New development of atmospheric pressure plasma polishing

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Atmospheric pressure plasma polishing (APPP) is a precision machining technology used for manufacturing high quality optical surfaces. The changes of surface modulus and hardness after machining prove the distinct improvement of surface mechanical properties. The demonstrated decrease of surface residual stresses testifies the removal of the former deformation layer. And the surface topographies under atomic force microscope (AFM) and scanning electron microscope (SEM) indicate obvious amelioration of the surface status, showing that the 0.926-nm average surface roughness has been achieved.

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Atmospheric pressure plasma polishing (APPP) is a noncontacting precision machining technology used for manufacturing high quality optical surfaces. It performs the atom scale material removal by chemical reactions excited by plasma. Since the process is chemical in nature, APPP avoids various surface/subsurface defects which usually appear in conventional machining processes[1−3]. Thus, it can be used as the final finishing step of optical surfaces to eliminate surface damage and improve the surface properties further. In this letter, the improvements of surface mechanical properties and surface topography by APPP are demonstrated.

All the experiments were conducted on single crystal silicon wafers. Before operation, the wafer was tested by commercial nanomechanical test system (Hysitron, TriboIndenter) to measure the modulus of the original surface. After machining, the same region was detected again to testify the change of the mechanical properties. Then, the surface topography and roughness were detected by atomic force microscope (AFM, Dimension 3100, Digital Instruments Inc., USA) and scanning electron microscope (SEM, AIS2100, MIRERO-SERON, Korea) to testify the improvement of the surface quality in more details.

Table 1 lists the tested reduced modulus and hardness of the surface before and after machining. The tested spots were chosen randomly in the same region. By contrast it is clear that after machining, the reduced modulus and hardness of the surface are both increased obviously, which demonstrates the improvement of the surface rigidity.

If the machined surface is thought to be with no residual stress and taken as the calculation reference status, by virtue of the other researchers' report, it is possible to deduce the relative value of residual stress σ_R on the original surface by[4]

$$\sigma_R = \begin{cases} H_0\left[\left(c_0 + \dfrac{1-c_0}{E^*}E_0^*\right)^2 - 1\right], & \sigma_R > 0 \\ \dfrac{H_0}{\sin\alpha}\left[1 - \left(c_0 + \dfrac{1-c_0}{E^*}E_0^*\right)^2\right], & \sigma_R < 0 \end{cases}, \quad (1)$$

where H_0 and E_0^* are the hardness and modulus of the machined surface; E^* is the modulus of the original surface; $\alpha = \pi/2 - \lambda$ with 2λ being the included angle of the indenter, here for Berkovich indenter, $\alpha = 24.7°$; c_0^2 is defined as the ratio of real contact area to nominal contact area by Carlsson and Larsson[5,6], and it can be easily acquired by[4]

$$c_0 = \frac{h'_c}{h_{nom}} = \frac{h_c + h_{ini}}{h_{max} + h_{ini}}, \quad (2)$$

where h_c is the contact depth; h_{max} is the maximum penetration depth; h_{ini} is the initial contact depth, and for the TriboIndenter used here, h_{ini} usually takes 10 nm. Equations (1) and (2) are adopted and the calculation results are shown in Table 2.

From Table 2, it is clear that the average residual stress on the original surface before operation is 8.99 MPa, larger than that of the machined surface. This is just the result after 60-s machining. If the polishing process were performed longer, more deformation layer would be

Table 1. Test Results of the Nanomechanical Test System

Spot No.		1	2	3	4	5	Average
Device Parameters	h_c (nm)	177.18	151.91	167.52	129.78	135.22	
	h_{max} (nm)	262.27	220.41	238.99	223.6	220.57	
Before Machining	E^* (GPa)	14.37	13.63	14.15	16.18	14.91	14.65
	H^* (MPa)	4.64	4.16	3.69	3.66	4.74	4.18
After Machining	E_0^* (GPa)	41.78	41.84	36.74	35.07	37.59	38.60
	H_0 (MPa)	5.80	6.14	5.14	8.11	7.55	6.55

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Table 2. Calculation Results of the Original Relative Residual Stress

No.	1	2	3	4	5	Average
c_0	0.69	0.70	0.71	0.60	0.63	
σ_R (MPa)	8.89	9.99	5.86	9.34	10.89	8.99

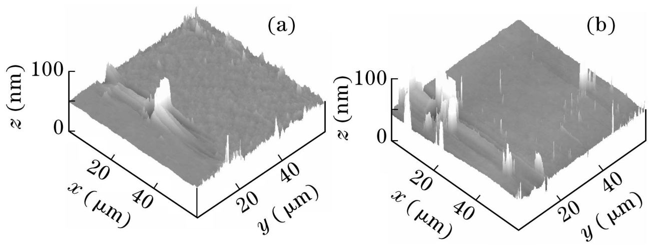

Fig. 1. AFM images of surface topography (a) before and (b) after machining.

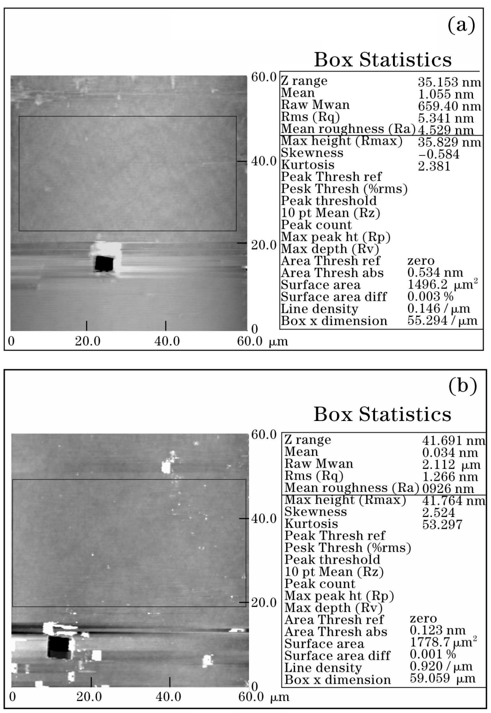

Fig. 2. Surface roughness (a) before and (b) after machining.

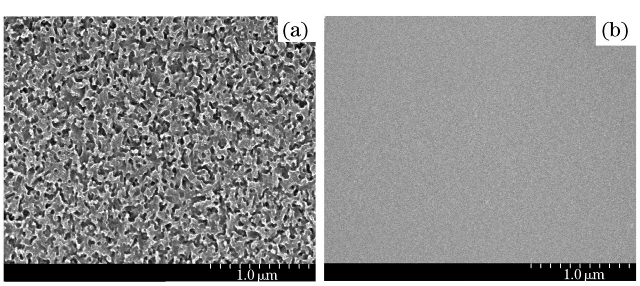

Fig. 3. SEM images of surface topography (a) before and (b) after machining.

removed, and as a result the residual stress left would be smaller. So APPP performs well on the elimination of surface stress or the removal of deformation layer.

The surface roughness detection results made by AFM indicate obvious improvement of the surface morphology. The contrast makes it clear that the APPP method has achieved very good surface quality. Figure 1 shows the three-dimensional (3D) views of the surface topography. The squared pit in the image is a reference object to make it more credible that the detections are performed in the same region. It can be seen that the raw surface is very rough with many "burs" on it. After machining, it is clear that the surface becomes much smoother and nearly all of the burs are removed. Thus, of course, the surface roughness gets much lower. Figure 2 shows the accurate values of the detected surface roughness. It indicates that the surface roughness becomes more than 3 nm lower after machining and reaches about roughness average (Ra) of 0.926 nm. Figure 3 shows the surface topography under SEM, which also testifies the improvement of the surface status. Therefore, it can be concluded that this APPP method has the potential to support the sub-nanometer scale machining process for high quality ultra-smooth surfaces.

In conclusion, by testing some characteristics of the machined surface polished by APPP process, the validity of APPP method has been demonstrated. The analysis on the mechanical properties indicates that APPP is suitable for the surface finishing which demands the removal of deformation layer. The surface topographies under microscopes also testify the significant improvement of the surface status. APPP is a prospective technology to manufacture the ultra-smooth surfaces with excellent properties.

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