The Design of Inductively Coupled Plasma Jet Processing System for High Power Laser Optics

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Abstract

Large-aperture aspheric and freeform fused silica optics are widely used in the high power laser system such as Inertial Confinement Fusion system for their high quality optical characteristics. Because of its low efficiency and distortion for form accuracy, traditional conformal polishing method is unacceptable to remove the thick sub-surface damage layer induced by grinding stage. Thus, atmospheric inductively coupled plasma processing based on chemical reaction is proposed as a non-contact, high-removal-rate solution to the problem. In the paper, a hybrid five-axis machine tool is designed as a platform of plasma processing, including mechanism design and analysis, control system design, and sensor monitoring integration. Meanwhile, trial processing test is conducted and analysed as a feedback to the system design for stability and better performance.

Keywords: Inductively Coupled Plasma Processing, Polishing Machine Design, Hybrid Mechanism

1 Introduction

In the Inertial Confinement Fusion system, large-aperture aspheric optical components are widely used, which can effectively eliminate coma, spherical aberration, astigmatism, and curvature of field and distortion¹. Moreover, reduction of energy loss and high quality optical characteristic are achieved. However, the design of aspherical non-symmetrical features makes it difficult for the latter fabrication and polishing process². After the stage of ultra-precision grinding, sub-surface damage layer about 15μm thickness will be
induced on the optics, which is extremely unfavorable for the subsequent polishing process\textsuperscript{[3]}. First of all, fused silica material is difficult to polish for the hard and brittle characteristics. Traditionally, asphalt disc polishing process is unacceptable because of its low efficiency and disruption of form accuracy. Thus, inductively coupled plasma processing under atmospheric pressure is proposed as a promising solution to polish silicon-based material. Based on the chemical reaction, no sub-surface damage will be induced to the optics after processing. Experiments have been fully conducted in the investigation of process parameters, form correction and surface quality\textsuperscript{[4][5][6][7]}. However, there is no comprehensive discussion and analysis on the system design.

2 Design of plasma processing system

In order to fabricate the large-aperture aspheric and freeform optics, the design of a hybrid five-axis machine tool is described in this chapter, including mechanism design and analysis, control system design, as well as sensor monitoring integration.

2.1 Hybrid five-axis mechanism

Inductively coupled plasma processing is sub-aperture tool computer controlled method. At least five freedom of motion is needed to achieve the nominal orientation between the tool and surface of optics. Other key requirements such as dynamics and work range should be considered. A hybrid five-axis mechanism is designed to realize the above requirements. X-Y stages, as serial mechanism, are chosen to meet the range of large-aperture optics, 400mm in the design. While the parallel mechanism has advantages of dynamics, to response the continuous curvature of the complex surface. Parallel mechanism where the plasma torch sets, has three freedom, one translation and two rotation. The 3D model of mechanism system is shown in Figure 1. Each linear motion is driven by the servo motor with screw.

![Figure 1: Layout of plasma processing system](image1)

![Figure 2: Hybrid 5-axis mechanism](image2)

Then vibration mode shapes and corresponding natural frequencies of the mechanism are analyzed using commercial FEM software. From the results
shown in Figure 2, in the 1st and 2nd modal shapes platform is mainly moving in a translational direction, which the corresponding frequency is around 50Hz; the 3rd and 4th modal shows parallel column twist and deflection of the column. Based on the analysis, it should be avoided to operate the mechanism near the above natural frequencies.

(a) 1st mode, natural frequency=44.8Hz  
(b) 2nd mode, natural frequency=45.0Hz  
(c) 3rd mode, natural frequency=53.3Hz  
(d) 4th mode, natural frequency=148.0Hz

Figure 3: First six mode vibration shapes and corresponding natural frequencies

2.2 Control system

To meet the demand of motion and process monitoring, a control system based on PMAC plus PC is designed[8]. The system structure is described in Figure 4. PMAC is high speed multi-axis card, controlling motion the hybrid mechanism. All linear motion is fully closed loop, with absolute linear scales as a feedback to PMAC. PC is used to monitor and analysis the data from sensors. The open-source system gives developers more flexibility to integrate multiple functions in the system. For example, in our application, plasma sensors and thermocouples are put in to monitor the light spectrum and workpiece temperature.

In terms of software development, device dynamic-link library and activeX plug-ins can be used as reference in Visual Studio environment. Thus, user
interface is developed to control motors and receive data from sensors in the computer terminal in Figure 5.

![Figure 4: Structure of control system](image)

Figure 4: Structure of control system

![Figure 5: Hardware and software of the control system](image)

Figure 5: Hardware and software of the control system

### 3 Preliminary processing test

Preliminary experiments are conducted to study several key issues for inductively coupled plasma jet processing. The results should be analyzed as a feedback to the design of system. A simple test rig, shown in Figure 6 with 3-axis has been developed to conduct these experiments.
3.1 The robustness of influence function

During the long time process, disturbance to the system is inevitable. The influence function of inductively coupled plasma jet processing is Gaussian\(^9\). The robustness plays a key role in the process stability and deterministic removal. Four factors are chosen, including distance, RF power, reactive gas flow, plasma gas flow. According to the possible disturbance to plasma system, manual variations are added to the process. The profile is characterized as etching depth and full width at half maximum. The result, in Figure X, shows that the influence function is comparatively stable to the disturbance. Moreover, the experience of the test can offer guidance to the device specification during the system design.

3.2 Edge effect

Either for traditional polishing or computer-controlled polishing, there comes a problem when dealing with the edge. When the polishing tool hang over the edge of the work-piece, the pressure distribution will change, thereby affecting the removal\(^{10,11}\). For inductively coupled plasma processing, the condition of gas flow and electromagnetic field will change when the torch is near the edge.
of workpiece. A trench along the whole surface was measured after the torch moved in the constant speed. As a comparison, the workpiece is enclosed with a frame in the same height as edge. What is clear in Figure 8, the edge effect can be mitigated using this method, which is applied in the fixture system in the machine tool. Future work will be focused on how to reduce edge effect by controlling the plasma parameters.

![Trench Frame](image1)

a) result without frame

![Trench Frame](image2)

b) result with frame

Figure 8: Edge effect experiment

### 3.3 Uniform material removal test

Five uniform removal tests are conducted to show if the processing is stable and fit for the removal of sub-surface damage. The profile is measured by the aspheric profilometer system (Form Talysurf PGI 1240). The result is the difference between the profile before and after processing. As shown in Figure 9, the largest PV error occurs in the third processing. However, it is no more than 0.33μm, compared to a 15μm uniform removal. The uncertainty is less than 2.2%, which can meet the processing requirement.

Another issue that is critical is whether the plasma processing can remove the sub-surface damage induced by grinding in the former stage. After the processing, firstly ultrasonic cleaning is used to remove some remaining on the surface. Then the entire surface is immersed in the hydrofluoric acid (HF Etching) in certain time. The optic was observed in a dark room. It can be seen in Figure 10, there is no apparent scratches and pits on the surface, indicating that sub-surface damage has been removed after plasma processing.
4 Conclusion

According to features of large-aperture optics, a system based on inductively coupled plasma processing is designed. In the paper, design and FEM analysis of hybrid mechanism, as well as control system design, is described. Meanwhile, trial processing test is conducted and analysed as a feedback to the system design for stability and better performance. It is concluded that the plasma processing is stable and has capacity to remove the sub-surface damage.

5 Reference


