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

Chengyun Li1 · Peiqi Ge1,2 · Wenbo Bi1

Received: 1 June 2021 / Accepted: 24 November 2021 / Published online: 4 January 2022
© The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2021

Abstract

Due to their excellent physical and mechanical properties, third-generation super-hard semiconductor materials (such as SiC, GaN) are used widely 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. Slicing is the first machining procedure that directly affects the subsequent process. Fixed abrasive diamond wire saw (DWS) has been widely used in cutting hard and brittle materials. However, the diamond abrasives are attached to a core wire by resin or electroplated, that slicing super hard crystals is very difficult and inefficient. In order to improve the slicing efficiency, it is necessary to improve the holding strength and wear resistance of the DWS. 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 DWS 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 DWS (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 selected the discharge interval time base on the simulation results can ensure the continuous production of the ESDDWS.

Keywords  Diamond wire saw (DWS) · Electro-spark deposition (ESD) · Continuous pulse discharge · Thermal simulation

Abbreviations

c  Specific heat capacity
h  Convection heat coefficient
I  Discharge current
k  Thermal conductivity
m  Number of discharge
q0  Maximum heat flux
R  The radius of the plasma channel
Rj  The radius of the saw wire
r  Coordinates of cylindrical work domain
T  Temperature
T0  Environment temperature
t  Time
ton  Pulse duration time
toff  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
\( \theta \) Coordinates of cylindrical work domain
\( \rho \) 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 abrasive DWS has become the main tool for slicing hard and brittle materials [8, 9]. At present, fixed abrasive DWS mainly includes resin DWS and electroplated DWS. The diamond abrasives are attached to a core wire by resin or electroplated [10]. Diamond abrasive particles are less strongly bonded and have shorter service life due to easy drop-off and wear of the abrasive layer [11, 12]. Slicing the super hard crystal is very difficult and inefficient [13]. In addition, wire lifetime and wire wear during slicing have important effects on the wafer quality and cutting cost [14–18]. In order to improve the slicing efficiency and the wafer quality, 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 [19, 20]. 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 [21]. Obviously, this is only for large-size workpieces. Adam et al. [22] found that the range of the heat-affected zone was 10 to 20 \( \mu \text{m} \). At present, the diameter of the DWS matrix is 50 to 450 \( \mu \text{m} \), and there is a decreasing trend. Therefore, the thermal effect on the saw wire cannot 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 [23]. 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. [24] 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. [25] considered that the duty factor of the ESD should be less than 6%. Furutani and Suzuki [26–28] 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 [29]. 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 the local 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.

According to the characteristics of the ESDDWS process, the movement modes of electrode and wire can be divided into two styles. (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 (as shown in Fig. 1a). (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 (as shown in Fig. 1b).

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

1. In the manufacturing process, the electrodes and wires are arranged in which the electrode’s column face toward the wire surface (show as Fig. 1);
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 [30, 31] is given by Eq. (1):

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

where $r$ and $z$ are the coordinates of the cylindrical work domain; $T$ is temperature; $\rho$, $c$, $k$, 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 [29] can be given as Eq. (2):

$$q(\theta, r) = q_0 \exp(-4.5 \frac{r^2}{(a^2 \cos^2 \theta + b^2 \sin^2 \theta)}) \cos \beta;$$

$$\begin{cases}
R(t) < R_j, \ a = b = R(t) \\
R(t) > R_j, \ a = R(t), \ b = R_j
\end{cases}$$  (2)

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

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

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

where $h$ is the convection heat transfer coefficient, $k$ is the thermal conductivity, $R$ is the radius of the plasma channel, and $m$ is the number of discharges. Initial temperatures of the core wire are assumed to be uniform at environment temperature, $T_0 = 25 \ ^\circ C$.

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. 2a). However, due to the long action time and the high total heat input, the limited model cannot meet the requirements in the continuous pulse discharge deposition process, which increases the saw wire temperature (shown in Fig. 2b). Based on the element independence analysis (shown in Fig. 3), the element size is determined to be $3 \times 2 \times 2 \mu m$. 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.

### 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 that the melting volume of electrode material are the volume of diamond grit’s 5, 10, and 15 times. According to the prediction range of the process parameters [29], the discharge parameters corresponding to the electrode melting volume are shown in Table 1. The current is 19A, and the pulse duration time is 12 μs, 20 μs, and 30 μs, respectively. The thermal simulations of continuous pulse discharge of ESDDWS under two motion modes are analyzed. Under motion mode 1, when the current is 19 A, the pulse duration time is 20 μs, the pulse interval time is 600 μs, and the moving speed is one discharge channel diameter per period. The temperature field of continuous pulse discharge deposition is shown in Fig. 5a. Under motion mode 2, when the current is 19 A, the pulse duration time is 20 μs, and the pulse interval time is 8 ms. The temperature field of continuous pulse discharge deposition is shown in Fig. 5b.

From Fig. 6a, 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 $6 \times 10^9 ^\circ C/s$. 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

![Fig. 2 Temperature field of ESDDWS: a Single period temperature field; b Continuous pulse discharge temperature field without infinite element](image-url)
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 has obtained, as shown in Fig. 7.

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 2.

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 °C [32]. Therefore, the local equilibrium temperature of the saw wire should maintain at about 300 °C 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 12 μs, the pulse interval time is set to 1 ms, 3 ms, 4 ms, and 5 ms. When the pulse duration time is 20 μs, the pulse interval time is set to 4 ms, 6 ms, and 8 ms. When the pulse duration time is 30 μs, the pulse interval time is set to 6 ms, 8 ms, and 10 ms. During the experiment, when the pulse duration time is 12 μs 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 12 μs and the pulse interval time is 1 ms, the wire breaking force is 10 N 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 °C during the ESDDWS process. And selected the pulse interval time of ESDDWS process should be based on the simulation results.

| Table 1 Discharge parameters corresponding to electrode melting volume |
|---------------------------------------------------------------|
| Parameter                        | Value  |
| Electrode melting volume (μm³) | 384,000 640,000 960,000 |
| Current (A)                     | 19     |
| Pulse duration time (μs)        | 12 20 30 |

Fig. 4  Meshing model of saw wire

Fig. 5  Temperature field of continuous pulse discharge deposition: (a) Move motion 1; (b) Move motion 2
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
Fig. 7 The relationship of balance temperature of wire and pulse interval duration time: a Move model 1; b Move model 2

Table 2 Experiment parameter

| Parameter                      | Value                        |
|--------------------------------|------------------------------|
| Workpiece (cathode)           | 304-ss (φ0.2 mm)             |
| Electrode (anode)             | Cu (10 μm):Ni (10 μm): 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                          |
Fig. 8 Load and displacement curve of tensile test: a 12 μs; b 20 μs; c 30 μs
6 Conclusion

1. According to the characteristics of the ESDDWS process, 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 are 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 °C during the ESDDWS process.
6. The balance temperature of the wire saw varies according to the conditions of movement style, discharge current, and pulse duration time. And selected the pulse interval time of the ESDDWS process should base on the simulation results.

Author contribution 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.

Funding This work is financially supported by the National Natural Science Foundation of China (No. 51775317) and the Key Research and Development Program of Shandong Province, China (No. 2019JZZY020209)

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

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

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

Competing interests The authors declare no competing interests.
22. Adam B, Wood W, Kadali J, Talla R, Langston T (2017) Heat affected zone formation in electrospark deposition additive manufacturing on ultrahigh strength steel. Mater Perform Charact 6:375–393
23. Peng ZL, Li YN (2012) The deposition and removal process for micro machining based on electrical discharge. Adv Mater Res 472–475:2448–2451
24. Jain V K, Seshank S, Sidpara A, Jain H (2013) Some aspects of micro-fabrication using electro-discharge deposition process. ASME/ISCIE (ISFA2012), St Louis, MO 419–424
25. Mohri N, Saito N, Tsunekawa Y, Kinoshita N (1993) Metal surface modification by electrical discharge machining with composite electrode. CIRP Annals - Manuf Techno 42(1):219–222
26. Furutani K, Suzuki K (2015) Experimental investigations of deposition conditions for saw wire fabrication by electrical discharge machining. Int J Adv Manuf Tech 76(9–12):1643–1651
27. Furutani K, Kanai M, Mieda Y, Suzuki M (2010) Proposal of abrasive layer fabrication on thin wire by electric discharge machining. Int J Automation Technol 4(4):394–398
28. Furutani K, Suzuki K (2009) A desktop saw wire coating machine by using electrical discharge machining. IEEE Int Conf Cont Autom, Christchurch, New Zealand 2165–2170
29. Li C, Ge P, Bi W (2021) Thermal simulation of the single discharge for electro-spark deposition diamond wire saw. Int J Adv Manuf Tech 114(11–12):3597–3604
30. Wang Y, Xie B, Wang Z, Peng Z (2011) Micro EDM deposition in air by single discharge thermo simulation. T Nonferr Metal Soc 21(s2):450–455
31. Shahri HRF, Mahdavinejad R, Ashjaee M, Abdullah A (2017) A comparative investigation on temperature distribution in electric discharge machining process through analytical, numerical and experimental methods. Int J Mach Tools Manuf 114:35–53
32. Alinia S, Khamedi R, Ahmadi I (2018) An investigation into deep drawing parameters on deformation induced martensitic microstructure transformation of an austenitic stainless steel. Metallogr Microstruct Anal 7(6):724–734

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.