Jet shape analysis and removal function optimization of atmospheric plasma processing applied in optical fabrication

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Abstract
When inductively coupled plasma (ICP) is used as a machining tool, its chemical etching-based processing method has the advantage of no contact stress between the tool and the material, thus without any mechanical damage. In recent years, this issue has been widely concerned in optical fabrication. However, there are many differences between low power ICP jet and conventional ICP jet, one of which is that the former does not easily form a rotation-symmetric removal function due to its obvious pinch effect. In this research, the electromagnetism principle of the plasma pinch effect was analyzed firstly, and the jet shape under the pinch effect was classified. Then, experiment was carried out to investigate the plasma jet shape under the pure Ar and mixed gas of CF$_4$-Ar, and the influence law of the reaction gas on the jet propagation shape was analyzed. Finally, the rotational symmetry of the removal function of plasma jet processing was optimized, and the nozzle design criteria were proposed based on pinch effect.

Keywords Optical fabrication · Plasma etching · Atmospheric plasma jet · Beam nozzle · Removal function

1 Introduction
Due to the unique advantages of high processing efficiency and no sub-surface damage, plasma processing has been widely investigated by scholars around the world. Bollinger et al. proposed Plasma Assisted Chemical Etching (PACE) [1]. They verified the basic principle of plasma processing for the first time to form a flat optical surface using PACE, proposed the advantages of plasma in optical processing, such as no mechanical pressure, no mechanical deformation in processing brittle materials, precise material removal rate, no edge effect, no sub-surface damage, and no surface pollution. Bollinger discussed the pre-processing methods and removal depth strategies suitable for fused silica to ensure that final PACE-finished surfaces meet low-scatter optical standards [2]. Hoskins from Hughes Danbury Optical Systems (HDOS) researched the processing of aspheric optical mirrors using PACE [3], which greatly reduced the time and cost of figuring large optics by its rapid convergence to the final figure requiring, with only 2–3 measurement/figuring cycles reaching 1/50 wave surfaces.

Takino from Osaka University was the first to propose plasma chemical vaporization machining (PCVM) [4], where plasma was generated around the tip of a pipe electrode. Mori et al. pointed out that the damage density of workpiece surface by PCVM was 1/100 of that of traditional machining and ion beam etching [5]. Takino et al. figured optical surfaces by PCVM with a pipe electrode [6], in which an RF plasma generated at the electrode tip under approximately atmospheric pressure moved over the surfaces. Shibahara pointed out that the wire electrode, flake linear electrode, wafer electrode, and annular flake electrode featured by capacitive coupling can used to cut the workpiece without damage, and the high-speed rotating cylindrical electrode was used to realize the flattening of the workpiece [7]. Yamamura et al. developed pulse width modulation control unit to control the removal volume distribution [8], removal error at the position where the set removal depth steeply change drastically decreased to less than 4%.

Carr from Cranfield University proposed the Reactive Atom Plasma Technology (RAPT) [9]. Through RAPT, a variety of optical element materials could be reshaped, such as ultra-low expansion glass, fused silica, silicon,
borosilicate glass, and silicon carbide. Subrahmanyan pointed out that due to the high temperature and high activity of RAPT, the removal efficiency of the optical materials including fused silica, ULE, glass ceramics, silicon, and silicon carbide could be comparable to that of the traditional mechanical polishing method, and the removal rate of silicon carbide and fused silica reached 3 mm³/min and 14 mm³/min, respectively [10]. Yu et al. analyzed the power dissipation of ICP torch under E mode [11]. The analytical results showed that 15.4% and 33.3% were dissipated by the nozzle and coil coolant channels, respectively. Yu optimized plasma jet nozzles using computational fluid dynamics. The experimental results proved that the efficiency of the optimized nozzle was improved by 5% compared with that of the original one [12, 13].

Böhm et al. proposed plasma jet machining (PJM) technology, and employed the technology to process the fused silica element, reaching a processing error of 56 nm [14]. Schindler applied coaxial tube electrodes to pass Ar/He to excite plasma, with NF3/CF4/SF6 as the reaction gas [15]. Arnold et al. pointed out that the 2.45-GHz microwave power source or 13.56-MHz radio frequency (RF) power source was used to realize the fast machining of 30 mm³/min or precise reshaping of 0.1 mm³/min [16]. However, he indicated that the surface deposition caused by PJM worsened the roughness to 10 nm RMS, which required the subsequent polishing methods to reduce the roughness.

Li et al. from Harbin Institute of Technology in China proposed Atmospheric Pressure Plasma Processing (APPP) [17, 18]. In APPP, the ultra-smooth surface and complex free-form surface were processed using a 13.56-MHz RF power source in capacitively coupled plasma (CCP) mode or 40.68-MHz RF power source and ICP mode. Xin from Harbin Institute of Technology explored the material removal mechanism and damage evolution process in the APPP of fused silica [19]. Jin researched the surface roughness evolution of SiC processed by APPP [20]. Ji et al. analyzed the thermal effect of non-linearity on the figuring process using APPP [21]. The results showed that the tool influence function (TIF) constantly changed with velocity distribution. They also proposed an optimization strategy of velocity distribution based on TIF selection to suppress the non-linearity.

Liao et al. from National University of Defense Technology proposed the rapid machining of silicon carbide using SF6 as the reaction gas [22], and studied the electrical properties and material removal characteristics of the enhanced plasma. For the high-temperature nonlinearity of the ICP-Torch, Dai et al. proposed an algorithm based on nested pulse iteration method to calculate and compensate the time-varying nonlinearity by changing the dwell time [23].

In the above-mentioned research, plasma processing based on CCP mode has disadvantages such as electrode loss and poor stability. However, the temperature of ICP has been reported to be about several thousand kelvin degrees [24]. So plasma processing based on ICP mode has disadvantages such as high processing temperature and serious thermal damage. For this reason, Jin et al. proposed the low temperature ICP jet technology [25], which avoided the inherent high temperature while retaining the advantages of high stability, large adjustment range of removal function, and high processing efficiency. However, due to the low power, the plasma density and range are smaller than traditional ICP. Therefore, low temperature ICP is more obviously affected by pinch effect, and it is more difficult to form a rotation-symmetric removal function. Therefore, in view of this problem, this paper analyzes the jet shape of low power ICP, and tries to improve the rotational symmetry of the removal function by optimizing the jet shape.

**2 The influence of pinch effect on the plasma jet**

In the process of plasma propagation, the movement of electrons in the plasma will generate current which further generates the magnetic field. The Lorentz force, produced by the interaction between the strong current flowing through the plasma and the magnetic field generated by this current, causes the plasma jet to gradually shrink or become thinner. The Lorentz force produced by the plasma itself attempts to push them toward the axis. Since the plasma belongs to a fluid, it will shrink, thereby increasing its density and temperature [26]. Figure 1 is a schematic diagram of the electromagnetic model of the pinch effect of plasma jet.

According to Maxwell electromagnetic equation, the magnetic field strength $H$ can be expressed as

$$J = \nabla \times H$$

where $J$ is the current density.

![Fig. 1 Schematic diagram of the electromagnetic model of the pinch effect of ICP](image)
The annular integral along the distance axis \( r \) can be obtained as
\[
H = \frac{I}{2\pi r}
\]  
(2)
where \( I \) is the current; the current distribution of ICP is a thin annular layer by ignoring its thickness. The Lorentz force \( F \) of the charge in the plasma jet is
\[
F = ev \times B
\]  
(3)
where \( e \) is charge quantity, \( v \) is charge velocity, and \( B \) is magnetic induction intensity. The Lorentz force \( P \) is transformed into the form of magnetic pressure
\[
P = \frac{HB}{2} = \frac{B^2}{2\mu} = \frac{\mu H^2}{2}
\]  
(4)
where \( \mu \) is the magnetic conductivity. This magnetic pressure will make the plasma produce a strong centripetal thrust, which causes the self-pinching effect of the plasma jet, makes the plasma shrink and become fine, and further surges its density. This phenomenon is not important in traditional ICP processing, which uses high power parameters and short-size moment tubes, and impacts the workpiece surface when the plasma jet is not fully pinched. Therefore, the design of traditional ICP system does not need to consider pinch effect. However, the torch in this paper is excited at lower power, and longer excitation region length is designed. In this case, the pinch effect will obviously make the plasma thinner and increase the density, and it is difficult to form a rotation-symmetric Gaussian removal function. Therefore, the pinch effect needs to be studied and analyzed in this paper.

ICP jet in pinch state can be divided into three basic forms according to its parameters such as power and gas flow rate, internal jet, external jet, and plasma ray. The combination of these three basic forms can form different combined forms, as shown in Fig. 2.

The three ICP jet forms all contain the plasma body jet as the base. The difference is that pure Ar plasma only excites the two-phase jet, which is composed of inner jet and ray jet, as shown in Fig. 2c. CF\(_4\)-Ar plasma introduces additional external jet according to the different power and gas flow rate, which will show two forms of Fig. 2a, b. Different forms of plasma have different removal functions, and the merits and disadvantages of rotational symmetry are also different.

3 Jet propagation shape of ICP processing

3.1 Jet shape of pure Ar plasma

The power of ICP jet machining is generally below 600 W, and the Ar plasma jet formed by low temperature ICP is different from that by the traditional ICP. In this section, 40.68 MHz RF power source and 3-turn coil were used to carry out pure Ar plasma excitation test under atmospheric pressure environment. The power changed from 250 to 600 W, and the jet shape of Ar plasma under different powers was observed. The test results are shown in Fig. 3.

In Fig. 3, it can be observed that the plasma jet formed by pure Ar could be divided into two stages in the propagation process, i.e., the initial core excitation region and the downstream propagation region. Although the plasma formed by ICP was hollow annular plasma near the coil, its pinch effect caused the plasma channel to taper and tighten gradually after it left the coil, which made the plasma on the right side of the coil form a shuttle shape. The plasma shape on the left side of the coil has been analyzed in our previous research, and it is mainly affected by the radial pushing effect.

Downstream of the initial core excitation region, the plasma was fully pinched and became slender dense plasma rays. The plasma rays from this pinch effect had both positive and negative effects. On one hand, the plasma rays under the pinch effect made the plasma be far away from the inner wall of the tube and avoid the loss of plasma on the device. As a result, ICP could propagate over a long distance, and the inner cavity could be processed with a long-curved nozzle. On the other hand, under the strong pinch effect, the plasma ray diameter was too slender, the full width at half maximum (FWHM) of the removal function formed by it was too small and the energy density was too large. Too small removal function could hardly be applied to low-frequency surface processing and its high energy density could easily cause thermal damage to optical elements.

In order to study the propagation of pure Ar plasma under pinch effect, the plasma functions at different powers were plotted with the last turn coil as the zero point, as shown in Fig. 4.

In Fig. 4, plasma jets at different power had similar shapes. The core excitation region in the first half and pinch
ray region in the second half were fitted by $f_1$ and $f_2$, respectively, as shown in Eq. (5).

$$
\begin{align*}
  f_1(x_{\text{axial}}) &= a \cdot x_{\text{axial}}^2 + b \cdot x_{\text{axial}} + c \quad x_{\text{axial}} < x(f_1 = f_2) \\
  f_2(x_{\text{axial}}) &= d \quad x_{\text{axial}} \geq x(f_1 = f_2)
\end{align*}
$$

where $c$ determines the maximum width of the plasma in the core region after leaving the last turn of the coil, and $a$ and $b$ determine the length and fatness of the plasma in the axial length direction. As can be seen in Fig. 4, the maximum width of the plasma core excitation region decreased with the reduction of the power, but the difference was not significant. When the plasma width decreased from 600 to 250 W, the plasma width changed linearly from the initial 18.1 to 16.0 mm. The length of the core region decreased significantly with the reduction of power, from 600 to 250 W, and the width decreased linearly from 23 to 8 mm. With the reduction of power, the length of downstream plasma rays decreased linearly from 212 to 94 mm, and the width decreased from 2.3 to 2.02 mm.

In order to realize the removal function of different FWHM and increase the flow rate to improve the rigidity of the jet, a beam nozzle is often used to rectify the plasma jet. Therefore, even at the power of 600 W, the plasma only had a core region length of 23 mm, which could barely exceed the distance from the last turn of the coil to the outlet of the beam nozzle. The plasma would leave the beam nozzle in the form of plasma pinch rays and could not fill the beam nozzle at most diameters. This would make it difficult to maintain the rotational symmetry of the removal function and reduce the processing accuracy. The plasma with the mixing of reactive gas and Ar would modulate the pinch effect and bring favorable effects. Therefore, the low-temperature ICP technology at low power needs to accurately control the ratio of reactive gas to suppress the plasma ray phenomenon caused by pinch effect.

The jet shape of pure Ar plasma is affected not only by the RF power, but also by its own Ar gas ratio. The ratio of auxiliary Ar gas to main Ar gas is called gas ratio. The plasma generated at different gas ratios is also different. The test results are shown in Fig. 5.

Figure 7 indicates that the refluxed plasma has a long tail flame for the absence of auxiliary gas in Fig. 5a. In Fig. 5b–d, the auxiliary gas produces a good pushing effect on the plasma, pushing the high-temperature plasma forward and away from the inner moment tube. However, as the auxiliary Ar gas is far away from the coil, it easily causes the extinction while pushing the plasma away and protecting the inner tube. Therefore, too large gas ratio results in the phenomenon of extinction in Fig. 5e, f. These phenomena are simulated, as illustrated in Fig. 6.

The simulation uses the model and boundary conditions reported in [26]. As can be seen from Fig. 6a, a large-range negative flow velocity field is formed when no auxiliary Ar gas is injected. This is because the large flow of the main Ar gas causes the part of inner tube to generate negative pressure, causing massive plasma to flow back. According to Fig. 6b–f, a positive pressure can be applied to the backflow plasma due to the introduction of auxiliary gas, so that the initial position of the plasma is pushed forward.

The relationship between the axial velocity of the plasma and the axial position is obtained, as shown in Fig. 7. The simulation results are compared with the test results. Since the plasma will be extinguished when the gas ratio exceeds 1/4, only the simulation and test shown in the figure are compared.

The axial velocity components of the plasma on the axis were counted as shown in Fig. 7 and compared with the test.
results. Since the plasma will be extinguished when the gas ratio exceeds 1/4, only the simulation and test shown in the figure are carried out.

As can be seen from Fig. 7, the axial velocity is both positive when the gas ratio is 1/2 and 3/4, but the excitation of Ar plasma cannot be maintained in this case. When the gas ratio drops to 1/4 or below, the excitation of Ar plasma can be maintained. Moreover, with the decrease of gas ratio, the gas reflux effect on the axis will also become more obvious. Excessive axial push will lead to the extinction of the plasma, which is necessary to give the plasma enough space to flow back. The red mark in the figure represents the

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**Fig. 4** Jet function of pure Ar plasma under pinch effect

**Fig. 5** Tail flame length of Ar plasma jet at different gas ratio. a 0, b 1/32, c 1/8, d 1/4, e 1/2, f 3/4
plasma tail flame length under different gas ratios in the test. By comparing the axial velocity field and the plasma tail flame length, a simple relation can be obtained as follows.

\[ y = 1.04x + 13.15 \]  

where \( y \) is the tail flame length of Ar plasma from the first coil, and \( x \) is the length of negative flow in the axial velocity field.

### 3.2 Jet shape of Ar-CF\(_4\) mixed plasma

It can be seen from the analysis in Sect. 3.1 that the plasma produced by pure Ar had strong pinch effect. After exceeding the core excitation region of the tube, the plasma would gradually taper under the action of its own current, so that the plasma rays formed could not fill the full beam nozzle. If the diameter of plasma jet is smaller than that of beam nozzle, the shape of jet function is completely dependent on the electric field driving characteristics of plasma. For optical element processing, CF\(_4\) gas should be added to form fluorine ion which can react with silicon ion. The mixing of CF\(_4\) reaction gas and Ar plasma will modulate the pinch effect. This modulation usually has a positive effect, increasing the diameter of the plasma jet, fully filling the beam nozzle, and obtaining a more rotation-symmetric removal function. However, inappropriate parameters will make the plasma beam diameter exceed the beam nozzle too much, resulting in plasma loss and reducing the material removal efficiency. In this section, a 40.68-MHz RF power source was used in the tests, with the parameter setting shown in Table 1.

The plasma jet shape during the test is shown in Figs. 8, 9, 10 and 11. Each image shows the plasma jet variation when the power reduced from 600 to 250 W, and also shows the plasma shape variation under different CF\(_4\) flow rates.

As can be seen from Figs. 8, 9, 10 and 11, the shape of the mixed plasma jet after adding CF\(_4\) was significantly different from that of the pure Ar plasma jet. The modulation of plasma caused by CF\(_4\) could be divided into two
aspects. On one hand, it could suppress the plasma ray phenomenon. With the increase of CF$_4$ flow rate, the plasma ray phenomenon was gradually suppressed and the jet width was increased. On the other hand, the modulation of the Ar plasma jet by CF$_4$ was not uniform. As shown in Figs. 9, 10 and 11, due to the increase of CF$_4$ flow rate, the plasma jet was divided into inner jet and outer jet. The high-brightness inner jet was concentrated in the core excitation region of the plasma, and the low-brightness outer jet surrounded the outer side of the inner jet. With the addition of CF$_4$ gas, the plasma ray phenomenon was gradually suppressed, which was beneficial for filling the beam nozzle to form a rotation-symmetric Gaussian removal function. However, due to the phenomenon of inner-outer dual plasma jets, if the parameters of the section location of the nozzle outlet were not appropriate, the jet function at the outlet would also show the phenomenon of inner-outer dual jets, resulting in non-rotational symmetry of the removal function. Therefore, the modulation caused by CF$_4$ reaction gas needed to be controlled precisely.

So, the inner-outer dual plasma jet problem of CF$_4$ was investigated here. With the last coil as the zero point, the plasma functions in Figs. 8, 9, 10 and 11 tests are displayed in Fig. 12 by using Eq. (1). The solid line is the high-brightness plasma inner jet function, and the dotted line is the low-brightness plasma outer jet function.

Figure 12a shows the jet function when CF$_4$ = 10 sccm. Due to the small flow rate of reactive gas, the jet function shape was similar to that of pure Ar plasma jet shape shown in Fig. 2. Both were composed of a shuttle-shaped plasma

### Table 1 Test parameters of pinch effect

| Group | Power  | CF$_4$ Flow rate | Ar Flow rate | Group | Power  | CF$_4$ Flow rate | Ar Flow rate |
|-------|--------|------------------|-------------|-------|--------|------------------|-------------|
| No. 1 | 600 W  | 10 sccm          | 16 slm      | No. 3 | 600 W  | 30 sccm          | 16 slm      |
|       | 550 W  |                  |             |       | 550 W  |                  |             |
|       | 500 W  |                  |             |       | 500 W  |                  |             |
|       | 450 W  |                  |             |       | 450 W  |                  |             |
|       | 400 W  |                  |             |       | 400 W  |                  |             |
|       | 350 W  |                  |             |       | 350 W  |                  |             |
|       | 300 W  |                  |             |       | 300 W  |                  |             |
|       | 250 W  |                  |             |       | 250 W  |                  |             |
| No. 2 | 600 W  | 20 sccm          |             | No. 4 | 600 W  | 40 sccm          |             |
|       | 550 W  |                  |             |       | 550 W  |                  |             |
|       | 500 W  |                  |             |       | 500 W  |                  |             |
|       | 450 W  |                  |             |       | 450 W  |                  |             |
|       | 400 W  |                  |             |       | 400 W  |                  |             |
|       | 350 W  |                  |             |       | 350 W  |                  |             |
|       | 300 W  |                  |             |       | 300 W  |                  |             |
|       | 250 W  |                  |             |       | 250 W  |                  |             |
core region and a plasma ray with a constant width. But the difference was that, the introduction of CF$_4$ produced the phenomenon of inner-outer dual jet. From 600 to 250 W, the length of the inner jet in the core region linearly shortened from 26.5 to 0.2 mm, and the length of the outer jet linearly shortened from 64 to 9.3 mm. The length of the plasma ray was shortened linearly from 216 to 108 mm, and the width was narrowed from 1.4 to 0.85 mm. However, it was worth noting that from 600 to 250 W, the starting point of plasma rays was clearly bounded by the outer jet. It was clear that the starting position of the ray was 32 mm, 27 mm, 23 mm, 18 mm, 13 mm, 9 mm, 4 mm, and 0.2 mm. The overlap range with the outer jet was 32 mm, 29 mm, 25 mm, 22.5 mm, 19.5 mm, 15.8 mm, 13 mm, and 9.1 mm, respectively, and the removal function generated in this overlapping region could hardly maintain rotational symmetry. This meant that at this low CF$_4$ flow rate, although the modulation produced a wide external jet, it could only be applied to the processing of conventional beam nozzles with diameters above 3 mm. However, a considerable length of the outer jet contained bright plasma rays, which would seriously affect the rotational symmetry of the removal function and reduce the processing convergence rate.

Figure 12b shows the jet function when CF$_4$ = 20 sccm. Compared with Fig. 11a, although there was still plasma ray phenomenon, there was no clear boundary between plasma ray and outer jet. The low-brightness plasma jet at this flow ratio could be effectively applied to the processing of conventional caliber nozzles. From the power of 600 to 250 W, the inner jet length was linearly reduced from 14.5 to 0.2 mm, and the outer jet length was linearly reduced from 73 to 18 mm. From 600 to 350 W, the starting point of plasma rays was 73 mm, 65 mm, 57 mm, 50 mm, 42 mm, and 34 mm, respectively, and the end point was 144 mm, 138 mm, 119 mm, 95 mm, 71 mm, and 45 mm, respectively, and the width was about 2.8 mm. Besides, there was no obvious dividing line with the outer jet. For the plasma jet with this flow ratio, the inner jet region within the range of
14.5 mm was too short to meet the design requirements of most caliber nozzles. The outer jet of 73 mm could meet the design requirements of beam nozzle for length, and there was no obvious boundary between the plasma ray and the outer jet, which would not affect the rotational symmetry of the removal function after the outer jet left the beam nozzle. The 2.8-mm plasma rays could also be applied to the beam nozzles with small diameters to achieve the removal function of small FWHM at a long distance.

Figure 12c, d show the jet function when $\text{CF}_4 = 30$ sccm and $\text{CF}_4 = 40$ sccm, respectively. Compared with Fig. 12a, b, the plasma ray phenomenon in Fig. 12c, d was fully suppressed. Under the two flow ratios, the plasma jet consisted of the high-brightness inner jet and the low-brightness outer jet. When $\text{CF}_4 = 30$ sccm, the length of the inner jet decreased linearly from 50 to 5 mm, and the outer jet decreased linearly from 120 to 20 mm. At the two flow ratios, both the inner and outer jets had a longer jet length.

By comparing Fig. 12a, d, it can be seen that if the plasma ray was also counted as the outer jet, the length ratio of the inner jet to the outer jet was 0.122, 0.131, 0.42, and 0.66, respectively. The ratio of the inner jet to the outer jet would increase with the increase of the ratio of the reactive gas flow, and the plasma separation phenomenon would gradually weaken. The ICP plasma system presented in this paper can be estimated using the following simplified formulas:

$$f_{\text{inner}}(x_{\text{axial}}, p, r) = (0.0024p + 0.01r - 1.54) \cdot x_{\text{axial}}^2 - 0.3 \cdot x_{\text{axial}} + 0.006 \cdot p + 14.5$$

$$f_{\text{outer}}(x_{\text{axial}}, p, r) = (0.000125p + 0.0006r - 0.08) \cdot x_{\text{axial}}^2 - 0.2 \cdot x_{\text{axial}} + 0.006 \cdot p + 14.5$$

(7)
where \( f_{\text{inner}} \) is the inner jet function in plasma, \( f_{\text{outer}} \) is the outer plasma jet function in plasma, \( x_{\text{axial}} \) is the axial position with the last turn as the zero, \( p \) is power, and \( r \) is the reaction gas flow rate.

### 4 Relationship between plasma jet shape and removal function

Under the pinch effect, there are three plasma jet forms, i.e., inner jet and outer jet and plasma ray, different forms of plasma jet will produce different shapes of removal functions. The rotational symmetry of the removal function will be affected if there are more than two types of plasma jets at the nozzle outlet. Different nozzles will produce different plasma jets, as illustrated by Fig. 13.

In Fig. 13, if the position of the beam nozzle is shorter than the propagation distance of the internal jet, and the nozzle diameter is smaller than the width of the inner jet, then a single plasma jet with a rotation-symmetric removal function will be generated, such as Mode 1 nozzle. If the position of the beam nozzle does not exceed the propagation distance of the internal jet and the nozzle diameter is greater than the width of the inner jet, a plasma jet with two forms of inner jet and outer jet will be generated, which will affect the symmetry of the removal function, such as Mode 2 nozzle. If the position of the beam nozzle is longer than the propagation distance of the inner jet, and the nozzle diameter is less than the width of the outer jet. In this case, a single plasma jet and a rotationally symmetric removal function can also be generated, such as Mode 3 nozzle. If the position of the beam nozzle is longer than the propagation distance of the inner jet and smaller than the propagation distance of the outer jet, but the nozzle diameter is larger than the width of the outer jet, the rotation symmetry of the removal function will be influenced despite of the single plasma jet because the plasma jet cannot fill the whole nozzle. Therefore, the design of a beam nozzle should follow the principle of adjusting the parameters to make the plasma jet at the outlet of beam nozzle in a single form and the width be larger than the nozzle diameter.

When power \( P = 400 \text{ W} \), \( \text{Ar} = 16 \text{ slm} \), \( \text{CF}_4 = 20 - 50 \text{ sccm} \), the removal function generated by 3 mm beam nozzle is shown in Fig. 14.

As can be seen from Fig. 14, within the range of test parameters, the plasma impinging jet contained the high-brightness inner jet and the low-brightness outer jet, forming the yellow Mode 1, the blue Mode 2, and the green Mode 3. When the flow rate of the reaction gas was 20
sccm, only the outer jet was formed due to the insufficient distance of the inner jet. It could produce a good rotation-symmetric removal function. With the increase of the flow rate of the reaction gas, the diameter of the outer jet basically remained the same because the beam nozzle had a certain diameter. The diameter of the inner jet increased with the increase of the flow rate of the reaction gas, and the ratio of the inner jet to the outer jet also increased. When the inner jet could not sufficiently fill the beam nozzle, it would form the plasma jets of two forms, as shown in Nos. 2 ~ 5. The lower the ratio of the inner jet to the outer jet, the worse the rotational symmetry of the removal function. When the flow rate of the reactive gas continued to increase, the inner jet could basically fill the beam nozzle, and the plasma jet shown in No. 6 would be generated when the diameter ratio of the inner jet and the outer jet was small. At this time, due to the existence of a single jet mode, the removal function with good rotational symmetry was also produced.

5 Optimization of removal function under pinch effect

According to the statistics of jet shape and the processing parameters in a single jet mode, the effective jet shape diagram can be obtained, and then, the removal function can be optimized to improve the rotational symmetry of the removal function. As the plasma activity decreased with the increase of the propagation distance, the distance from the beam nozzle outlet to the coil was generally less than 50 mm, and the nozzle diameter was between 2 and 20 mm. The plasma jet function within this range and in a single shape was counted, as shown in Fig. 15.

Figure 15a–d show the maximum nozzle diameter forming a single form of jet function under different reaction gas flow ratios and powers. As the inner jet was inside the outer jet within a certain range from the outlet, the jet function of a single shape could be formed as long as the nozzle diameter was smaller than the width of the inner jet function. As the outer jet overlapped with the inner jet within a certain range of distance from the coil, the outer jet could only be applied in the axial position where the width of the inner jet decreased to 0.

In Fig. 15a, since the length of the inner and outer jets below 350 W was less than 10 mm, only the jets in the range of 400 to 600 W could be regarded as effective machining jets. Besides, the inner and outer jets decreased to zero after 33 mm, so the distance between the beam nozzle and the coil should be within this range. In Fig. 15b–d, due to the increase of CF$_4$ flow ratio, the propagation distance of both inner and outer jets was enhanced, so the nozzle could be designed at a distance of 50 mm.

By counting and drawing all jet functions in a single mode, the nozzle can be optimized through the jet shape figure, including nozzle diameter, power, and nozzle length. The optimization method is illustrated in Fig. 16. Nozzle diameter, power, and nozzle length all affect the shape of the removal function. However, since the axial distance from the nozzle to the coil involves the solution of the RTCP pose of the machine tool, the nozzle length is usually fixed, and the nozzle diameter and excitation power are the terms to be optimized. There are two options for optimization, i.e., forward optimization and backward optimization. The former optimizes the excitation power according to the size of the required removal function, while to the latter optimizes the diameter of the removal function according to the required removal efficiency. For forward optimization, as shown in Fig. 16a, the nozzle diameter affects the FWHM of the removal function and has a one-to-one correspondence relationship. In this way, under the flow rate of each reaction gas, the two lines, i.e., axial distance of the nozzle ($x$) and diameter of the beam nozzle ($y$) determine an intersection point, as indicated by the red dotted line in Fig. 16a. Then, the width of plasma morphology above this intersection point is the value of FWHM.

![Fig. 14 Impinging jets and removal functions at different reaction gas flow rates](image-url)
point will be larger than the beam nozzle diameter, forming a removal function with rotational symmetry. When the jet width is exactly equal to the nozzle diameter, this is the lowest power to maintain the rotational symmetry of the removal function. Appropriate power may exist at multiple reactive gas flows and should be selected according to other actual conditions. For backward optimization as shown in Fig. 16b, different powers correspond to different jet functions under fixed nozzle length. An intersection point between effective jet function and nozzle length under required power will be determined, as indicated by the blue dotted line in Fig. 16b, which is the optimized nozzle diameter. This diameter is the maximum value to maintain a single jet shape.

6 Conclusions

In order to achieve highly rotation-symmetric removal function in optical fabrication, the ICP jet at atmospheric pressure has been experimentally studied. The design criterion of the outlet diameter of the beam nozzle has been analyzed, and the removal function has been optimized. The conclusions are summarized as follows:

1. Under atmospheric pressure, the low power ICP jet presents three forms, i.e., inner jet, outer jet, and ray jet. In different cases, there are three kinds of combinations, i.e., inner jet-ray jet combination, inner jet-outer jet-ray jet combination, and inner jet-outer jet combination.

2. The plasma jet generated by pure Ar under atmospheric pressure is in the form of inner jet-ray jet. After the addition of reactive gas for silicon-based optical elements, the plasma jet generated by CF$_4$-Ar at atmospheric pressure shows the shape of inner jet-outer jet-ray jet at low CF$_4$ flow rate and high power state, and inner jet-outer jet at high CF$_4$ flow rate and low power state. With the increase of the flow rate of CF$_4$, the ray jet is inhibited. When the flow rate of CF$_4$ exceeds 20 sccm, the plasma jet presents the shape of inner jet and outer jet in the range of 250–600 W.

Fig. 15 Effective jet function in single jet mode at different reaction gas flow rates (a) 10 sccm; (b) 20 sccm; (c) 30 sccm; (d) 40 sccm
According to the diameter and position of the beam nozzle, four jet modes can be presented. Only in the mode of single inner jet or single outer jet can the rotation-symmetric removal function be generated. If the plasma jet leaving the beam nozzle has both the high-brightness inner jet and the low-brightness outer jet, the rotation symmetry of the removal function will be destroyed.

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Declarations

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