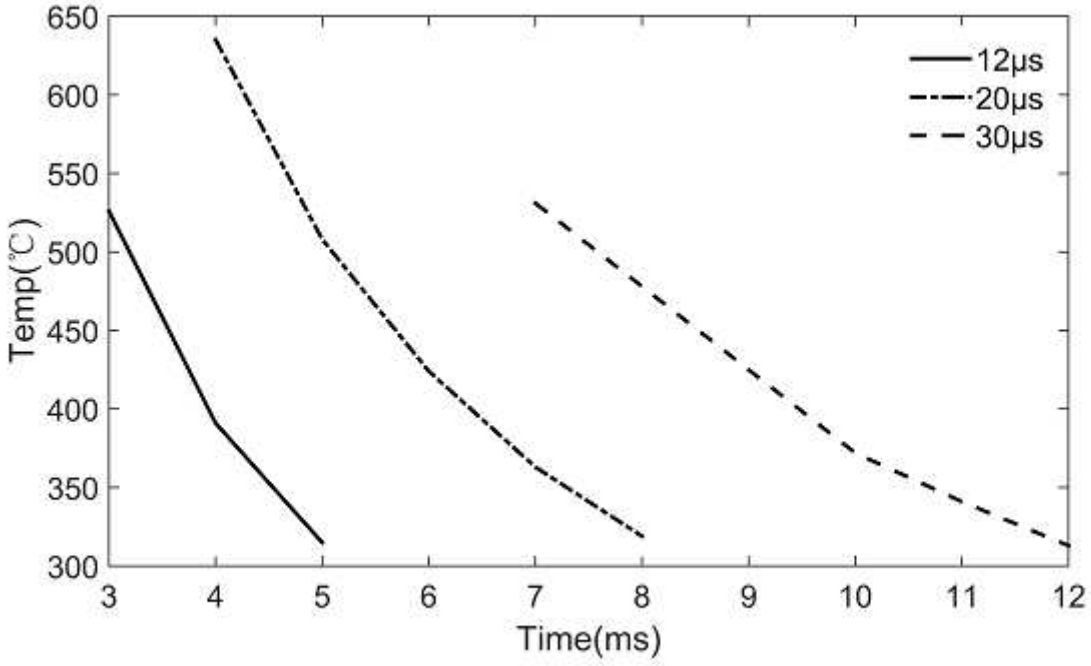

Figure 7

The relationship of balance temperature of wire and pulse interval duration time(move model 2)

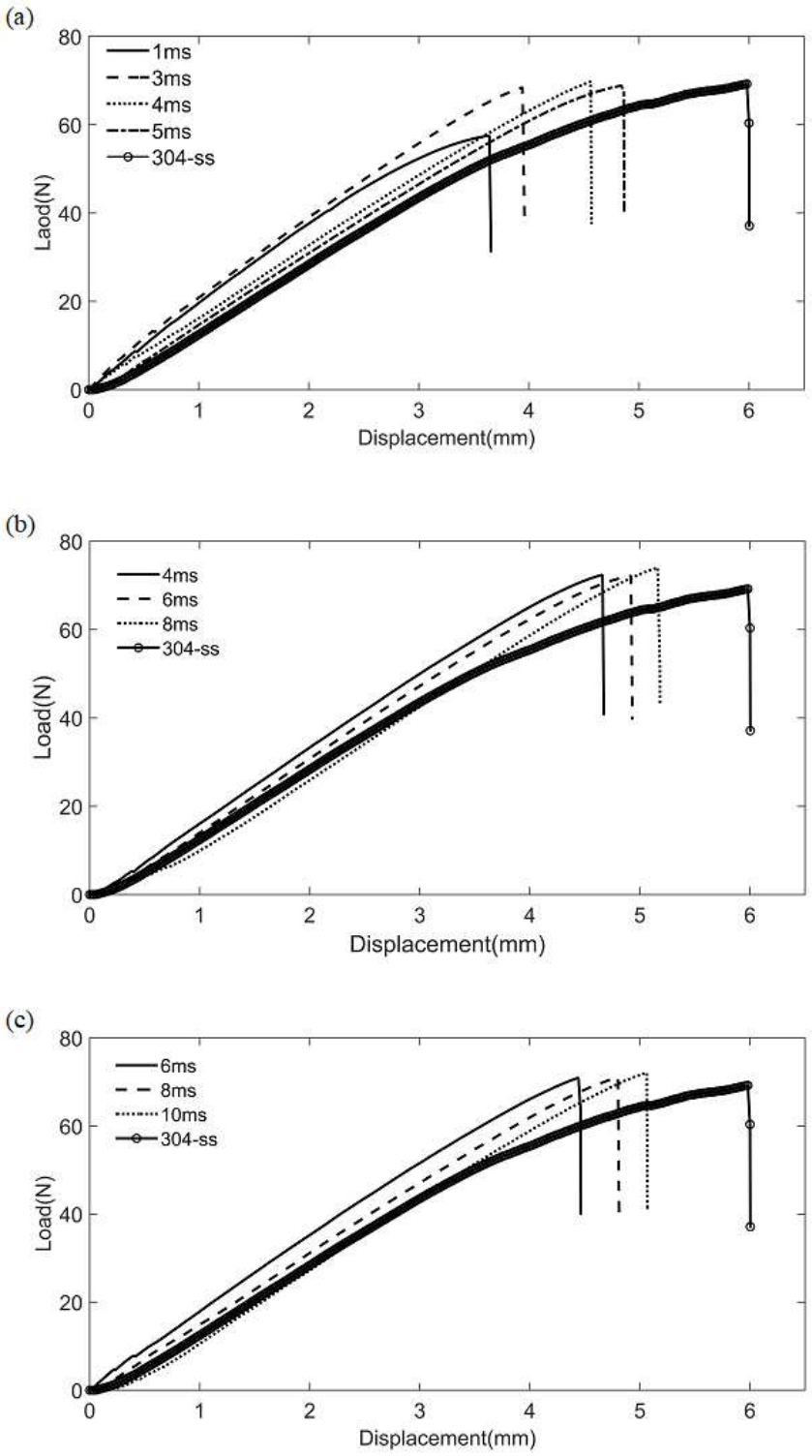

Figure 8

Load and displacement curve of tensile test:(a) 12μs; (b) 20μs; (c) 30μs