Rare Metal Materials and Engineering
Volume 52, Issue 9, September 2023
Available online at www.rmme.ac.cn

Science Press

Cite this article as: Zhao Dongcai, Qiu Jiaxin, Qiu Jiawen. Review of Macroparticle Suppression Methods in Arc Source[J]. Rare Metal Materials and Engineering, 2023, 52(09): 3076-3088.

REVIEW

Review of Macroparticle Suppression Methods in Arc Source

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Abstract: Vacuum arc deposition has become one of the indispensable techniques in the coating field, and it is widely studied and applied in the metal, decoration, hard wear resistance, and other fields. The application research of coating techniques promotes the investigation on arc source technique, which mainly focuses on the fields of long life, high reliability, and macroparticle suppression. The realization of macroparticle suppression is based on the satisfaction of long life and high reliability. With reducing the residence time of arc spots on the target surface, the macroparticle suppression can be obtained. This result can be achieved by ingenious design of permanent magnet or electromagnetism, thereby obtaining a target surface with strong transverse magnetic component. However, when the magnetic field intensity increases, the internal characteristics of target and the proportional relationship between the longitudinal magnetic field and the transverse magnetic field should be comprehensively considered. Another macroparticle suppression method is the pulsed arc technique. The pulsed arc source frequently strikes the arc, which is very different from the direct current arc source in structure design. The instantaneous current can reach thousands, even more than ten thousands amperes, therefore obtaining a high deposition rate. At the same time, the anode design leads to the directional jet of plasma, which can filter out most large particles.

Key words: arc source; magnetic circuit structure; macroparticles; pulse arc source

Vacuum arc deposition (VAD) or arc ion plating (AIP) refers to the arc technique coupled with vacuum coating technique, which uses arc to evaporate the target under vacuum environment, thereby achieving coating. Arc has been gradually developed and applied in the recent decades[1–2]. VAD has the characteristics of high ionization rate, which can be used to prepare metal[3–4], nitride[5–7], oxide[8–9], carbon film[10–11], carbon-nitrogen film[12], and multicomponent compound[13–14] for the enhancement in wear resistance and oxidation resistance[12,15–16]. Hence, VAD technique attracts much attention[10–13]. Through proper adjustment, anode can be used to deposit film[17–18] and to prepare nanoparticle powders[19].

The mechanisms of arc discharge, arc plasma, arc anode, arc coating, and pulse arc are thoroughly researched[21–20], and these techniques are gradually applied in engineering[20–23]. Up to now, some key technical problems are still unsolved, such as arc striking efficiency, service life, stable arc discharge, large particle suppression, and plasma area control, which involve the stable arc operation. The macroparticle suppression is the key method to achieve high-quality film deposition in the arc coating process. The plasma area control involves the substrate treatment during the coating process. Arc stability represents the long working cycle and short maintenance time, which is very important in engineering application. The deposition of high-quality film is crucial. In order to reduce or even eliminate the macroparticles, the discharge pulse is carefully controlled and the filter devices are applied[24].

This review discussed the progress of arc source from the perspective of technical requirements of arc source. The research progress and application status in macroparticle suppression were emphatically summarized.

1 Arc Spot Target Surface Maintenance Technique

When the magnetic field is not dominant, it can still

Received date: February 28, 2023
Foundation item: Anhui Provincial Key Research and Development Program (202004b11020011); Natural Science Foundation of the Anhui Higher Education Institutions (KJ2021A0392)
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maintain the arc spot movement on the target surface[25–26]. In the arc source design, the motion of arc spot is affected by the state of target surface under the dominant magnetic field. The arc spot moves randomly on the target surface and to the designed non-ablative surface, which is detrimental to the arc coating. Therefore, it is necessary to constrain the arc spot, and the magnetic field constraint is the most common and the easiest method.

The acute angle rule indicates the characteristic that the arc spot moves along the direction of acute angle formed by the magnetic field and discharge surface[27], which can effectively control the movement direction of the arc spot and prevent the arc spot from overflowing from the target surface. The magnetic field layout[28] is shown in Fig. 1. According to this principle, in order to move the arc spot on the target surface, the design of the magnetic field sometimes cannot meet the acute angle rule. Even it meets the acute angle rule, a protrusion is generated on the edge of the target material, and the arc spot can be constrained in the target surface because the constrain force is not strong enough.

Additionally, the arc spot sometimes does not move on the target surface even with the acute angle condition. This is because the arc spot movement on the target surface is also related to the magnetic field strength and target material.

The most representative case of the acute angle rule is that the arc spot is concentrated in the area with 0 in the vertical component of magnetic field[29–30]. Therefore, the uniform evaporation of target surface can hardly be achieved based on the acute angle rule. On the uniformly evaporated target surface, the magnetic field has a certain angle with the target surface, which is beneficial to control the magnetic field on the arc spot. Because the constraints on the arc spot are related to the electric field, target material, and magnetic field, the arc spot sometimes jumps out of the constraint area of the magnetic field and appears in other areas. Thus, in the arc source design, the constraint must be applied to the arc spot at any position to prevent its detachment from the evaporation surface.

According to the acute angle rule, the most convenient way for the magnetic field addition on the arc source is to directly add a magnetic field excitation device on the back side of the target. For example, a permanent magnet is added on the back side of the circular arc source, as shown in Fig. 2[31]. B represents the magnetic field, B_z represents the magnetic field

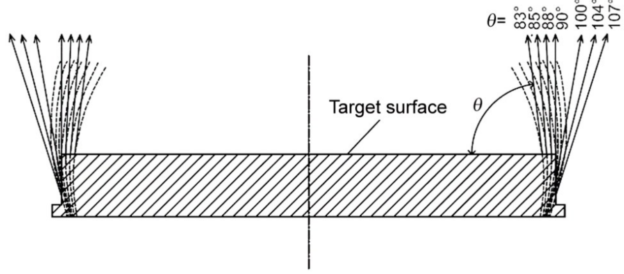

Fig.1 Angles formed by discharge surface and magnetic field of arc evaporation source[28]

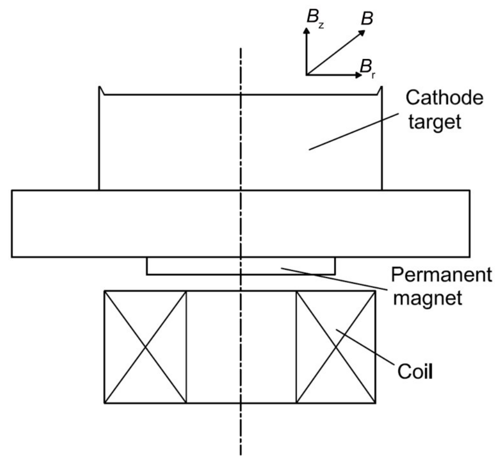

Fig.2 Schematic diagram of arc source with simple magnetic field structure[31]

component of the vertical target surface, and B_r represents the magnetic field component of the parallel target plane. In Fig.2, an electromagnetic coil is added on the evaporation surface with the opposite direction. Applying a constant current to the coil is equivalent to increasing or canceling the magnetic field provided by the permanent magnet, presenting the similar effect caused by a single permanent magnet structure. In the design of single-structural permanent magnet, the magnetic field provided by the permanent magnet on the target surface cannot be too strong. Otherwise, the arc spot will be constrained at a fixed position, resulting in serious uneven evaporation. The typical value of the target magnetic field is tens of Gauss, as shown in Fig. 3. Generally, the target diameter of the designed arc source should not be too large. Otherwise, the non-uniformity of evaporation cannot be avoided.

Because the strength and direction of the magnetic field can influence the arc spot to gather at the target center or to diffuse at the target edge, the superposition of the electromagnetic field based on permanent magnet can strengthen or weaken the magnetic field of the permanent magnet, thus moving the arc spot towards the target surface center or the target edge and achieving dynamic control[32]. In

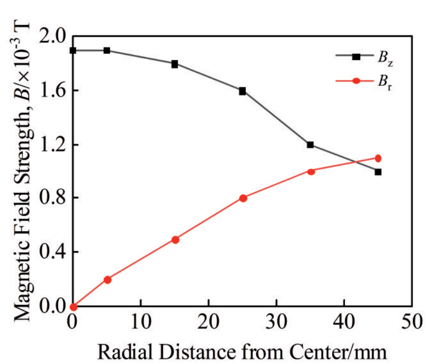

Fig.3 Typical value of magnetic field of single-structural permanent magnetic structure

addition, the movement of arc spot can be clearly observed. The arc source with electromagnetic dynamic control is shown in Fig. 4[32]. The coil in Fig. 5 is connected to a direct current (DC) power supply under periodic change, and the frequency of periodic change is 5 – 50 Hz. Through proper adjustment of current, when the magnetic field intensity of the target surface changes between 5×10^{-4} and 3.5×10^{-2} T, the arc spot on the target surface shows divergence or aggregation to avoid repeated movement of the arc spot in adjacent areas and to achieve the uniform evaporation of target surface. Without coils, the position of the magnetic field generator can assist in the control of magnetic field intensity on the target surface, therefore preventing the uneven evaporation of target surface and resulting in more precise targeting of magnetic field[33]. However, this device is too complicated and not conducive to industrial applications. If the magnets are set at the front and back sides of the target and their north and south poles are opposite[34–35], as show in Fig. 5, the magnetic induction line can pass through the target surface, and the magnetic field can be relatively stable even during the target evaporation. However, this type of arc source requires a larger installation space, compared with the arc source with the permanent magnet placed on the back side of target.

The arc spot can be moved from the center of target surface to the edge area and from the edge area to the target center through the coil, so the composite target design should be considered. This composite target is made from different materials, which results in the deposition of different materials. The related reactants can be determined through the controlling of operation time of arc spot, as shown in Fig. 6[36]. The upper part shows the magnetic field structure of the composite target in the arc source. The magnetic field excited by the coil can directly change the magnetic field intensity and direction of the target surface, moving the arc spot from the target center to the edge area or from the edge area to the target center. This motion directly determines the evaporation at different positions of the target surface, so the target changes into the structure shown in the lower part of Fig. 6. When the arc spot is scanning the specific material, the evaporation of the specific material occurs, and thus the preparation of multilayers or mixed structure film layers of different materials is completed. Arranging insulating layers between different target materials as well as changing the power supply and different target materials can achieve the arc evaporation of different materials and complete the preparation of multilayer films[36].

In addition, the magnets can also be placed on the sides of target[37–38], as shown in Fig. 7. A structure similar to the magnetic ring is formed. The magnetic pole can be either the axis towards the target or the axis parallel to the target axis. In this case, an effective controlling magnetic field is formed on the target bottom, and the arc spot on the sides of target can be pushed onto the target surface. This layout requires that the target diameter should not be too large. This is because when the diameter is too large, the central part of the target cannot be controlled by the magnetic field, and the arc spot is randomly located. The arc spot path on the graphite surface is much more difficult to control. Thus, a strong magnetic field

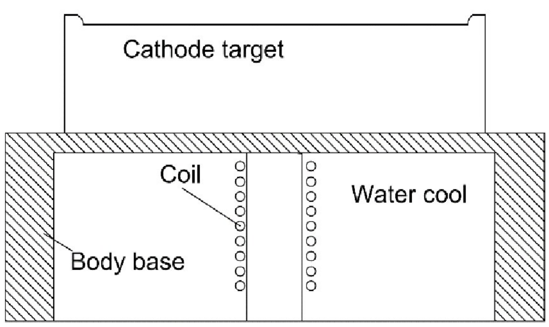

Fig.4 Schematic diagram of arc source with electromagnetic dynamic control on arc spot movement[32]

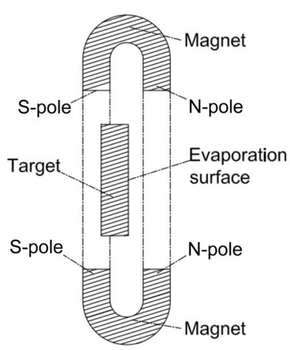

Fig.5 Schematic diagram of arc source with relatively small changes in magnetic field direction and intensity due to target evaporation

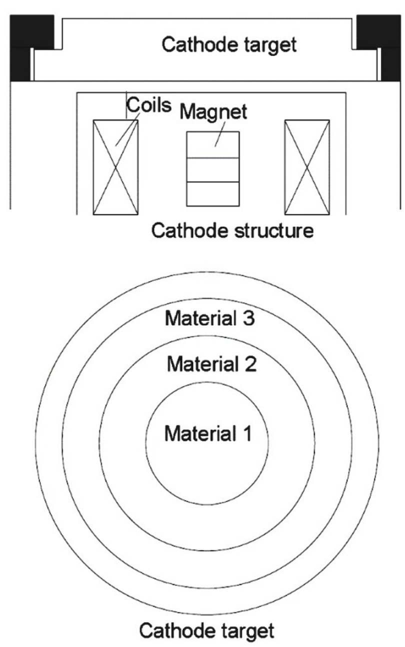

Fig.6 Schematic diagram of arc source and its composite target structure[36]

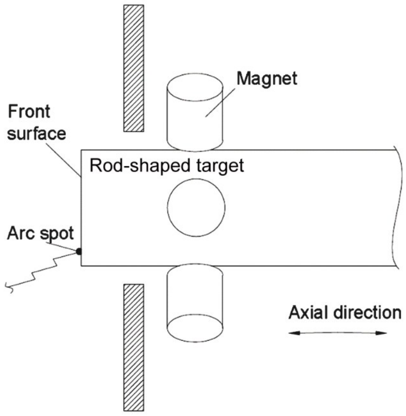

Fig.7 Schematic diagram of arc source structure with magnets on cathode side[39]

is required to complete the restriction of the arc spot on graphite target. To constrain the arc spot movement in the area from the target side to the target surface, two conditions must be satisfied[39]. One condition is that the angle between the magnetic induction line and the target surface should be less than a certain value, such as 45°. The other is that the magnetic field parallel to the target surface must be greater than a certain value, such as 0.02 T. The magnetic field on the target side is strong, and the angle between the magnetic induction line and the target side is acute, leading to the fact that the arc spot is constrained on the target surface by the magnetic field. Additionally, the design can ensure that the arc spot is at the best position for long-term service by moving the rod-shaped target back and forth[39].

2 Arc Source with Arc Spot of High-Speed Rotation

Macroparticles are the most concerned influence factor in VAD technique, and they strongly affect the film quality. In order to eliminate the influence of macroparticles, externally additional mechanisms are often used, such as solenoid[25] and auxiliary anode[40–41]. Macroparticles are produced by the droplet spray and explosive fragments due to the ion reflux[42–43]. The effective way to reduce macroparticles is to decrease the area temperature near the arc spot and form a small molten pool, therefore reducing the sprayed macroparticles. As for the arc source, the residence time of the arc spot at the same position should be shortened to avoid the temperature rise in the area near arc spot, which involves the rapid movement technique of arc spot, the pulsed arc technique, and the water-cooling technique.

Usually, the reduction in residence time of arc spot at the same location can be achieved by increasing the transverse magnetic field of the target surface. In the arc source structure, which is similar to that in Fig.2, when the transverse magnetic field increases from 0 T to 0.03 T, the macroparticles on the target surface of the deposited film decrease significantly, and the arc spot moves faster[44], as shown in Fig. 8. When the transverse magnetic field increases from 0.06 T to 0.15 T, the macroparticle density decreases by about 4 times. When the transverse magnetic field increases from 0.15 T to 0.25 T, the macroparticles on the target surface barely change[45]. The relationship between the macroparticles on the target surface and the motion speed of the arc spot is show in Fig.9.

It is known that the transverse magnetic field is beneficial to reduce the macroparticles. Besides, the longitudinal magnetic field can control the arc spot. Therefore, once the transverse and longitudinal magnetic fields can jointly form

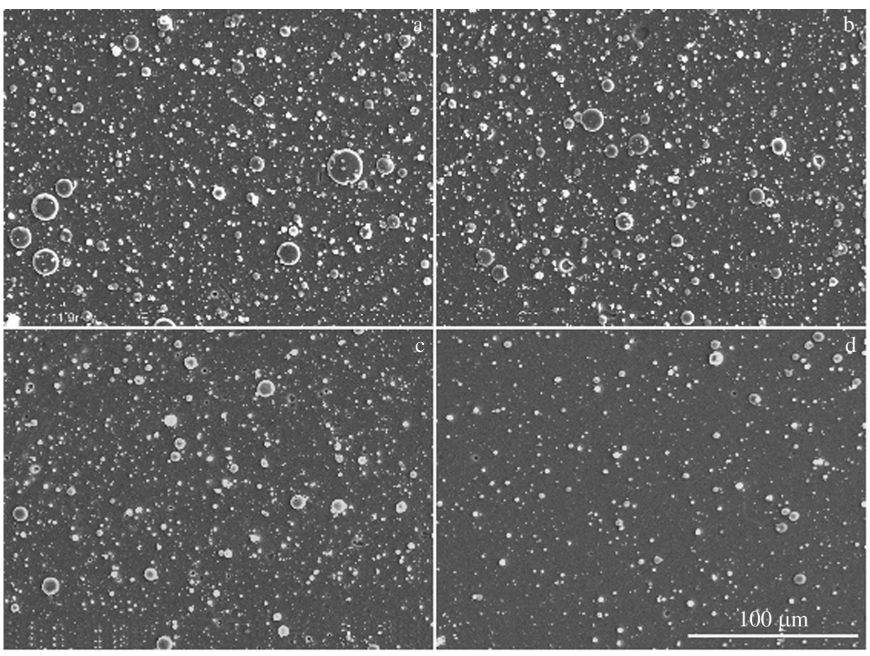

Fig.8 SEM morphologies of macroparticles on target surfaces of TiN films under different transverse magnetic fields: (a) 0 T, (b) 0.01 T, (c) 0.02 T, and (d) 0.03 T[44]

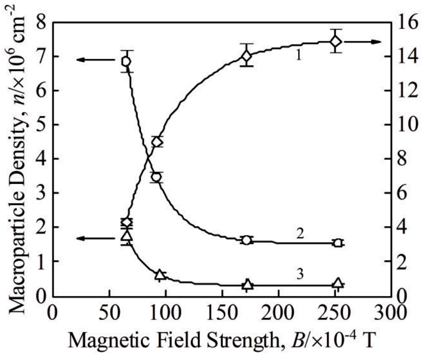

Fig.9 Macroparticle densities on target surface after exposure for 0.5 min under anode potential (line 2) and under pulsed negative bias (line 3) at different magnetic fields; relationship between cathode spot velocity and magnetic field strength (line 1)[45]

an acute angle with the target surface, the arc spot can be maintained on the target surface. Additionally, when the magnetic field is strong, the angle can be fixed within a certain range. Otherwise, the unstable discharge or uneven erosion may occur[28–31].

2.1 Arc source with dominant horizontal component of magnetic field

The magnetic field with the dominant horizontal component can form a circle movement path for the arc spot. If the arc spot moves fast enough, the temperature rises. On the basis of Fig.2, Fig.5, and Fig.6, if the device can excite magnetic field far away from the target, the distribution area dominated by transverse magnetic field can be formed in a small area on the target surface. Because the distance between the permanent magnet and the target surface is relatively long and the magnetic field is weak, a magnetic field area dominated by parallel components can be obtained. Although this arrangement can obtain a magnetic field area dominated by parallel components on the target surface, the acceleration in rotation speed of the arc spot is restricted. If the magnetic field excitation devices with opposite magnetic properties are arranged below the target surface, which is similar to the design of magnetron sputtering source, the magnetic field parallel to the target surface can be formed, therefore promoting the arc spot to rotate rapidly in this area, avoiding the local high temperature, and refining particles. At the target surface center, the transverse magnetic field component is small, and the longitudinal magnetic field is large. In order to avoid the capture of arc spot by the magnetic field, the cathode target can be covered with the insulating material or the conductive material. In addition, the central area of the target can be connected to a material with relatively smaller electron emissivity[46–47]. Thus, the target center cannot supply enough electrons to force the arc spot to move along the orbit. If the target is ceramic material, the rapid arc spot movement can also avoid the cracking caused by local overheating of the target material. Fig. 10 shows the schematic diagram of the structural layout of the ceramic target[48]. Similar results can be

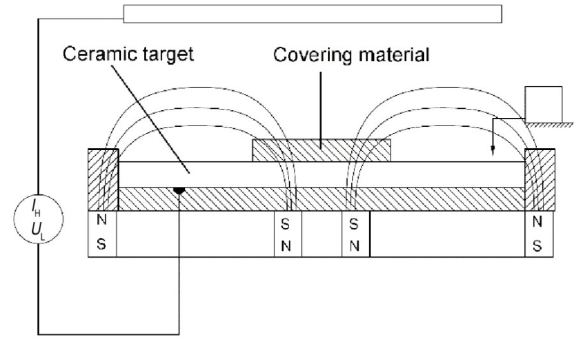

Fig.10 Schematic diagram of magnetic field layout of plane target with dominant horizontal magnetic field component[48]

achieved through the coil layout[49–50], but their principle applications are quite different. At the same time, the design can also be obtained in the rectangular plane target[51]. If the target materials are the same, the area with vertical magnetic field component layout in the middle can capture the arc spot and cause evaporation of the central area. The evaporation amount depends on the specific layout of the magnetic field. Therefore, the uniformity of the target evaporation can be improved by designing the permanent magnet as an eccentric structure and the rotation of the back side of the cathode target[28,52]. This design is a common method in the magnetron sputtering design of circular target structures. If the direction of the permanent magnetic pole changes, the area of the magnetic field component of parallel target surface is larger, as shown in Fig.10–Fig.12. The magnetic field layout (Fig.11) is more conducive to the uniform evaporation of the target surface[52].

The abovementioned structures in Fig. 10 and Fig. 11 are relatively simple, and the complex design involves the magnetic field excited by the multiple groups of coils, as shown in Fig. 13[54–57]. The iron core can be adjusted through the adjust rod. These coils cooperate with each other, forming a more flexible magnetic field distribution on the target surface and completing the evaporation of design area. In this case, the target structure is also relatively complex. Obviously, when the target of this composite structure evaporates in one

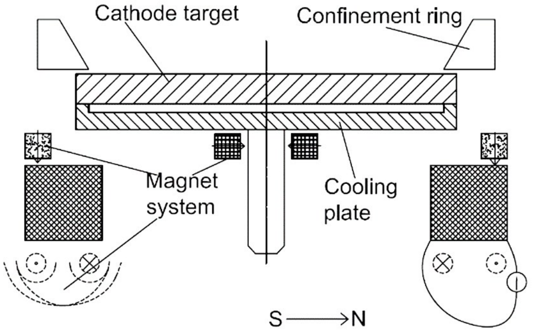

Fig.11 Amelioration of magnetic field layout of plane target with dominant horizontal magnetic field component[52]

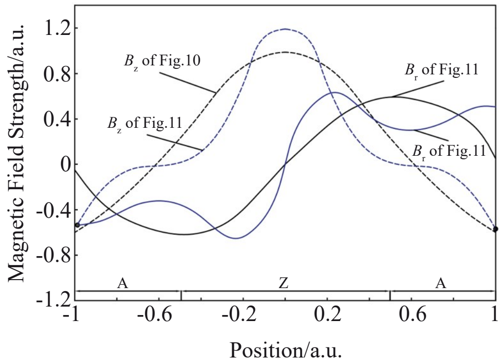

Fig.12 Distribution of magnetic field component on plane target[53]

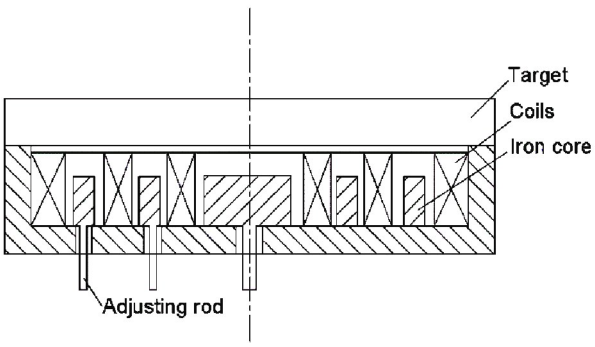

Fig.13 Schematic diagram of magnetic field structure of arc source for composite target[57]

area, it is unavoidable to pollute other areas, therefore restricting the application of this composite target. As shown in Fig. 10, the magnetic field must be arranged to ensure that the local area on the target surface is large enough to be covered by the magnetic field on the parallel target surface. Otherwise, along the radial direction, the parallel and vertical components of the magnetic field change rapidly, resulting in a sharp change in the arc stabilization force, which thereby causes the repeated adjustments by arc power supply and leads to a sharp change in the arc current.

The horizontal and vertical components of the magnetic field on the surface of arc cathode have different effects on the arc spot. The arc source should be connected to the solenoid filter subsequently. Thus, in the design of arc source, if the magnetic field direction of the target and the magnetic field direction in the solenoid are the same, the magnetic field component in the vertical direction of the target surface is often too large, which is not conducive to the rapid movement of the arc spot. Therefore, as shown in Fig. 14, the coil 1 is arranged at the front of the cathode target to ensure that the magnetic field is located from bottom to top, and the coil 2 is arranged near the back side of the cathode target to ensure that the magnetic field direction is from top to bottom[54]. The mutual cancellation of the magnetic field in the vertical direction near the evaporation surface and the mutual reinforcement of the magnetic field in the horizontal direction can be completed. In this design, there is a zero point in the magnetic field perpendicular to the target surface. Through the adjustment of the current in coil, the zero point[56] is generated above the target surface. The zero point is 20–60 mm away from the target surface. Along the horizontal direction, the magnetic fields generated by the two coils can strengthen each other, and their strength is 15 – 35 mT, which meets the requirements of arc source operation. When the horizontal component of the magnetic field is strengthened, the arc spot on the target surface moves circularly under the effect of horizontal component of the magnetic field, which is conducive to the macroparticle reduction. In this method, the as-pressed and as-sintered graphite targets are usually used as arc cathode, which can generate plasma and deposit Ta-C film.

According to Fig. 14, when the discharge current is small, the stability of arc source is poor. The coil 3[57–58] is added to the target surface. The magnetic field generated by the coil is coaxial with the coil 2, and the magnetic field direction is from top to bottom. At this time, the horizontal magnetic field component excited by coil 3 can offset that excited by coil 1 and coil 2, as shown in Fig. 15. The magnetic field strength changes slightly along the direction of target radius. By adjusting the current in three coils, the points, where the horizontal and vertical components of the magnetic field are zero, can be adjusted near the target surface, and the zero point is located above the target surface. It should be noted that the longitudinal and transverse magnetic fields on the target surface are not zero. At the same time, due to the mutual offset between the coil magnetic fields, the situation that the magnetic field in the target center area is too large can be avoided in the normal design.

The arc spot of the arc source with the dominant horizontal component moves very fast, but it may be captured by the area with larger vertical component of the magnetic field.

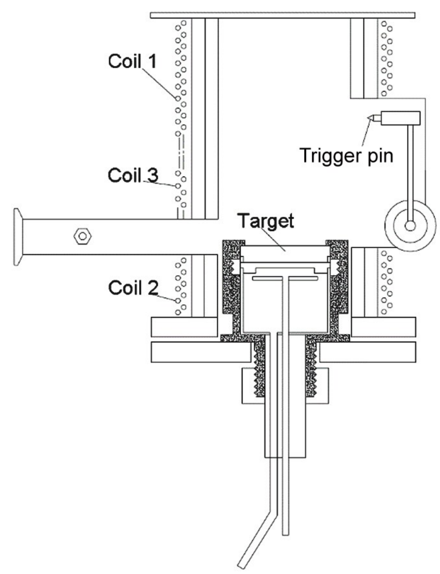

Fig.14 Schematic diagram of arc source device with zero point of magnetic field component on vertical cathode target surface[40,58–62]

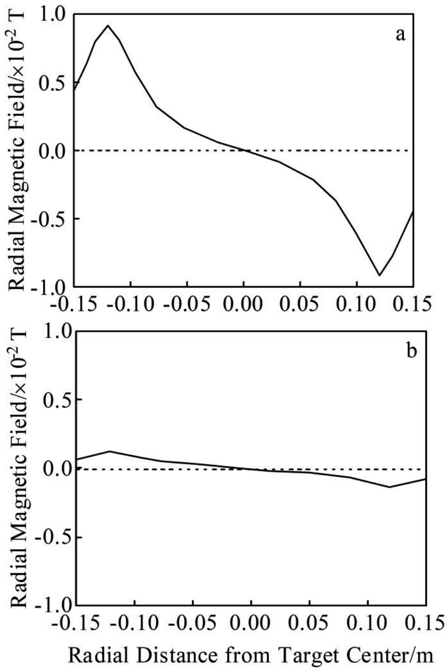

Fig.15 Comparison of horizontal component magnetic fields without (a) and with (b) coil 3[56,60]

During the capture period, the movement speed of arc spot is small. At the same time, the arc spot movement is concentrated in the area with the dominant parallel component of magnetic field, which may cause uneven evaporation of the target surface. This result is not conducive to improve the utilization ratio of the target material. If the evaporation surface is at the side part of the cathode, as shown in Fig.16, the magnetic field generated by the permanent magnet forms a magnetic field component parallel to the target evaporation surface on the side part of cathode, and the evaporation of the target surface is also uneven[19,59]. This design is completed through the film deposition from the inside to the outside, which is not friendly to the layout of vacuum chamber. Meanwhile, the device occupies a large space and cannot do anything for the inner wall of small diameter of pipes. Therefore, this design is a little bit useless.

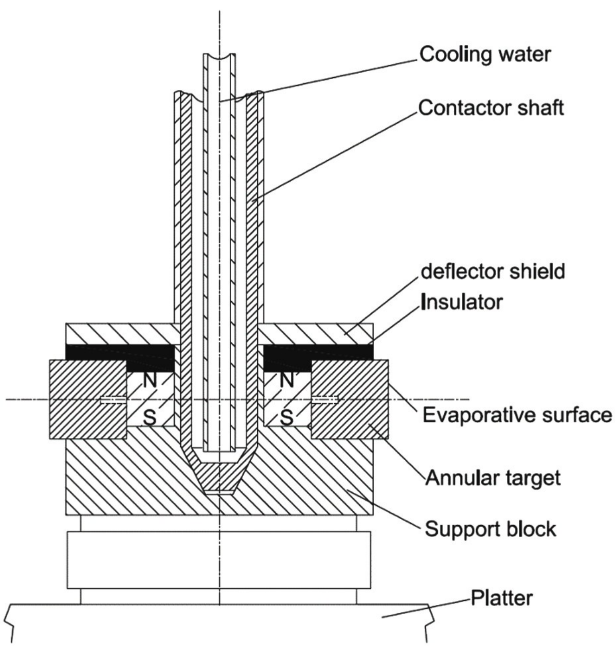

Fig.16 Schematic diagram of annular target arc source structure[61]

2.2 Arc source with consideration of horizontal and vertical magnetic field component layouts

The horizontal magnetic field can promote the arc spot movement, and the longitudinal magnetic field can ensure the distance between the arc spot and the cathode center. If the magnetic field can extend to reach the substrate, the plasma can be guided from the cathode to the substrate. Therefore, the film deposition is directly completed. At the same time, the neutral particles move along the direction of spraying from the target surface, and some particles are not deposited on the substrate, which may exert the inhibition effect on macroparticles to a certain extent. Therefore, a relatively flexible arc source can be designed, as shown in Fig. 17[60–64]. There are many adjustable variables of the magnetic field in this arrangement, including the distance A1 between the magnetic ring 2 on the target surface and the target surface, the distance A2 between the magnetic ring 5 and the target non-evaporation surface, and the distance A3 between the magnetic ring 4 and the non-evaporation target surface. To manufacture these magnetic rings, the mosaic structure of multiple permanent magnet columns can be selected. The magnetic field intensity excited by each magnetic ring can be easily changed by varying the number of embedded permanent magnets. These variables can also be adjusted in the arc source of the finished product through proper design, which provides great convenience for the process. The ameliorated structures based on Fig. 2 also have a better magnetic field structure, i. e., the permanent magnet can be changed into multiple magnetic ring structures[61]. Magnetic rings can change the magnetic field through size design, so the magnetic field component can be effectively adjusted.

The abovementioned structure can also be achieved through the coil amelioration. A common structure of DC arc source is shown in Fig.18[21,46]. The restriction of arc spot on the cathode evaporation surface is realized by three coils (or two coils)

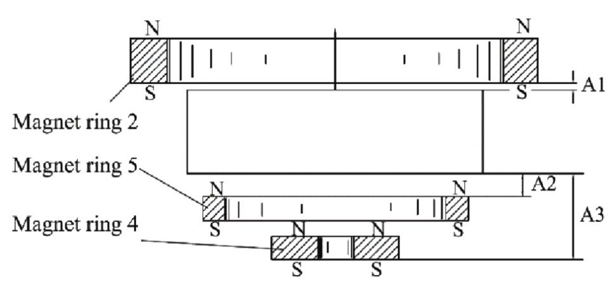

Fig.17 Schematic diagram of arc source with multi-magnetic ring structure[64]

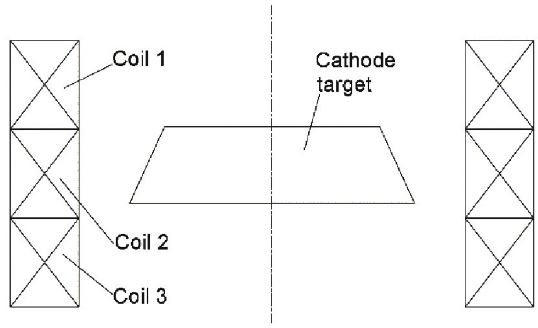

Fig.18 Schematic diagram of DC arc source coil structure[21,46]

which are adjacent to each other. This arc spot restriction technique is commonly used in recent years, and the arc striking device of the arc source is near the cathode base. When the arc spot is on the side part, it is constrained to the cathode surface by applying current to the coil 1. The coil 1 is the focusing coil. By applying current to coil 2, the stable rotation of arc spot is realized, and the coil 2 is regarded as the arc stabilizing coil. When the cathode reduces due to evaporation, the arc spot can be restrained through coil 2 and coil 3. Thus, the cathode should be thicker. After the adjustment of coil current parameters, the evaporation surface is convex, concave, or uniform. Because there are many coils involved in the arc source, sufficient power supplies are necessary. At the same time, because the coil encroaches on the space, the selection of the ignition needle is based on the surface discharge arc striking method, which almost does not occupy space. However, this ignition method may fail due to the deposition of the facial mask layer on the ignition ceramic surface. Thus, the ignition needle needs regular maintenance. Because the magnetic field is adjusted through the coil, the adjustment of magnetic field strength is very flexible, and the researches on magnetic field change, arc spot movement speed, and large particle distribution can be easily conducted[46].

Oerlikon surface solution AG can release an arc source with magnetic shielding and arc spot control[62–67], and the arc source structure is shown in Fig. 19. The magnetic field

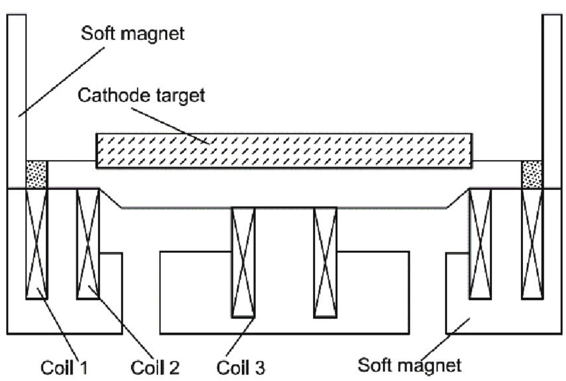

Fig.19 Schematic diagram of magnetic shielding structure of arc source[68]

excited by the coil can control the movement track of arc spot on the cathode surface, and it can also adjust the field strength of target surface by changing the distance between the soft magnetic material and the back side of cathode target. This arc source structure has magnetic conductive materials around the evaporation surface of the target, so the magnetic field is restricted within the range of arc source. Similar result is reported in Ref. [65]. When the magnetic field divergence is restricted, the electromagnetic interference will not occur to the nearby arc source, and the arc source can be arranged more closely.

The arrangement of magnetic conductive materials can form a magnetic field shield. If the permanent magnets are arranged, the magnetic field is introduced into the vacuum chamber, and even the magnetic induction line can pass through the substrate, forming a certain filtering effect. Therefore, the arrangement of the arc source has an important impact on the coating process[62]. If the arc source is arranged side by side and the magnetic field in the vacuum chamber is in the opposite direction, the magnetic force line will start from one target and end at the adjacent target. This process is equal to the formation of magnetic field component parallel to the plane where the arc source is arranged between the adjacent targets. When the plasma moves in this space, the electrons interact with these magnetic induction lines, greatly increasing the motion paths of the electrons, which is conducive to the ionization of the process gas. If two arc sources with opposite magnetic fields are arranged on the opposite positions of the vacuum chamber, the magnetic induction line will start from one arc source and end at the other arc source. Thus, the magnetic induction line will cross the vacuum chamber and pass through the sample placement area. In this case, the electrons move along the direction of magnetic induction line, leading to the deposition of more ions on the substrate. Additionally, the high ionization rate is obtained, which is beneficial to improve the film quality.

When the magnetic field leaves from the target surface, the divergence of abovementioned magnetic field layout occurs quickly, which is not conducive to the plasma covering on the workpiece area. Through the design of magnetic field, the magnetic field can guide the electrons to move towards the substrate, as shown in Fig. 20[69–71]. If the arc source and the deposited workpiece are all incorporated into the closed loop magnetic field, the magnetic field guidance plays an important role[68].

In order to achieve the uniform evaporation of the target surface, the magnetic field constrains the target surface, which is still applicable to the acute angle rule. However, because the magnetic field is very strong, the constraint ability is very strong. The evaporation of the target surface must be uneven. A specific design that the magnetic field direction of the target surface and the normal of the target surface are at an angle of 10° – 30° should be conducted for the enhancement in magnetic field and controlling of rapid movement of the arc spot on the target surface, so the rapid movement of the arc spot can be maintained on the target surface during the

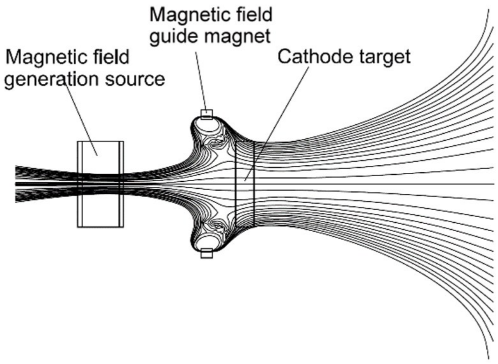

Fig.20 Schematic diagram of constrained magnetic arc source[70–71]

relatively uniform evaporation[69]. The angle between the magnetic field and the target surface is related to the magnetic field strength. Therefore, in order to move the arc spot more quickly, the balance between uniform evaporation and rapid movement should be considered. Additionally, the type of target material also has an important impact on the arc spot.

3 Pulsed Arc Sources

The most obvious difference between DC arc source and pulse arc source can be reflected by the working mode: DC arc source is powered by DC power supply, whereas the pulse arc source is powered by pulse DC power supply. During the operation of DC arc source, the plasma is continuous and can maintain a stable discharge state. During the discharge process of the pulse arc source, the discharge process ends after one pulse. Meanwhile, the high discharge voltage increases the energy of electrons overflowing from the target surface, and the high discharge current leads to the fact that the arc spot on the target surface occupies a large area, i. e., the plasma density is improved and the consumption of arc target material is faster[70–71]. In order to maintain the discharge of the pulsed arc (to avoid repeated arc ignition), the superimposed pulse above DC is maintained. The advantage of pulse arc source is that it can be triggered and ended instantaneously, so the temperature at the arc spot changes rapidly, which is beneficial to reduce the macroparticles in the high-temperature molten state at the arc spot during the spraying process. The DC-superimposed pulse method obviously has the advantages of stable discharge and pulsed arc.

When the general DC arc source faces the high-temperature refractory target, a small number of particles that have not been completely melted will be doped in the molten material at the arc spot, resulting in a discharge phenomenon similar to the sprayed fireworks. To overcome this problem, it is necessary to increase the discharge current during discharge to completely melt the target of high melting point and to avoid the not-completely-melted macroparticles. The most common example of arc technique for high-temperature refractory targets is graphite target. Graphite targets are often used to deposit hard carbon films and barrier conductive films, leading to various design cases focusing on the stable discharge[56,59] or self-cleaning[72–76]. The design of graphite arc source can be taken as an example to illustrate pulse arc sources.

The multi-stage trigger arc source is designed based on the principle of stepwise amplification, as shown in Fig.21[77]. The primary ignition power supply outputs pulses according to the set pulse. Before the next pulse output, both the secondary pulse ignition power supply and pulse arc power supply are in full power and at output state. Each DC pulse output corresponds to one pulse arc discharge. A design similar to this structure involves the addition of a magnetic field behind the cathode, thereby forming a cathode with magnetron sputtering. Then, the sputtering power supply connects the cathode with auxiliary anode. Thus, the target surface starts glowing. Subsequently, add a pulse arc power supply between the cathode target and the main anode to form the pulsed arc discharge, as shown in Fig. 22[78]. The ignition pin of some pulse arc sources is at the target center[79–80], as shown in Fig.23. Additionally, it is also possible to design a laser arcing

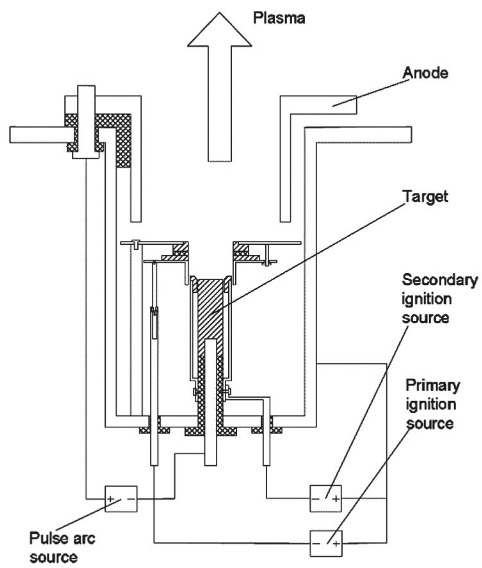

Fig.21 Schematic diagram of multi-stage trigger pulse arc source[77]

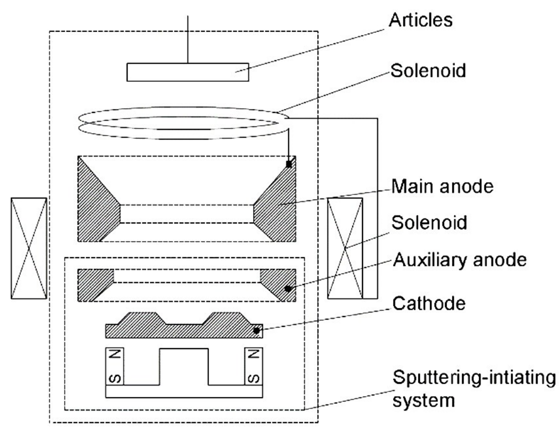

Fig.22 Schematic diagram of magnetically controlled arc striking pulse arc source[78]

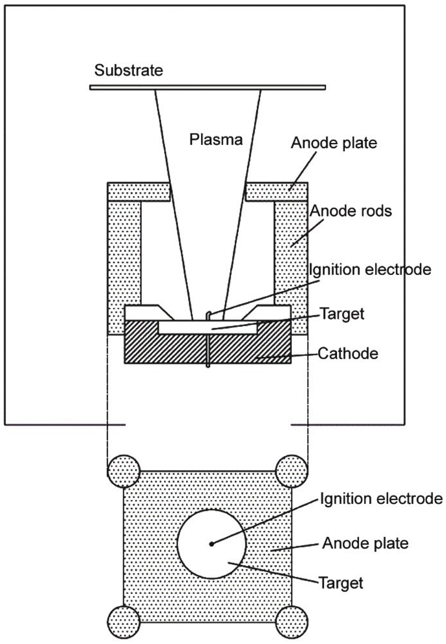

Fig.23 Schematic diagram of pulse arc source with ignition electrode in the middle of the target[79]

mode[81–82] for convenience, which has the advantage of pulsed laser characteristics and allows to design an arc source with over 100 pulses per second while maintaining the high deposition efficiency. To avoid contaminating the windows, a very small incidence angle between laser and target surface is usually used during the operation of this mode. The distinguishing feature of these pulse arc sources is that the plasma is "pulled out" through the anode, forming a channel guided by electric field direction. During the plasma expansion, macroparticles with negative charges are attracted by the anode, so the macroparticles are reduced.

In order to maintain the high deposition efficiency, the pulsed arc technique can achieve the peak discharge current of thousands or even tens of thousands of amperes, which leads to higher deposition efficiency than that of DC arc. Different positions of the arc spot between the two pulses of the pulse arc source provide opportunities for the complete cooling. Therefore, a complete pulse only takes a few microseconds[72], resulting in the fact that the pulse frequency can reach thousands of hertz and providing conditions for efficient deposition. Large discharge current is also beneficial to the target of high melting point. When the discharge current increases, the arc spot of the discharge presents split phenomenon[83], which is caused by the large discharge current of several thousand amperes. This technique is also applied to the nitride deposition, which has flat surface and excellent film performance, as shown in Fig.24[84].

The abovementioned techniques can be applied to graphite cathode, because on the surface of graphite cathode, the movement speed of arc spot is slower than that of the metal surface by 2–3 orders of magnitude[73], which easily causes the pits[74]. Based on Fig.9, a circle magnet around the evaporation surface of the cathode target can complete the movement of arc spot in the relatively fixed area of the target surface, thus completing the selective evaporation of the target[75]. By arranging an eccentric anode on the surface of the cathode target and then rotating the cathode target, the arc spot can also be guided to the evaporation position of the target surface, therefore achieving the uniform evaporation[76]. However, this method requires the entire filtration system.

To prepare a carbon film by arc deposition technique, the sp^3 component in the film is very small in the area where the macroparticles are concentrated, and the film layer is loose

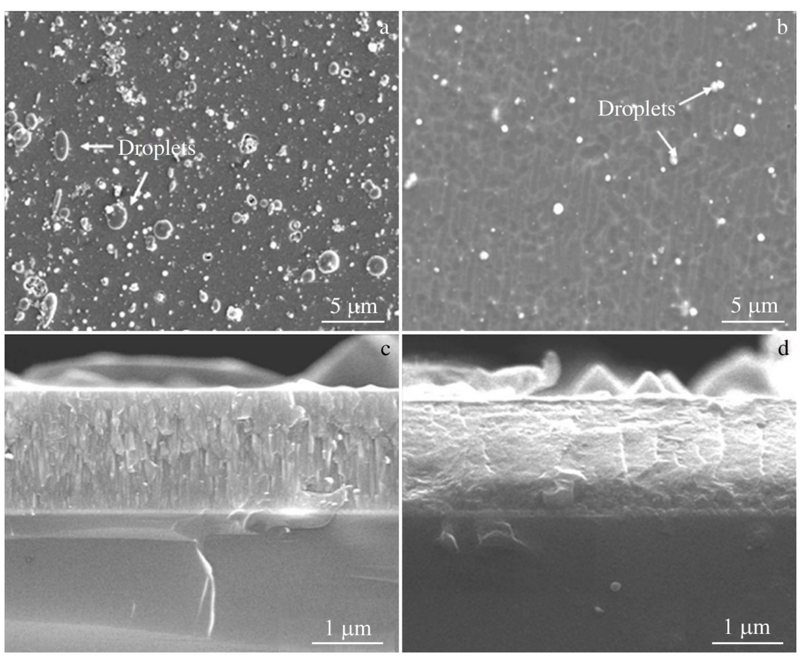

Fig.24 SEM images of surface (a–b) and cross-section (c–d) of nitride coatings deposited by conventional arc (a, c) and splitting arc (b, d) [84]

and easy to fall off. This characteristic causes the chamber of carbon plating to be dirty, but it can be used in the coating process to complete the cleaning of some areas. The pulse arc carbon source with self-cleaning function can be achieved[74,77–78], and the graphite target is also applicable. Through the expansion and contraction of the target, the evaporation surface of the target is always in the proper position[85–90].

4 Conclusions

Since the development of arc ion coating technique in the last century, it has become an indispensable technique in film deposition and has been widely used in the fields of metal film, decorative film, and hard wear-resistant film. Afterwards, the related principles have been thoroughly researched, as well as their practical application and structure design.

Starting from the technical difficulties related to arc source structures and requirements raised by film deposition needs, key technical challenges can be classified into two categories: stable discharge technique for arc sources and large particle suppression technique. More researches have been conducted on the macroparticle suppression. High temperature gradient between the cathode target arc spots and surrounding materials is beneficial to the macroparticle suppression. Hence, the rapid movement of arc spot or pulsed arc technique attracts much attention due to their effectiveness during film deposition.

Arc ion coating technique is widely applied in many fields, and it can be considered as a mature technique. However, the enhancement in structure details can also significantly expand its application field and reduce the equipment manufacturing as well as operating costs. Therefore, the structure of the arc source should be further researched, which requires a lot of technical parameters accumulation. A small change in the structure of the arc source may have a significant effect on the film performance. However, only the simple distinction can be conducted in the preparation process, such as the amelioration in the arc source layout. Additionally, the structure of arc source is rarely investigated, the technical details are not specific, and the process reproducibility is poor, which all require further study.

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电弧源自身大颗粒抑制技术研究进展

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摘 要：电弧离子镀技术已经成为镀膜技术中不可或缺的技术之一，并在金属、装饰、硬质耐磨等领域被广泛研究和应用。膜层技术的研究应用促使对电弧源技术的研究主要集中在长寿命、高可靠性和大颗粒抑制这几方面，且后者的开展必须建立在前者的基础上。大颗粒抑制的关键在于减少弧斑在靶面的驻留时间，可通过巧妙的永磁或电磁设计来实现具有较强横向磁场分量的靶面，但当磁场强度增大时，必须综合考虑纵向磁场和横向磁场的比例关系，考虑靶材本身的特点。另一种抑制大颗粒的方法是脉冲电弧技术，脉冲电弧源引弧频繁，在结构设计上和恒流电弧源有很大的区别，瞬时电流能达到数千、甚至一万安培以上，能够获得很高的沉积速率，同时阳极的设计使等离子体形成定向喷射，过滤掉大部分大颗粒。

关键词：电弧源；磁路结构；大颗粒；脉冲电弧

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