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Magnetorheological Polishing Technology Application for High-Precision Optical Elements

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ABSTRACT

The technology of magnetorheological polishing is widely utilized in the processing of high-precision optical elements. One of the critical factors in magnetorheological polishing technology is the nature and quality of the nanocrystalline abrasives present in the magnetorheological suspension. This study presents a method for the magnetorheological polishing of water-soluble Potassium Dihydrogen Phosphate (KDP) crystals, which are employed in the fabrication of nonlinear optical elements in laser technology. The magnetorheological suspension is enhanced with a nanocrystalline abrasive composed of amorphous silicon dioxide, synthesized through the sol-gel process. The incorporation of nanocrystalline abrasives contributes significantly to the uniformity and surface quality of optical elements processed with the magnetorheological suspension. The introduction of SiO2 nanocrystalline abrasive into the magnetorheological suspension has enabled the achievement of high processing quality and surface purity, facilitating the final polishing of KDP single-crystals to a roughness value not exceeding 6 Å.

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Abbreviations

RMS: Root Mean Square Roughness of the Surface, Å
RA: Arithmetic Average Deviation of the Surface Profile, Å
F: Shear: Shear Force
F: Normal Force

Introduction

Monocrystals of Potassium Dihydrogen Phosphate (KDP) are an extremely valuable and indispensable material for nonlinear optics. They are widely utilized as frequency converters and electro-optic switches across various fields of physics and engineering [1]. Moreover, KDP crystals exhibit a brittle-ductile behavior, making them challenging to mechanically process due to their thermal sensitivity, susceptibility to fracture, hygroscopic nature, and ease of scratching [2].

One area of research within the development of magnetorheological polishing technology for optical materials involves investigating the physicochemical principles underlying the controlled removal of material from the surface of Nonlinear Optical Elements (NOEs) as well as examining the factors that determine the surface roughness of NOEs.

The current state of laser technology demands that the surface roughness of optical components approaches an atomically smooth finish. This imposes stringent requirements on the shape, size, and dispersity of the abrasive materials utilized in magnetorheological polishing compositions. For finishing the polishing of high-tech materials and laser optical products, compositions containing SiO_2 particles have gained significant application. Currently, one of the most commonly used materials as an abrasive component in finishing polishing formulations is aerosil (Pyrogenic Silicon Dioxide). However, a primary drawback of aerosils is the broad size distribution of particles and their irregular shape. In this study, nanosized abrasive silica powder (SiO_2) was produced via a modified sol-gel method, which enabled the control of particle shape and size, yielding a product of high chemical homogeneity and purity.

Magnetorheological materials are liquid compositions whose viscosity changes in the presence of a magnetic field. Magnetic fluids, being artificially synthesized materials, can be easily manipulated by magnetic fields. When a magnetic fluid is subjected to an external magnetic field, its behavior and physical properties, such as viscosity and elasticity, can be readily altered [3]. Magnetorheological materials consist of ferromagnetic or paramagnetic particles with a diameter of no less than 0.1 µm, dispersed within a base fluid. In the presence of a magnetic field, these particles become polarized and organize into chains. The formation of these particle chains results in an increase in the hydrodynamic resistance of the material and its viscosity. In the absence of a magnetic field, the particles revert to a free, disorganized state, which results in a decrease in the hydrodynamic resistance of the material. Hence, various compositions of magnetic fluids exhibit controllable magnetorheological properties.

Magnetorheological Polishing (MRP) of optical element surfaces is globally recognized as one of the most promising smart methods for the finishing treatment of optical surfaces. MRP enhances surface roughness, eliminates microcracks and surface imperfections, and reduces residual stresses. MRP is a high-quality surface processing method based on the controlled alteration of the rheological properties of the polishing magneto sensitive material in the treatment zone induced by an external magnetic field. The mechanical (or Rheological) properties of the magneto sensitive material, which is a flowable suspension of a fine-dispersed filler in a dispersion medium, undergo significant changes in a magnetic field. This material transitions into a viscoelastic medium characterized by the emergence of a noticeable yield stress, with an increase in shear viscosity by several orders of magnitude [4].

It has been demonstrated that magnetorheological sub-aperture polishing effectively smooths various structural defects on surfaces. This method allows for the processing of challenging optical materials that are difficult to finish, such as soft polymer polymethyl methacrylate, microstructure polycrystalline zinc sulfide, and KDP. In study, the MRP method successfully removed surface waviness from KDP crystals, reducing the Root Mean Square Roughness (RMS) to 2 nm while improving the laser damage threshold [5]. Nanodiamond particles dispersed in a dicarboxylic acid ether were used as the abrasive. Cerium oxide (IV) (CeO2) can also be incorporated into the magnetorheological polishing composition for the finishing of optical products as an abrasive [4-6]. The authors of work utilized a complex magnetic composition based on a non-aqueous medium for polishing the surfaces of KDP crystals [7]. This composition contains a dispersive phase consisting of carbonyl iron powder (with an average particle diameter of 3 µm) at a concentration of 39.96 wt.% and Fe3O4 powder (with an average particle diameter of 20 nm) at 25.04 wt.%, which acts as the abrasive. The dispersive medium (carrier liquid) consisted of dodecanol (dodecan-1-ol) at a concentration of 20 wt.%, supplemented with surfactant (Triton X-100) and a thickening gelling component (α-cellulose). When treating the surfaces of KDP crystals with this magnetorheological composition, the principle of physicomechanical action of the abrasive within a microemulsion of the "water-in-oil" type is implemented. However, the stability and operational properties of such a magnetorheological composition are relatively low. In high-intensity shearing flow conditions, irreversible destruction of the spatial network of the thickener occurs, leading to a loss of the gelling properties and stability of the composition. The presence of the surfactant (Triton X-100) degrades the surface quality and optical properties of KDP crystals due to its adsorption.

The carrier liquid can be water or an organic indifferent solvent. For instance, in work, ionic liquids were incorporated into the magnetorheological composition. Our developed Magnetorheological Suspension (MRS) is employed in the polishing technology for optical surfaces of KDP monocrystals. From the perspective of colloid chemistry, MRS represents a stable, highly concentrated dispersed heterogeneous system of lyophobic type with a high degree of lyophilization of stabilized magnetic material particles and non-magnetic abrasive material particles in a dispersion medium. The primary physicochemical property that determines the operational conditions of MRS in magnetorheological polishing is the aggregative stability of this colloidal system coupled with the high dispersity of the magnetic phase [8-12].

The three main components of the MRS are magnetic iron particles, abrasive polishing powder, and the carrier liquid. Variations in these components enable the application of MRP in the production of precision optics from water-soluble crystals, glasses, ceramics, and other materials [13,14]. Carbonyl iron particles enhance the magnetic permeability of magnetorheological materials and modify it under the influence of a magnetic field, making it stiffer. The nanodiamond particles fill the voids between the magnetized chains of iron within the MRS structure. Figure 1 shows images of the MRS in the absence of a magnetic field (a) and in the presence of a magnetic field (b). The structuring of carbonyl iron powder particles in the magnetic field and the alignment of chains along the magnetic field lines are clearly visible. Picture of carbonyl iron particles obtained using a scanning electron microscope (c) shows the spherical shape of the particles and the smooth morphology of their surface. The main fraction (more than 90%) is represented by particles with a diameter of 5–6 microns.

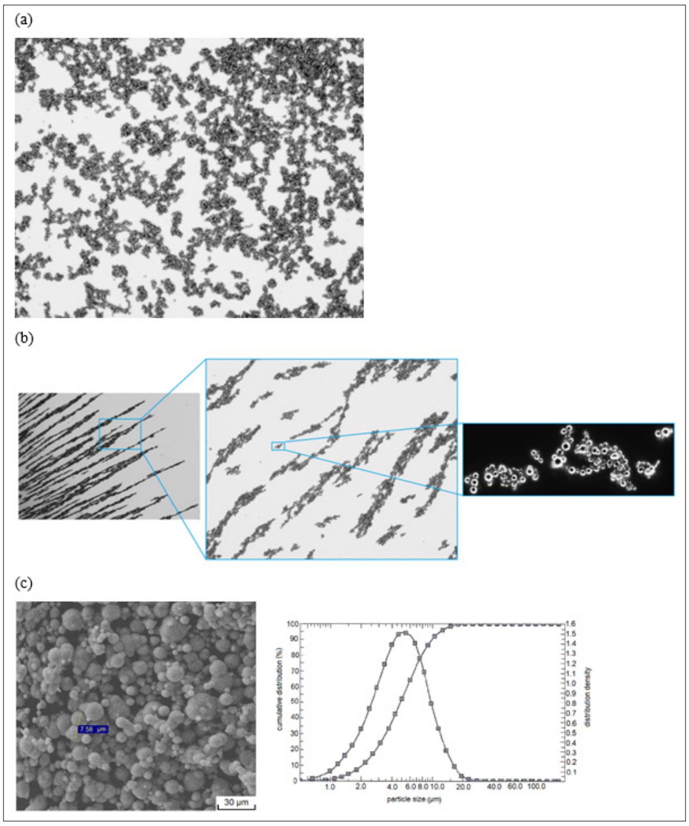


Figure 1a: Photograph of the magnetorheological suspension outside the magnetic field.
Figure 1b: Photograph of the magnetorheological suspension in the presence of a magnetic field.
Figure 1c: SEM image of the particles of carbonyl iron grade P-10 (with an inset showing the distribution density plots and the cumulative distribution curve of the P-10 carbonyl iron particles as a function of their size).

For water-based magnetorheological suspensions (MRS) that contain magnetic iron powder, a critical task is to prevent particle aggregation into agglomerates and sedimentation. Conditions must be created to ensure the aggregative stability of MRS. Traditional methods for addressing these issues, which involve reducing the size of solid-phase particles and increasing the viscosity of the dispersion medium, are not effective for stabilizing MRS. Firstly, the particle size is limited on the lower end to approximately 0.5 µm. Secondly, the use of highly viscous dispersion media in MRS is not practical due to the resultant decrease in the flowability of the suspension. In the case of low-concentration suspensions, colloidal stabilizers are introduced into the dispersion medium to provide reinforcing properties, creating a "spatial grid" that prevents the sedimentation of solid-phase particles. For concentrated MRS, stabilization can be achieved by the adsorption of surfactants (surfactants) onto the surface of the solid-phase particles. The adsorbed surfactant molecules improve the wetting of the solid particles by the dispersion medium and facilitate dispersion through the Rebinder effect (the wedging effect), thereby promoting an even distribution of particles throughout the MRS volume. The formation of agglomerates, as well as non-redispersible solid sediments, can be fully or partially avoided by using appropriate dispersing agents. In study, thiophosphorus and thiocarbamate compounds were proposed as dispersing agents for magnetizable particles to enhance their colloidal stability [15]. In study, the use of oleates, naphthenates, sulfonates, complex phosphate esters, laurates, stearates, oleates, and fatty alcohols as dispersing agents is described. Studies suggest using ethoxylated alkylamines as surfactants [16-18].

The thermodynamic and kinetic stability of water-based polishing MRS is dependent on the extent of corrosion susceptibility of the carbonyl iron particles. The formation of oxidation products on the surfaces of particles can irreversibly alter the physicochemical conditions at the "solid phase-liquid" interface, potentially impacting the rheological properties of MRS (effective viscosity, shear stress in the absence of a magnetic field). Inhibiting and protecting against corrosion is a significant challenge in developing MRS.

Achieving surfaces with sub-nanometer roughness is one of the primary goals in the optical and semiconductor industries [19]. Magnetorheological polishing allows for the removal of ultra-thin layers of material without destructively deforming the treated surface, making this method highly suitable for polishing thin films and layers on the nanometer scale.

The aim of the present work is to develop a magnetorheological polishing technology for the surface of nonlinear optical elements made from KDP monocrystals for application in laser technologies.

Experimental Section

Materials and Methods

The following reagents were employed in this study: monobutyl ether of diethylene glycol (reagent grade, ≥99.9%), isopropyl alcohol (IPA) (reagent grade, ≥99.9%), colloidal silicon dioxide "Polisorb MP", and carbonyl iron of radio technical grade "R-10".

Microphotographs of the surface of KDP monocrystals, as well as the solid-phase particles of the magnetorheological suspension, were obtained using an optical microscope ZEISS Axio Imager Vario. The roughness of the nonlinear optical elements (NOEs) surface post magnetorheological polishing was assessed using a Zygo Maxim GP-200 microprofilometer.

The morphology and microstructure of P-10 grade iron particles and SiO_2 silica were studied using scanning electron microscopy (SEM). Microphotographs of the samples were obtained on a JSMIT300LV microscope (JEOL) with an electron beam diameter of approximately 5 nm and a probing current of less than 0.5 nA. The surface topography of the samples was examined using low-energy secondary and backscattered electrons.

The morphology of the nano-abrasive was investigated with an atomic force microscope (AFM) NTEGRA II equipped with a SMENA head in Semi-Contact mode, utilizing high-resolution silicon cantilevers from the NSG01 series (resonance frequency of 150 kHz, spring constant of 5.1 N/m). The cantilevers are coated with a gold reflective layer to enhance the laser signal. The results were processed using the Nova SPM 1.2 software package.

To clean the surfaces of KDP crystals, an Ultrasonic Cleaner Set WUC-A03H was utilized, operating at a frequency of 50 Hz and an ultrasonic power of 70 W. Before and after mechanical polishing (MP), the KDP crystals were immersed in an inert organic solvent (IOS, isopentane) and treated in the ultrasonic bath for 10 to 15 minutes at a temperature of 18 to 22 °C.

The synthesis of SiO_2 abrasive nanoparticles was performed according to the methodology outlined in reference [20].

Magnetorheological Polishing of KDP. Magnetorheological polishing of the NOE surfaces made from KDP monocrystals was conducted using equipment produced by the State Scientific Institution "Institute of Thermal and Mass Transfer named after A.V. Lykov of the National Academy of Sciences of Belarus". Nonlinear optical elements were produced from KDP monocrystals, which were grown by a rapid crystallization method from a supersaturated aqueous solution [21]. Figure 2 shows the image of the NOE.

The surface of the KDP was initially treated using a dry micro-milling method with a diamond tool [22].

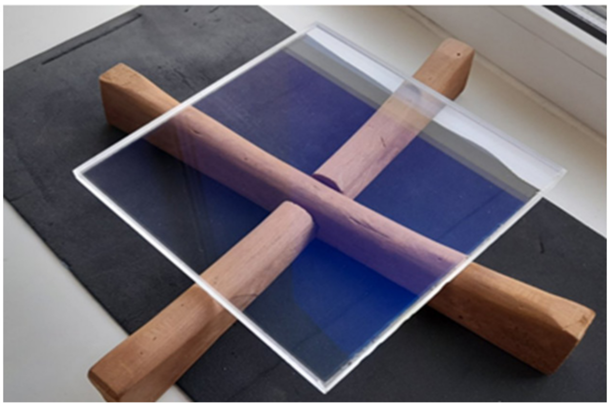


Figure 2: Photograph of a nonlinear optical element made from monocrystalline KDP crystal sized 180x180x10 mm.

The surface processing of the workpiece is conducted using the magnetorheological suspension, which serves as the working tool. The MRP method is based on the alteration of the rheological properties of the MRS under the influence of a magnetic field. In the magnetic field, the MRS transforms from a liquid consistency to a viscoplastic suspension capable of polishing surfaces. Our experiments have demonstrated that the use of colloidal magnetic fluids with ferromagnetic particles sized 5–50 nm is insufficient for implementing the technology of magnetorheological polishing of NOEs. The success of the new technology is ensured by MRS, which includes a Dispersive Phase (Organic Indifferent Carrier Liquid), magnetic particles (Carbonyl Iron), Nanomaterial (Nanosized SiO_2 Powder), and chemical stabilizers (Surfactants, Corrosion Inhibitors, etc.) [9]. Unlike typical magnetic fluids, this composition features relatively large ferromagnetic particles of carbonyl iron (Averaging 0.5 µm), which allows for the control of liquid shape and rapid changes in its internal structure when a magnetic field is applied. The time for restructuring (Structuring and Magnetic Sedimentation of the Liquid) in the magnetic field is a few milliseconds. The carbonyl iron particles have a spherical and smooth surface with diameters ranging from 200 nm to 4 µm. They are significantly harder than the KDP crystal, making them capable of removing material and potentially causing scratches on NOE surfaces during magnetorheological processing (see Figure 3).

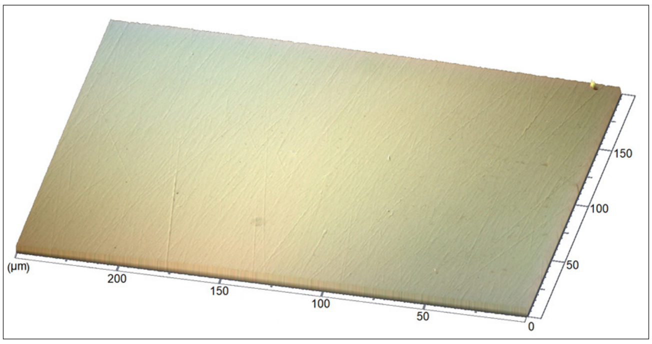


Figure 3: Surface topology of the nonlinear optical element with scratches caused by the impact of iron particles during polishing.

For the magnetorheological polishing of KDP monocrystal surfaces, the carrier liquid must be non-aqueous, low-volatility, non-flammable, and inert towards the crystal surface and carbonyl iron particles. In this study, monobutyl ether of diethylene glycol was used.

The principle of MRP involves positioning the optical element to create a gap between the surface of the NOE being processed and the stream of MRS. When the MRS stream approaches the NOE surface, a working zone (contact spot) is formed where material is removed from the NOE's surface. The magnetorheological polishing module consists of a tool block and a circulation block for the MRS (Figure 4).

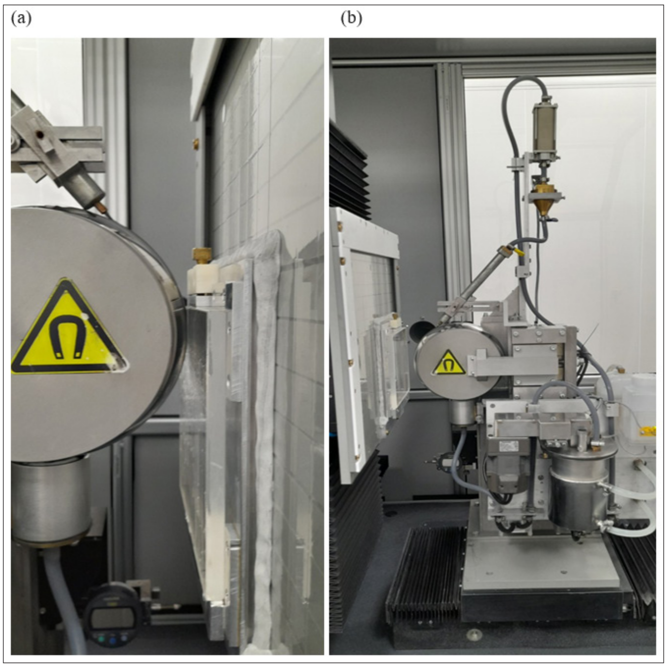


Figure 4a: Photograph of the magnetorheological polishing module: tool working block.
Figure 4b: Photograph of the magnetorheological polishing module: magnetorheological suspension circulation block.

During the magnetorheological polishing process, the suspension is delivered from a nozzle onto the solid, non-magnetic surface of a rotating tool (wheel). A permanent magnet is situated inside the wheel. The magnetic field imparts plastic properties to the MRS, characterized by a yield stress that depends on the magnetic field strength and the composition of the suspension. The surface of the part being processed is brought into contact with the MRS while maintaining a constant gap between them. The influence of a non-uniform magnetic field (around 0.3 T) occurs in the contact zone between the processing surface and the MRS, forming a sufficiently small local working processing area – the contact spot. In the working area, a solid core forms, while in the region between the core and the processing surface, where shear stresses are minimal, a shear flow of the thin liquid phase of the MRS occurs. The solid core and the liquefied layer together form the polishing system. The core acts as an elastic substrate, while the thin layer of liquid phase containing the abrasive nanoparticles SiO_2 serves as the polishing medium. Unlike traditional hard grinding technology, which requires prolonged adjustment (lapping) of the tool to the processing surface, MRP allows for instantaneous adaptation of the processing surface and MRS in the contact zone. To process a specified area, the working zone must be moved according to a specific algorithm, which is implemented through a defined kinematic scheme of the equipment. A processing program is created for this purpose, taking into account the number of passes, the trajectory, and the speed of the part's processing surface relative to the tool base. The effect of the MRS on the material can be studied by measuring the topography of the processed surface.

One of the primary objectives of this study is to develop a magnetorheological suspension with high stability that achieves the Required Surface Roughness (RMS no more than 15 Å) for water-soluble crystals of the KDP group during polishing. The technical result was achieved by including a nanoabrasive in the form of SiO_2 powder, which was produced via a modified sol-gel method [9].

Results and Discussion

Figure 5 shows the topography of KDP sample surfaces obtained by treatment with a magnetorheological suspension that did not contain SiO_2 abrasive nanoparticles. As shown in Figure 5, after magnetorheological polishing, the surface of the KDP sample exhibited a high number of scratches and comet-tail type defects. However, the surfaces of the KDP samples after MRP with a suspension containing SiO_2 nanoparticles (Figure 5b) showed significantly fewer scratches and defects. These results demonstrate that using spherical SiO_2 nanoparticles ensures a considerable improvement in the surface processing quality of KDP crystals.

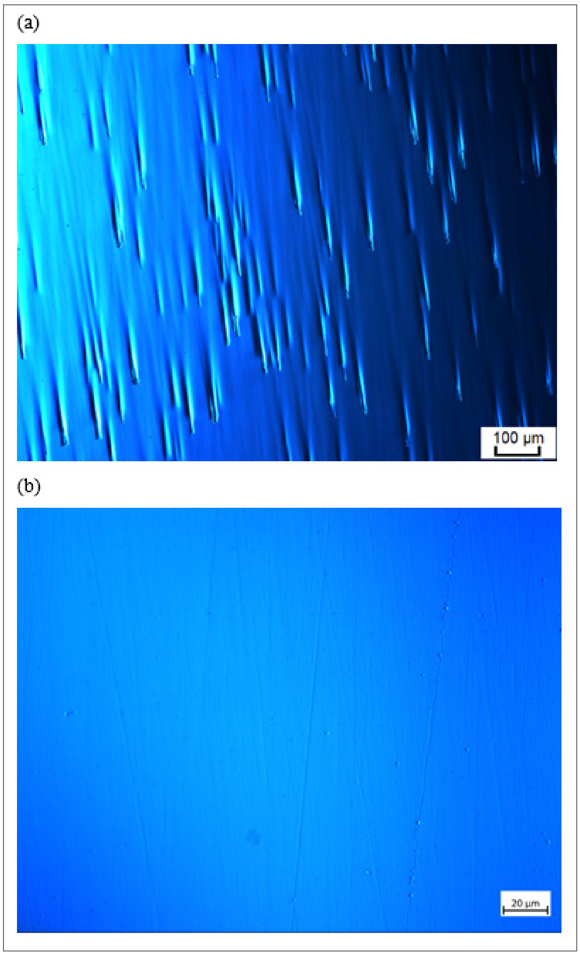
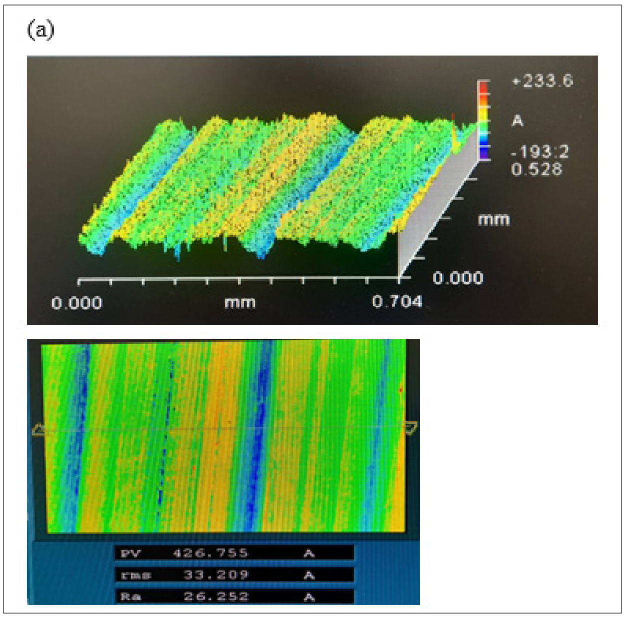
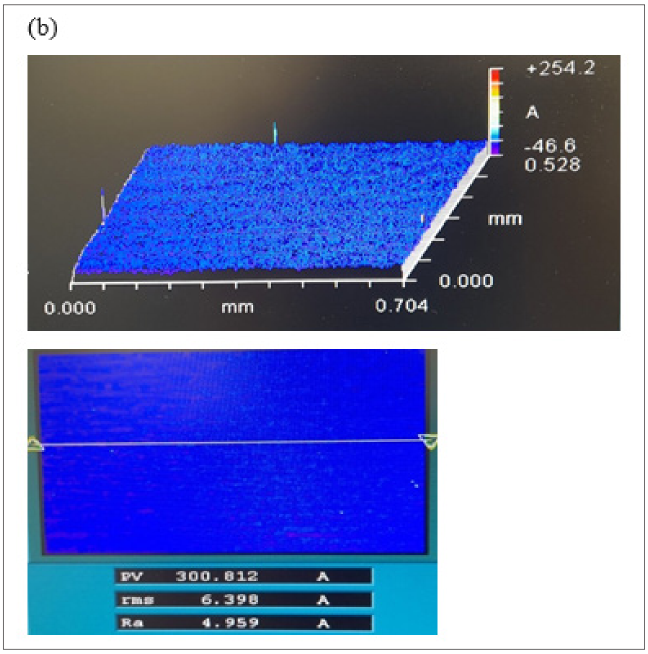


Figure 5a: Photograph of the nonlinear optical element surface after magnetorheological polishing: without SiO_2 nanoabrasive.
Figure 5b: Photograph of the nonlinear optical element surface after magnetorheological polishing: in the presence of SiO_2 nanoabrasive.

Figure 6 presents the results of the characterization of the polished KDP surface.



PV 426.755 A
rms 33.209 A
Ra 26.252 A



PV 300.812 A
rms 6.398 A
Ra 4.959 A

Figure 6a: Surface roughness assessment before magnetorheological polishing, rms = 33.2 Å.
Figure 6b: Surface roughness assessment after magnetorheological polishing, rms = 6.4 Å.

Analysis of the surface topography of the KDP sample before and after magnetorheological polishing (MRP) indicated that after diamond micro-milling, the surface relief was formed under the influence of the motion of the cutting tool. In contrast, the topography of the sample surface after MRP does not exhibit a diffraction grating and is represented by a less textured profile, shaped by the action of the magnetorheological suspension. After MRP, there is a fivefold reduction in the surface roughness parameters (RMS). The roughness of the KDP sample surface (Ra, arithmetic mean deviation of the profile) after MRP was measured at 5 Å.

We conducted a study on the synthesized nano-abrasive. Atomic force microscopy (AFM) revealed that the spherical silica (SiO_2) nanoparticles exhibit a monodisperse distribution and are subject to agglomeration (see Figure 7a, b, and c). The AFM results indicate that the nanopowder contains particles with sizes ranging from 10 to 50 nm, with the majority (over 80%) falling within the 10 to 20 nm range. These findings are illustrated in the form of a histogram depicting the particle size distribution (refer to the inset in Figure 7a).

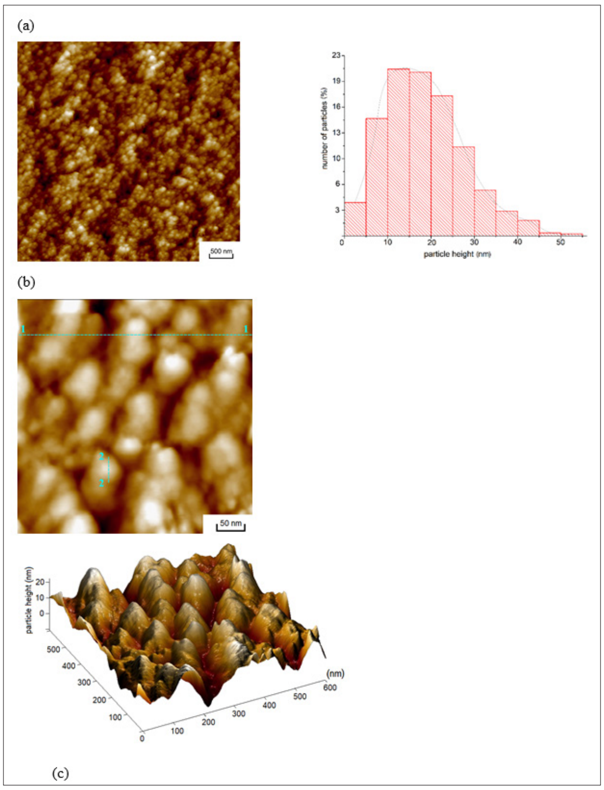


Figure 7a, 7b: AFM images of the synthesized silica (SiO_2) nano-abrasive particles, with an inset showing the histogram of the particle height distribution of the SiO_2 nano-abrasive.
Figure 7c: Topography of the SiO_2 nano-abrasive particles on a quartz substrate, with insets displaying the surface profile sections along the measurement lines 1–1 and 2–2.

On the surfaces of some KDP samples after MRP, we recorded isolated point depressions and elongated cavities with depths of 5–10 nm. These defects are likely due to imperfections in the internal structure of the crystal, which become exposed during MRP. Upon re-processing, these defects become less noticeable as they are completely smoothed out.

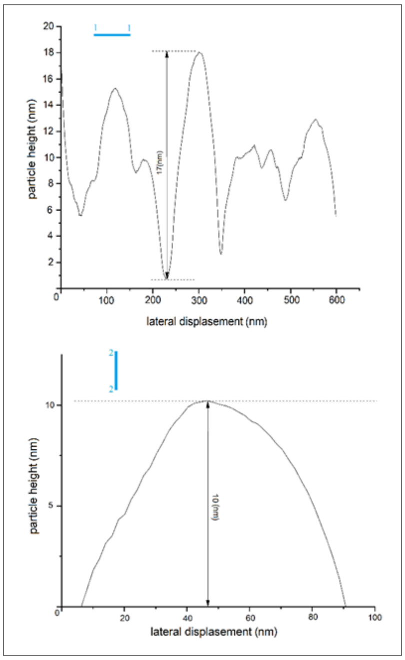


Figure 8: Surface topology of the nonlinear optical element with defects in the form of chips and pits.

During MRP, growth defects manifested as surface scratches on some KDP samples. As seen in Figure 9, the scratches exhibit varying depths, directions, and shapes. The morphology of the scratches differs significantly in various directions due to the anisotropy of the KDP crystals. Some growth defects are observed as rough steps.

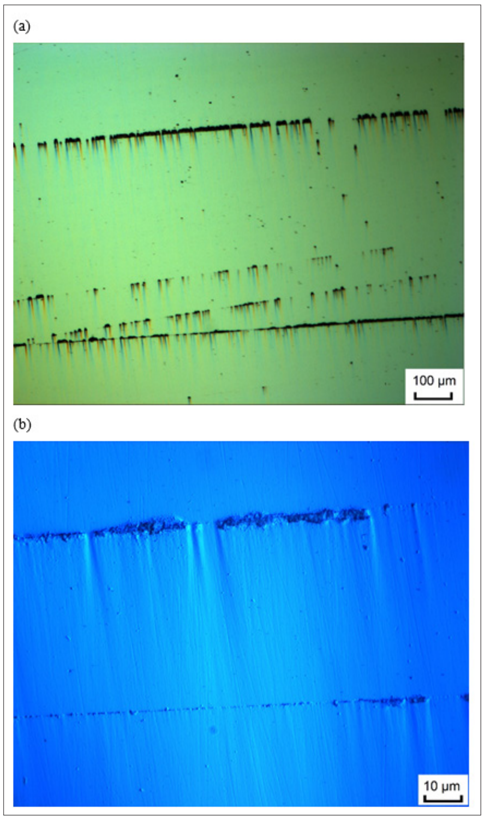


Figure 9a: Photograph of the nonlinear optical element surface with growth defects in the form of elongated scratches that occurred during magnetorheological polishing.
Figure 9b: Photograph of the nonlinear optical element surface with growth defects in the form of steps that occurred during magnetorheological polishing.

Contamination of the NOE surface may occur during MRP. This is likely caused by the adsorption of certain MRS components onto the active regions of the KDP surface. Figure 10 shows the formation of a pattern consisting of amorphous SiO_2 particles adsorbed onto the NOE surface.

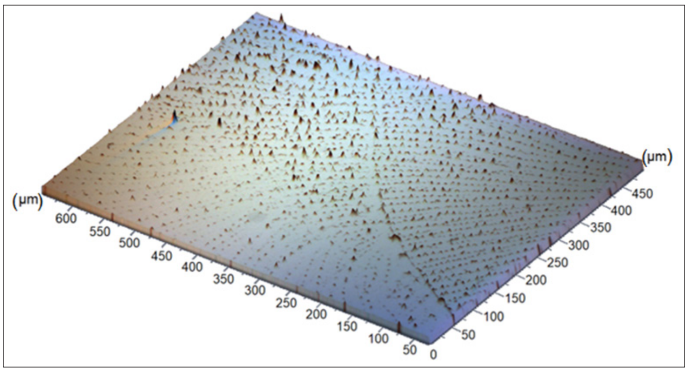


Figure 10: Surface topology of the nonlinear optical element contaminated with residues of the magnetorheological suspension.

To remove residual contaminants after magnetorheological polishing, the NOE surface was subjected to ultrasonic cleaning in an inert organic solvent (IPA).

Since KDP is an important nonlinear optical material, a critical problem in high-intensity lasers is the damage to NOEs caused by high energy density of laser radiation. Any defects and contamination of the NOE can reduce the threshold for laser-induced damage to the KDP surface by more than 30% [23]. Our experiments have shown that MRP effectively removes mechanical damage and defects from the NOE, achieving a high surface quality resistant to intense laser pulses.

On the mechanism of magnetorheological polishing. The mechanism of material removal in magnetorheological polishing remains a topic of considerable debate and is not yet fully understood [24]. Polishing using fine abrasive powder materials can be represented as a combination of processes involving mechanical action of the solid phase of the MRS, surfactant adsorption on the processed surface, wetting of the surface by the liquid phase of the MRS, and removal of the surface layer material due to abrasive action. Thus, the finishing MRP represents a mechanochemical process occurring in the surface layer of the processed material [25,26].

Within the theoretical framework of the MRP mechanism, we assume that all abrasive nanoparticles of SiO_2 have the same size and spherical shape. The magnitude of the normal component of the magnetic force acting on each abrasive particle, transmitted by the chains of iron particles formed under the influence of the magnetic field, is assumed to be uniform.

The material removed from the surface, when mixed with the MRS, does not alter its magnetic, rheological, or mechanical properties. There is no chemical interaction between the MRS and the KDP surface.

Within the MRS volume, the abrasive nanoparticles SiO_2 and iron particles are randomly mixed with the liquid phase. As a result, many abrasive particles do not come into contact with the KDP surface and remain inactive. Active abrasive particles are in direct contact with the KDP surface and are responsible for its processing. During MRP, abrasive particles move toward the region of low magnetic field (the surface of the NOE), while iron particles move toward the area of high magnetic field (the surface of the wheel) [27]. Consequently, the levitation force of the magnetic field compresses the abrasive particles against the KDP surface. It is assumed that only SiO_2 abrasive nanoparticles that participate in material removal operate in the contact spot with the KDP surface. During movement, the abrasive particles also experience a compressive force in the narrowing gap of the MRS relative to the surface of the KDP crystal. The components of this force combine with the normal force.

In polar liquid media, SiO_2 nanoparticles are prone to strong agglomeration. For this reason, it is reasonable to introduce surfactants into the MRS to reduce the surface energy of the particles and prevent their agglomeration. Experimental data indicate that effective control can be achieved through the ultrasonic treatment of MRS prior to use.

Under the influence of a strong magnetic field (greater than 0.3 T), the viscosity of the magnetorheological suspension increases by more than a thousand times, causing the suspension to "freeze," thereby separating into two layers: the first consisting of structured, loosely bound ferromagnetic particles, and the second composed of the liquid phase with nanoabrasives. The difference in the velocity of movement between the base of the polishing tool and the processed part generates shear deformations in the MRS, allowing the removal of thin layers of material from the surface (see Figure 11a). Upon removal of the magnetic field, the MRS returns to its original unstructured state. This behavior characterizes it as a smart material and the process as rapid.

The embedding of nanoabrasive particles into the surface layers of the KDP crystal occurs due to the normal force applied to them by the surrounding magnetic particles and the force generated by the compression of the MRS stream (see Figure 11b).

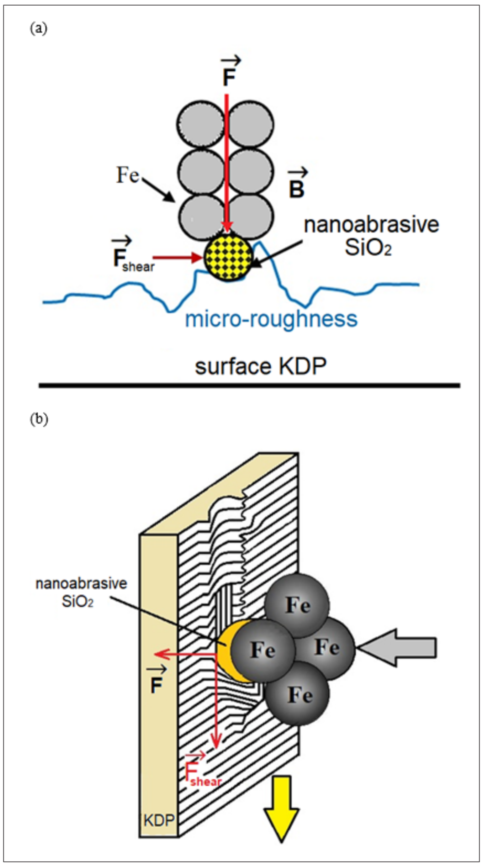


Figure. 11a: Schematic representation of the mechanism of action of SiO_2 nanoabrasive during magnetorheological polishing of the KDP monocrystal surface – removal of the finest material layers from the surface.

Figure 11b: Schematic representation of the mechanism of action of SiO_2 nanoabrasive during magnetorheological polishing of the KDP monocrystal surface – embedding of nanoabrasive particles into the surface layers of the material.

The combination of shear force (F-shear) and the normal force (F) applied to each nanoparticle generates sufficient pressure to ensure that each nanoparticle penetrates the surface layer of the material to a certain depth. This process results in material removal from protrusions and the reduction of surface micro-roughness.

Conclusion

The introduction of SiO_2 nanoabrasives into the composition of the magnetorheological suspension enabled the achievement of high processing quality and surface cleanliness, as well as the finishing polishing of KDP monocrystal surfaces. Magnetorheological polishing utilizing SiO_2 nanoabrasives facilitates the removal of defective surface layers, thus reducing surface roughness to sub-nanometer levels.

The results of this work are of interest for optimizing the MRP process and advancing the technology. Furthermore, analyzing the needs of high-tech industrial production in precision surface processing and the potential modes of magnetorheological polishing reveals key directions for the application of this technology, including:

- Elimination of crack-prone and defective layers formed during preceding operations to enhance the beam strength of laser system components made from water-soluble crystals;
- Finishing treatment of thin films, coatings, layers with nanometer thickness, as well as polishing of aspherical and metal-optical elements.

The authors of this work declare that they have no conflict of interest.

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