Experimental investigations on optimizing manufacturing parameters for electrospark deposition diamond wire saw

Chengyun Li1 · Peiqi Ge1,2 · Wenbo Bi1 · Qihao Wang1

Received: 21 December 2021 / Accepted: 8 July 2022 / Published online: 25 July 2022
© The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2022

Abstract
The third generation of superhard semiconductor materials, represented by single-crystal SiC, is used widely in microelectronics due to their excellent physical and mechanical properties. However, their high hardness and brittleness have become bottlenecks in their development. A diamond wire saw (DWS) has become the mainstream tool for sawing hard and brittle crystal materials. However, the diamond abrasive is consolidated on the core wire through resin or electroplated nickel, and the holding strength is not high. When sawing superhard crystal materials, the efficiency is low. To improve the sawing efficiency of superhard crystal materials, it is of great significance to improve the wear resistance of the wire saw and the holding strength of abrasive particles. Electrospark deposition (ESD) can deposit electrode materials on the substrate with low heat input to achieve metallurgical bonding between metal materials. It can effectively improve the gripping strength of the abrasive grains. The sawing ability of the wire saw to make the consolidated DWS by the ESD process. In this paper, ESD equipment was designed according to the characteristics of the ESDDWS process. The discharge gap size and electrode consumption are monitored in real time by a single-chip microcomputer (SCM). Orthogonal experiments were carried out for the two motion modes. The effects of process parameters, such as (A) grain size, (B) abrasive content, (C) pulse duration time, (D) compacting pressure, (E) current, (F) electrode diameter, (G) pulse interval time, (H) reciprocating times, and (I) wire feed speed, on the quality of ESDDWS were analyzed. Through extreme difference analysis (EDA), the optimal parameter combinations of ESDDWS were obtained. In motion mode 1, a combination of grain size W10, abrasive content 1 wt%, pulse duration time 20 μs, compacting pressure 400 MPa, current 19 A, electrode diameter 3 mm, and pulse interval time 2 ms can obtain the optimal value of the number of deposition points and protrusion abrasive particles at the same time. The sequence of manufacturing parameters affecting the two indicators is F > A > G > E > B > D > C. In motion mode 2, the combination of grain size W40, abrasive content 4 wt%, pulse duration time 20 μs, compacting pressure 300 MPa, current 23 A, electrode diameter 3 mm, reciprocating times 1, and wire feed speed 2 mm/step can obtain the optimal value of the number of deposition points and protrusion abrasive particles at the same time. The sequence of manufacturing parameters affecting the two indicators is C > I > F > E > B > H > D > A.

Keywords Diamond wire saw (DWS) · Electrospark deposition (ESD) · Orthogonal experiments · Extreme difference analysis (EDA)
Nomenclature

- \( K_{\text{bond}} \): Abrasive consolidation ratio (\( K_{\text{bond}} = 1 \))
- \( L_{\text{dis}} \): The effective length of single pulse deposition is equivalent to the diameter of the discharge channel (mm)
- \( N_{\text{discharge}} \): The number of times of electrode reciprocating continuous discharge (\( N_{\text{discharge}} = 1 \))
- \( N_{\text{duration}} \): The number of abrasive particles in the molten droplet after the electrode reciprocates for one time
- \( N_{\text{saw}} \): The number of abrasive grains consolidated on the substrate after reciprocating deposition
- \( N_{\text{single}} \): Amount of abrasive particles in melting volume of electrode materials for single pulse discharge
- \( V_{\text{diamond}} \): The volume of diamond (m³)
- \( V_{\text{melt}} \): The melting volume of electrode material in single pulse discharge (m³)
- \( w_r \): Mass fraction of diamond particles in the electrode
- \( \rho_{\text{diamond}} \): The density of diamond (3510 kg/m³)
- \( \rho_{\text{mix}} \): Mixing density of molten droplet of electrode material (8808 kg/m³)
- \( \rho_{\text{saw}} \): Abrasive density on saw wire surface (piece/mm)

1 Introduction

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 broad application prospects in the field of microelectronics [3]. However, their high hardness and brittleness have become bottlenecks in their development [4].

DWS has become the mainstream tool for slicing hard and brittle materials [5]. DWS mainly includes resin DWS and electroplated DWS [6]. The diamond abrasives are attached to a core wire by resin or electroplated. Diamond abrasive particles are less strongly bonded and have shorter service life due to easy drop-off and wear of the abrasive layer. Slicing a superhard crystal is very difficult and inefficient. 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 the cathode and anode. It has become a new surface treatment technique to improve the wear and corrosion resistance of the workpiece. Furutani et al. proposed the manufacturing technology of wire saw by EDM. At first, they used suspending Ti powder to make a saw wire with a hard deposition tumor, which can be used to cut copper bars and glass. However, this method has difficulty depositing abrasive particles on the core wire [7]. Then, they put forward an electrode made by compacted powder and made a wire saw containing alumina abrasive particles [8–10]. However, they did not make a theoretical analysis of the selection of discharge parameters. The wire was broken in the experiment. Meanwhile, they did not study the distribution of wear particles on the deposition layer. However, the distribution of abrasives has an important impact on the sawing process.

In the process of ESD, the deposition rate and the quality of the deposited layer are affected by many factors, such as the grain size, material content, compacting pressure, current, electrode diameter, pulse interval time, and pulse duration time. To obtain better results, many scholars have discussed the relationship between process parameters and deposition properties. Sujoy et al. [11] used the application of the utility concept of the Taguchi method to find the best possible combination values of ESD parameters to maximize the microhardness and minimize the surface roughness during deposition of SiC/Cu over the surface of an Al-6351 alloy. Chakraborty et al. [12] combined Taguchi and FTOPSIS to solve the multiresponse optimization problem in the ESD process. They analyzed the sensitivity of ESD response parameters (such as material deposition rate, tool wear rate, surface roughness, layer thickness, and microhardness) by varying process parameters. Anshuman et al. [13] used the Taguchi-based VIKOR method combined with a harmonic search algorithm to optimize the surface properties of ESD specimens and reported the optimal parameter settings for the ESD process. Ananthi et al. [14] discussed the relationship between process parameters and deposition properties. Sujoy et al. [11] used the application of the utility concept of the Taguchi method to find the best possible combination values of ESD parameters to maximize the microhardness and minimize the surface roughness during deposition of SiC/Cu over the surface of an Al-6351 alloy. Chakraborty et al. [12] combined Taguchi and FTOPSIS to solve the multiresponse optimization problem in the ESD process. They analyzed the sensitivity of ESD response parameters (such as material deposition rate, tool wear rate, surface roughness, layer thickness, and microhardness) by varying process parameters. Anshuman et al. [13] used the Taguchi-based VIKOR method combined with a harmonic search algorithm to optimize the surface properties of ESD specimens and reported the optimal parameter settings for the ESD process. Ananthi et al. [14] discussed the relationship between process parameters and deposition properties. Sujoy et al. [11] used the application of the utility concept of the Taguchi method to find the best possible combination values of ESD parameters to maximize the microhardness and minimize the surface roughness during deposition of SiC/Cu over the surface of an Al-6351 alloy.
However, this method requires a fixed sampling time and cannot respond to the conditions in the deposition process in time.

In this article, ESD equipment is designed according to the characteristics of the ESDDWS process. The discharge gap size is monitored in real time and adjusted by an SCM. Orthogonal experiments were carried out for the two motion modes. The effects of process parameters, such as (A) grain size, (B) abrasive content, (C) pulse duration time, (D) compacting pressure, (E) current, (F) electrode diameter, (G) pulse interval time, (H) reciprocating times, and (I) wire feed speed, on the quality of ESDDWS were analyzed. Through the EDA, the optimal parameter combinations of ESDDWS were obtained.
2 Experimental setup

2.1 ESDDWS deposition equipment

The manufacturing principle of ESDDWS and two motion modes of deposition have been introduced [21, 22]. The deposition device was designed according to the characteristics of the ESDDWS process, as shown in Fig. 1. The device is equipped with two deposition stations for horizontal and vertical deposition. Each deposition station can realize the deposition of two sides of the saw wire. To satisfy the deposition of the saw wire from four directions, in this experiment, only one side of the saw wire was deposited to analyze the effect of deposition process parameters on the quality of the deposition layer.

To achieve real-time detection and response, the limit feedback laser is adopted to detect the discharge gap and electrode consumption. Then, the signal is fed back to the SCM. The control schematic diagram is shown in [22].

In motion mode 1, the electrode rotates at a uniform speed. Meanwhile, the core wire feeds at a uniform speed. The electrode and the core wire maintain a fixed gap. It is dynamically controlled by the SCM. The motion control flow chart of motion mode 1 is shown in Fig. 2. Presetting is required before the program, such as laser position, electrodeposition, and program debugging. After starting, the core wire starts to feed first, and then the electrode moves. When the electrode reaches the discharge position, the electrode covers the laser beam and the signal of the laser receiver changes. The SCM receives the signal and controls the electrode to stop moving. Then the wire and electrode are kept at a fixed distance to carry out normal deposition. During the deposition process, the electrode material is gradually consumed. The laser receiver signal changes again when the electrode material cannot shield the laser beam. Then the SCM controls the motor to adjust the position of the electrode.
In motion mode 2, the electrode rotates and reciprocates intermittently. Meanwhile, the core wire feeds intermittently. The discharge gap and material consumption are also dynamically controlled by the SCM during electrode reciprocation. The motion control flow chart of motion mode 2 is shown in Fig. 3. Presetting is also required before deposition starts. After the program starts, the electrodes feed close to the core wire until fed at a fixed distance. Then, it reaches the discharge position and begins to deposit. After discharging, the electrode moves backward until the laser signal changes. Then, the electrodes stop moving and rotate at an angle. At the same time, the wire feeds for a distance. Continuous deposition occurs in this cycle. The stepping motor driver model is TS DMA860H, and the electrical parameters are shown in Table 1. The guide of the ball screw is 5 mm, so the minimum feed of the electrode is 0.1 µm. That is, the positioning accuracy of the electrodes is 0.1 µm. It met the requirements of the deposition process.

Fig. 3 The motion control flow chart of the deposition process for move model 2
2.2 Experimental parameter settings

In this work, the diamond abrasive grains were chosen as W10 and W40. Generally, the content of the components of the mixture is determined by mass percentage. However, the density of diamond abrasive particles in a DWS is usually measured by quantity. Due to the change in diamond size, the density of diamond abrasive particles in the electrodes varies greatly with the same mass fraction. The density of abrasive particles contained in the melting droplets is too high to cause the accumulation of abrasive particles in the deposition layer. Therefore, the mass fraction is converted into the relationship of the density of abrasive particles (as shown in Eqs. (1) to (5)).

\[
N_{\text{single}} = \frac{V_{\text{melt}} \times \rho_{\text{mix}} \times W_t}{\rho_{\text{diamond}} \times V_{\text{diamond}}} \tag{1}
\]

\[
N_{\text{duration}} = N_{\text{discharge}} \times N_{\text{single}} \tag{2}
\]

\[
N_{\text{saw}} = K_{\text{bond}} \times N_{\text{duration}} \tag{3}
\]

\[
\rho_{\text{saw}} = \frac{4N_{\text{saw}}}{L_{\text{dis}}} \tag{4}
\]

\[
w_t = \frac{\rho_{\text{saw}} L_{\text{dis}} \rho_{\text{diamond}} V_{\text{diamond}}}{4K_{\text{bond}} N_{\text{discharge}} \rho_{\text{mix}} V_{\text{melt}}} \tag{5}
\]

We assume that the amount of abrasive deposited on the surface of the wire after one discharge is 1. The mass fraction of diamond abrasives in the electrodes is shown in Table 2. The amount of abrasive in the deposited layer is increased due to repeated discharge. Therefore, for W40 abrasives, the density value should be reduced appropriately. However, because the diameter of the W10 abrasive is small, more abrasives need to be used in the same area. Therefore, the mass fractions of the two abrasives are set to 1%, 2%, and 4%.

The pressing pressure of green compacted electrodes has an important impact on the deposition quality [23]. The prepressing test shows that the electrode often breaks down when the pressing pressure is 100 MPa. Therefore, the pressing pressures of the green compacted electrodes are set to 200 MPa, 300 MPa, and 400 MPa.

At the same time, the discharge area between the electrodes and the wire will affect the uniformity of the deposited layer, considering the randomness of the electro spark discharge. In the experiment, the diameters of the electrodes

| Parameter | Value |
|-----------|-------|
| Electrode melting volume (μm³) | 384000 | 640000 | 960000 |
| Abrasive content (%wt) | W40: 6.64 | 3.99 | 2.66 |
| | W10: 0.1 | 0.06 | 0.04 |

Table 3 Experimental parameters with different levels

| Parameter | Level/value |
|-----------|-------------|
| (A) Grain size | W40 | W10 |
| (B) Abrasive content (%wt) | 1 | 2 | 4 |
| (C) Pulse duration time (μs) | 12 | 20 | 30 |
| (D) Compacting pressure (MPa) | 200 | 300 | 400 |
| (E) Current (A) | 15 | 19 | 23 |
| (F) Electrode diameter (mm) | 10 | 3 | 0 (equivalent) |
| Move model 1 | G) Pulse interval time (ms) | 2 | 4 | 8 |
| | Wire feed speed (mm/s) | 25 |
| Move model 2 | Pulse interval time (ms) | 10 |
| | (H) Reciprocating times (cycle/step) | 1 | 2 | 3 |
| | (I) Wire feed speed (mm/step) | 0.5 | 1 | 2 |
are selected as 3 mm and 10 mm. In addition, single-point discharge of the substrate and the electrode can be realized by aligning the circumference of the electrode with the core wire, which can be equivalent to an electrode diameter of 0 mm.

The discharge current and pulse duration time have an important influence on the melting amount of the electrode material. Moreover, the thickness of the abrasive layer of the diamond wire saw is not as good as the thickness. The proper process parameters must be found so that the abrasive particles on the surface of the saw wire do not accumulate and are well consolidated. According to the research results, the pulse duration time is set to 12 μs, 20 μs, and 30 μs [22]. In addition, to explore the effect of the discharge current on the deposition quality, the current is carried out at 15 A, 19 A, and 23 A.

The effect of pulse interval time on different modes of motion has been studied [22]. In move mode 1, the value of the pulse interval time can be small, but the wire velocity is related to the distance of the adjacent deposition points. Therefore, when setting the pulse interval time, the kinematic performance of the machine tool is taken into account. Theoretically, the spacing should be the diameter of the discharge channel so that adjacent deposition points do not interfere with each other. In practice, the spacing can be reduced appropriately, considering that the deposited material does not cover the entire discharge channel area. That is, the pulse interval time can be reduced appropriately. In the experiment, the velocity of the wire is set to 25 mm/s. The pulse interval time is set to 2 ms, 4 ms, and 8 ms. In move mode 2, to ensure the smooth progress of the experiment, the pulse interval time can be determined to be 10 ms based on the simulation results.

In summary, the experimental parameters are shown in Table 3. Orthogonal experiments are performed for the two motion modes. Experiments were conducted using an $L_{18}(2^1 \times 3^7)$ orthogonal array, and the orthogonal parameter combinations are shown in Tables 4 and 5.

### 3 Results and discussion

The abrasive layer of DWS directly affects the quality and efficiency of the slicing process [24]. The abrasive layer of ESDDWS is formed by the repeated superposition of deposition points. The number of deposition points per unit length can characterize the uniformity of the abrasive layer distribution of the wire saw. We obtained the surface morphology of the saw wire through the optical microscope INSIZE ISM-PM200 (as shown in Fig. 4). According to the calculation formula of the radius of the electric spark discharge channel [21], the diameter of the discharge channel is approximately 200 μm. Therefore, we assume that the range of a deposition point is the area covered by the circle, in which the diameter is 200 μm. The number of deposition points within the length of the wire saw of 100 mm is counted. The results of the two motion modes are shown in Table 6 (see count 1) and Table 8 (see count 1), respectively.

On the other hand, the cutting action of DWS is mainly achieved by the exposed diamond abrasives. Therefore, the number of protrusion abrasive grains in the deposition layer

| No. | A   | B | C | D | E | F | G |
|-----|-----|---|---|---|---|---|---|
| 1   | W40 | 1 | 12| 200| 15| 10| 2 |
| 2   | W40 | 1 | 20| 300| 19| 3 | 4 |
| 3   | W40 | 1 | 30| 400| 23| 0 | 8 |
| 4   | W40 | 2 | 12| 200| 19| 3 | 8 |
| 5   | W40 | 2 | 20| 300| 23| 0 | 2 |
| 6   | W40 | 2 | 30| 400| 15| 10| 4 |
| 7   | W40 | 4 | 12| 300| 15| 0 | 4 |
| 8   | W40 | 4 | 20| 400| 19| 10| 8 |
| 9   | W40 | 4 | 30| 200| 23| 3 | 2 |
| 10  | W10 | 1 | 12| 400| 23| 3 | 4 |
| 11  | W10 | 1 | 20| 200| 15| 0 | 8 |
| 12  | W10 | 1 | 30| 300| 19| 10| 2 |
| 13  | W10 | 2 | 12| 300| 23| 10| 8 |
| 14  | W10 | 2 | 20| 400| 15| 3 | 2 |
| 15  | W10 | 2 | 30| 200| 19| 0 | 4 |
| 16  | W10 | 4 | 12| 400| 19| 0 | 2 |
| 17  | W10 | 4 | 20| 200| 23| 10| 8 |
| 18  | W10 | 4 | 30| 300| 15| 3 | 8 |
is an important factor in evaluating the quality of DWS \cite{25}. The number of protrusion abrasive grains in the deposition layer is counted to evaluate the depositional quality. We used the scanning electron microscope (SEM) COXEM EM-30 Plus to obtain the micromorphology of the ESDDWS. The micromorphology of ESDDWS can be divided into four cases (as shown in Fig. 5). (a) The deposition contains only metal materials but no diamond abrasives. (b) The deposition contains diamond abrasives but in small quantities. (c) The deposition contains diamond abrasives with a moderate number of abrasives. (d) The deposition is thicker, and the abrasive particles are heavily accumulated. Due to the severe accumulation of abrasive particles, it is difficult to count protrusion abrasive particles. In addition, it is not good for slicing all the same. In this case, the number of protrusion abrasive grains is counted as 0. The results of two motion

![Micromorphology of ESDDWS by INSIZE ISM-PM200](image)

Fig. 4 Micromorphology of ESDDWS by INSIZE ISM-PM200

| No. | A   | B | C  | D  | E  | F  | H  | I  | L: 1.000mm |
|-----|-----|---|----|----|----|----|----|----|-------------|
| 19  | W40 | 1 | 12 | 200| 15 | 10 | 1  | 0.5|             |
| 20  | W40 | 1 | 20 | 300| 19 | 3  | 2  | 1  |             |
| 21  | W40 | 1 | 30 | 400| 23 | 0  | 3  | 2  |             |
| 22  | W40 | 2 | 12 | 200| 19 | 3  | 3  | 2  |             |
| 23  | W40 | 2 | 20 | 300| 23 | 0  | 1  | 0.5|             |
| 24  | W40 | 2 | 30 | 400| 15 | 10 | 2  | 1  |             |
| 25  | W40 | 4 | 12 | 300| 15 | 0  | 2  | 2  |             |
| 26  | W40 | 4 | 20 | 400| 19 | 10 | 3  | 0.5|             |
| 27  | W40 | 4 | 30 | 200| 23 | 3  | 1  | 1  |             |
| 28  | W10 | 1 | 12 | 400| 23 | 3  | 2  | 0.5|             |
| 29  | W10 | 1 | 20 | 200| 15 | 0  | 3  | 1  |             |
| 30  | W10 | 1 | 30 | 300| 19 | 10 | 1  | 2  |             |
| 31  | W10 | 2 | 12 | 300| 23 | 10 | 3  | 1  |             |
| 32  | W10 | 2 | 20 | 400| 15 | 3  | 1  | 2  |             |
| 33  | W10 | 2 | 30 | 200| 19 | 0  | 2  | 0.5|             |
| 34  | W10 | 4 | 12 | 400| 19 | 0  | 1  | 1  |             |
| 35  | W10 | 4 | 20 | 200| 23 | 10 | 2  | 2  |             |
| 36  | W10 | 4 | 30 | 300| 15 | 3  | 3  | 0.5|             |

Table 5 Orthogonal experimental combination for move mode 2

| No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|-----|---|---|---|---|---|---|---|---|---|
| 1   | 106| 288| 187| 258| 212| 118| 142| 172| 209|
| ES  | 2.12| 5.76| 3.74| 5.16| 4.24| 2.36| 2.84| 3.44| 4.18|
| Count 1 | 0 | 2 | 0 | 1 | 1 | 1 | 0 | 1 | 3 |
| Total score | 2.12| 7.76| 3.74| 6.16| 5.24| 3.36| 2.84| 4.44| 7.18|
| No. | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 |
| Count 1 | 192| 132| 140| 246| 183| 218| 219| 260| 172|
| ES | 3.84| 2.64| 2.8 | 4.92| 3.66| 4.36| 4.38| 5.2 | 3.44|
| Count 2 | 9 | 1 | 8 | 0 | 8 | 4 | 2 | 0 | 1 |
| Total score | 12.84| 3.64| 10.8 | 4.92| 11.66| 8.36| 6.38| 5.2 | 4.44|

Table 6 Scoring table for move model 1
modes are shown in Table 6 (see count 2) and Table 8 (see count 2), respectively.

According to the EDA, in motion mode 1, the sequence of influence of manufacturing parameters is $F > A > G > E > B > D > C$. The optimal combination of process parameters is $A_2B_1C_2D_3E_2F_2G_1$ (see Table 7).

According to the EDA, in motion mode 2, the influence sequence of manufacturing parameters is...

### Table 7 EDA for move model 1

| No. | A    | B    | C    | D    | E    | F    | G    |
|-----|------|------|------|------|------|------|------|
| K1  | 42.84| 40.9 | 35.26| 32.66| 28.06| 30.84| 43.38|
| K2  | 68.24| 39.7 | 37.94| 36   | 43.9 | 50.04| 40.36|
| K3  | 30.48| 37.88| 42.42| 39.12| 30.2 | 27.34|
| k1  | 4.76 | 6.82 | 5.88 | 5.44 | 4.68 | 5.14 | 7.23 |
| k2  | 7.58 | 6.62 | 6.32 | 6.00 | 7.32 | 8.34 | 6.73 |
| k3  | 5.08 | 6.31 | 7.07 | 6.52 | 5.03 | 4.56 |
| R   | 2.82 | 1.74 | 0.45 | 1.63 | 2.64 | 3.31 | 2.67 |

### Table 8 Scoring table for move model 2

| No. | 19  | 20  | 21  | 22  | 23  | 24  | 25  | 26  | 27  |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Count 1 | 162 | 356 | 305 | 333 | 237 | 190 | 272 | 248 | 252 |
| ES   | 3.24| 7.12| 6.1 | 6.66| 4.74| 3.8 | 5.44| 4.96| 5.04|
| Count 2 | 2   | 2   | 1   | 4   | 5   | 1   | 3   | 5   | 5   |
| Total score | 5.24| 9.12| 7.1 | 10.66| 9.74| 4.8 | 8.44| 9.96| 10.04|
| No.  | 28  | 29  | 30  | 31  | 32  | 33  | 34  | 35  | 36  |
| Count 1 | 311 | 236 | 175 | 292 | 218 | 195 | 236 | 261 | 318 |
| ES   | 6.22| 4.72| 3.5 | 5.84| 4.36| 3.9 | 4.72| 5.22| 6.36|
| Count 2 | 3   | 3   | 6   | 2   | 7   | 1   | 1   | 7   | 0   |
| Total score | 9.22| 7.72| 9.5 | 7.84| 11.36| 4.9 | 5.72| 12.22| 6.36|
C > I > F > E > B > H > D > A. The optimal combination of process parameters is A1B3C2D2E3F2H1I3 (see Table 9). The verification experiment is carried out by using the obtained parameter combinations. The micromorphology of ESDDWS by SEM for the verification experiment is shown in Fig. 6. In move model 1, the results of the two indicators are 436 and 10, respectively. In move model 2, the results of the two indicators are 409 and 11, respectively. The results of the validation experiment are better than the original experimental results. However, even under the optimal process combination, there are still the following problems: (1) There are still a considerable number of areas without spark discharge. (2) The deposition point left a pit without deposited materials and abrasives. (3) Material accumulation at the deposition point, especially in motion mode 2. These problems need to be further solved.

### 4 Conclusion

In this paper, ESD equipment was designed according to the characteristics of the ESDDWS process. The discharge gap and the supply of electrode material can be adjusted dynamically by the SCM.

Orthogonal experiments were carried out for the two motion modes. The number of deposition points on the saw wire and protrusion abrasive particles at the deposit points are used as the evaluation indexes. The optimal combination of the manufacturing process of ESDDWS was obtained under different motion modes by EDA. In motion mode 1, a combination of grain size W10, abrasive content 1 wt%, pulse duration time 20 μs, compacting pressure 400 MPa, current 19 A, electrode diameter 3 mm, and pulse interval time 2 ms can obtain the optimal value of the number of deposition points and protrusion abrasive particles at the same time. The sequence of manufacturing parameters affecting the two indicators is F > A > G > E > B > D > C. In motion mode 2, the combination of grain size W40, abrasive content 4 wt%, pulse duration time 20 μs, compacting pressure 300 MPa, current 23 A, electrode diameter 3 mm, reciprocating times 1, and wire feed speed 2 mm/step can obtain the optimal value of the number of deposition points and protrusion abrasive particles at the same time. The sequence of manufacturing parameters affecting the two indicators is C > I > F > E > B > H > D > A.

**Author contribution** Chengyun Li is the executor of article writing and experimental operation. Peiqi Ge contributed to the conception of the work. Wenbo Bi contributed to the experimental preparation. Qihao Wang contributed to the equipment design.

**Funding** This work is financially supported by the National Natural Science Foundation of China (No. 52175418, No. 51775317) and the Key Research and Development Program of Shandong Province, China (No. 2022CXGC010201, No. 2019JZZY020209).

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

1. Yadlapalli RT, Kotapati A, Kandipati R, Balusu SR, Koritala CS (2021) Advancements in energy efficient GaN power devices and power modules for electric vehicle applications: a review. Int J Energ Res 45(9):12638–12664

2. Wellmann PJ (2017) Power electronic semiconductor materials for automotive and energy saving applications – SiC, GaN, Ga2O3, and diamond. Z Anorg Allg Chem 643(21):1312–1322

3. Wang P, Ge P, Bi W, Liu T, Gao Y (2018) Stress analysis in scratching of anisotropic single-crystal silicon carbide. Int J Mech Sci 141:1–8

4. Wang P, Ge P, Gao Y, Bi W (2017) Prediction of sawing force for single crystal silicon carbide with fixed abrasive diamond wire saw. Mat Sci Semicon Proc 63:25–32

5. Kao I, Chung C (2021) Wafer manufacturing: shaping of single crystal silicon wafers. Wiley, 1st edn. Hoboken, NJ

6. Tsai P, Chou Y, Yang S, Chen Y, Wu C (2013) A comparison of techniques for the New Frontier. Tokyo, Japan, 361–364

7. Furutani K, Murase Y (2008) Fabrication of wire saw with patterned hard bumps by electrical discharge machining with powder suspended in working oil. In: The 41st CIRP Conference on Manufacturing Systems. Manufacturing Systems and Technologies for the New Frontier. Tokyo, Japan, 361–364

8. Furutani K, Suzuki K (2009) A desktop saw wire coating machine by using electrical discharge machining. In: IEEE International Conference on Control and Automation. IEEE International Conference on Control and Automation ICAA. Christchurch, New Zealand, 2165–2170

9. 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

10. 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

11. Chakraborty S, Kar S, Ghosh SK, Dey V (2017) Parametric optimization of electric discharge coating on aluminium-6351 alloy with green compact silicon carbide and copper tool: a Taguchi coupled utility concept approach. Surf Interfaces 7:47–57

12. Chakraborty S, Kar S, Dey V, Ghosh SK (2018) Multi attribute decision making for determining optimum process parameter in EDC with Si and Cu mixed powder green compact electrodes. J Sci Ind Res 77(4):229–236

13. Ananthi N, Elaiyarasan U, Satheeshkumar V, Senthilkumar C, Sathyamurthy S (2022) Effect of WC–Cu composite electrodes on material deposition rate, microhardness and microstructure of electrical discharge coated magnesium alloy. Surf Rev Lett 29(4):2250050

14. Belik VG, Litvinov VN, Kovalchenko MS, Rogozinskaya AA (2007) Effect of pulse duration and size of interelectrode interval on electrospark spraying. IL Effect of pulse duration and size of interelectrode interval on composition and mechanical properties of coatings. Powder Metall Met Ceram 46(1–2):95–99

15. Kuptsov KA, Shevevoyko AN, Zamulaeva EI, Sidorenko DA, Shtansky DV (2019) Two-layer nanocomposite WC/a-C coatings produced by a combination of pulsed arc evaporation and electrospark deposition in vacuum. Mater Design 167:107645

16. Frangini S, Masci A (2010) A study on the effect of a dynamic contact force control for improving electrospark coating properties. Surf Coat Tech 204(16–17):2613–2623

17. Wang X, Wang Z, Lin T, He P (2017) Mass transfer trends of A1CoCrFeNi high-entropy alloy coatings on TC11 substrate via electrospark – computer numerical control deposition. J Mater Process Tech 241:93–102

18. Wang X, Wang Z, He P, Lin T, Shi Y (2015) Microstructure and wear properties of CuNiSiTiZr high-entropy alloy coatings on TC11 titanium alloy produced by electrospark — computer numerical control deposition process. Surf Coat Technol 283:156–161

19. Wang Q, Bi W, Ge P (2018) Developing equipment for electro-depositing diamond wire saw. Diamond Abrasives Eng 38(2):61–65

20. 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

21. Li C, Ge P, Bi W (2022) Thermal simulation of the continuous pulse discharge for electro-spark deposition diamond wire saw. Int J Adv Manuf Tech 119(5–6):2923–2933

22. Mohri N, Saito N, Tsunekawa Y, Kinoshita N (1993) Metal surface modification by electrical discharge machining with composites electrode. CIRP Annals - Manuf Techno 42(1):219–222

23. Zhao Y, Bi W, Ge P (2021) An on-line inspection method for abrasive distribution uniformity of electroplated diamond wire saw. J Manuf Process 71:290–297

24. Xie Q, Ge P, Meng J, Bi W, Ma X, Zheng C, Gong Y (2020) Study on mechanical properties of nickel-plated layer and abrasive holding force of electroplated diamond wire saw. Diamond Abrasives Eng 40(1):50–55

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