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Effect of multi-mode dynamic coupling magnetic field on arc spots movement in arc ion plating

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Abstract

The work investigated the movement characteristic of arc spots under direct current coupling magnetic field, triangular wave coupling magnetic field and rectangular wave coupling magnetic field with different frequency. The results showed that reversed polarity focusing magnetic field combined with an axial-symmetric magnetic field forming an arched magnetic field with a proper curvature under direct current mode, which could accurately

control the position of arc spots. Under the periodic dynamic mode, with the increase of frequency, the effect of focusing magnetic field on movement of arc spots under strong divergent axial-symmetric magnetic field gradually increased in 0-20Hz, then weakened in 20-40Hz, and finally disappeared at the frequency of 50Hz. Under linear triangular wave or stepped rectangular wave coupling magnetic field, "e"-shape spiral motion frequently appeared in the frequency of 0-20Hz and gradually disappeared from 20Hz to 40Hz. Arc spots only presented "e"-shape spiral motion at the frequency 15Hz. The variation of circular motion at the edge of target was opposite to that of "e"-shape spiral motion. The most effective frequency range of dynamic coupling magnetic field was 8-15Hz..

Keywords: ARC SPOTS MOVEMENT, MULTI-MODE DYNAMIC COUPLING MAGNETIC FIELD, DIRECT CURRENT COUPLING MAGNETIC FIELD, TRIANGULAR WAVE COUPLING MAGNETIC FIELD, RECTANGULAR WAVE COUPLING MAGNETIC FIELD

1. Introduction

Arc ion plating was the preferred preparation technology for surface protective coatings of tooling and machinery parts [1, 2]. Its working principle was cold cathode vacuum arc discharge; high-current discharge was concentrated in a small-size cathode spot of target surface [3, 4]. High-energy discharge generated arc plasma with high density and ionization rate. Under effects of negative bias, high-density ions formed protective coating with compact structure on the work-piece surface. Although generation of plasma is beneficial to obtaining high performance coatings, vacuum arc discharge also led to «macro-particles» seriously affecting quality and performance of the coating [5-7]. Solution to the pollution of macro-particles had become the mainstream of development for arc ion plating. «Magnetic filter « arc [8-11], magnetic-assisted ion plating arc source [12] and their corresponding forms emerged. Wherein magnetic field-assisted ion plating arc source, aimed at high-efficiency industrial applications, avoided decrease of deposition efficiency and deposition windows. It was a measure solving the problem of macro-particles from the origin source, with more potential for development.

Magnetic field-assisted ion plating arc source could reduce ejection of macro-particles due to effective and reasonable control of arc spots through magnetic field [13-19], thus improving characteristics of arc spots discharge. In process of arc ion plating, arc spots was the dense accumulation area of plasma. Applied magnetic field could control position, morphology and motion of arc spots, thus arrangement of magnetic field directly affected characteristics of cathode target. People have studied effects of applying different forms of magnetic field. From magnetic field component, static magnetic field patterns mainly included longitudinal magnetic field [13], transverse magnetic field [14, 15], cusp-shaped magnetic field [16, 17], axisymmetric magnetic field [18] and arched magnetic field [19]. In industrial applications, the in-

fluence of magnetic configuration on arc spots movement resulted from integrated effects of arc spots retrogression with inverse ampere force under transverse component and "acute angle principle" under cusp-shaped magnetic field. Utilization of the target was reduced when movement velocity and discharge stability of arc spots were improved. It was difficult to eliminate this interactive influences. In order to achieve combined effects of decreasing macro-particles and increasing target utilization, a multi-mode alternating coupling magnetic field-assisted arc ion plating arc source was designed by Wenchang Lang et al. [20], taking into account increase of plasma transfer efficiency and coating deposition uniformity. In the design, arc spots movement were dynamically controlled through superposition of multi-mode reversed-polarity dynamic focusing magnetic field and axisymmetric divergent magnetic field or arched magnetic field, thus improving arc discharge and reducing particle emission. Meanwhile, the plasma was stably transmitted under guidance of focusing magnetic field; probability of particle collision was enhanced with improved ionization rate and density of the plasma.

Alternating coupling magnetic field showed significant advantages in reducing macro-particles and increasing ionization and ion density of arc ion plating. However, specific influence of coupling magnetic field on discharge characteristic and motion morphology of arc spots and its influencing mechanism should be further researched. Aimed at effect of multi-mode dynamic coupling magnetic field on ion plating arc discharge, Finite Element Method Magnetics (FEMM) was used to simulate distribution of magnetic field. The effect of direct current coupling mode on arc discharge was explored; then, the work analyzed the evolution of motion patterns for arc spots under triangular-wave coupling magnetic field and rectangular-wave coupling magnetic field in different frequencies. The effect of coupling frequency and coupling mode on arc spots movement of ion

plating was discussed considering physical mechanism of arc discharge.

2. Experimental methods

The self-designed arc ion plating arc source assisted by multi-mode alternating coupling magnetic field was adopted in the experiment (See Figure. 1). In the figure, target diameter was 100mm, with indirect water cooling; permanent magnet steel group was placed in the grooves outside water-cooled channel, forming strong axis-symmetry diverging magnetic field on target surface. Reversed-polarity focusing magnetic field coil was placed in front of the target, coaxial with the target; the center of device was parallel to target surface or slightly higher than target surface. Excitation current of focusing guiding magnetic field was driven by a multi-waveform signal power, which was used to generate excitation signal of high-power direct current, and direct current biased alternating current, including rectangular wave, triangular wave, steamed buns wave and sine wave. Waveform frequency was adjustable from 0.01 Hz to 1 KHz, with resolution ratio of 0.01Hz; duty cycle was adjustable from 10% to 90%; output voltage was adjustable from -40V to +40V. Positive terminal peak value of waveform V_{max} and negative terminal peak value V_{min} could be arbitrarily set in [+40.0V, -40.0V]. Thus, V_{max} and V_{min} could be set as biased positive voltage or biased negative voltage excitation, or as symmetrical or asymmetrical positive and negative voltage excitation, with adjustable output current from -30A to +30A. Multi-wave signal could excite electromagnetic coil to generate multi-mode dynamic focusing reverse-polarity magnetic field. Strong divergent magnetic field was generated through permanent magnet group in the back of coupled target, controlling the movement of arc

spots to improve arc discharge and plasma transmission of arc spots.

Focusing magnetic coupling modes of direct current, triangular wave and rectangular wave (sine wave mode was similar to triangular wave in variation of excitation current) were selected in the research. Discharge behavior and patterns of arc spots on Ti target was explored under dynamic coupling alternating magnetic field in three different modes. According to the technical design, the model was established to simulate distribution of coupling magnetic field under direct current mode, using Finite Element Method Magnetics (FEMM) [21]. Then, distribution of different magnetic components on the target surface was analyzed. Figure.2 showed structure model used in finite element simulation. This model was designed for circular target with wider application. Therefore, the simulation only needed to be conducted for half of the circular target, because the circular target was circularly symmetric with the central axis. In simulation of magnetic field, the values of material properties had important implications on accuracy of simulation results. Size parameters of specific structures used for magnetic field simulation were set as follows: diameter of target was 100mm; axisymmetric magnetic field on the back of target was NdFeB (N35) permanent magnet material; outer diameter of focusing coil was 255mm, inner diameter 210mm, and height 50mm. Mixed boundary conditions were selected based on impedance characteristics of electromagnetic field. The selected areas were divided into triangular element meshes with different sizes using the software. The entire program started from equations of Maxwell electromagnetic field, solving relevant values for describing entire areas of static magnetic field. Post-processing of FEMM software was

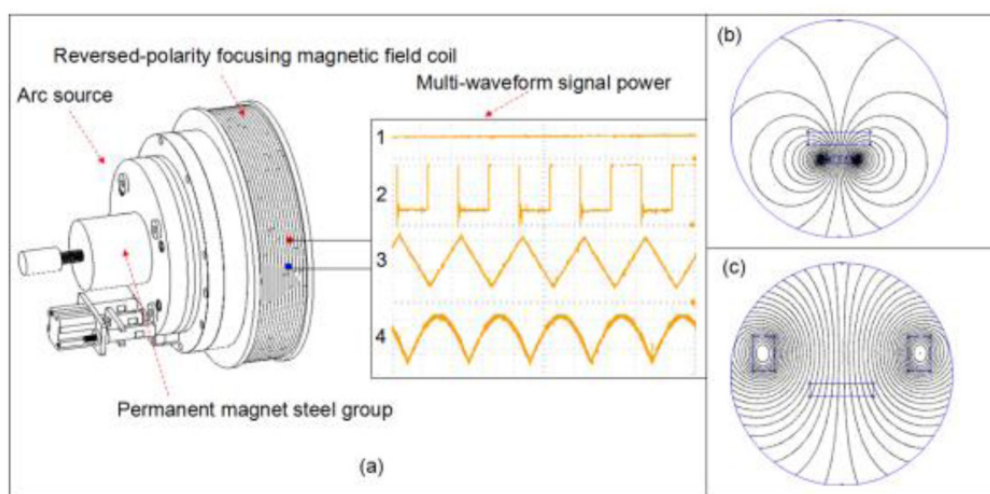


Figure 1. Schematic map of alternating coupling magnetic field assisted arc source (a), configuration of the axial-symmetric magnetic field (b), and configuration of the reversed polarity focusing and steering magnetic field (c)

implemented based on boundary conditions and plane graph of the painted area, presenting distribution of the solving magnetic field with a graphic program. The intensity of magnetic field was measured using SHT-V magnetometer. A glass filter was set in the observation window; a camera with exposure time of 0.001 second was used to dynamically screen movement of arc spots under different parameters. Then, topographies of arc spots at different times were randomly extracted through post-processing software. The work analyzed the influences of different-mode dynamic coupling magnetic field on movement of cathode spots; meanwhile influencing mechanism of multi-mode dynamic coupling magnetic field on discharge of cathode spots was discussed

3. Results and Discussion

3.1. Direct current coupling mode

Figure.2 showed the effects of direct current intensity in reversed-polarity focusing magnetic field coil on distribution of coupling magnetic field with axisymmetric diverging magnetic field and the arc discharge. The previous study about effects of axisymmetric diverging magnetic field on the movement of arc spots [22] showed that the movement of arc spots resulted from integrated effects of arc retrogression with inverse ampere force under transverse magnetic field, and “acute angle rule” under effect of cusp-shaped magnetic field. Axisymmetric diverging magnetic field generated a force to promote outwardly-extended rotational movement of arc spots. The velocity of arc spot movement increased with magnetic field intensity. Dwell time of arc spots at one point was shortened, reducing emission of macro-particles. However, the enhanced axisymmetric magnetic field drove arc spots to the edge of target, resulting in non-uniformity of target erosion and divergence of plasma transmission, as the case of $I = 0A$ shown in Figure. 2.

In order to increase transmission efficiency of the plasma, a reversed-polarity focusing magnetic field was set in plasma transfer space, reducing divergence of the plasma [20]. Meanwhile, an acute angle towards the target center could be formed by the focusing axial magnetic field and target surface, which constrained arc spots to concentrate at the center of target. With increase of strength in focusing magnetic field, the constraint force became stronger, and the formed spots were more concentrated. This rule was confirmed by the results of Figure.2. Magnetic field strength was enhanced with increase of current in reversed-polarity focusing magnetic field coil; axisymmetric diverging magnetic field gradually gathered at the center of target, forming an arched magnetic field with certain curvature on the target surface. The apex

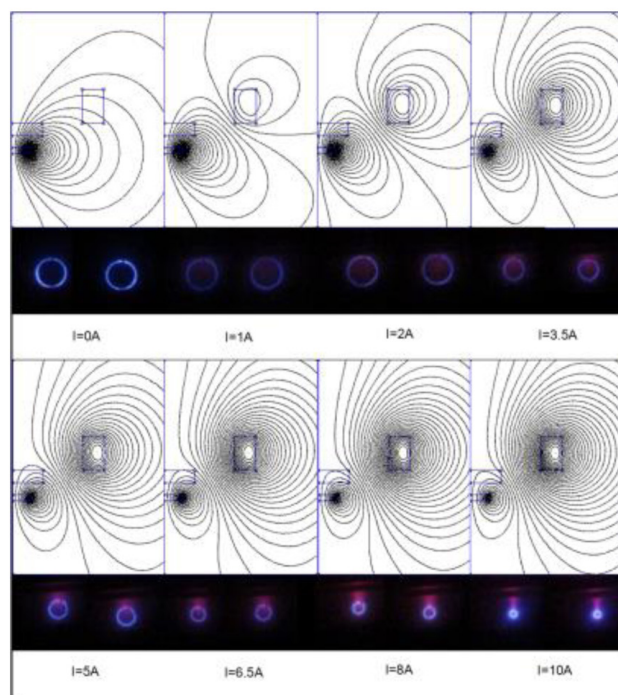


Figure 2. Effect of current intensity in the coil under direct current mode on configuration and distribution of the magnetic field, and movement of arc spots

of arched magnetic field (the position where vertical component of magnetic field was zero) also gradually moved towards the center of target with increase of coil current. Results of Reference [19] indicated that arched magnetic field could be divided into horizontal magnetic field $B_{//}$ and vertical magnetic field B_{\perp} . According to reverse motion of arc spots under transverse magnetic field, $B_{//}$ could drive arc spots to circular “track” movement on target surface. Meanwhile, two angles towards the arched apex was formed by arched magnetic field and the target surface. Thus, arc spots was constrained in the arched area under the effect of “acute angle rule”, forming random circular motion near the apex. The degree of constraint for arc spots was related to curvature of the arched magnetic field similar to constraint rule in magnetic field of magnetron sputtering on secondary electrons. Figure.2 indicated that arc spots generated regular circular motion trajectory with the increase of coil current in reversed-polarity focusing magnetic field. In other words, the dynamically direct current coupling magnetic field could have accurate control of the position of arc spots. The radius of circular motion trajectory changed with movement of the “apex” on arched magnetic field.

Figure.3 showed distribution of different coupling components and their ratios on target surface, with the change of coil current in focusing reversed polarity magnetic field. Similar to distribution of transverse

component of diverging axisymmetric magnetic field in Literature [22], transverse component with different coil current was zero at the center of target surface; strength of transverse component gradually increased with target radius, reaching a maximum near the edge of target; then, it was slowly decreased, as shown in Fig 3(a). There was no large variation in the increasing trend of transverse component in coupling magnetic field with the increase of coil current. Maximum increasing magnitude of transverse magnetic field reached about 20Gs when the coil current increased from 0A to 12A. Different from transverse component, vertical component in the same position of target surface had great variation when coil current increased from 0A to 12A. The zero point of vertical component under coupling magnetic field moved gradually from target edge (R=5cm) closed to center of the target (R=2cm), as shown in Figure.3 (b). The ratio of vertical component and transverse component also showed similar variation, as shown in Figure.3 (c).

Combining results of Figure.2 and Figure.3, with the “apex” of arched magnetic field gradually moving from target edge (R=5cm) closed to target center (R=2cm), the trajectory radius of arc circular

motion gradually reduced from the edge of target to the center. In other words, the strength of focusing magnetic field enhanced with increasing coil current in reversed-polarity focusing magnetic field, thus strengthening the constraint trend of arc spots. Different from effect with only focusing magnetic field, coupling magnetic field could accurately locate arc spots on circumference with different radius on target surface, achieving precise control of arc spots position. Studies on effect of magnetic field on arc spots movement [13-19] have explored influencing principle of different components; and few different arc sources of ion plating assisted by magnetic field was developed, but most with fuzzy control. Accurate control of arc spots movement had not been achieved. The trajectory radius of arc circular motion gradually reduced with increasing strength of reversed-polarity focusing magnetic field. However, the strength of transverse component was sufficient to drive rapid rotational movement of arc spots, avoiding emission of large-size droplets. According to Figure.2 and Figure.3, velocity of circular movement of arc spots changed with trajectory radius of circular motion, thus ensuring approximate consistency of movement periods of arc spots. Figure.2 indicated that the in-

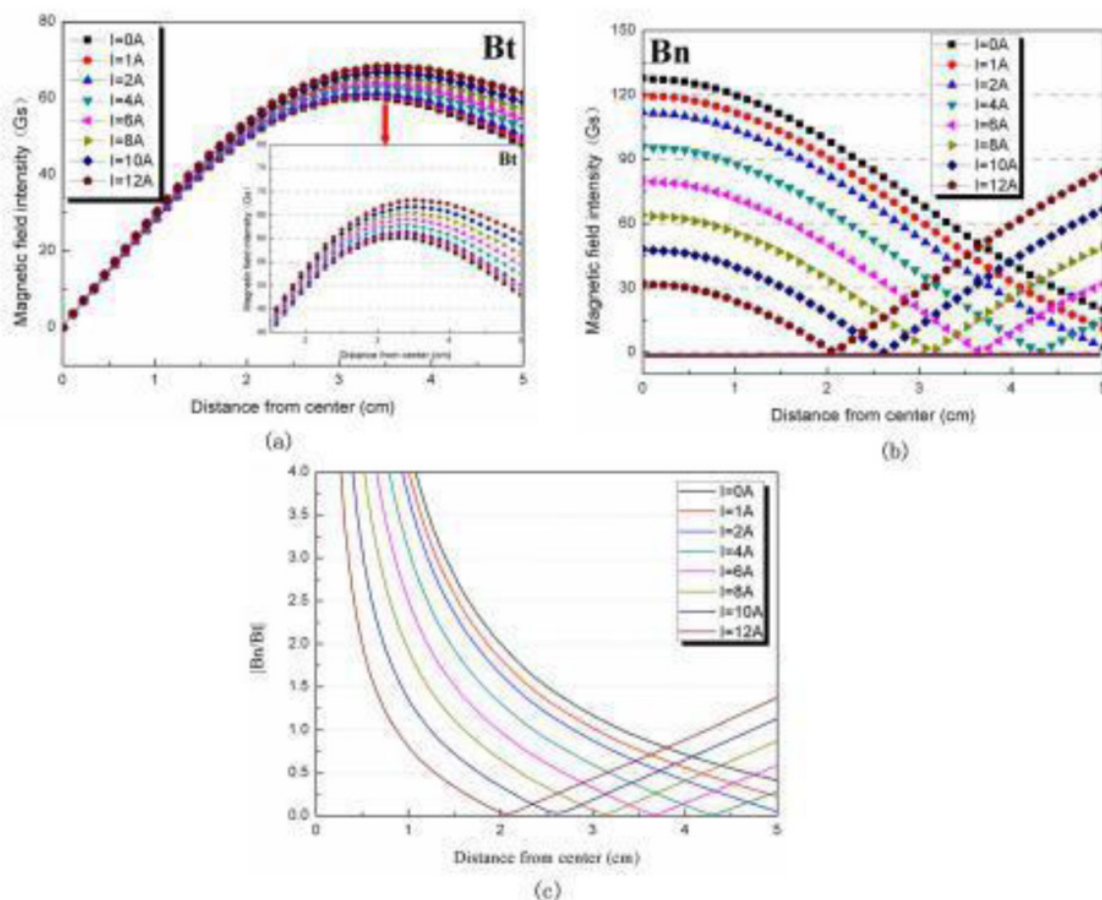


Figure 3. Effect of different coil currents under direct current mode on transverse component(a), vertical component(b) and their ratio(c) of the magnetic field

crease of reversed-polarity focusing magnetic field strength not only accurately altered radius of arc spots movement, but also strengthened distribution of magnetic field from target surface to work-piece. Focusing magnetic field was an axial magnetic field, thus enhancing transmission efficiency of plasma under the guidance of focusing magnetic field. Meanwhile, the probability of particle collisions for plasma was strengthened to increase ionization and ion density. This analysis was proved by the strengthening light intensity of plasma beam (observed from lenses).

In summary, precise control of arc spots positions was achieved through direct current mode. However, due to long-time discharge under static direct current coupling mode, reversed-polarity focusing magnetic fields with different strengths formed etching tracks with different radius on target surface, thus reducing utilization of the target. The work [19] advocated to form distribution of dynamic coupling arched magnetic field on target surface, through periodical variation of reverse-polarity magnetic field strength. Therefore, arc spots generated dynamic annular distribution with variation of coupling magnetic field. Discharge of arc spots was improved, enhancing utilization rate of target with lower emission of macro-particles. Meanwhile, focusing magnetic field improved transmission efficiency of the plasma with less divergence of the plasma. The results of two dynamic magnetic modes were described as follows.

3.2 Triangular wave coupling mode

Through triangular excitation current with constant current peak and different frequencies, reversed-polarity magnetic field coil generated “triangular wave” magnetic field with periodic and linear dynamic variation. Triangular wave magnetic field was coupled with strong divergent magnetic field, forming triangle wave coupling magnetic field mode. The strength of axisymmetric divergent magnetic field was the same as that of direct current mode. In order to achieve distribution of arc spots on the whole target surface and reduce power density, triangular wave excitation current was set as 0-12A with duty ratio of 50%, based on the research results of direct current mode. Rise time and fall time of current occupied half of a period, respectively. The effect of frequency on arc spots discharge was mainly studied in this section.

Figure. 4 and Figure.5 showed transient morphologies of arc spots discharge on Ti target in Ar gas, under different frequencies of triangular wave excitation current. Current peak value of focusing magnetic field coil was set as 0-12A. Therefore, arc spots would performed periodic, extended and contracting movement along the edge and center of the target. When

current frequency was 1Hz, current change period was 1S. Meanwhile, arc spots presented regular and circular motion with changing radius similar to water ripples, and the change period of 1S. Thus, discharge of arc spots was not greatly affected by frequency, but mainly by strength of coupling magnetic field. Under this frequency mode, arc spots performed fast circumferential motion and slow radial motion on the entire target surface (improved utilization of the target). However, the slow change frequency of magnetic field strength led to periodical change of plasma density in the front of target. When current frequency was 3Hz, arc spots still presented regularly circular motion, with faster change of the radius and larger frequency of circulation, extension and contraction. When current frequency was 5Hz, change rate of the radius in radial motion increased; superimposed by rotary movement, arc spots presented spiral trajectory with large radius. However, due to inflection point of current peak, there was not dramatic change at the edge of the target and center of target surface, with regularly circular motion of arc spots. When current

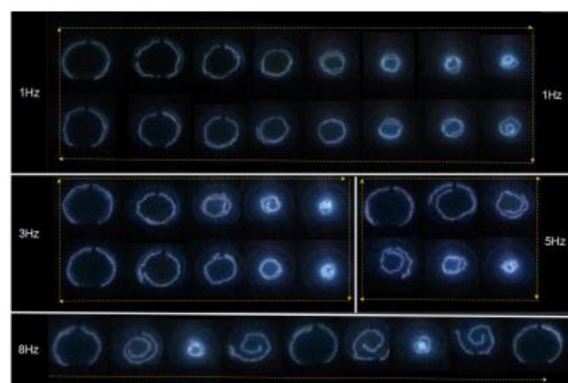


Figure 4. Morphology of arc spots under triangular wave coupling mode with frequency from 1Hz to 8 Hz

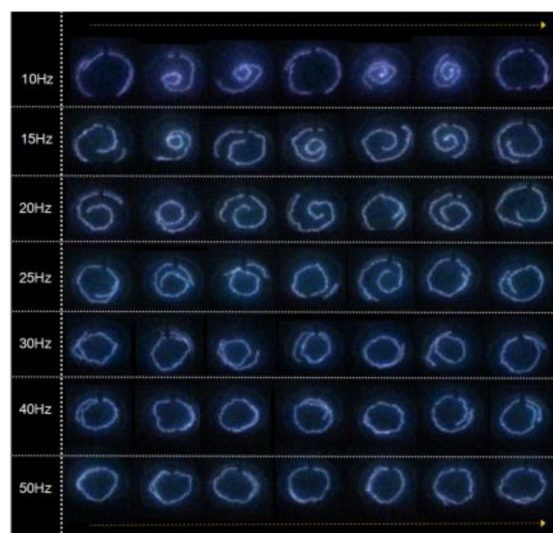


Figure 5. Morphology of arc spots under triangular wave coupling mode with frequency from 10Hz to 50Hz

frequency was increased to 8Hz, the velocity of radial motion became much higher. Arc spots presented three modes of motion: large-diameter circular motion at the target edge, collective flocculating motion at the center of target surface and "e"-shape spiral motion in the transition area. In every period of current change, arc spots were composed of the three motion modes and four motion states. When current frequency was 10Hz, the collective flocculating motion disappeared at the center of target surface, and arc spots only conducted two modes of motion: large-diameter circular motion at the target edge and "e"-shape spiral motion on target surface. Trajectory of spiral motion became more curved and extended than that at 8Hz. In every variation period of current, arc spots carried out circular motion at edge of the target, "e"-type spiral contraction and "e"-shape extension. Large-diameter circular motion disappeared when current frequency was 15Hz. Arc spots only presented two "e"-shape spiral motion states with different curved degrees. Therefore, under dynamic triangle wave focusing magnetic field, fixed-radius circular motion of arc spots was superimposed by radial movement with changing radius. Circular motion gradually disappeared with current frequency increasing from 1Hz to 15Hz. Arc spots conducted "e"-shape spiral motion with changing radius and curvature.

Arc discharge is different from glow discharge. The necessary condition for self-sustaining arc discharge was sufficient energy input to ensure large amount of effective electron emission. Lots of studies [1-4,12,13] showed that, motion of arc spots was actually the effective movement of arc spots position; more precisely, arc spots motion resulted from generation of new arc spots and extinguishment of old arc spots, which was caused by movement of maximum value positions for positive charge density. Distribution of maximum density in space charge layer could be altered by magnetic field. In direct current coupling mode, focusing magnetic field with different intensities was coupled with axisymmetric divergent magnetic field, forming arched magnetic field. Transverse component of arched magnetic field presented centrosymmetric circular distribution on target surface. Thus, maximum density in space charge layer conducted circumferential variation at the "apex" of arched magnetic field, while arc spots presented circular motion with fixed radius. Under effect of dynamic focusing magnetic field, the "apex" of arched magnetic field was constantly changed; thus, the position of maximum density value of space charge layer was constantly changed at the same time, presenting spiral movement on target surface. Therefore,

arc spots presented spiral trajectory. With increase of frequency, residence time of triangular wave current at the inflection point was gradually reduced; meanwhile, circular motion of arc spots gradually became difficult to be maintained, presenting more frequent "e"-shape spiral movement. Arc spots only presented "e"-shape spiral movement when frequency increased to 15Hz. Expansion and contraction of "e"-shape spiral motion was distributed on the entire target surface, extending transient motion trajectory of arc spots; meanwhile, discharge power density is reduced, with less emission of particles and improved utilization of the target. However, curvature of "e"-shape spiral trajectory was reduced when frequency increased to 20Hz; circular motion reemerged at the edge of target when frequency reached 25Hz, with decreasing trend of "e"-shape spiral motion. When the frequency was 30Hz, circular motion at the edge of target was strengthened. Thus, "e"-shape spiral movement was further weakened, showing intersecting circular trajectory lines. State of "e"-shape spiral motion disappeared when frequency was 40Hz, only presenting larger-diameter circular motion between the center of target surface and the edge of target. When it reached 50Hz, arc spots only presented circular motion at the edge of target, the same as situation that only with axisymmetric diffused magnetic field—focusing guiding magnetic field had almost no impact on the movement of arc spots.

In summary, with the increase of frequency under periodic triangular dynamic mode, the effect of focusing magnetic field on movement of arc spots under strong divergent axisymmetric magnetic field was firstly increased in frequencies between 0 and 20Hz, then gradually weakened in the range of 20-40Hz, and finally disappeared at the frequency of 50Hz. Generation of new arc spots was caused by changes of work function on target surface, which resulted from redistribution of space charge layer on target surface. Therefore, distribution of space charge layer had decisive influence on motion of arc spots. It would take certain time to complete redistribution of space charge layer and generation of new arc spots. In the range of 0-20Hz, the position of "apex" in arched magnetic field rapidly changed with increasing frequency; space charge layer could completely follow variation of magnetic field, changing its distribution and generating new arc spots with sufficient time, thus presenting "e"-shape helical motion of arc spots. With further increase of the frequency, the induction of space charge layer to magnetic field was gradually weakened, decreasing response speed of redistribution with change of magnetic field; meanwhile, there

was not enough time to generate new arc spots. Thus, the effect of dynamic focusing magnetic field on arc spots became lower and finally disappeared with increasing frequency. Therefore, the frequency should be set in the range of 1-20Hz, in order to achieve combined results of increasing velocity of arc spots, less power density of discharge as well as improved target utilization and transmission efficiency of plasma. In terms of the etching pits at the center, the frequency could be set in the range of 20-40Hz; arc spots could be driven to the edge of target with high velocity, enhancing utilization of the target. Variation trend of sine wave mode was similar to that of triangular mode, so it was not analyzed in the work.

3.3. Rectangular wave coupling mode

Based on triangle wave coupling mode, the effect of stepped rectangular wave coupling mode on arc spots movement was also studied in the work. Reversed-polarity magnetic field coil generated “rectangular wave” magnetic field with periodic and stepped dynamic variation, through rectangular wave (square wave) current excitation with constant current peak and different frequencies, Rectangular wave magnetic field was coupled with strong divergent magnetic field, forming rectangular wave coupling magnetic field mode. Similar to triangular wave coupling mode, positive and negative peak values of excitation current were set as 12A and 0A, respectively, with duty ratio of 50%, thus achieving distribution of arc spots on the whole target surface to increase etching uniformity of the target. In other words, rise time and fall time of current each occupied half of a period; effect of frequency on arc spots discharge was mainly studied in the work.

Figure.6 and Figure.7 showed transient morphologies of arc spots discharge on Ti target in Ar gas under different frequencies of rectangular wave excitation current. Change period of current was 1S when the frequency was 1HZ. The peak values of current for the focusing magnetic field coil were set as 0A and 12A. Therefore, arc spots would stay at the edge and center of the target for 0.5s, respectively. There was no distribution of arc spots on other regions of target surface; arc spots presented interrupted, flexible, extended and contracting movement. When the frequency was 3Hz, periodic time of current variation was reduced; arc spots still stayed on the edge and center of target at most of the time. When the distribution of arc spots was altered from the edge to the center, "e"-shape spiral movement trajectory appeared on the entire target surface. When the frequency was 5Hz, periodic time of current variation was further reduced; time and probability of arc spots staying on

the edge and center of target was half of that in 3Hz; "e"-shape spiral movement trajectory also appeared when the distribution of arc spots was altered from the edge to the center. Change period of current was 0.1s when the frequency was 10Hz. Arc spots no longer stayed at the center of target, while circular motion on the edge of target still existed. In process of current change, arc spots rotated to target center with "e"-shape spiral trajectory, and rotated back to the edge of target with ""e"-shape spiral trajectory. Then, arc spots kept short-time circular motion on the edge of target. The above variation was repeated to generate periodic motion of arc spots. Periodic time of current variation was 0.067s when the frequency was 15Hz. Circular motion on the edge of target disappeared. In process of current change, arc spots rotated to target center with "e"-shape spiral trajectory, and rotated back to the edge of target with ""e"-shape spiral trajectory. The rotating-in and rotating-out motion states were constantly repeated, generating periodic motion of arc spots.

With further increase of frequency, effect of rectangular wave focusing magnetic field on arc spots movement was similar to that of triangular wave mode. Curvature of "e"-shape spiral trajectory was reduced at 20Hz. When frequency reached 25Hz, cir-

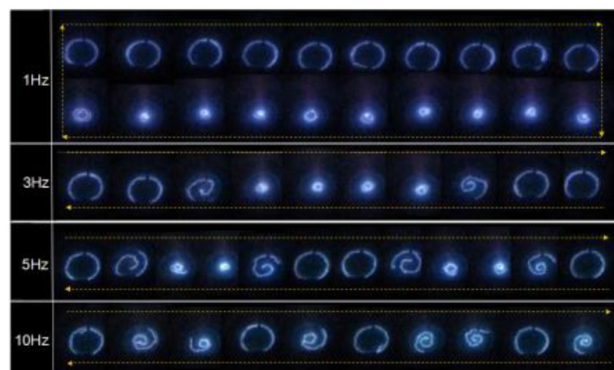


Figure 6. Morphology of arc spots under rectangular wave coupling mode with frequency from 1Hz to 10Hz

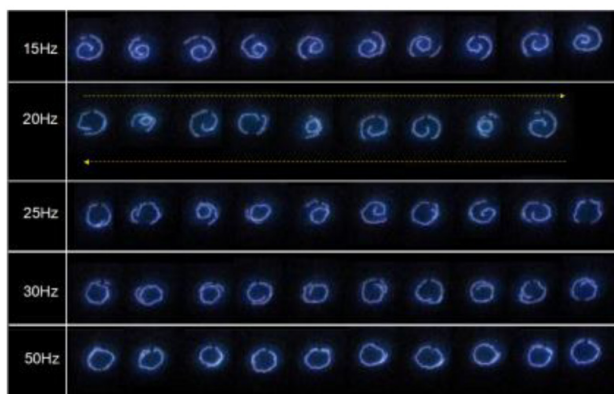


Figure 7. Morphology of arc spots under rectangular wave coupling mode with frequency from 15Hz to 50Hz

cular motion reemerged at the edge of target without staying at the center of target, with decreasing "e"-shape spiral motion. When the frequency was 30Hz, circular motion of arc spots at the edge of target was strengthened, while "e"-shape spiral movement was further weakened, showing intersecting circular trajectory lines. When it reached 50Hz, arc spots only presented circular motion at the edge of target, the same as that only with axisymmetric diffused magnetic field—focusing guiding magnetic field had almost no impact on the movement of arc spots.

In summary, effect of frequency under dynamic rectangular wave magnetic field on arc spots movement under strong divergent axisymmetric magnetic field was similar to that of dynamic triangular wave mode. The effect of frequency was firstly increased in 0-20Hz, then gradually weakened in the range of 20-40Hz, and finally disappeared at the frequency of 50Hz. The most effective frequency range that dynamic coupling magnetic field influenced movement of arc spots was 8-15Hz. At low frequencies, arc spots motion could completely keep up with variation of magnetic field; at high frequencies, arc spots motion lagged behind radial changes of magnetic field, thus the effect of magnetic field was gradually decreased. Linear triangular wave focusing magnetic field resulted in variation of arc movement by changing the "apex" positions of arched magnetic field. However, the "apex" of arched magnetic field was only at the edge and center of target under stepped rectangular wave coupling magnetic field. Change of magnetic field gradient at target edge and center would generate an induced electric field with spiral distribution on the target surface. Space charge layer was redistributed with variation of spiral electric field, generating new arc spots in sufficient time, thereby leading to spiral trajectory. It would take certain time to complete redistribution of space charge layer and generation of new arc spots. In the range of 0-20Hz, space charge layer could completely keep up with changes of magnetic field. The distribution was changed with induced spiral field, generating new arc spots with sufficient time, thus presenting "e"-shape helical motion of arc spots. With further increase of the frequency, the induction of space charge layer to magnetic field was gradually weakened, decreasing response speed of redistribution with change of magnetic field; meanwhile, there was not enough time to generate new arc spots. Thus, the effect of dynamic rectangular wave focusing magnetic field on arc spots gradually decreased and disappeared with increasing frequency.

The effects of frequency on arc spots movement under both rectangle and triangle wave modes were analyzed above. In summary, under dynamic magnetic field (except for rotating magnetic field), the frequency should be set in the range of 8-15Hz, in order to increase velocity of arc spots, reduce power density of discharge with improved target utilization and transmission efficiency of plasma. Reducing strength of reversed-polarity magnetic field and increasing frequency of excitation current could drive arc spots to perform movement at the edge of target; increasing strength of focusing guiding magnetic field and decreasing strength of axisymmetric divergent magnetic field could drive arc spots movement near the center of target. The two effects should be combined with appropriate magnetic field strength and certain frequency range (8-15Hz). Thus, arc spots could perform fast spiral movement on target surface to reduce discharge power density and emission of particles, with increase of target utilization. In addition, under effect of focusing magnetic field, transmission efficiency of plasma was improved, increasing probability of particle collision; meanwhile, ionization rate and ion density was enhanced, providing plasma condition with high efficiency for advanced decorative coating and tool coating.

Conclusions

The work adopted ion plating arc source assisted by multi-mode coupling alternating magnetic field to generate strong divergent axisymmetric magnetic field on target surface. Multi-mode reversed-polarity focusing magnetic field with adjustable frequency is coupled with axisymmetric divergent magnetic field, forming multi-mode dynamic coupling magnetic field. Thus, arc spot improvement can be dynamically controlled, improving arc discharge conditions with less emission of particles. Plasma can be stably transmitted under focusing magnetic field, enhancing probability of particle collision, ionization rate and ion density. In focusing magnetic field with coupling modes of direct current wave, triangular wave and rectangular wave, the effect of focusing magnetic field frequency on arc spots movement under axisymmetric divergent magnetic field is gradually increased in 0-20Hz; then, the effect is gradually weakened in 20-40Hz, and finally disappeared at the frequency of 50Hz.

Reverse-polarity focusing magnetic field is coupled with axisymmetric divergent magnetic field through different direct currents, forming coupling arched magnetic field with different radii. Coupling magnetic field can accurately position arc spots on circumference with different radii on target surface,

achieving precise control of arc spots position. Linear triangular wave focusing magnetic field results in variation of arc movement by changing the “apex” position of arched magnetic field. The continual changes of the “apex” in arched magnetic field result in the variation of maximum density position in space charge layer, with spiral movement on target surface. Therefore, arc spots presents spiral trajectory. Under stepped rectangular wave coupling magnetic field, the “apex” of arched magnetic field only stays at the edge and center of target. Change of magnetic field gradient at target edge and center generates induced electric field with spiral distribution on the target surface. Space charge layer is redistributed with variation of spiral electric field, generating new arc spots in sufficient time, thereby leading to spiral trajectory. Under linear triangular wave or stepped rectangular wave coupling magnetic field, “e”-shape spiral motion frequently appears in the frequency of 0-20Hz and gradually disappear from 20Hz to 40Hz. Arc spots only presents “e”-shape spiral motion at 15Hz. The variation of circular motion at the edge of edge is opposite to that of “e”-shape spiral motion. With further increase of the frequency (> 20Hz), the induction of space charge layer to magnetic field is gradually weakened; meanwhile, there is not enough time generating new arc spots. The effect of focusing magnetic field on arc spots gradually reduces and finally disappears with increasing frequencies. Therefore, the frequency should be set in the range of 8-15Hz, in order to increase velocity of arc spots with reduced power density of discharge, and improved target utilization and transmission efficiency of plasma.

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Multi-Granular Application Management Platform and Multi-Core-Aware Parallel Scheduling Model

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Abstract

This study proposes a novel multi-granular application management platform between PaaS and IaaS layers that uses application virtualization techniques. A multi-core-aware parallel scheduling model is then investigated on the platform. Assisted by fine-grained application units, new functions can be created by combining the application units in different granularities based on business requirements. The multi-core-aware parallel scheduling model was developed to process application requests, and not only increases system flexibility and applicability but also improves fine-grained computing resource allocation, resource utilization of the fundamental infrastructure, and system throughput.

Keywords: APPLICATION SERVICE, WEB SERVICE, MULTI-CORE-AWARE, PARALLEL SCHEDULING, MULTI-GRANULAR APPLICATION