The mechanical properties of K9 glass based on nano-scratch experiments

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Abstract. To investigate the nano-mechanical properties of K9 optical glass, linear loading nano-scratch experiments were carried out on K9 glass and the results were analyzed. The elastic rebound was researched by constant loading nano-scratch experiments. The results showed that the plastic-brittle transitions under nanoscale were between 3mN and 4mN. In constant scratch experiments, the plastic deformation was stable, however, the surface quality was affected by brittle deformation seriously and the friction coefficient value in brittle deformation region exceeded double of that of plastic deformation. The concept of elastic rebound was introduced. The elastic rebound of plastic deformation was stable, whereas the elastic rebound in brittle region fluctuated acutely.

Introduction

Optical glass has been widely applied in various industrial areas as lens and reflectors for a long time. The internal damage and surface quality would directly affect transmission and reflection of optical glass. Therefore, obtaining the high-quality optical glass is required in mechanical process. However, as a hard and brittle material, the processing of brittle materials is mainly brittle removal in conventional machining. The ultra-low cutting depth processing of American scholar Bifano [1] showed that when the brittle crystal’s cutting depth was low enough, the crystal would achieve ductile remove in processing of brittle materials. Diamond turning on optical glass commenced in the 1960s. F Z FANG et al [2] reviewed the historical development of diamond-cutting optical glasses. Lu Zesheng [3] conducted a systematic review about the mechanism of brittle-ductile transition of hard and brittle materials and research methods. Zhang Bei [4,5] investigated the surface roughness and subsurface damage by brazed grinding wheel and in different grinding parameter. However, all researches of the brittle-ductile transition were conducted by macroscopic cutting experiments and lack the research of mechanism of the brittle-ductile transition.

Nano-scratch tests is a common method to simulate the actual grinding and cutting process and have a widely application to research brittle materials in the domain of ductility. In nano-scratch, elastic-plastic transition point and brittle-ductile transition point have important significance for the study of ductility and the critical cutting depth. R. THONGGOOM [6] investigated transition in repeated scratching of optical glasses. Weibin Gu, et al [7-9] have studied material removal of BK7 and surface and subsurface cracks by single and double scratch tests. ZHAO Qingliang, et al [10] researched the deformation and subsurface damage by indentation and grinding on optical glasses. Zhang Feihu et al [11,12] studied the surface roughness and subsurface damage of K9 glass based on scratch and grinding experiments.

At present, the study about surface and subsurface cracks and damage during processing and scratch under micro scale has been completed by scholars. However, that in nano scale lacks further research and the critical loading in nano scale have not been proposed. Furthermore, the elastic rebound after unloading in scratch which is significant for surface qualities has not been researched before. In this paper, the optical glass K9 was used as the experimental specimen of linear loading nano-scratch. The removal region and surface morphology under nano scale were analyzed and compared. After unloading, the elastic rebound of the surface was also investigated in this paper.

Experiment

The physical parameters of K9 glass is shown in Tab.1. The samples were prepared by double-surface polishing for good surface quality and flatness of both two surfaces. The samples were cut into 30mm×30mm×1mm, the average surface roughness R_a is 2.45nm within the field of 0.256mm ×0.215mm observed by AFM. The schematic diagram of a section about nano-scratch process is shown in Fig.1.

Tab. 1 Some physical parameters of K9 glass

parameters	Value
Density/(g cm^{-3})	2.52
Young modulus(GPa)	81.3
Poisson ratio	0.21
Compressive strength(GPa)	0.6
Tensile strength (MPa)	30

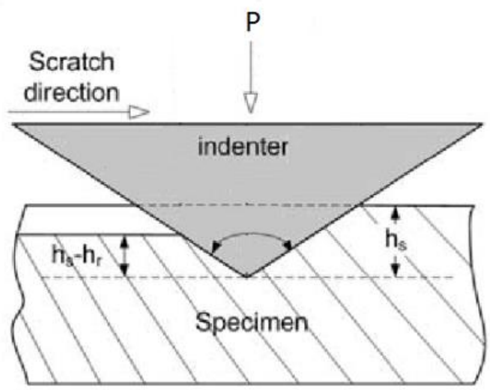


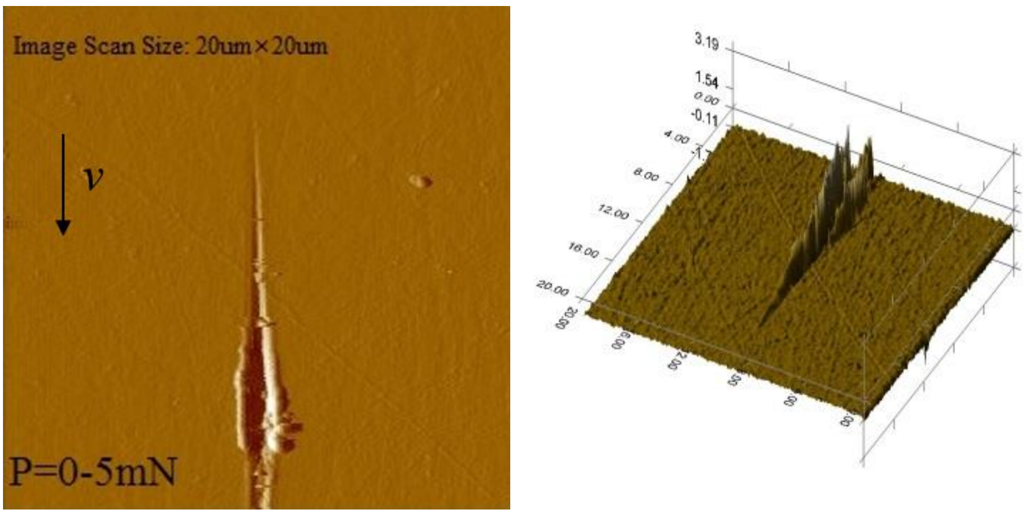
Fig. 1 Illustration of scratch process and elastic rebound

TI 950 TriboIndenter (Fig.2) with a cone diamond indenter of which radius of the tip is 1μm was used in nano-scratch tests. The loading increased from 0 to 5mN linearly. The loading time was 100s. After experiments, the scratch morphology was scanned by the AFM. All the experiments were conducted in an ultra-clean environment at room temperature.

Fig.2 TI 950 TriboIndenter System

Experiment Results and Analysis
1.Nano scratch

Shown in Fig. 3, in nano-scratch experiment, the plastic deformation can be observed obviously and the scratch depth and width gradually increased with the load. The accumulation of material could be observed along two sides of the scratch, but the scratch bottom was smooth and flat, which indicates the deformation form is plastic remove and have no crack. With the increasing of load, the brittle deformation could be observed. In brittle deformation region, the scratch significantly increased deeper and wider. The material was accumulated along the two sides and the bottom was rough, which can be deemed that the material is removed in brittle region.



(a) The morphology of scratch (b) The 3D scanning morphology

Fig. 3 The in-situ scanning morphology of linear nano-scratch from 0 to 5mN.

Shown in Fig.4, the normal loading increased linearly while the lateral force increased slowly. When the normal loading was over 3mN, the lateral force reached the peak 1.5mN. The fluctuation of friction coefficient was similar with that of lateral force.At the beginning,it fluctuated at 0.15.When the normal loading was over 3mN, the friction coefficient reached the peak value 0.3.In nano-scratch experiment, the plastic-brittle critical loading of optical glass K9 was between 3mN and 4mN.

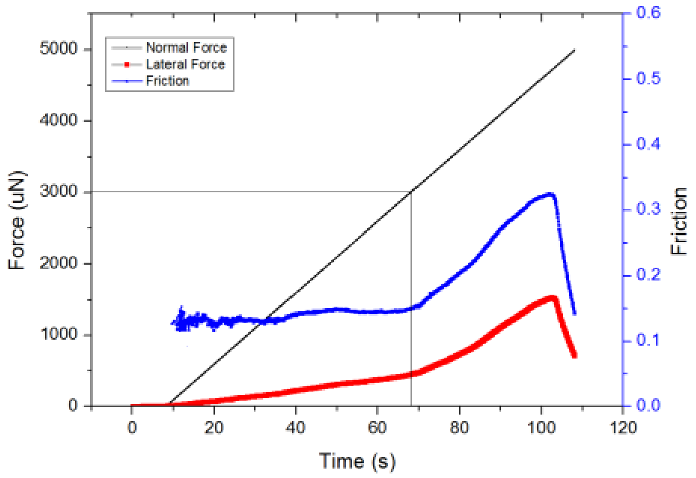


Fig. 4 The relationship of normal force, lateral force and friction during scratch.

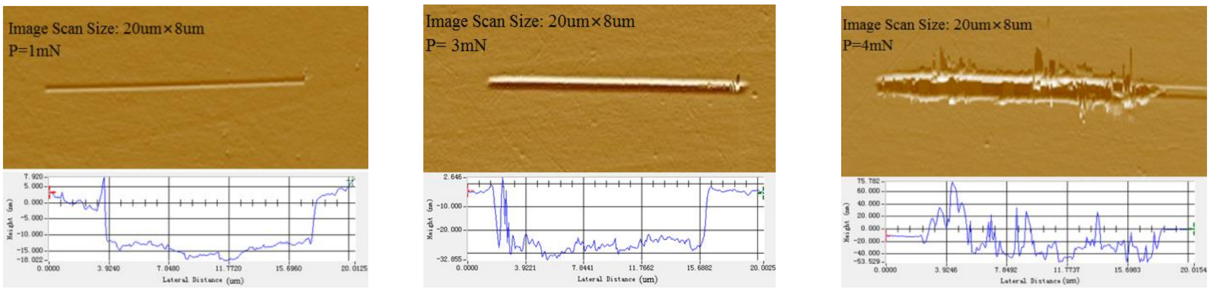
During the scratching hard-brittle materials, before the material fractures generated, the extent of plastic deformation was decided by static pressure of indenters and the plastic strain was decided by the value of the static pressure. Whether the material was plastic or brittle removed was decided by the value of strain.

In nanoindentation, the loading direction and the moving direction were the same. The contact area would be the surface of the indenter. Though the breaking tenacity of K9 glass is low,the maximum stress can not reach the break limit stress due to large contact area. Bowdon, et al [13] argued that the sliding frictional resistance of scratch comes from the adhesion effect and the furrow effect. During the cracks propagation, micro fracture was observed intermittently in brittle materials surface, which causes the lateral force changing, so when the frictional resistance acutely fluctuated, fracture in scratch process was generated. Therefore, during plastic deformation, when micro fracture was not generated, the friction coefficient increased slightly without obvious fluctuation. With the increasing of loading, the friction coefficient increased rapidly because of brittle deformation.

In processing, if the cutting depth is litter enough, the removal form of material could be in plastic region and the smoothed surface quality could be obtained. In addition, fractures from processing could be avoided in small cutting force, as well as the energy consumption could also be declined and it's a positive effect for the protection of the device.

2.The constant loading scratch

For further research on plastic and brittle deformation, the constant loading nano scratch tests were conducted. The plastic-brittle transition point is between 3mN and 4mN according to the conclusion of the nano scratch. Therefore, the constant loading scratch of 3mN and 4mN were carried out. The loading of 1mN was also conducted for comparison. Shown in Fig.5 (a) that there was no material accumulating, and the surface and bottom were both smooth, which means the material deformation totally in plastic region. In (b), with the depth and width increasing, the deformation was still in plastic region. In (c), it was absolutely brittle deformation that materials accumulated along both sides of the scratch, and the bottom fluctuated significantly.



(a)1mN (b) 3mN (c) 4mN

Fig.5 The in-situ scanning morphology and the scratch depth of the constant loading nanoscratch

Shown in Fig.6, the friction coefficients of 1mN and 3mN had the same fluctuation. With loading 1mN, the friction coefficient reached the peak about 0.15 and reduced slowly. Loading 3mN, the peak vaule was 0.2 and the curve was paralleled with that of 1mN. The friction coefficient of 4mN fluctuated dramatically compared with others, while it was also stable in 0.35 with loading process. In plastic deformation region, dislocation occurs in the material, resulting in a large amount of stress. With the increase of the dislocation, the interaction among dislocation will stop moving, which means that the more the loading is, the larger the friction coefficient will be.

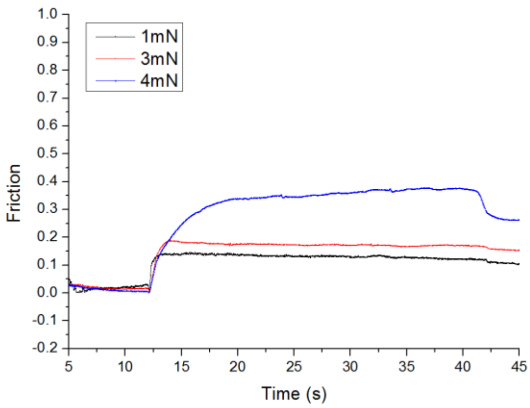


Fig. 6 The friction coefficient curves of various loadings

3.The elastic rebound

In plastic or brittle deformation, the surface is reformed by the elastic rebound after unloading, which means the elastic rebound will directly affect the surface quality after processing. In Fig. 9, the residual displacement is much lower than the normal displacement, which demonstrates that the surface was made by elastic rebound. Before the normal loading reaches 3mN, the residual displacement increases nearly linearly. By contrast, After 3mN, it changes sharply. In order to research the elastic rebound, here the concept of elastic rebound rate is introduced

(1)

where h_s is the normal displacement, h_f is the residual displacement and δ is the elastic rebound rate [14], in Fig.1.

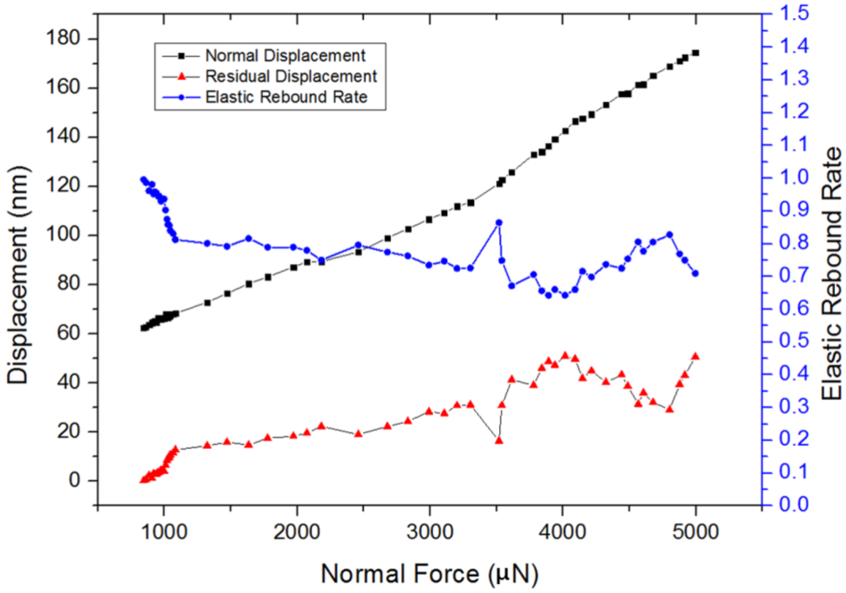


Fig. 9 The curves of the normal displacement, residual displacement and elastic rebound rate

During plastic deformation, the elastic rebound rate decreases slightly with the normal loading increasing. However, during the brittle deformation, it fluctuates acutely. As the brittle deformation and fractures, the measured residual depth would not be totally caused by elastic rebound. The fractures and accumulation of the material could also influence the residual depth. Due to the effect of the pressure from the indenter, some physical properties in the plastic region will be changed, such as the density, the refractive index and so on. The physical changes would affect the route of light propagation. The influence of this issue requires some effective measurements to solve in actual processing.

Conclusion

By the nano-scratch experiments, it was found that in a certain depth and loading, plastic remove could be fulfilled on K9 specimen. The critical load of plastic-brittle transition is between 3mN and 4mN. In constant scratch tests, the plastic deformation was stable, while the brittle deformation affected the surface quality seriously and the friction coefficient of this period exceeded double of that of plastic deformation. From the research of elastic rebound, the elastic rebound of plastic deformation was stable, whereas that of brittle deformation experienced huge fluctuations. In actual processing, if the cutting depth is small enough, the plastic deformation could be achieved and the high quality surface could be obtained. The fractures in processing could be reduced in small cutting force and the surface precision could be improved.

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