Experimental study of scientific hypotheses used in the processing of optical parts by diamond turning

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***Abstract*— The article presents three scientific hypotheses about the impact of technological factors influencing the quality factors of optical details (crystals) processed by diamond turning. Diamond turning is an innovative process for processing details with complex geometric shapes, it is also used in the processing of optical details with crystal structure (germanium, silicon). The experiments were conducted in real production conditions reflecting the influence of technological factors on the quality of surfaces in the processing of optical parts. The three hypotheses related to the machine parameters are confirmed by the conducted research, and the results are presented in tabular form.**

***Keywords*— Hypotheses, diamond turning, optics, experiments, optical crystals.**

I. INTRODUCTION

Single Point Diamond Turning (SPDT) ultra-precision diamond turning is one of the most successful technologies in the field of precision engineering in the last few decades. This is not only because SPDT integrates a number of state-of-the-art precision engineering technologies, such as ultra-precision machine tool design, high-speed machining and ultra-precision air damage, high strength and ultra-precision hydrostatic sliders, multi-axis servo computer program control (CNC), finely polished single crystal diamond cutting tool, precision metrology. Purely informative SPDT technology is already applied in a wide range of science and technology: protection, energy, consumer products [1].

Ultra-precision diamond turning is a technology that uses single-crystal diamond tools and ultra-precision machine tools to produce precision-shaped components with a deviation of less than a micrometer and a surface roughness of less than ten nanometers. [2].

The precision of diamond turning and the ability to process different types of materials make this process suitable for the processing of crystalline optical elements. Diamond turning is used in optical production for the processing of complex optical crystals. Examples of such details are fresnel lenses. Fresnel lenses differ from other lenses in that one of the surfaces has a stepped profile in meridional section. This is done in order to obtain an image without aberrations of the axial object point. The steps can be distinguished by concentric, spiral or parallel channels. In the first two cases the surface of the steps is part of a sphere or cone, and in the third - part of a plane or cylinder. The smaller the distance between adjacent steps, the more precisely the condition for reduction of residual aberrations at small lens thickness is fulfilled. Diffractive and hybrid optical elements belong to the complex optical surfaces. This is due to their far more complex geometric shape compared to other optical details. Typical for them is the presence of multi-stage microrelief or continuous microrelief, with varying sizes from microns to millimeters and the amplitude of the relief in the order of several microns. The new structures can be made, complementing and surpassing the capabilities of traditional lenses, prisms and mirrors. Almost all types of shapes can be realized, including asymmetric aspherical surfaces, which provides a great deal of freedom in the design of these optical details. Fig. 1 shows several variants of diffractive optical elements [3].

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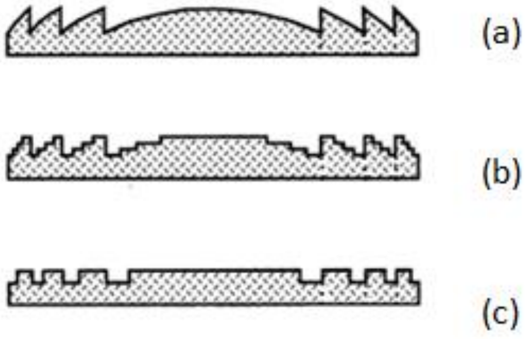

Fig. 1 Diffractive optical elements, as follows: (a) with a continuous profile; (b) a multilevel profile; (c) binary profile;

According to the studies made in the production, the technological factors with the greatest influence on the quality of the optical surfaces are the machine factors. These include: depth of cut (mm), feed (mm / min) and speed (min-1). The one that is most important for the quality indicators is the depth of cut (mm), the next factor according to its influence on the quality indicators is the feed (mm / min). The factor with the least impact on surface quality is the speed (min-1) [4].

The second group of factors influencing the quality indicators related to the devices. This category includes all devices for basing and securing (locking) the workpiece to the spindle of the machine. The locking devices are usually precisely made and their influence on the quality indicators is almost insignificant [5].

The third group of influencing factors are the tool ones - this group includes diamond machining tools, which are selected according to the type of workpiece and the geometric features of the workpiece. Diamond turning is a process that allows all transitions (rough turning, clean turning and finishing) to be performed with the same tool, therefore their impact is assessed as "weak" [6].

External factors - this group of factors includes: atmospheric pressure, ambient temperature, operator temperature, temperature in the work area, pre-tempering of the workpiece and cutting tool, anti-vibration coatings and others.

The development of technology in the last decade reduces the influence of these factors to insignificant.

II. SCIENTIFIC HYPOTHESES

Based on the analyzes of scientific research, a scientific theory, an idealized concept is presented and three scientific hypotheses are raised. Scientific theory and scientific hypotheses are based on the theory of surface quality of Vyacheslav Feoktistovich Bezyazychny (2012) and Royall's (2008) research on the crystal lattice of glass [7]. In support of the proposed scientific theory and scientific hypotheses are considered researches related to the processing of optical crystals (Germany and Silicon) processed by diamond turning. Such is the study of Lai, Xiaodong Zhang, Fengzhou Fang (2013) and a team on the topic: "Study of nanometric cutting of germanium by MD simulation"

In building the scientific theory, an idealized concept is introduced, based on the theory of surface quality of Bezyazychny (2012), Royall's study (2008) on dynamic arrest and the study of MD simulation in nanometric germanium cutting. The idealized concept represents a simplified crystal structure of the glass (respectively the optical detail), built of regular icosahedrons and is shown in Fig. 2.

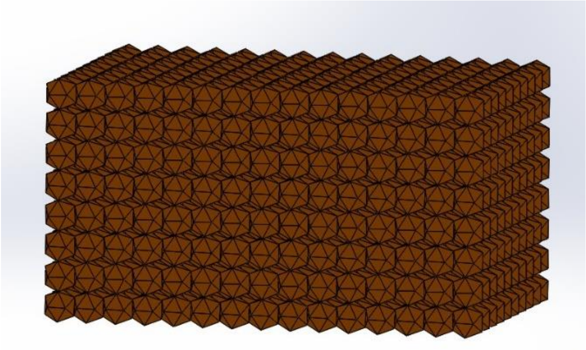

Fig. 2 Icosahedral crystal structure

- **Hypothesis 1 -** Influence of cutting depth. The depth of cut directly affects the quality of the surface, as it depends on where the height of the icosahedrons will be cut. If the depth of cut is such that it is removed from the material being processed, such a layer that leaves behind whole or approximately whole icosahedrons, then optimal surface quality could be achieved. The integrity of the icosahedral structure is preserved when the cutting tool passes over the tips of the icosahedrons. With this type of processing, the roughness (Rq/RMS) should be of the best quality.

- **Hypothesis 2** - Influence of feed rate. As the cutting feed increases, the roughness (Rq/RMS) of the resulting surface deteriorates, as does the chip separation. At lower feed rates, chips are expected to separate in the form of flakes and better-quality surfaces in terms of roughness (Rq/RMS). As the feed increases, the roughness parameters (Rq/RMS) are expected to deteriorate and shavings are formed in the form of hanging connections. The reason is the higher coefficients of friction, the increased temperature, the increased pressure in the cutting zone, the chemical reactions between the workpiece and the diamond tool.
- **Hypothesis 3** – Influence of rotation frequency on the quality of the treated surface. Increasing the speed leads to an increase in kinetic energy in the technological system. At the tip of the knife, the kinetic energy is converted into heat. The heat is transferred to the upper layer of the workpiece surface, thus creating a heat field in front of the tip of the knife. The thermal field transfers energy to the ions from the crystal lattice of the silicates, makes them unstable and when the knife passes through the ions, they are released very easily without causing defects in the lower layers. The increase in heat is accompanied by the release of such ions from the technological system. At one point, a dynamic equilibrium occurs in which the heat generated in the technological system is equal to that released due to cooling. From this point on, the surface roughness improvement (Rq/RMS) stops.

III. SCHEME OF THE EXPERIMENTAL SETTING

The experimental setup scheme is a complex system of high-tech machines and operations arranged in a certain sequence. The scheme of the experimental setup includes: machine tool, tool, tool, machined part, control and measuring equipment and recommended cutting modes.

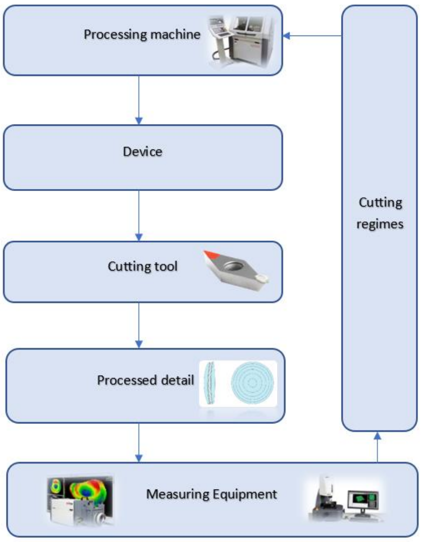

Fig. 3 Scheme of the experimental setting

In order to test the hypotheses, a planned experiment was performed. The following steps have been taken to ensure the planned experiment:

- Description of the system machine - device - tool - detail
- Pre-planning the experiment
- Single-factor experiment
- Full factorial experiment

Description of the system machine - device - tool - detail

- The machine used for the planned experiments is: Moore nanotech 250 lathe (Fig. 4). This is a compact diamond turning machine, providing high precision applied to optical elements operating in the infrared spectrum of light. The Nanotech 250UPL has similar technical characteristics compared to the Nanotech 350UPL. The main difference is that due to their more compact dimensions, the workpieces are limited to 300 mm in diameter and 200 mm in length.

Fig. 4 Moore Nanotech 250 lathe [8]

- Device - for basing and fixing the processed details a specially made copper mandrel is used. A solid blocking is used to attach the optical element to the device.
- Tool - the machining tool is a single crystal diamond from Contour-diamonds.com. Diamond tools from this manufacturer can have a radius of 1 um to 2 mm. An instrument with r = 0.55 mm was used in the planned experiment, an example of which is shown in (Fig. 5).

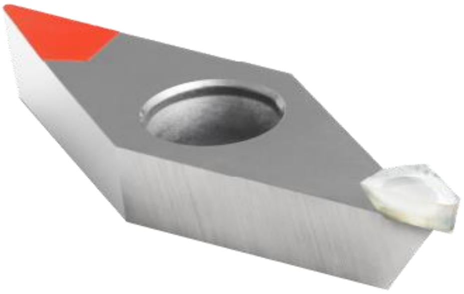

Fig. 5 Single crystal diamond turning knife "Contour" with radius r = 0.55 mm

Processed details - germanium lenses with an aspherical surface were used in the experiments. Figures 6 and 7 show the machined details. In Fig. 6 shows the aspherical lens used in the single-factor experiments, and Fig. 7 shows the lens used in the full factorial experiment.

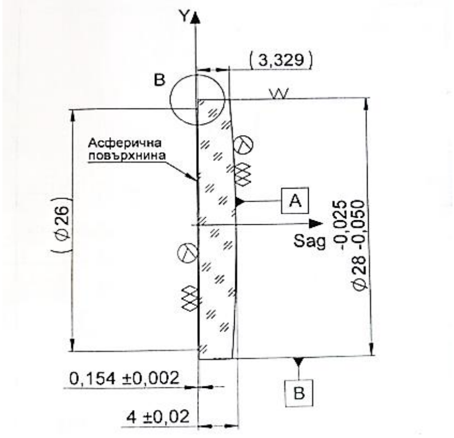

Fig. 6 Aspherical lens ø 26 - single-factor experiments

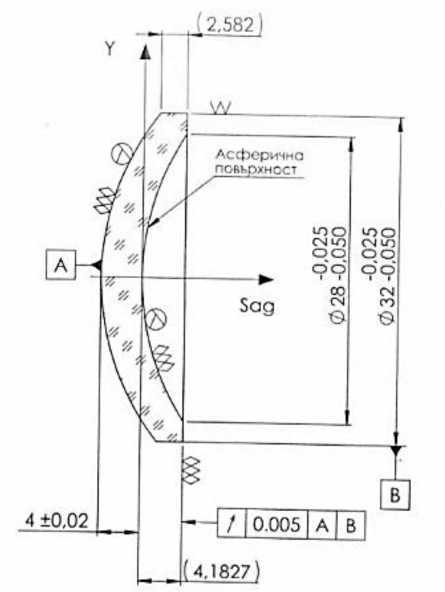

Fig. 7 Aspherical lens ø32 - full factor experiment

IV. PRE-PLANNED EXPERIMENT

To prove the scientific hypotheses, a methodology for planned experiment is used, including single-factor experiments and full factorial experiment, detailed information about the method can be found in the book "Fundamentals of Engineering Research" by Irina Alexandrova (2003) [9].

At this stage of the planning of the experiment, the technological factors that influence the quality parameters in the processing of germanium lenses by diamond turning are determined. The qualitative indicator whose change is the subject of the study has also been determined. The technological factors and their levels have been determined with the help of the expert assessment of the team of OPTIX AD Panagyurishte, using their extensive experience in diamond turning of crystals. Table 2 presents the values of the assessments of technological factors adopted on the basis of the expert assessment of the team of OPTIX AD Panagyurishte.

The expert assessments of the factors are presented in Table 1. The assessment was performed as follows: “I” - the highest assessment, and “IV” - the lowest assessment. According to the estimates in Table 1, the Kendall coefficient is presented (coherence / concordance between expert assessments).

Table 1

Evaluation of the factors

	Depth of cut		**Feed rate**	**Spindle speed**	**External factors**
Expert 1	II		III	I	IV
Expert 2	II		III	I	IV
Expert 3	II		III	I	IV

There is unanimity among the surveyed experts, therefore, the concordance coefficient W = 1.

Table 2

Coefficients of weight adopted by the experts

Depth of cut; mm	Feed rate; mm/min	Spindle speed; min $^{-1}$	External factors
0,35	0,24	0,40	0,01

After the analysis and the determined technological factors and qualitative indicators, single-factor experiments and full factorial experiment have been realized, aiming to confirm or reject the raised scientific hypotheses.

A. Single – factor experiments

The experiments were divided into 3 groups of 5 experiments. As for group 1 the spindle speeds have changed, the other technological factors remain unchanged. Roughness change (Rq/RMS) is reported. The actions are similar in groups 2 and 3, where the changed technological factors are Cutting depth (group 2) and Feed rate (group 3).

Table 3

Changing the speed

Spindle speed, min $^{-1}$	Depth of cut, mm	Feed rate, mm/min	Roughness (Rq/RMS), nm
2000	0,01	10	11,737
2500	0,01	10	7,553
3000	0,01	10	3,505
3500	0,01	10	1,718
4000	0,01	10	1,722

Table 4

Changing the depth of cut

Spindle speed, min $^{-1}$	Depth of cut, mm	Feed rate, mm/min	Roughness (Rq/RMS), nm
3000	0,001	10	1,263
3000	0,005	10	2,854
3000	0,01	10	3,212
3000	0,015	10	4,459
3000	0,02	10	6,094

Table 5

Changing the cutting speed

Spindle speed, min $^{-1}$	Depth of cut, mm	Feed rate, mm/min	Roughness (Rq/RMS), nm
3000	0,01	2	1,656
3000	0,01	5	1,768
3000	0,01	10	3,16
3000	0,01	15	10,326
3000	0,01	20	20,338

Analysis of single-factor experiments:

All the single-factor experiments is subjected to correlation and regression analysis in order to determine the relationship between technological factors and quality indicators (roughness). The results of the correlation analyze show a strong dependence at a correlation coefficient> 0.92 for all three groups of experiments. The results of the regression analyze show values of the Fischer criterion "Significance F" less than 0.05, therefore, the equations are significant for all three single-factor experiments.

B. Full factorial experiment:

A full factorial experiment (FFE) was chosen to complete the planned experiment. The full factor analysis was performed using Minitab 19. This is software adapted to data processing and engineering research.

- Base model of the experiment
  - Factors: 3; Base model: 3;8;
  - Experiments: 8; Results: 1 (Roughness)

Regression analysis of a full factorial experiment

Regression equation in uncoded units:

$$Ra= 3,82 – 0,000715*n + 0,0264*f + 54,8*D$$

The results of the regression analysis show a value of the criterion "Significance F" = 0.0177, at a significance level F = 0.05. From the analyzes made it follows that the equation is adequate and the coefficients are significant.

Table 6

Experimental data

Spindle speed, min^{-1}	Feed rate, mm/min	Depth of cut, mm	Roughness (RMS), nm
3000	2,5	0,002	2,425
3000	2	0,001	2,425
3000	2	0,005	1,771
3000	2	0,0002	2,938
3000	1	0,001	1,831
3000	5	0,001	3,077
2000	2	0,001	1,278
3500	2	0,001	3,436

V.RESULTS

The results from the full factorial experiment are represented in three graphs. Each graph shows the change in the roughness when changing the technological parameters.

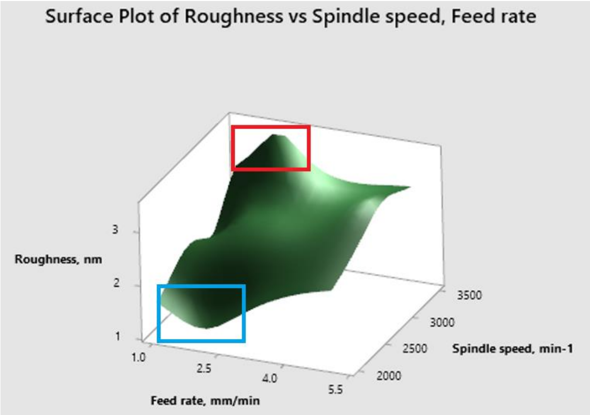

Fig. 8 Surface plot of Roughness vs Spindle speed and Feed rate

- **Graph 1 -** The presented graph (Fig.8) is between the technological factors "feed rate" and "Spindle speed" relative to the quality indicator - roughness (Rq/RMS). The highest (worst) values of the quality indicators are shown in red, at feed values around 2 mm / min - 2.5 mm / min and the spindle speed around 3500 min^{-1}. The lowest (best) roughness values (Rq/RMS) are indicated in blue, with a feed between 1.5 mm / min - 2.5 mm / min and a spindle speed between 2000 min^{-1} - 2500 min^{-1}. As the values of the technological factors increase, the quality parameter deteriorates.

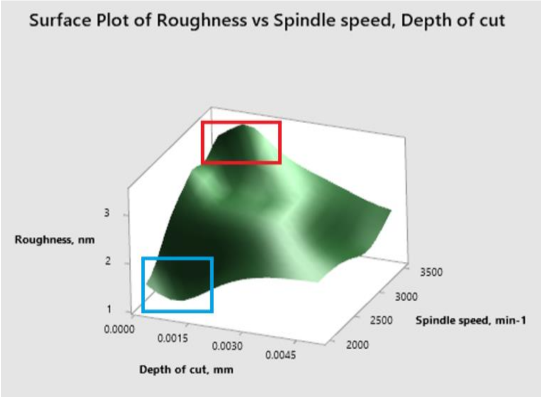

Fig. 9 Surface plot of Roughness vs Spindle speed and Depth of cut

- **Graph 2 -** Graph 2(Fig. 9) illustrates the change in roughness (Rq/RMS) when changing the depth of cut and Spindle speed. Maximum roughness values (Rq/RMS) are observed in the area marked in red rectangle, at approximate values of depth of cut about 0.0015 mm and spindle speed about 3500 min^{-1}. The best is the roughness (Rq/RMS) marked in blue, with a depth of cut about 0.0015 mm and a speed between 2000 min^{-1} - 2500 min^{-1}. An increase in roughness (Rq/RMS) is observed when the depth of cut changes from 0.0015 mm to 0.0045 mm and the spindle speed in the range 2500 min^{-1} - 3500 min^{-1}.

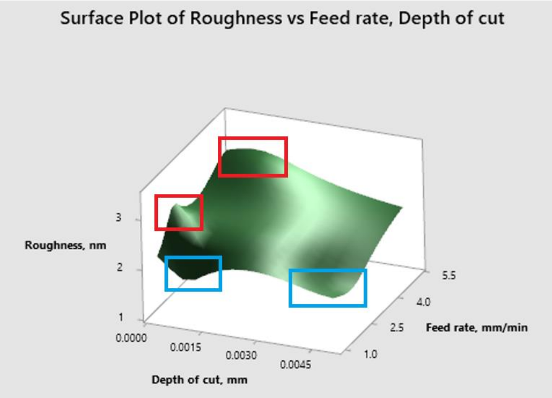

Fig. 10 Surface plot of Roughness vs Feed rate and Depth of cut

- **Graph 3 -** A graph between the depth of cut and the feed rate to roughness (Rq/RMS) is shown. The sections of the graphs with the highest values of the quality indicator are presented in red. The areas in blue illustrate the lowest roughness values (Rq/RMS). By increasing the feed rate and depth of cut between 0.0015 mm - 0.004 mm, higher roughness values (Rq/RMS) are obtained. Similar roughness (Rq/RMS) is observed with simultaneous change of feed rate and depth of cut;

VI. CONCLUSIONS

1. Diamond turning is a precise machining process that satisfies the high-quality requirements of optical production and is therefore applicable in this production.

2. Single-factor experiments show that the selected technological factors affect the quality of the processed surface.

3. All technological factors are subjected to correlation and regression analysis. The results of the analyzes shows that the technological factors (spindle speed, depth of cut and feed rate) have a dependence close to the functional one to the controlled parameter (roughness (Rq/RMS)) and are significant enough.

4. The derived regression equation: RMS = 3.82 - 0.000715 * n + 0.0264 * f + 54.8 * D, shows the value of Fisher's criterion "Significance F" = 0.0177, at significance level F = 0.05. The equation is adequate and the coefficients involved in the equation are significant.

5. Presented three-dimensional response graphs: roughness (Rq/RMS) to spindle speed and feed rate; roughness (Rq/RMS) to spindle speed and depth of cut and roughness (Rq/RMS) to feed rate and depth of cut, show the change in roughness (Rq/RMS) when changing the various technological indicators.

6. The change of the technological factor "depth of cut" affects the quality of the machined parts. Shallower turning results in lower roughness values (Rq/RMS). This confirms hypothesis 1.

7. By reducing the technological factor of "feed rate" the quality indicators of the processed details improve, this is confirmed by hypothesis 2.

8. Experimental studies and their results confirm hypothesis 3 and show that increasing the technological factor "spindle speed" significantly improves the quality of the optical surface.

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