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High-spatial Resolution Figuring by Pulse Width Modulation Controlled Plasma Chemical Vaporization Machining

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Abstract

Numerically controlled plasma chemical vaporization machining (NC-PCVM) is an ultra-precision figuring technique using chemical reactions between radicals generated in atmospheric pressure plasma and surface of the workpiece. Figure error consists of waviness which has long spatial wavelength and roughness which has short spatial wavelength. In the case of NC-PCVM using the cylindrical electrode with a diameter of 3-6 mm, it is difficult to remove the small wavelength components (several millimetres in wavelength). Therefore, improvement of spatial resolution in figuring is required for NC-PCVM. To resolve this issue, pulse width modulation (PWM) control unit was developed to control the removal volume distribution instead of scanning speed control of the worktable. Removal error at the position where the set removal depth steeply change drastically decreased to less than 4% by applying PWM controlled figuring, while the maximum removal error of figuring which applied the scanning speed control of the worktable to control the removal depth distribution was 20%. And a new electrode, which limits the irradiation area of plasma by installing of a alumina ceramics cover having a small orifice with a diameter of 1.0 mm, was also developed. By applying this electrode, the full width at half maximum (FWHM) of the removal spot was reduced from 4.68mm to 1.10 mm. Small spatial wavelength components of 4 mm were successfully corrected by NC-PCVM which was combined PWM control and orifice electrode.

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Keywords: Plasma CVM; Figuring; High-spatial resolution; Pulse width modulation; Numerically controlled

1. Introduction

Numerically controlled plasma chemical vaporization machining (NC-PCVM) is one of the ultra-precision chemical dry figuring technique for fabrication of optical components [1, 2] and for correction of thickness distribution of silicon on insulator [3] and quartz crystal wafer with nanometer order form accuracy [4]. In our previous research, the removal volume distribution on the workpiece was controlled by changing the scanning speed of the worktable. However, in the case of steep change of the scanning speed, the inertia of the worktable causes a discrepancy between the set scanning speed and the actual scanning speed, which degrades the form accuracy of the workpiece. To resolve this issue, we proposed an application of the pulse width modulation (PWM) control of RF power for generating atmospheric pressure plasma to control the material removal volume distribution on the workpiece because the response of electrical change is much faster than that of speed change of the worktable[4]. Schindler have applied PWM control to ion beam figuring (IBF) and succeeded in improvement of spatial resolution of figuring [5]. Furthermore, the modified electrode which covered by alumina ceramics with a small sized orifice (ϕ1 mm) was installed to improve the spatial resolution of the figuring. In this study, we describe the results of a comparison of spatial resolution of the PWM controlled PCVM figuring with the small orifice electrode and the conventional PCVM figuring.

2. Experimental setup

Figure 1 shows the schematic diagram of open-air type NC-PCVM system. The electrode made of aluminum alloy is

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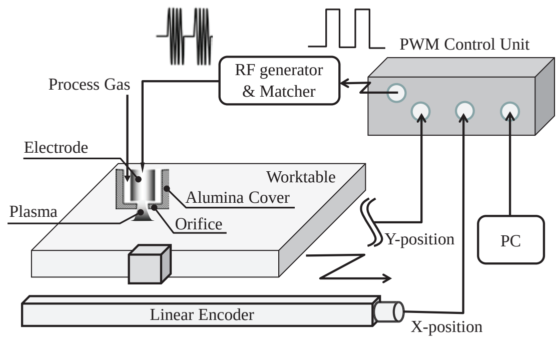

Fig. 1 Schematic of NC-PCVM system with PWM control.

covered by alumina ceramics with a small orifice. Outer diameter of the electrode, inner diameter of the ceramics cover, and diameter of the orifice were 2.5 mm, 4 mm, and 1 mm, respectively. This alumina ceramics cover enables to suppress a spread of plasma. The process gases, the flow rates of which are controlled by mass flow controllers, are supplied through the clearance between the electrode and the alumina ceramics cover. The relative position between the electrode and the workpiece and the scanning speed of the worktable were controlled by AC servo motors. The information of x-y position of the worktable was sent from x-y linear encoders to the PWM control unit. The PWM control unit controlled the output of the RF (f = 13.56 MHz) power supply according to the data set of the duty ratios corresponding to the positions on the workpiece, and data set was stored to the PWM control unit in advance.

3. .Results and discussion

Figure 2 shows a response of the PWM RF power control system. Square pulse of 5 V was applied to control the RF output of 80 W. Both rise and fall time of RF output were less than 10 μs. If the scanning speed of the worktable is 1000 mm/min, travel in 10 μs is less than 3 nm. Generation and attenuation of plasma follow the electric field without delay [6]. Therefore, developed PWM control system has enough performance to control the removal volume distribution in numerically controlled figuring.

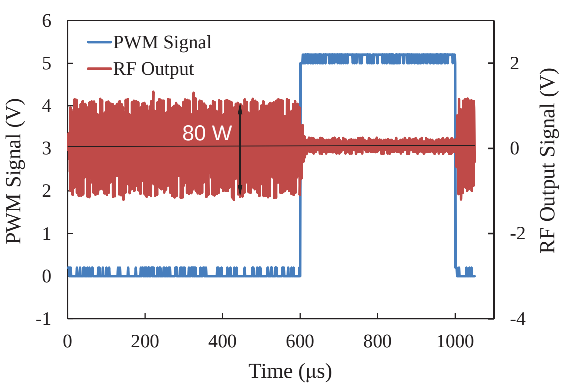

Fig. 2 Response of the RF power controlled by PWM.

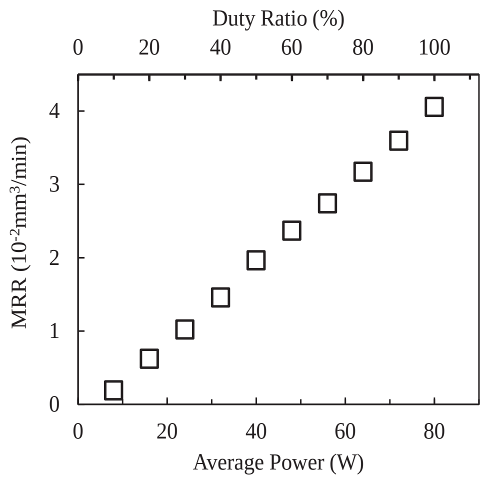

Fig. 3 Relationship between the MRR of Si wafer and the duty ratio.

Table 1. Experimental parameters.

He (sccm)	750
CF_4 (sccm)	20
O_2 (sccm)	2.5
Applied RF power (W)	80
Duty ratio (%)	10 – 100
Repetition rate (kHz)	1
Spot removal time (min)	2
Diameter of the electrode (mm)	3

Figure 3 shows the relationship between the material removal rate (MRR) of Si wafer and the duty ratio. Experimental parameters are listed in Table 1. MRR of Si was linearly changed according to the change of the duty ratio. This result shows that duty ratio control enables us to control the removal volume distribution on the workpiece precisely instead of control of the dwell time distribution of plasma.

To compare the figuring accuracy in the scanning speed control mode and the PWM control mode, responses of removal distribution in steep change of removal depth were evaluated by forming the removal trenches on the Si wafer by 1-dimensional reciprocal scanning. Figures 4(a), (b) show the removal depth distribution of trenches formed by scanning speed control mode and PWM control mode. Figure 5 shows the removal error in both control modes. Scanning speed of the worktable was changed from 2100 mm/min to 1050 mm/min in the scanning speed control mode, and duty ratio was changed from 19% to 38% with a constant scanning speed of 400 mm/min in the PWM control mode. Both data set of scanning speed and duty ratio were provided every 0.5 mm in scanning direction. In the case of scanning speed control mode, large discrepancy between the predicted and actual removal depth distribution was seen at around of the position where the data of scanning speed of the work table changed steeply because actual scanning speed of the worktable cannot follow the steep change of set speed due to the inertia of the worktable. In the case of PWM control mode, removal error was less than 4%, while the maximum removal error in the scanning speed control mode was 20% as shown in Fig. 5.