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Experimental exploration of the hydrodynamic effect polishing machinability for different types of material

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Abstract. Hydrodynamic effect polishing (HEP), in which the material removal relies on the chemisorption between nanoparticles and the workpiece surface in elastic mode, can realize automatic level smooth surface without surface/subsurface damage. The machinability of different types of optical material (such as monocrystalline silicon and crystalline quartz, amorphous silicate glass, Zerodur and so on) were investigated experimentally. The workpiece surfaces before and after being polished by HEP was observed by atomic force microscopy. The experimental results show the surface roughness of monocrystalline silicon and quartz, amorphous silicate glass have decreased from Rms 0.737nm to Rms 0.175nm, Rms 0.490nm to Rms 0.187nm, Rms 0.469nm to Rms 0.157nm respectively, and meanwhile all the defects and bumpy structures have been removed clearly. However the surface roughness has increased from Rms 0.213nm to Rms 0.321nm with the obvious increment of micro unevenness. By comparison, we can conclude that excellent performance is shown when HEP is applied on the optical material structure with a single monocrystalline or amorphous component. However the ultrasmooth surface cannot be obtained when HEP was applied on the combinational materials such as Zerodur glass. The micro unevenness increases gradually along with polishing process due to the different material removal of the monocrystalline and amorphous component.

1. Introduction

The development of modern optical technology has put high requirement on the optical component surface quality. Taking the extreme ultraviolet lithography (EUVL) for example, the mirror surface roughness should be fabricated at atomic level [1-2]. It also requires that there is no defects and crystalline destroy on the processed surface. Although the surface roughness can be restricted at a relative low level by using the ultra-smooth polishing method with the material removal in plastic mode, surface/subsurface damage and residual stress can't be avoided. Therefore the traditional ultrasmooth polishing method can't meet the demand of ultrasmooth surface for modern optical system. How to fabricate the ultra-smooth and defect-free surface has become a hot research point in ultra-precision machining area. Different optical systems need different optical components. While different optical material is composed of different unit. How to obtain an ultrasmooth surface of different optical component is a difficulty problem in the polishing area.

Elastic emission machining, an ultra-smooth polishing method presented by Mori [3, 4], has been considered as the highest precise polishing method so far. The good machinability on semiconductor materials such as silicon and silicon carbide has been validated through experiment research.

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Hydrodynamic effect polishing (HEP), a non-contact polishing method, was present based on the theory of float polishing [5-7] and elastic emission machining. The atomic-level material removal rate of HEP is realized by the chemisorption between nanoparticle and workpiece. Defect-free surface with surface roughness at atomic-level can be obtained [8-11]. As the chemisorption relies on the workpiece material construction, which types of material can be polished by HEP is still unknown. Up to now the reports about the machinability for different types of optical materials are very limited. In this paper, the machinability of different types of material was explored experimentally, and the structure characteristic of machinability material by HEP has been summarized.

2. Experiment procedure

For the sake of the exploration becoming universal and pertinent, four typical workpiece made up by different optical materials were selected as experimental sample. The four different types of optical materials were silicon, monocrystalline silicon and crystalline quartz, amorphous silicate glass and Zerodur glass. The silicon and quartz are crystalline material while the silicate glass is amorphous material. Zerodur glass is composite material which is composed by crystalline and amorphous material. Therefore three different types of construction are involved. The optimal process parameters are set for polishing experiment. The polishing slurry is a mixture of deionized water, some dispersant and silicon-oxide nanoparticles with average diameter of 20nm. The uniform raster scan with the scan step size of 10μm was selected as the polishing path. After HEP process, all the samples were rinsed with the deionized water under irradiation with a 1.3M supersonic wave to remove the adsorbed nanoparticle on the surface. At last, the surface before and after polishing was observed by atomic force microscopy (AFM, Bruker's Dimension Icon) with scanning area of 10μm×10μm at a resolution of 512 × 512 pixels. By contrast of surface morphology and surface roughness before and after HEP, the machinability can be concluded.

A monocrystalline silicon sample with the thickness of 3mm was selected as the sample, and the polishing area was 15mm×8mm. As a treatment before HEP, the sample was dipped into hydrofluoric acid (HF) with concentration of 5% for 30min to remove the oxide layer. Then the sample was rinsed by deionized water for 1 minute to remove the residual solution. Then HEP was used for polishing the sample with the removal depth about 140nm.

A circular crystalline quartz (Beijing Brightcrystals Techonlogy INC.) with crystal surface direction of (1 0 0) was selected as the sample. The diameter of sample is 50mm, and the size of 5mm×5mm on the sample surface was choose as the polishing area with removal depth of 200nm for the HEP treatment process.

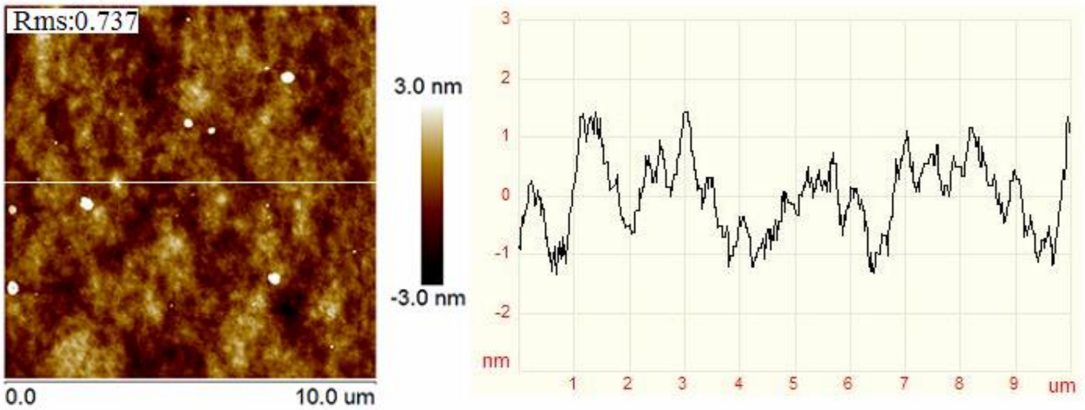
As the amorphous silicate was mainly consisted of silica, we chose the silicate glass as the polishing sample representing the typical amorphous silicate material. The machinability of silicate glass by HEP was then conducted. The size of 5mm×5mm was chosen as the process area, and the removal depth is about 160nm.

The Zerodur glass was produced by Schottag Corporation in German. The diameter of sample is 50mm, and the size of 5mm×5mm on the sample surface was choose as the polishing area with removal depth of 160nm for the HEP treatment process.

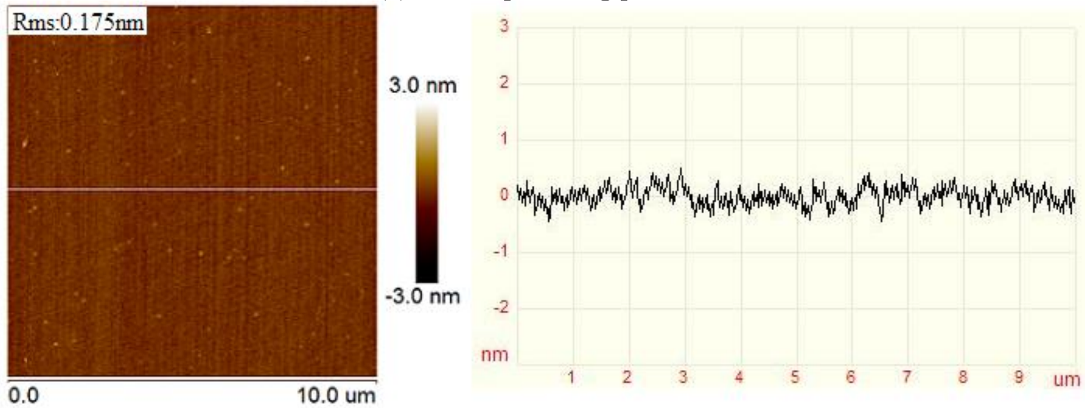
3. Results and discussion

3.1. Monocrystalline Silicon

Figure 1 shows the AFM images of 10μm×10μm of the silicon sample surface before and after HEP process. There are lots of un-uniform plastic pits and bumpy structure on the initial surface, as shown in figure 1(a). After removal depth of 140nm, the initial defects have been removed clearly, and the surface looks very smooth, as shown in figure 1(b). Meanwhile surface rms roughness has decreased from 0.737nm to 0.175nm. By comparing with the section profiles before and after HEP process, the profile fluctuation has been greatly depressed when the surface was polished by HEP. The surface height was almost at the same level with the micro-unevenness within ±0.3nm. By comparison we can see HEP has good smooth ability on the monocrystalline silicon material surface. The silicon material is composed of uniform silicon unit cell. Each removal rate of the unit cell is the same. Experiment results also demonstrate the machinability of silicon by HEP is feasible.



(a) Before polishing process

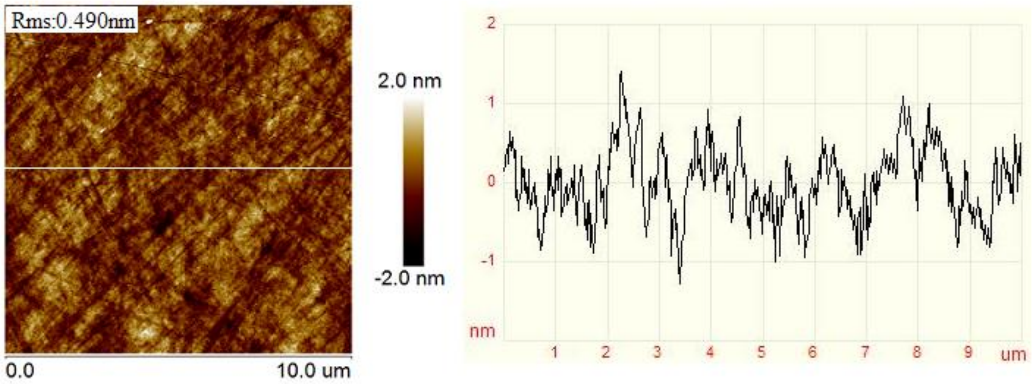


(b) After polishing process

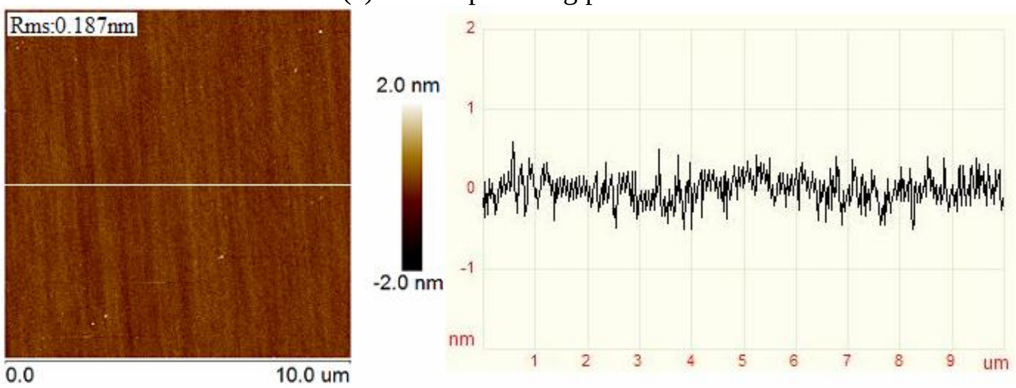
Figure 1. AFM images of silicon surface before and after polishing process.

3.2. *Crystalline quartz*

Figure 2 shows the AFM images of crystalline quartz before and after HEP process. There are many micro plastic scratches on the initial surface, as shown in figure 2(b). The initial surface profile fluctuation was restricted within ±1nm, and the surface rms roughness was 0.490nm. When the sample was polished by HEP, all the plastic scratches and bumpy structures have been removed clearly. The processed surface looks much smooth, and the profile fluctuation has been depressed within ±0.5nm, as shown in figure 2(b). The surface rms roughness has decreased to 0.187nm. It demonstrates that the feasibility of HEP machinability of crystalline quartz is very effective. For crystalline quartz glass is composed of uniform crystalline unit cell, each unit cell has the same removal rate.



(a) Before polishing process

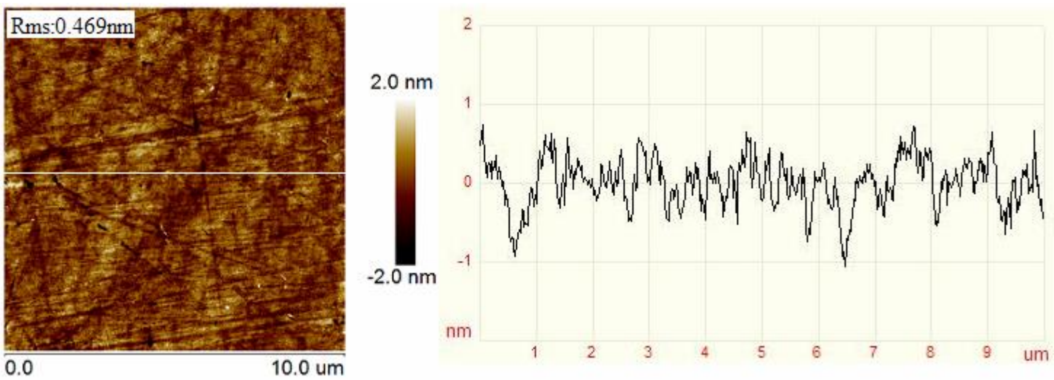


(b) After polishing process

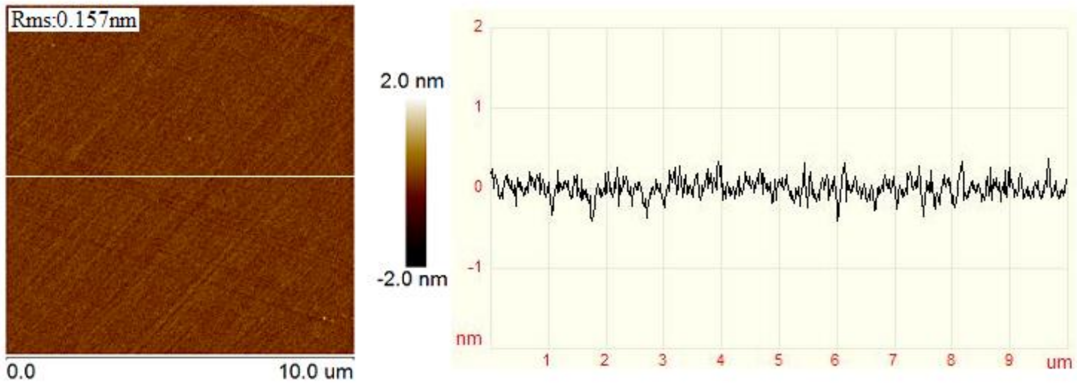
Figure 2. AFM images of quartz surface before and after polishing process.

3.3. *Silicate glass*

The AFM observation of processed surface of silica glass is shown in figure 3. The mechanical damages such as the scratches and cracks on the initial surface have been removed clearly when the surface was processed by HEP. Meanwhile the degree of micro-unevenness has greatly depressed, and the surface looks much smooth with the surface rms roughness decreasing from 0.469nm to 0.157nm. It demonstrates that HEP has great effect on removal of mechanical damages and improvement of the surface quality. As the silicate glass has the similar compositions with the silica glass, we can conclude HEP has good smooth ability on the silicate glass. It also means the machinability of amorphous structure is very well. Silicate glass is amorphous material, and the material of each amorphous phase is the same.



(a) Before polishing process

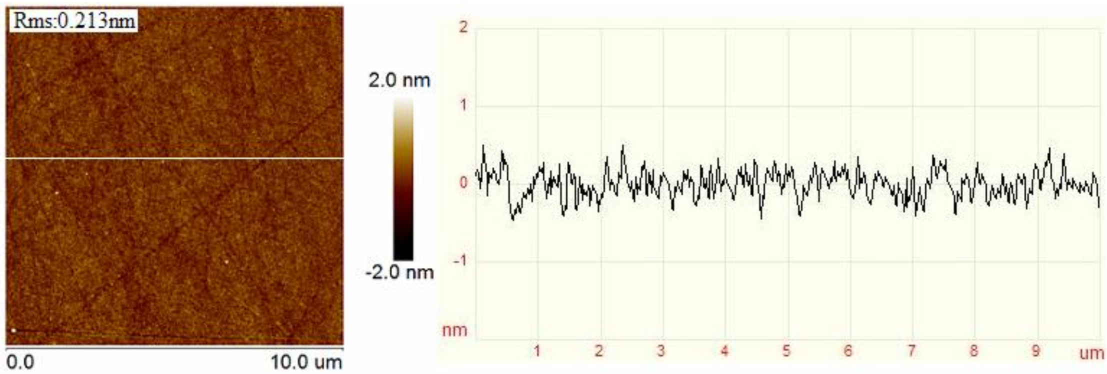


(b) After polishing process

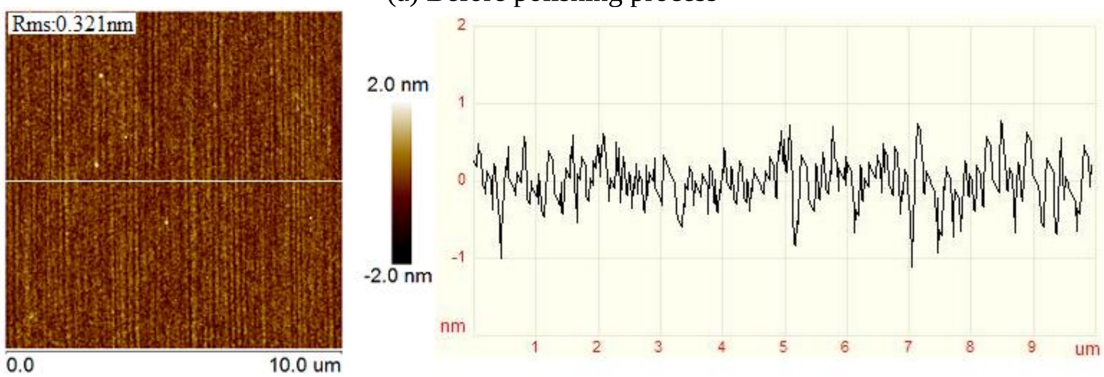
Figure 3. AFM observations of silica glass surface before and after polishing process.

3.4. *Zerodur glass*

Figure 4 shows the AFM images of the Zerodur glass before and after HEP process. Although the scratches on the initial surface have been removed, the profile fluctuation is not depressed but increased at some extent. From the value of the surface roughness, we can see the surface rms roughness has increased from 0.213nm to 0.321nm. As the wheel was manufactured by the single point diamond turning, the turning marks on the wheel has greatly duplicated on the processed surface [6].



(a) Before polishing process



(b) After polishing process

Figure 4. AFM observations of Zerodur glass surface before and after polishing process.

The Zerodur glass is a composite phase structure made up of crystalline and amorphous phase material. The crystalline phase, which is formed by micro crystalline particles, is uniformly distributed in the amorphous structure, as shown in figure 5. Because of the difference of manufacturing process, the size of the crystalline particle is different but normally about 50nm [9]. Crystalline phase is negative thermal expansion material, while the amorphous phase is positive thermal expansion material. By controlling the components of these two materials at a proper ratio, the Zerodur glass is zero thermal expansion. That is why it has good thermal stability and has wide application in modern optical system such as EUVL and spatial telescope mirrors and so on.

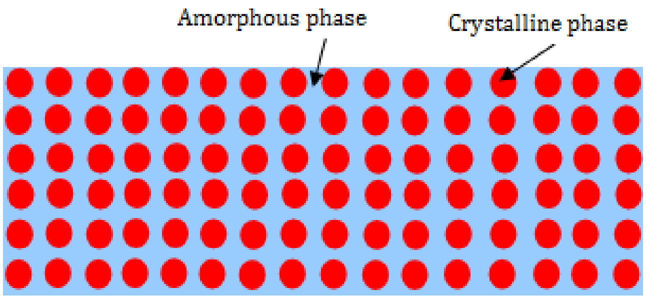
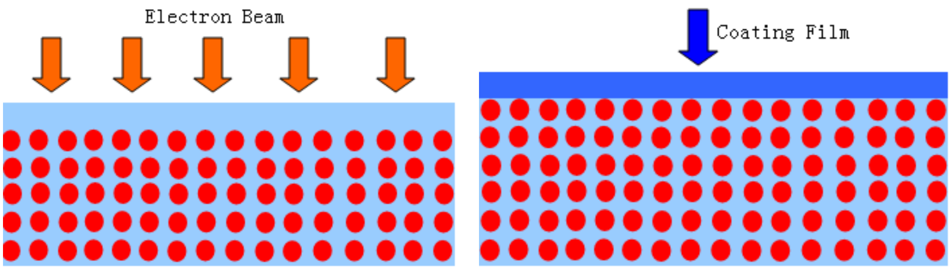


Figure 5. Structure mode of Zerodur glass.

As the different structure of crystalline and amorphous phase, the average surface atom bonding energy is incongruent. So the material removal rate of these two phases is different even if the process is at the same condition. That is mean the material removal rate of one phase is higher than that of the other. Therefore the surface will become coarse and the profile fluctuation will increase as the HEP process progresses. That is why the bumpy structure on processed surface and the surface roughness increased, as show in figure 4. It demonstrates that HEP process is not suitable for polishing the composite phase structure such as Zerodur glass. From the above analysis we can know the machinability of the silicon, quartz and silica is very well. Although they have different structures, they have the same characteristic that is they are all consisted of (crystalline or amorphous phase). Thereby if there is a post-treatment method that can change the thin surface layer on Zerodur glass into a single phase, then ultra-smooth fabrication can be realized by HEP process. One method is electron beam irradiation technology. It is reported that *Mori* [12] has successfully changed the crystalline structure on Zerodur glass into amorphous structure by electron beam irradiation technology, as shown in figure 6(a). Another way is adding technology that is a thin amorphous phase film is coated on the Zerodur glass, as shown in figure 6(b). *Liao ea tl.* [13] has obtained a ultra-smooth surface by ion beam figuring when the Zerodur glass surface was coated a thin silicon or silica film. Therefore, the ultra-smooth surface can be polished when the surface has been changed into a single phase.



(a) Electron beam irradiation technology (b) Adding technology

Figure 6. Surface post-treatment technology for Zerodur glass.

4. Conclusions

The HEP machinability of different types of optical material was investigated experimentally in this paper. It demonstrated that HEP has good smooth ability on single phase structure such as monocrystalline silicon, crystalline quartz and amorphous silica glass. The surface defects on these materials can be effectively removed and the surface roughness can be reached at atomic level. As the material removal rate of different phase is different, the HEP can't be directly applied on the composite phase structure material such as Zerodur glass. However, ultra-smooth surface can be obtained when the surface was changed into a single phase.

Acknowledgements
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