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Processing of brittle materials in the nanometer range of thickness of layers cut¹

M A Shavva¹, V V Lapshin¹, S V Grubyy²

¹Russian Research & Development Tooling Institute VNIINSTRUMENT, 49, Bolshaja Semyonovskaya, Moscow, 107023, Russia

²Bauman Moscow State Technical University, 5, Baumanskaya 2-ya, Moscow, 105005, Russia

E-mail: katapu@mail.ru

Abstract. The article deals with the results of experimental research in the ultra-precision diamond machining of brittle materials – potassium dihydrogen phosphate, single-crystal quartz, quartz glass, crystalline glass, sapphire, and germanium. The processing modes at which the nanometer roughness of the processed surface was achieved are specified.

Introduction

The traditional technology to process surfaces of details made of brittle optical materials includes the pregrinding with diamond wheels with the granularity of various granulometric compositions in strict consecutive order from large to small fractions. Then the final chemical and mechanical polishing with classified flours (loose abrasive) is applied. This technology has major deficiencies – rather low production and stability of the process, complexity of automation and control, influence of the polisher's skills on the processing quality.

1. Plasticity of brittle materials

At Russian Research & Development Tooling Institute VNIINSTRUMENT and Bauman Moscow State Technical University, a complex of technological research and design developments directed at the improvement of performance, accuracy and quality of the processing of brittle optical materials is being performed within the framework of the Agreement for the Federal Target Program. The research is based on the clause relating to the quasi plasticity of brittle materials. The quasi plasticity is the manifestation of plastic properties of a surface layer of brittle materials in some processing modes. When cutting a layer with nanometer thicknesses, the contact interaction of the tool with the surface processed creates the conditions when there is a directed quasi-plastic removal of a surface layer of a material with forming some roughness within a few nanometers and a minimum defective layer.

The first installation specially created to research the processes during diamond grinding in the nanometer range of thickness was designed by Yoshioko [1]. Later the research was continued by T.G.

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Bifano and T.A. Dow in the eighties of the twentieth century with the PEGASUS machine [1]. As a result of the conducted experiments with a considerable quantity of amorphous glasses, single-crystals and ceramic materials, the authors found the conditions of the brittle-ductile transition when all the materials, irrespective of their hardness and brittleness, transfer from a brittle mode of destruction to the quasi-plastic one during mechanical surface treatment [2].

The diamond machining of brittle optical materials in the quasi-plastic cutting mode can be performed if there are:

- Ultra-precision rigid equipment providing the cutting depth within the limits of 0.5 to 2 μm , blank feed within the limits of 0.1 to 5 $\mu\text{m}/\text{rev}$, cutting kinematics with thickness of the layer cut from a few nanometers to a few tens of nanometers;
- Single-crystal diamond cutters with the corner radius of cutting edges of 30 – 50 nm;
- Diamond wheels on a metal or ceramic holder, the granularity of a diamond-bearing layer of which is 1 – 5 μm .

2. Experimental research

Experimental research was conducted with special ultra-precision test stands for the grinding and milling by a single-cutter diamond head – Fig. 1 and 2. Parameters of the stands are specified in Tables 1 and 2.

The objects of research during the diamond grinding and milling were the blanks of brittle optical materials: single-crystal potassium dihydrogen phosphate (KDP), single-crystal quartz, quartz glass, crystalline glass, single-crystal germanium, and sapphire.

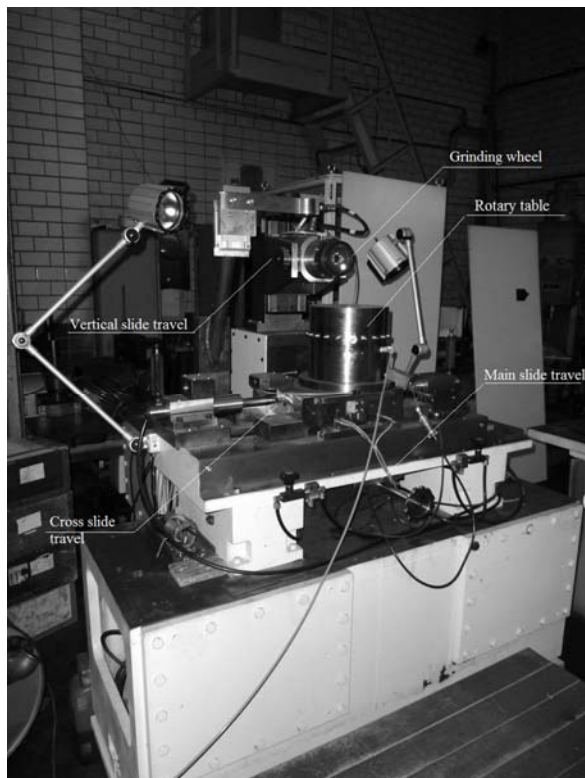


Figure 1. Special ultra-precision grinding stand.

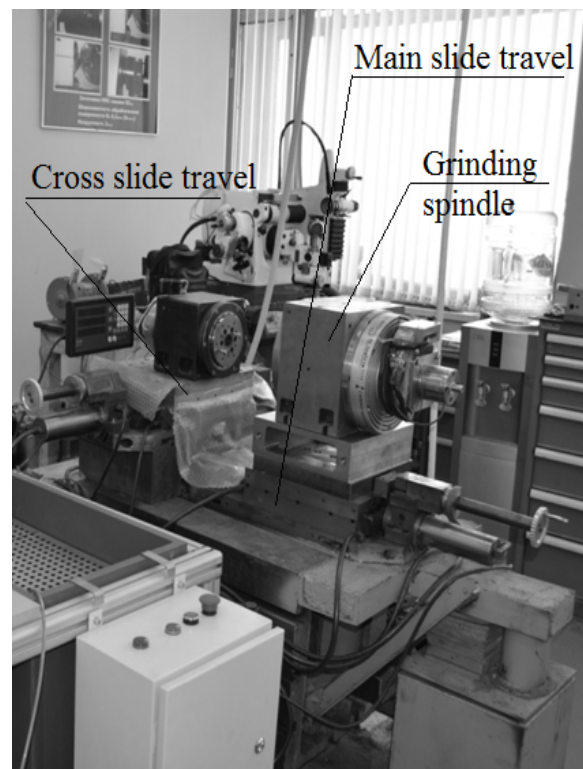


Figure 2. Special ultra-precision milling stand with single-cutter diamond head.

Table 1. Parameters of the ultra-precision grinding stand.

No.	Parameter name	Parameter value
1	Grinding wheel RPM range, min^{-1}	200...6000
2	Rotary table RPM range, min^{-1}	0.01...300
3	Main slide travel, Z axis (penetration slide), mm	100
4	Cross slide travel, X axis, mm	150
5	Vertical slide travel (wheel height adjustment), Y axis, mm	100
6	Rotary table travel (setting motion), B axis, angular degree	20
7	Number of axes, pcs X axis – cross slide; Z axis – main slide (penetration slide); B axis – rotary table; S axis – grinding wheel rotation	4
8	Cutting feed of main slide, mm/min	5...200
9	Movement resolution of cross slide, μm	0.1
10	Movement resolution of main slide, μm	0.1
11	Positioning accuracy of Z and X axes at length of 100 mm, μm	0.5
12	Positioning accuracy of B rotation axis, arcsec	1
13	Power of electric motor of grinding wheel, kW	1

Table 2. Parameters of the ultra-precision stand for diamond milling.

No.	Parameter name	Parameter value
1	Spindle RPM range, min^{-1}	200...6000
2	Main slide travel, Z axis (penetration slide), mm	0.01...300
3	Cross slide travel, X axis, mm	100
4	Number of axes, pcs X axis – cross slide; Z axis – main slide (penetration slide); S axis – grinding wheel rotation	150
5	Cutting feed of main slide, mm/min	100
6	Movement resolution of cross slide, μm	20
7	Movement resolution of main slide, μm	4
8	Positioning accuracy of Z and X axes at length of 100 mm, μm	5...200
9	Power of electric motor of grinding wheel, kW	0.1

To control the processed surface roughness, the NanoFocus® μSurf ® system was used. The system is based on the confocal measurement principle with a white-light source. It is an

autonomous and complete workplace for 3D measurements and is intended for the quality control of surface roughness of up to 1 nm. Triple roughness measurements of the surface were performed; Table 3 includes the processing modes, maximum thickness of the cut layer for the diamond wheel, as well as results of measurement of the processed surface roughness.

Table 3. Diamond grinding modes for brittle optical materials.

Material processed	Speed of rotation of rotary table, rpm	Blank feed per grinding wheel turnover, $\mu\text{m}/\text{rev}$	Maximum thickness of cut, nm
Potassium dihydrogen phosphate	0.07	33	29
Single-crystal quartz	0.02	9.4	34
Quartz glass	0.05	24	22.6
	0.07	33	31
Crystalline glass	0.05	24	22.6
	0.03	14.1	13.3
	0.01	4.7	4.1
	0.07	33	31
Sapphire	0.05	24	22.6
	0.03	14.1	13.3

Note: surfaces with roughness less than 10 nm belong to the optical class

3. Results

Fig. 3 shows the processed surface of a sample of potassium dihydrogen phosphate.

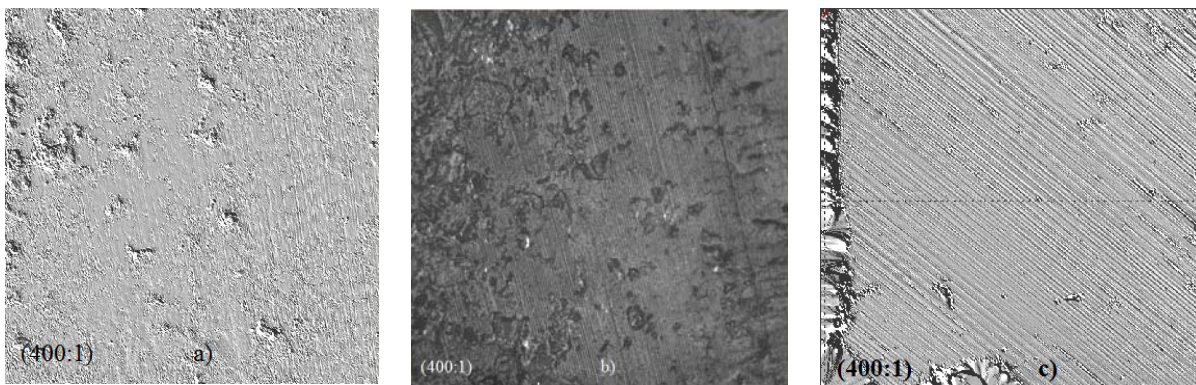


Figure 3. Surfaces of brittle material blanks processed by the method of ultra-precision diamond grinding (400:1 scale): a) potassium dihydrogen phosphate; b) single-crystal quartz; c) quartz glass.

As seen from the figure, during the processing the material was in a borderline state, i.e., in the brittle-ductile transition state. This is evidenced by the simultaneous availability of chips on the processed surface and of feed marks made by the cutting tool. The feed marks are the machining marks on the processed surface in the quasi-plastic mode, which coincide with the motion trajectory of the cutting tool. Since the material in the cutting zone was in a borderline state, the processed surface roughness is

rather large – 29 nm. It is possible to assume that the thickness of the cut 31 nm layer does not ensure the full transition of the material into the quasi plasticity state.

Fig. 3-b shows the processed surface of a single-crystal quartz. As in the case with the potassium dihydrogen phosphate processing, the single-crystal quartz also is in the brittle-ductile transition state, therefore the processed surface roughness is 34 nm. Fig. 3-c shows the processed surface of quartz glass. On the processed surface, there are practically no chips and cracks; the feed marks prevail. The surface is processed in the quasi-plastic cutting mode. The processed surface roughness was 6 nm. Similar results were obtained after the diamond grinding of crystalline glass with the 4 $\mu\text{m}/\text{rev}$ feed (thickness of cut of 4.1 nm, roughness $R_a = 3$ nm) – Fig 4-d.

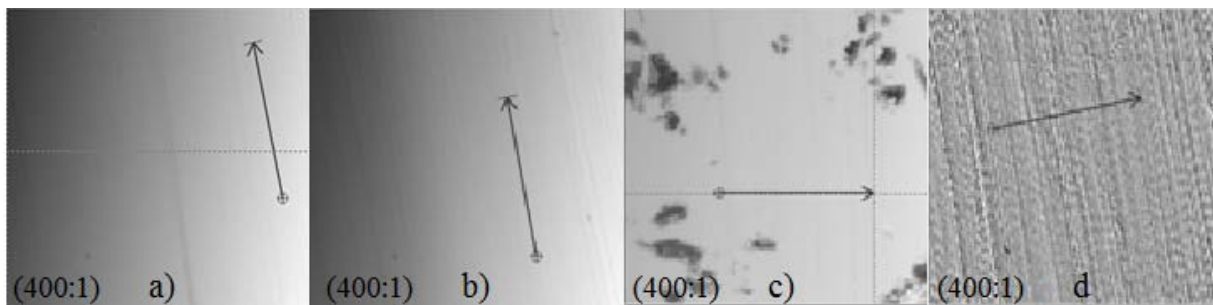


Figure 4. Processed surface of crystalline glass in case of longitudinal feed (250:1 scale): a) – 33 $\mu\text{m}/\text{rev}$; b) – 24 $\mu\text{m}/\text{rev}$; c) – 14.1 $\mu\text{m}/\text{rev}$; d) – 4.7 $\mu\text{m}/\text{rev}$

According to the results of the ultra-precision diamond grinding of various brittle materials, the processed surface roughness was 1 to 34 nm. In case of the grinding in the quasi-plastic cutting mode, the processed surface roughness of quartz glass, crystalline glass, sapphire does not exceed 6 nm, i.e., it belongs to the optical class.

Blanks of single-crystals of potassium dihydrogen phosphate and germanium by a diamond single-crystal tool in the nanometer range of thickness of the layer cut were processed in a special ultra-precision stand with the use of the milling method with a single-cutter head. The parameters of the diamond cutter used in the head, the milling modes and the processed surface roughness are specified in Table 4. The diameter of the single-cutter head is 35 mm. All the experiments were conducted with the spindle rotational speed of 1000 rpm.

Table 4. Diamond milling modes for brittle optical materials

Material processed	Radius of diamond cutter at cutting point, mm	Corner radius of cutting edge, nm	Front rake angle, degree	Back rake angle, degree	Cutting depth, μm	Thickness of cut layer, nm	Number of passes	R_a , nm
Potassium dihydrogen phosphate (KDP)	2	50	0	-7	1	77.4	3	12
	2					31.3	8	16
Germanium	3.6					5.6	3	1

Fig. 5 shows photos of surfaces of the brittle materials processed by a single-cutter diamond milling head with various thickness values of the layer cut.

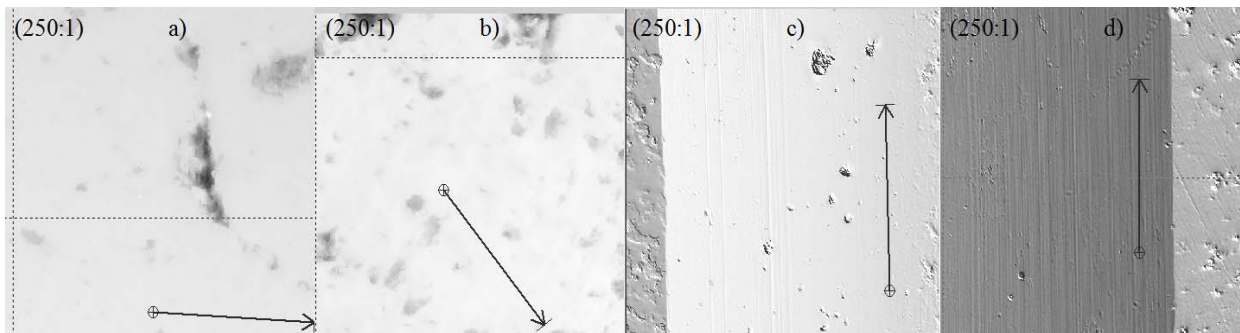


Figure 5. Surfaces of samples after diamond milling with various thickness values of the layer cut (250:1 scale): a) KDP – 77.4 nm; b) KDP – 31.3 nm; c) KDP – 5.6 nm; d) germanium – 5.6 nm

It follows from the photos in Fig. 5 that if the thickness of the layer cut is reduced the feed marks made by the cutting tool are clearly seen on the processed surface, i.e., the surface layer passes into the quasi plasticity state [3]. With reducing the thickness of the layer cut, the processed surface roughness is decreasing. Optical and microelectronic elements of potassium dihydrogen phosphate and germanium can be processed by the diamond single-crystal tool with achieving the optical class roughness [4, 5, 6].

In case of the ultra-precision diamond machining of brittle materials in the nanometer range of thickness of cut, cuttings with a variable nanometer thickness are formed. Appearance of the cuttings is shown in Fig. 6.

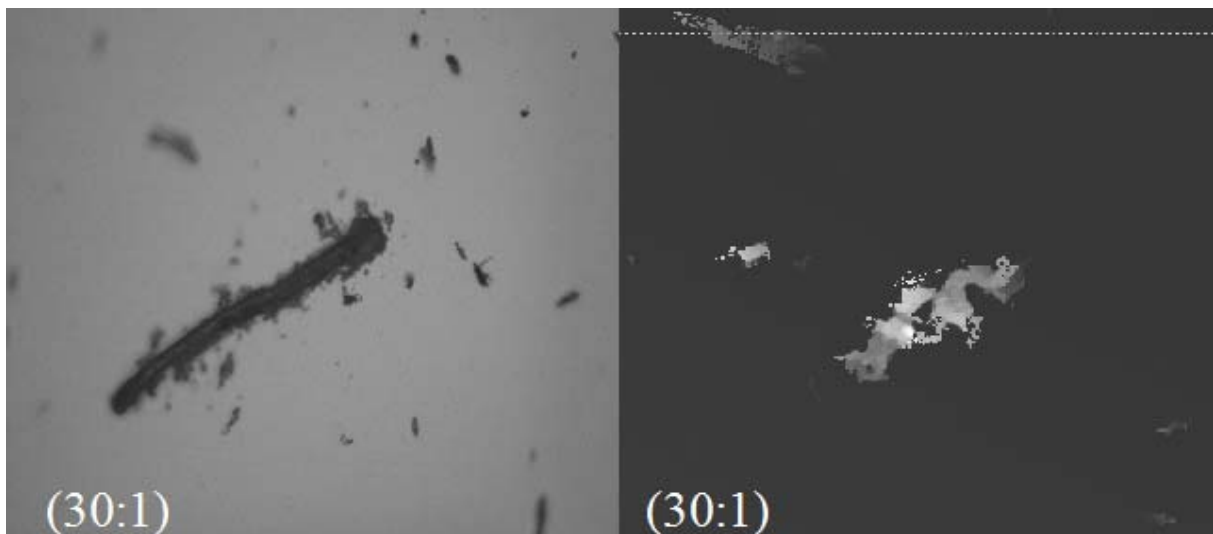


Figure 6. Cuttings after the diamond ultra-precision edge cutting machining of potassium dihydrogen phosphate (30:1 scale)

During the diamond grinding, such cuttings are accumulated in the intergranular space of the diamond-bearing layer, which leads to the glazing of the wheel. It is possible to avoid the glazing of the wheel surface by dressing the wheel. The diamond grinding wheels the granularity of which is less than 5 μm cannot be dressed by a mechanical method for the reason of the impregnation of the diamond-bearing layer with particles of the dressing tool. Since the dressing of the grinding wheel outside the machine tool affects the accuracy of the processed surface and reduces the processing productivity, it is recommended to use continuous electrochemical dressing (ECD dressing) [7].

According to the results of design studies, an installation was simulated, developed and made to provide the continuous electrochemical dressing of the diamond wheel directly during the ultra-precision diamond grinding of brittle material blanks.

Conclusion.

The conducted experimental research shows that in the cutting modes providing nanometer values of the layer cut, the brittle material surface layer passes into the quasi plasticity state, the surface is formed without chips and cracks, with the roughness of a few nanometers.

To obtain the required quality of the surfaces made of brittle materials: roughness $R_a = 1$ nm, minimum working error – 10 nm on the area of 100x100 mm, and minimum size of the fissured layer – it is necessary to increase the stiffness and accuracy of the equipment used. Within the framework of the further research, it is planned to create a special ultra-precision stand for the nanoscale processing of optical materials by the diamond single-crystal and abrasive tool in the quasi-plastic cutting mode with air-bearing units having increased stiffness.

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