

Finishing technologies for processing of optical microelectronic items

K R Muratov¹, T R Ablyaz¹, E A Gashev¹, A M Khanov¹ and N V Varlamov²

¹Perm National Research Polytechnic University, Komsomolsky prospekt 29, 614990 Perm, Perm krai, Russian Federation

²National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe shosse 31, 115409 Moscow, Russian Federation

Corresponding author's e-mail address: ¹karimur_80@mail.ru

Abstract. This article discusses comparative studies of the influence of specific pressure and speed of relative motion of tool and item on polishing capacity and quality of processed surface of lithium niobate single crystal. The equation for calculation of total depth of layer destroyed upon finishing and time of polishing required for its removal. Analysis of polishing tool has accounted for strength properties of the polishing material, removal capacity, and quality of processed surface of lithium niobate single crystal. It is experimentally established that upon basic pressure both for woven and unwoven polishers with the highest capacity the lower limit of grain coarseness of polishing suspension is 1/0.5 μm . A reserve of increase in shape accuracy and polishing quality is the use of polishers with equal thickness and structure of working surface.

1. Introduction

Recently the list of crystalline materials used in commercial microelectronics has been sufficiently expanded. Lithium niobate single crystals (LNC) are the most widely applied in integral optics due to high values of non-linear optical and electric optical coefficients, as well as possibility of commercial crystal growth and fabrication of plates. Integral optical phase modulators on the basis of LNC are at present widely applied in fiber optics gyroscopes, electric current sensors, and other devices. Upon mechanical processing of working surfaces of LNC plates finishing procedures are the most labor-consuming. The main technological difficulties of these procedures are stipulated by physicomechanical properties of material, as well as by high requirements to the quality of processed surface. Hence, mechanization and automation of finishing procedures together with steady quality and processing cap is an urgent task.

2. Formulation of the problem

Upon polishing, as upon abrasive finishing or fine grinding, the main process variables are the speed of relative motion of tool and processed surface, the contact pressure between them and processing time, depending on numerous factors, mainly on the aforementioned engineering and kinematic processing variables. The influence of polishing modes of brittle optical and ceramic materials on capacity and quality of processed surface was studied elsewhere [1, 2, 3, 4, 5], from where it follows that the dependences upon finishing and polishing are similar with quantitative differences.

In the course of abrasive finishing or fine grinding microcracks are generated in the surface layer of the processed item as a consequence of the non-spherical shape of abrasive grains, which roll over and collide. The microcracks intersect each other; indents are generated upon repeated impact of abrasive



grains. The processed surface acquires peculiar dull relief, composed of bosses and cavities, microcracks remain under the surface in the bulk of the material. Therefore, ground glass surface or any other brittle material consists of visible relief layer and invisible subsurface fissured layer. The combination of these layers is known as destroyed or broken layer of the polished surface.

The researchers of finishing of brittle materials [2, 6, 7, 8, 9] established that the ratio of total depth F of destroyed and visible relief layer h for various grades of optical glass and minerals with close values of brittleness is qualitatively constant and in the first approximation equals to $F/h = K \approx 4$, Figure 1.

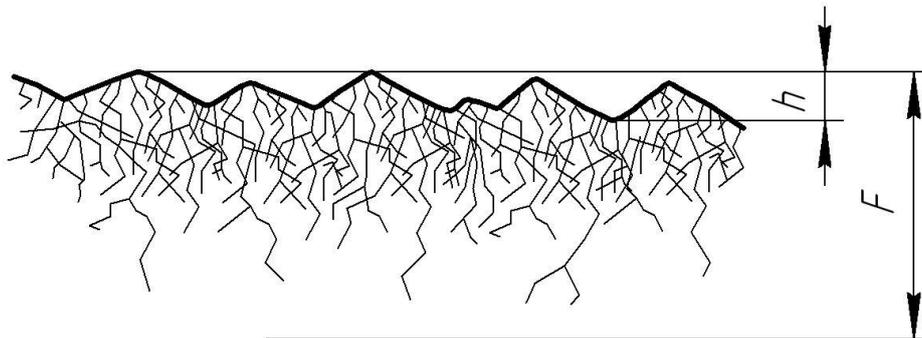


Figure 1. The structure of destroyed layer upon abrasive finishing or fine grinding.

It is experimentally established that the highest influence on the depth of relief layer is exerted by the size of abrasive grain and its hardness, and, to a lower extent, by the hardness of abrading tool and no influence by the pressure between tool/item and processing speed. Upon finishing of crystalline materials, for instance, single crystals of lithium fluoride and fluorite, the propagation direction of cracks and occurring stresses sharply differs from their direction in glass and depends on their structure. Thus, the microrelief of ground crystal surface also related with their structure and crystallographic direction of polishing [10]. The depth of destroyed layer at cube edge is slightly higher than at rhombic dodecahedron edge and by 1.5 times greater than in glass. The latter fact is obviously related to the value of angle at which cracks propagate in glass and crystals.

Perm University analyzed abrasive polishing of the surface of lithium niobate single crystal; the aim was to select the material of polishing tool as well as polishing technological conditions. Lithium niobate plates with the sizes of $12 \times 36 \times 1$ mm and edge inclination of 10° to symmetry axis were used as samples. The main requirements to the quality of processed surface: surface coarseness R_a – not higher than $0.010 \mu\text{m}$, no fractures, indents and notches at the plate edges.

3. Experimental

Tables 1 and 2 summarize the experimental results of the influence of specific pressure and speed of relative motion on polishing capacity and quality of processed surface of lithium niobate single crystal, obtained in Perm University. The experiments were performed with VelTex polisher (Buehler), ASM 1/0.5 basic suspension. Constant process variables: $V_{\text{avg}} = 1$ m/s, (60 m/min); pressure $P = 65$ kPa. Time of one polishing cycle $T_{\text{pc}} = 6$ min.

The experimental results demonstrated that polishing capacity (Q , $\mu\text{m}/\text{min}$) increases linearly actually in proportion to specific pressure. The coarseness of polished surface of the single crystal in the pressure range of 44 kPa – 104 kPa does not depend on pressure. It is established that in the region of minor specific pressures from 31 kPa and lower there is certain deterioration of coarseness as a consequence of insufficient polishing. Probably, at moderate specific pressures, firstly, elastic properties of polisher are more pronounced, and secondly, only coarse grains participate in the process. The pressure is restricted by polisher strength and danger of dry friction.

Table 1. Influence of specific pressure on polishing capacity and quality of processed surface of lithium niobate single crystal ($V_{\text{avg}} = 1$ m/s).

P , kPa (kg/cm ²)	Coarseness parameters, μm					Q , $\mu\text{m}/\text{min}$
	R_a	R_z	R_q	R_{max}	R_t	
31.8 (0.32)	0.002	0.013	0.002	0.015	0.015	1.5
44.5 (0.45)	-	-	-	-	-	2.0
65.4 (0.65)	0.001	0.009	0.002	0.009	0.009	3.0
75.6 (0.76)	-	-	-	-	-	3.5
83.3 (0.83)	-	-	-	-	-	4.0
104 (1.04)	0.001	0.010	0.002	0.010	0.011	5.0

Table 2. Influence of cutting speed on polishing capacity and quality of processed surface of lithium niobate single crystal ($P = 6$ kPa).

V_{cp} , m/s (m/min)	n_{pol} , rpm	Coarseness parameters, μm					Q , $\mu\text{m}/\text{min}$
		R_a	R_z	R_q	R_{max}	R_t	
0.5 (30)	57	0.001	0.009	0.002	0.009	0.009	1.1
1.0 (60)	140	0.001	0.009	0.002	0.009	0.009	3.0
1.5 (90)	227	-	-	-	-	-	4.2
1.94 (116)	300	0.001	0.010	0.002	0.011	0.012	5.7

The polishing capacity of the single crystal is directly proportional to the average speed of relative motion (Table 2). The increase the rate by about four times does not influence on the coarseness of polished surface of the single crystal. The speed is restricted by the same reasons as upon finishing (fine grinding): the danger of dry attrition and polisher strength.

The time of polishing cycle (T_{pc}) is determined mainly by removal capacity (Q) or speed of polishing-off and depth of layer destroyed by grinding. The obtained experimental results (Table 3) demonstrated that with increase in polishing time in the range from 3 min to 12 min the removal of material Δ_{Aavg} , μm increases proportionally and polishing capacity Q , $\mu\text{m}/\text{min}$ remains unchanged, which completely agrees with the experimental results of polishing of optical glass in [4].

Table 3. Influence of polishing time on removal capacity

Polishing cycle time, T_{pc} , min	Polisher material			
	Woven: Bologna fabric $P = 61$ kPa, $V_{\text{avg}} = 1$ m/s		Unwoven: Microlap Remet and VelTex Buehler $P = 39$ kPa, $V_{\text{avg}} = 1$ m/s	
	Δ_{Aavg} , μm	Q , $\mu\text{m}/\text{min}$	Δ_{Aavg} , μm	Q , $\mu\text{m}/\text{min}$
3	-	-	5.7	1.9
6	21.9	3.6	11.7	1.9
9	32.4	3.6	16.3	1.8
12	41.9	3.5	22.0	1.8

The following polishing modes of lithium niobate single crystal can be recommended for the proposed polishers, *Microlap* (*Remet*) and *VelTex* (*Buehler*): polisher rotation speed 150-250 rpm and pressure 50-100 kPa, which provides the required quality and sufficiently high polishing capacity. When polishing cycle time varies from 3 min to 12 min at constant suspension supply, the polishing capacity remains unchanged.

With known removal capacity, maximum depth h of relief layer, which is determined by R_{max} , and ratio [10] between the depth of destroyed F and relief h layers for crystalline materials $F/h \approx 6$, it is possible to calculate approximately minimum polishing time. Herewith, it should be taken into account that the depth h (R_{max}) of relief layer measured by stylus method on profilograph is by 2-2.5 times underestimated in comparison with the actual depth determined by polishing-off [2, 6, 11].

Therefore, upon finishing abrasive processing of crystalline materials, in particular, plate edges of lithium niobate single crystal, in the first approximation, in order to calculate total depth of layer destroyed by finishing and minimum polishing time required for its removal the following expressions can be applied: $F \approx 12 \cdot R_{max} \mu\text{m}$; $T_{\text{pol}} \approx F / Q$ min.

A further aim of the study of polishing of lithium niobate single crystal was a selection of the material of polishing tool, as well as technological conditions of polishing. Abrasive was made of synthetic diamond in the form ASM 1/0.5 suspension and deionized water. The main requirements to the quality of processed surface: surface coarseness R_a – not higher than $0.010 \mu\text{m}$, no fractures, indents and notches at the plate edges.

Figure 2 illustrates the scheme of motions upon mechanical polishing of single crystal on the polishing machine.

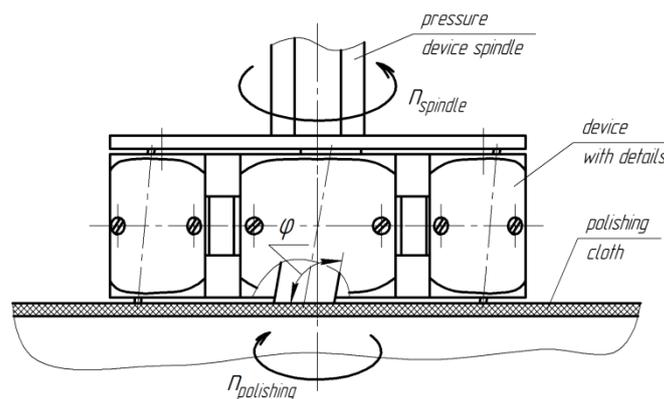


Figure 2. Schematic view of motions upon mechanical polishing of single crystal: n_{sp} - spindle RPM of device with details; $n_{pol.}$ - polishing tool RPM.

A pack of processed plates is located in the grooves of the device at an angle of 10° to the vertical axis (see Figure 2). As a consequence, the angle between the processed edge and right lateral plane are obtuse, that is, higher than 90° , and between the edge and left plane it is lower than 90° , that is, acute angle. Taking into account that spindle rotation of loading device (automatic module) and device with items is not reversed and always directed counter clockwise, the groove inclination in the body is made so that the vector of cutting speed is directed towards obtuse angle φ . Thus, to provide similar direction of the vector of cumulative cutting speed it is necessary to provide counter-rotation of the polisher, that is, clockwise.

Such polishing kinematics makes it possible to increase significantly the polisher strength and provides sufficiently high cutting speed at moderate rotation frequencies of the polisher. It should be mentioned that upon polishing it would be unreasonable to apply the mode of the free rotation since in this mode it is impossible to provide the required direction of the vector of cutting speed.

The comparative experiments involved the following woven and unwoven materials as polishers, their structure is illustrated in Figure 3.

In addition, composite polishers on the basis of cellulose were tested [12], their use is justified by availability and moderate cost. However, some restrictions exist in operation with cellulose polishers. No resistance against water does not permit to use them in combination with water-based suspensions. Thus, processing by cellulose polishers was performed in combination with fat-based diamond pastes, washed by organic solvents.

Polishing was performed by the suspension on the basis of deionized water and micro powder of synthetic diamonds ASM with the grain size of $1/0.5 \mu\text{m}$. The suspension concentration was 1/10. Experiments were carried out with basic polishing modes: average pressure $P = 61 \text{ kPa}$, average cutting speed $V_{\text{avg}} = 1 \text{ m/s}$, (60 m/min), polishing cycle time $T_{\text{pc}} = 6 \text{ min}$. The results of comparative experiments on polishing capacity (Q) and quality of processed surface are summarized in Table 4. The resistance of polishers, Table 5, was estimated by cumulative machine time Σt_{mach} of operation until the occurrence of local points of physical wear on working surface or until a significant decrease in polishing capacity and occurrence of noticeable notches on the polished surface.

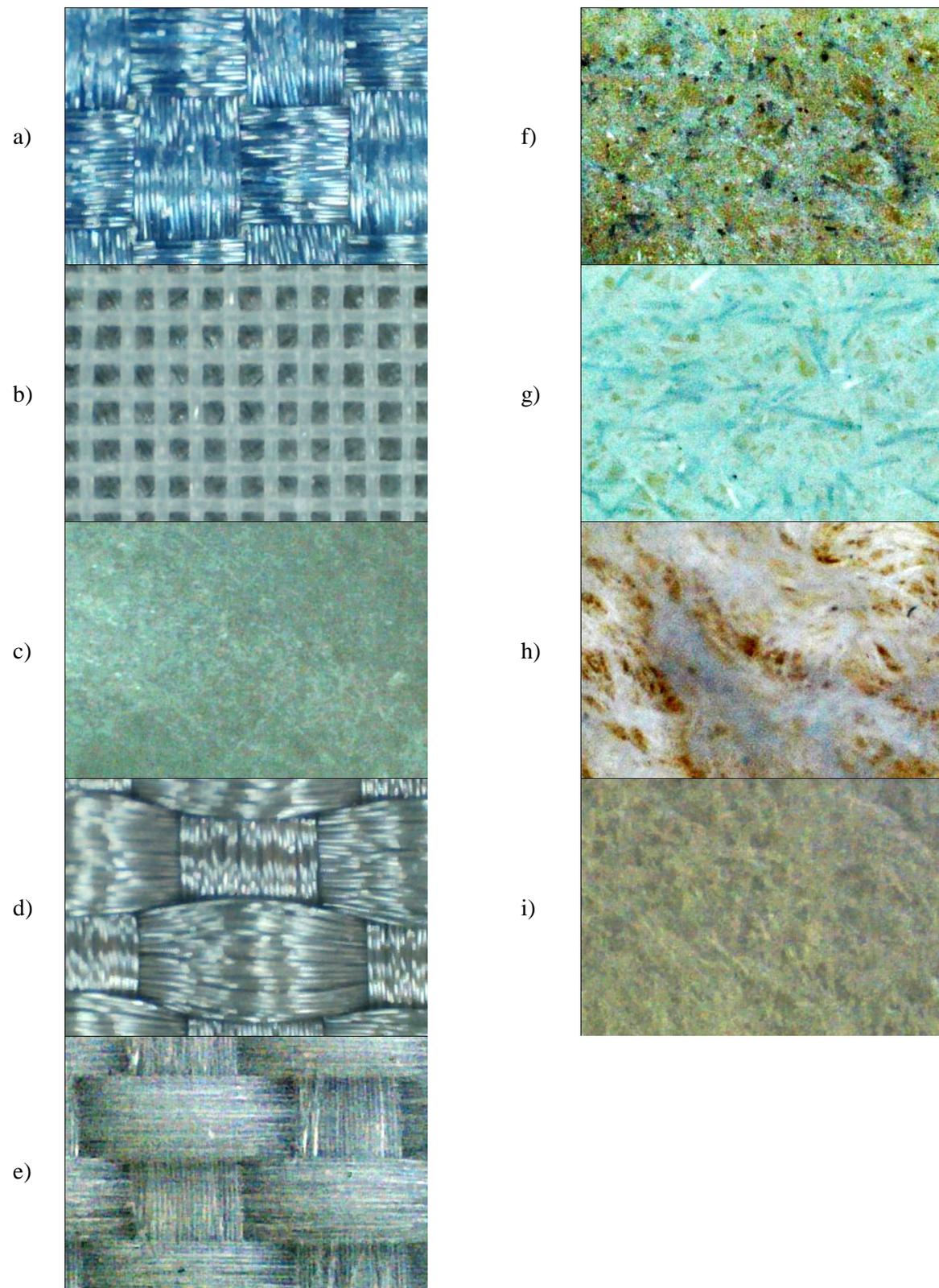


Figure 3. Polisher material (magnification $\times 45$): a) Bologna fabric; b) 0.09 mm Capron mesh, mesh size ~ 0.1 mm; c) 0.14 mm polyethylene film; d) laminated fabric (80% polyamide, 20% polyurethane); e) synthetic tent cloth with hydrophobic coating; f) VelTex polisher (Buehler); g) Microlap polisher (Remet); h) SK-8 artificial leather.

Table 4. Influence of polisher material on polishing capacity of lithium niobate single crystal.

	Polisher material	Coarseness parameters, μm					Q , $\mu\text{m}/\text{min}$
		R_a	R_z	R_q	R_{max}	R_t	
Woven	Bologna fabric	0.004	0.014	0.005	0.017	0.018	3.23
	0.09 mm Capron mesh, mesh size ~ 0.10 mm 0.12 mm;	0.001	0.010	0.002	0.012	0.013	0.61
	laminated fabric (80% polyamide, 20% polyurethane)	0.002	0.011	0.002	0.013	0.014	2.97
	synthetic tent cloth with hydrophobic coating	0.002	0.013	0.002	0.014	0.016	3.17
Unwoven	composite polisher on cellulose basis	0.001	0.007	0.001	0.008	0.008	0.29
	0.14 mm polyethylene film	0.001	0.009	0.001	0.011	0.012	1.78
	SK-8 artificial leather	0.001	0.005	0.001	0.007	0.007	1.12
	Microlap polisher, Remet and VelTex polisher, Buehler	0.001	0.006	0.001	0.006	0.007	2.91

It can be seen in Table 4 that the highest removal capacity was demonstrated by synthetic woven hydrophobic materials, such as laminated fabric, as well as by proprietary unwoven polishers: Microlap and VelTex. However, regarding coarseness, the woven polishers are slightly behind the unwoven ones. This can be attributed to higher elasticity and homogeneity of the structure of unwoven materials, providing more uniform grain protrusion in abrasive interlayer, as well as by good adaptiveness of polishers to processed surface of lithium niobate single crystal [4, 8].

Comparison of cumulative machine operation time Σt_{mach} summarized in Table 5, shows that upon processing of edge surfaces of a single crystal with low contact area the polisher resistance is determined not only by material strength but its structure as well.

Table 5. Polisher resistance.

	Polisher material	Resistance Σt_{mach} , min
Woven	Bologna fabric laminated fabric (80% polyamide, 20% polyurethane) synthetic tent cloth with a hydrophobic coating	~ 40-50
	0.09 mm Capron mesh, mesh size ~ 0.1 mm	~ 6-10
	Unwoven	0.14 mm polyethylene film
composite polisher on cellulose basis		~ 12-18
SK-8 artificial leather		More than
Microlap polisher, Remet and VelTex polisher, Buehler		120

As a consequence of the action of sharp edges of processed plates, the fibers of woven polishers are broken, local fractures and cuts appear on the polisher surface. Destruction of polyethylene film and composite polishers on the basis of cellulose occurs in a similar. The highest resistance was shown by unwoven polishers with pile structure: SK-8 artificial leather, Microlap polishers (Remet) and VelTex polishers (Buehler). Even after two hours of operation steady quality of polished surface was maintained, the polisher material was suitable for further processing.

Numerous studies in polishing of optic glass and some crystalline materials established [4, 13, 14] that the speed of polishing off or polishing capacity is proportional to average grain size of polishing powders. Herewith, depending on physicochemical properties of polisher and abrasive, there are upper and lower limits of grain size of the polishing powder. Thus, upon polishing of optical glass on pitch polisher by crocus grains finer than 0.4-0.5 μm no polishing takes place as a consequence of

incompressible water layer between polisher and processed surface [4]. The upper limit of grain size is restricted mainly by the quality of obtained surface.

In this regard polishing of lithium niobate by diamond suspension with the coarseness of 0.5/0 and concentration of 1/10 was tested in basic modes. The experiments were performed with polishers of different structure, thickness, and hardness of material: 0.14 mm polyethylene film, Bologna fabric, Microlap (Remet) and VelTex (Buehler). The obtained results are summarized in Table 6 and in Figs. 4-5. With the aim of comparison, the table shows data on polishing of single crystal by diamond suspension with the coarseness of 1/0.5 and the same concentration.

Table 6. Influence of suspension coarseness on polishing properties of lithium niobate single crystal.

Suspension	Polisher material	Coarseness parameters, μm			Q , $\mu\text{m}/\text{min}$
		R_a	R_z	R_{max}	
ASM 0.5/0	0.14 mm polyethylene film	0.001	0.009	0.010	2.44
	Bologna fabric	0.006	0.019	0.028	1.66
	Microlap polisher, Remet and VelTex polisher, Buehler	0.002	0.013	0.014	0.72
ASM 1/0.5	0.14 mm polyethylene film	0.001	0.009	0.011	1.78
	Bologna fabric	0.004	0.014	0.017	3.23
	Microlap polisher, Remet and VelTex polisher, Buehler	0.001	0.006	0.006	2.91

As can be seen in the table, upon polishing on thicker and softer (pile) polishers, such as laminated fabric, Microlap or VelTex, a decrease in suspension coarseness to 0.5/0 reduces significantly the speed of polishing off with the simultaneous deterioration of surface quality. Figures 4 and 5 shows photographs of polished surfaces of a single crystal with sufficiently large flat sections separated by sinuous lines looking like overlaps (Figure 3) or spotted slope cavities (Figure 5). In [3] such relief peculiarities of surface polished by fine abrasive are attributed to plastic flow of surface layers of crystals as a consequence of high local temperatures in the contact areas. Taking into account sufficiently high thermal stability of single crystals and relatively soft polishing modes, we suppose that such explanation of this fact is not consistent and requires additional experimental studies.

Our conclusions are confirmed by the results of polishing of single crystal by the same suspension but on 0.14 mm polyethylene film with more elastic and smooth working surface, summarized in Table 6 and in Figure 6.

Contrary to the previous case, upon polishing of single crystal on polyethylene film by ASM suspension with the coarseness of 0.5/0 the polishing capacity increased by about 30% and the coarseness parameters remained nearly unchanged. Herewith, the polished surface (Figure 6) has uniform smooth relief without noticeable defects. Moderate increase in polishing capacity at lower coarseness but the same weight concentration of the suspension can be attributed to increasing in the amount of cutting grains in the contact tool/processed surface.

Aiming at final substantiation of polisher selection we performed a comparative analysis of deviation from linearity of the surface of the single crystal. Deviation of shape upon mechanical polishing on SK-8 leather is by about three times lower than upon manual polishing. This is quite natural and can be explained by two reasons. Firstly, the proposed engineering equipment for fixation of plates of single crystals provides good self-adjustability of processed surfaces by at least three points. Secondly, processing of plate pack significantly increases contact surface area, provides more uniform removal over the surface and eliminates the generation of tumbles at the plate edges as it occurs upon manual polishing. Upon polishing on VelTex polisher (Buehler), the errors of geometry are even lower, which can be attributed to more uniform structure and thickness of working layer in comparison with SK-8 leather.

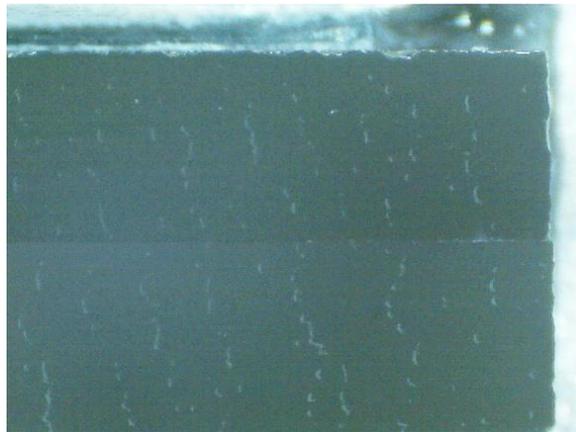
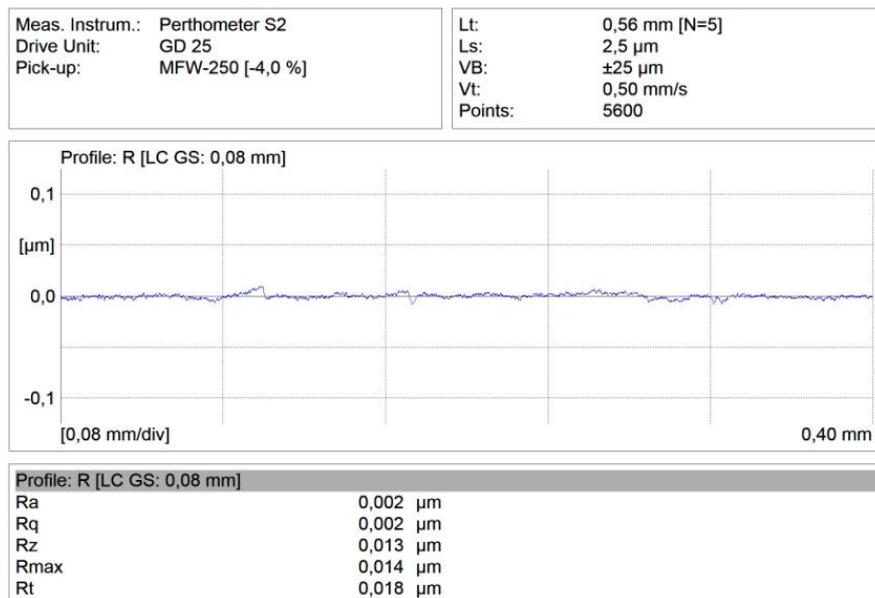


Figure 4. Coarseness and surface pattern of single crystal after polishing by ASM 0.5/0 suspension on VelTex polisher (magnification $\times 50$).

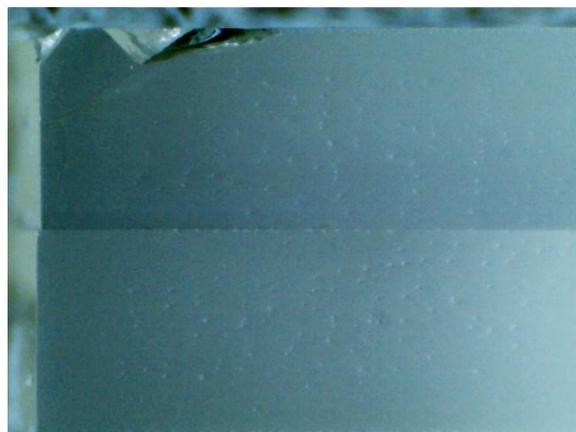


Figure 5. Surface pattern of single crystal after polishing by ASM 0.5/0 suspension on polisher made of Bologna fabric (magnification $\times 50$).

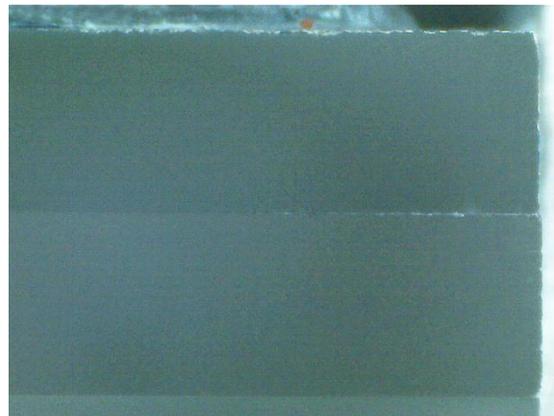
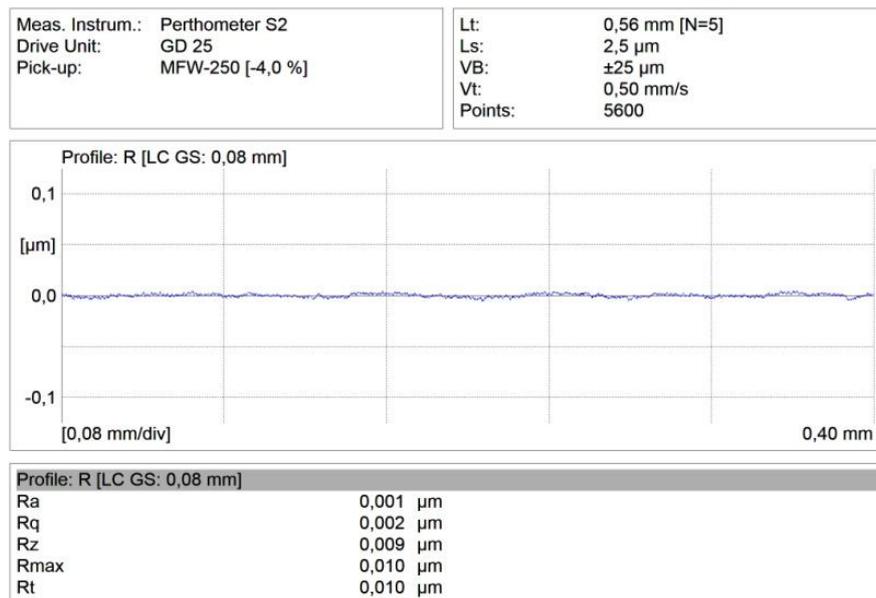


Figure 6. Coarseness and surface pattern of single crystal after polishing by ASM 0.5/0 suspension on polyethylene film (magnification $\times 50$).

4. Conclusions

The following polishing modes of lithium niobate single crystal can be recommended for the proposed polishers, *Microlap* (Remet) and *VelTex* (Buehler): polisher rotation speed 150-250 rpm and pressure 50-100 kPa, which provide the required quality and sufficient polishing capacity. When polishing cycle time varies from 3 min to 12 min at constant suspension supply, the polishing capacity remains unchanged. Upon finishing abrasive processing of crystalline materials, in particular, plate edges of lithium niobate single crystal, in the first approximation, in order to calculate total depth of layer destroyed by finishing and minimum polishing time required for its removal the following expressions can be applied: $F \approx 12 \cdot R_{max} \mu\text{m}$; $T_{un} \approx F / Q_{min}$.

Thus, it is experimentally established that upon basic pressure both for woven and unwoven polishers with the highest capacity the lower limit of grain coarseness of polishing suspension is 1/0.5 μm . Herewith, taking into account the best properties regarding resistance of polisher working surface and quality of processed surface of the single crystal, the following materials of overall considered list can be recommended for mechanized polishing: SK-8 artificial leather, *Microlap* polisher (Remet) and *VelTex* polisher (Buehler).

In addition, it has been established that mechanized polishing with the application of the proposed engineering auxiliaries in comparison with manual polishing enables an increase in accuracy of the

geometry of the processed plate surface in three times. A reserve of increase in shape accuracy and polishing quality is the use of polishers with equal thickness and structure of working surface.

Acknowledgments

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