# PROCESSING OF LARGE LASER GRADE MIRROR SUBSTRATES

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*This paper presents the technology designed for obtaining a mirror substrate made from fused silica with a flat face of large dimensions (ϕ 156 mm) with a surface roughness of less than 2 nm and a surface flatness deviation of λ/18 nm.*

*The processing type is conventional and then it is followed by a finishing step of super-polishing thus obtaining large mirror grade optics with the purpose of being used in high energy ultra-short pulse laser systems like the one on the ELI-NP (Extreme Light Infrastructure - Nuclear Physics) platform.*

**Keywords**: large optics processing, laser grade mirror substrate, high-level flatness, low surface roughness.

## 1. Introduction

Presently in Europe there are very few companies that produce large flat optics that could be used as substrates for high-energy laser mirrors. The reason is that it is very difficult to correctly assess if the optics will withstand high-energy laser beam pulses.

The project ELI-NP includes a laser with a peak power of 10 PW while CETAL has a laser with a peek power of 1 PW.

The objective of the project for which these large flat optics are manufactured is for so that the mirrors produced with the treated substrates to be used in studying the effect of ultra-short pulse laser beams on the material as well as to re-route the beam towards different laboratories on the research platform.

In order to test the feasibility of using the manufactured mirrors, a small sample of 25 mm diameter mirrors which were processed the same way as the final

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large flats, were sent to be tested by the TEWALAS laser at the CETAL research department in order to observe the threshold at which the mirror will start taking deeper than superficial damage - crack, pulverize, lose or chip its coating, etc.

This paper also treats the issues that arise during the manufacturing of these high-precision large mirror substrates process.

## 2. Substrate mechanical properties

High-energy lasers have a high destructive power on the optics that are integrated in their system. In order to avoid the waveform aberrations a very high surface precision is also demanded. Therefor the systems are limited by the damage threshold and the processing technology of the optics used. The destruction includes but is not limited to: thermal tension, mechanical mount stress, coating pulverization caused by cavitation upon laser firing on a specific area, etc.

A vicious circle is created when the laser beam impact area becomes damaged and the reflectance is reduced and the absorbance is increased, this in turn causes more damage to the optic by permitting more energy absorption and so on [1].

A suitable material to be used for the presented purpose had to have a low thermal expansion coefficient as to avoid dilatation and a high value of material hardness.

Known for all of the above is fused silica glass, an amorphous formed silicon dioxide glass which is a synthetic material with a non-crystalline state (different from the crystalline state of the crystal quartz, its natural counterpart). Even if fused silica has an irregular linked silicon-oxygen network it is well known for its toughness and it is widely used in space applications as well as laser systems [2].

To insure proper comparability between factory testing methods the specified reference glass will be S-BSL7 from Ohara - an equivalent for BK7 (the most used optical glass type ) - and it will be compared with SK-1300 from Ohara - one type of fused silica glass produced by the company.

*Table 1*

**Comparison reference glass type (BK7) and fused silica (SK-1300)**

| Property | S-BSL7 | SK-1300 | Observations |
|---|---|---|---|
| Knoop Hardness $kg/mm^2$ | 570 | 650-710 | |
| Expansion Coefficient α $x10^{-7}/°C$ | 72-86 | 5.5 | (-30→+70°C)-(100→300°C) for S-BSL7<br>(0→200°C) for SK-1300 |
| Density $g/cm^3$ | 2.520 | 2.201 | |

During the processing stage, the tool - work-piece friction force generates enough heat to influences the precision of the surface by modifying the shape of the polishing pitch below the piece.

Due to the high-energy density on a small area, the blasting site has an instant increase in temperature which can cause thermal tension cracks in the glass and even pulverization of the superficial layer of the optic piece. A thermal gradient is generated at the site during the absorption of energy, this radiates outwards towards the borders of the mirror. The small radial dilatation means that the mirror mechanical mounting will cause less stress tension on the periphery of the mirror therefor minimizing the modification of the mirror surface curvature [3].

Another reason for which fused silica is preferred as a substrate is that the multi-layer dielectric coating which will be done as a final step also contains $SiO_2$ as a "low index" material. Therefor this would be a very good match as the result of the fact that it will significantly reduce the stress on the optics because the dilatation of the coating will be approximately equal to the dilatation of the substrate.

During manufacturing, the hardness influences the material removal rate as well as the probability of scratches and deep cracks occurring on the surface of the optic piece. The removal of material is done slower which means that the whole process is more controllable.

Any chips created during processing have a lower chance to extend deeper in the material and there are lower chances of surface scratches occurring during the grinding and polishing process caused by impurities on the processing pitch.

Even if the density difference is quite small between the compared glass types, the weight of the optical piece is important when the large dimensions are taken into consideration. In this case the fused silica glass piece has 12.5% decrease in weight than it would have had if it was manufactured from the traditionally used glass.

## 3. Large-flat optics surface generation

The substrate geometry was generated first by water jet cutting a glass block with the desired thickness into a cylinder with a larger diameter than needed for the final piece. This piece presented some tapering caused by the water jet spreading inside the material while the cut was being made.

The final diameter was achieved using a rounding horizontal lathe which uses oil as a cooling liquid and a diamond cup wheel, the tool rotates at a small angle to the longitudinal axis of the piece and moves to and fro in a parallel fashion to the axis of the cylinder.

After the rounding step, when the piece had its perimeter defined and final, the piece was mounted in a special collet type chuck that was meant to be used as a flexible tool system and therefor was adapted for use on multiple conventional type machines in the optical processing workshop.

Fig.1. Collet-type chuck (a) 3D model sketch (b) manufactured mechanical part

The collet chuck was first used on a face generating machine, for which it was fitted with four threaded holes that allow it to be blocked on the machine. The machine uses a diamond cup wheel that can be positioned relative to the center of the optics face.

After the previously described machining with diamond tools and cooling liquid, the remainder of processing was done with loose abrasive plus water slurry where the slurry is forced at the work-piece - tool point of contact and the material removal is achieved due to the sliding friction forces.

The mechanism of loose abrasive processing is based on the creation of micro-chips at the contact point between the tool and work-piece with the cutting edges of the abrasive particles which produces very fine scratches across both surfaces with which the abrasive is in contact [4].

The main known issue with using loose abrasives as a processing method is the fact that the slurry distribution is not uniform. Additionally, the movement of the loose abrasives during the processing stage is unpredictable as it is described as being random [5].

It is thought that during the loose abrasive machining step only 0.5% of abrasives are used [5], this means that the remaining abrasive particles either undergo process transformations or are simply discarded in the water residue accompanied by glass debris.

In the case of grinding, the slurry has a mud-like consistency, while for polishing the slurry is more water based and therefor has a thinner cloudy water consistency.

The tool marks left previously by the generating machine are then removed by rough grinding on a 500 mm diameter flat grinding metal tool using loose abrasive powder in water.

The optical piece is then blocked in the chuck of a conventional type lathe for fine grinding this is achieved using an elastic blocking plate retrofitted with threaded holes symmetrically placed compared to the blocking device.

The movement of the work-piece has to encompass the entirety of the grinding plate so that the tool surface uniformity is maintained [6].

The work-piece is then conventionally polished using the same machine but using a pitch formed polisher and cerium oxide powder with water slurry [6].

The surface roughness becomes smaller with every processing step and it directly depends on the grit size of the used abrasive [7].

## 4. Large-flat optics surface super-polishing

The flatness and surface roughness of the mirror were achieved using a Lapmaster pitch lapping machine which combines a low speed lapping movement with the precision polishing properties of the pitch. This allows for very good control over the processing but low predictability of the flatness of the work-piece.

The behavior of the glass and pitch depends on many aspects, from the ambient temperature and environment cleanliness to the weight and glass type of the work-piece.

The lapping pitch's surface is controlled using a large conditioner plate that can be moved so that it corrects the convex or concave tendencies of the pitch while the processing is done.

The carrier in which the work pieces are kept is placed on an oscillating arm so that the movement along the pitch plate is as uniform as possible.

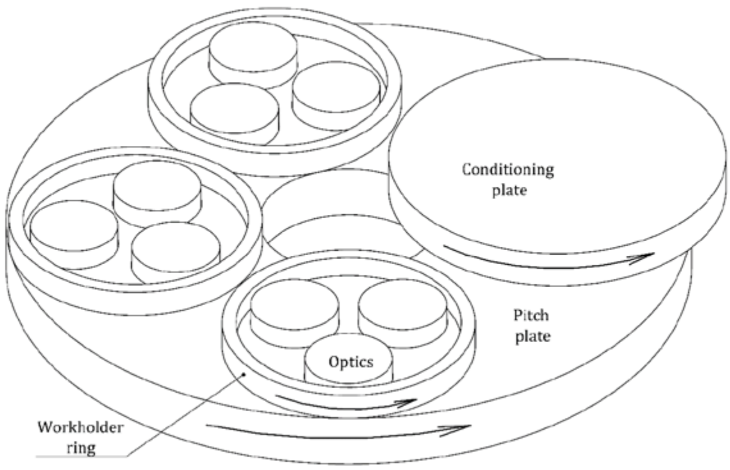


Fig.2. Lapping-type movement super-polishing machine

CEROX 1650 (cerium oxide powder) plus distilled water slurry is constantly fed by two tubes on the polishing pitch. The slurry flux is controlled using a pump system and the slurry is constantly mixed by a stirrer to insure uniform particle distribution uninfluenced by the powder settling time.

Flatness is tested as often as possible by visually testing a flat gauge that is placed in the same carrier as the working piece. The test gauge is the same dimensions and glass type as the final part but its only purpose is to assess the obtained pitch flatness.

Another purpose of the testing gauge is for balancing the carrier movements because the carrier rotation becomes jerked and exhibits erratic behavior if not properly balanced in at least three points symmetrically arranged around the carrier rotation axis.

The environment in which the super-polishing is done is very important as the presents of dust particles has a large influence on the quality of the obtained optic. The dust particles in air can act as abrasive grains when caught between the polisher and the work-piece and, depending on their composition and hardness, may cause fine scratches on the glass surface [4].

It is important to note that during loose abrasive processing, the grain size of abrasive lowers as the particles get crushed, for this reason the used abrasive should have a higher hardness value than that of the glass [4].

While the abrasive used, CEROX 1650, has a grain size of 1-2 μm the resulting optics surface roughness value is less than 1 nm this can be explained by the grain crushing phenomenon or by the fact that the abrasives become imbedded in the pitch plate.

The pitch becomes warmer which causes the surface to allow harder material to penetrate a thin superficial layer. This represents the mechanism with which the cerium oxide particles become imbedded in the pitch and therefor leave a smaller cutting edge area exposed to the work-piece.

During processing this phenomenon can be observed, the pitch surface becomes loaded with cerium oxide particle as well as proportionally sized glass residue.

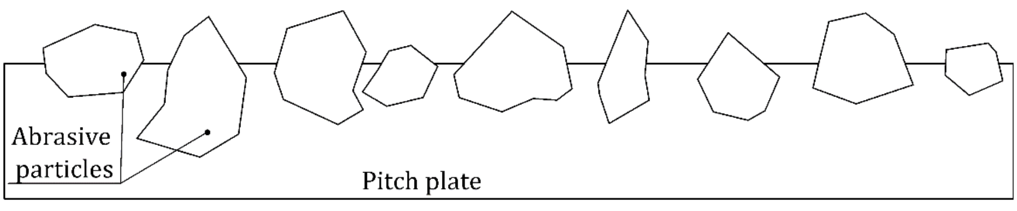


Fig.3. Imbedded particles in pitch

Meanwhile the polishing pitch becomes smoother which is a result of the reciprocating friction that acts upon the pitch at the same time as on the work-piece. As this takes place, the slurry particles become embedded in the pores of both the pitch and work-piece which become clogged with crushed smaller sized abrasive particles as well as glass particle residue. The described process causes the apparition of the glazing phenomenon on the surface of the pitch [8].

The pitch glaze layer may need to be removed by mechanical action as it will impede the transportation of slurry and glass debris to and fro the work area [8].

This phenomenon can also be accompanied by the creation of the vitreous layer known as the Beilby layer which is theorized to be the by-product of the chemical reaction of the oxides in both the used slurry as well as the optical glass itself when in contact with air.

The Beilby layer is phenomenon that appears on the surface of both metals and non-metals after the polishing step. It is a vitreous layer which forms at the surface of an amorphous material and can be caused either by the polishing compound mixture or the oxidation of a thin layer of the material itself [9].

It is indicated that the pH of the water plus polishing compound, as well as the negative or positive charge of the work-piece, may contribute to the creation of a thin chemically different layer between the optic and the pitch [10].

A surface chemical reaction is also described between cerium oxide particles and the water and it takes place at the contact point of the slurry solution and optic piece but in this case the reaction has a positive effect which promotes material removal by creating siloxiane bonds (cerium particles plus silicon from the glass surface) which are then broken and carried away as debris in the discarded slurry [4].

After the super-polishing step, the optical piece is submerged in distilled water before the outer layer of cerium oxide can solidify. This is done in order to insure the dislodgement of abrasive powder residue from the fine pores (the surface roughness defined valleys) and into the distilled water bath.

Surface contaminants can also be removed using an ultra-sonic cleaner with a solution of distilled water or by immersing the optic in a solution of fluorhydric acid for superficial cleaning of the Beilby layer [11].

It should be noted that the Beilby layer cannot be removed with a simple wash once it solidifies, the glass can either be etched with a solution of fluorhydric acid or re-polished.

## 5. Tests and results

The optical flats that were processed using the above described technology had a diameter of 156 mm and a thickness of 50 mm. The density of fused silica is 2.201 g/cm$^3$ so the final pieces weighed around 2.1 kg.

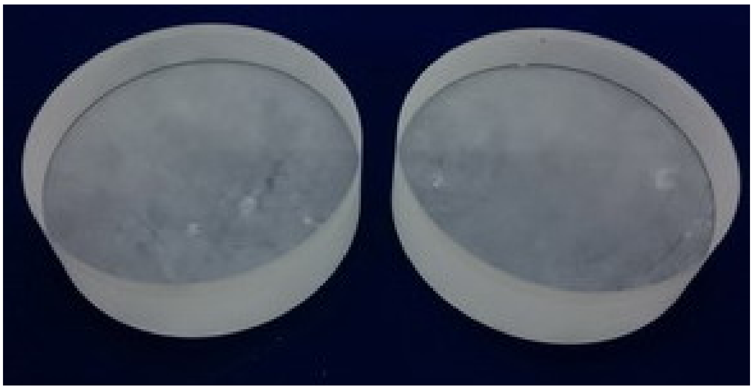

Fig.4. The final two pieces ready for coating

The noteworthy characteristics of the substrate were measured and the results are as expected or even exceed expectations.

For testing the surface roughness several test witnesses were used, these were processed at the same time therefor in the same conditions as the final pieces for this specific purpose.

The surface roughness was tested by using atomic force microscopy (AFM) and the results were an average of less than 2 nm RMS.

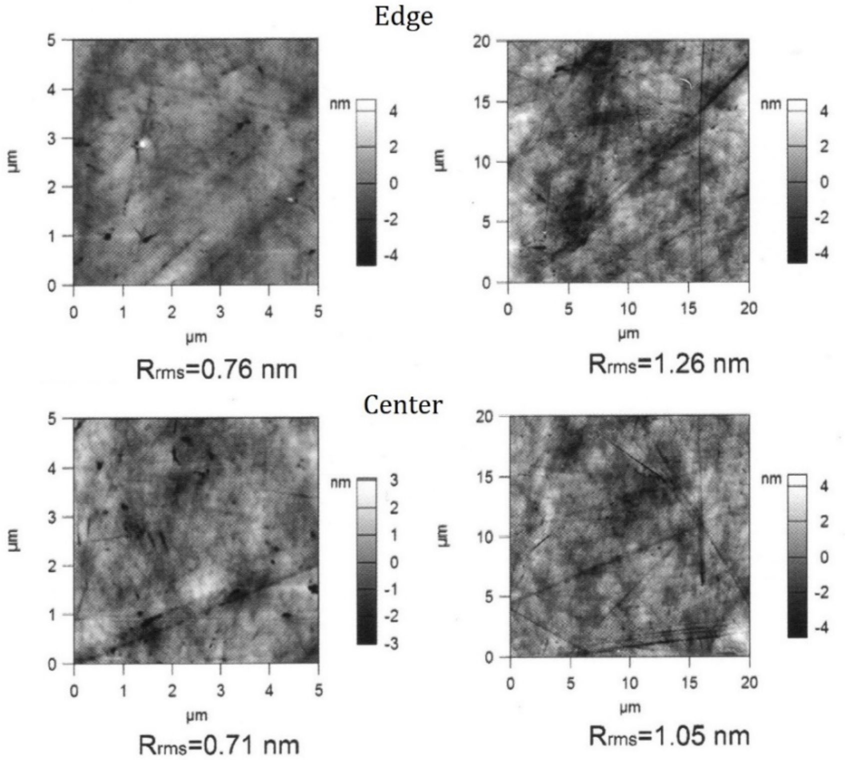


Fig.5. AFM results for surface roughness at the edge and center of the test witnesses

In Fig.5. it can be observed that the median value of surface roughness at the edges of the witness plate is between 0.76 nm and 1.26 nm and for the center of the witness plate the range is 0.71 nm to 1.05 nm.

The surface roughness was also measured using interferometric methods for comparison with the previous AFM results as can be viewed in Fig.6. and Fig.7.

Fig.6. presents a color coded 3D topology of the surface roughness peaks and valleys for an area in the center of the witness plate.

Fig.7. presents the same color coded 3D topology of the surface of the witness plate as Fig.6. but for an area situated at the right side perimeter of the witness plate.

The results for both areas are presented below each 3D topologic map and they show a graph of peak-to-valley amplitudes (Z axis) as a function of length (X axis).

As an example, for Fig.6. the tallest peak reaches 1 nm and the deepest valley 0 nm (which is the baseline).

The comparison of surface roughness results between the two different methods is conclusive of the fact that the values obtained from either source denote the real obtained surface roughness values.

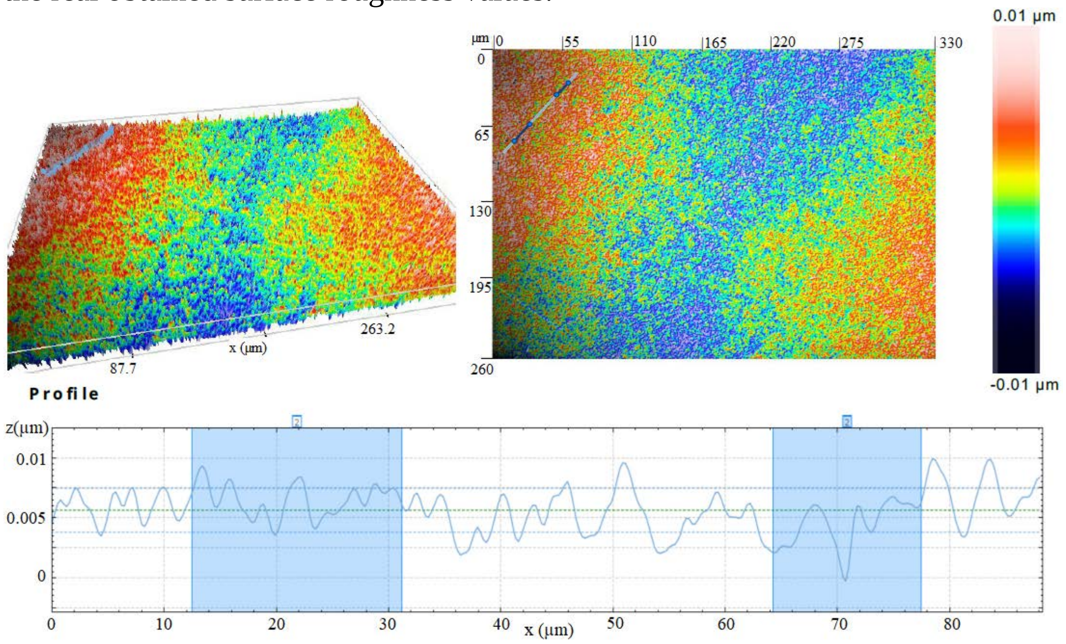


Fig.6. Interferometric results for surface roughness at the center of the witness plate

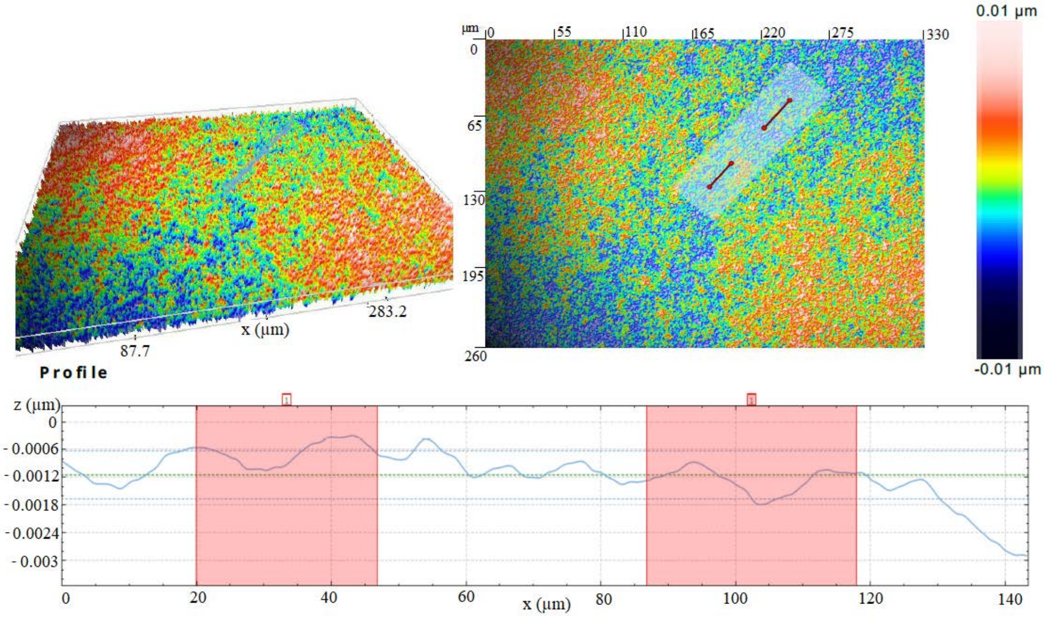


Fig.7. Interferometric results for surface roughness at the right side of the witness plate

Following the surface roughness tests the next step was to measure the flatness of the optical piece.

The surface flatness of the final two optical pieces was tested using a phase interferometer on the final pieces and the results can be seen in Fig.8. and Fig.9.

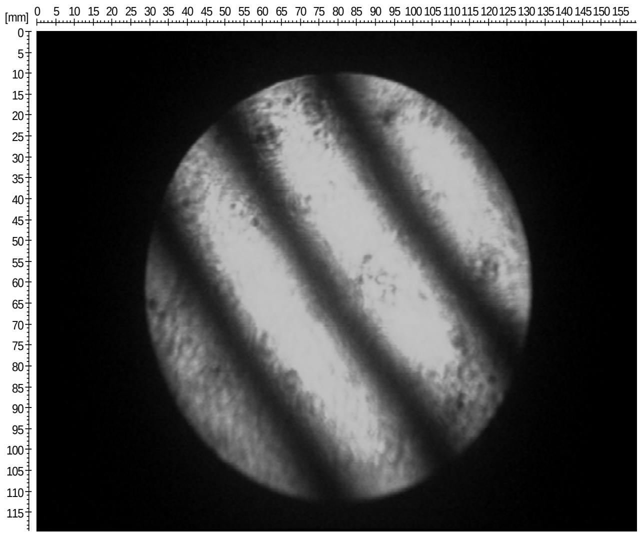


Fig.8. Surface flatness results for piece no.1

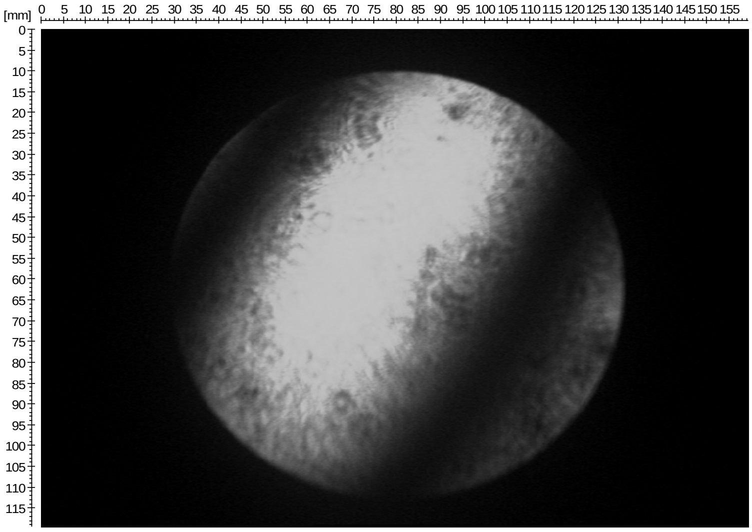


Fig.9. Surface flatness results for piece no.2

Surface flatness results for both pieces presented in Fig.8. and Fig.9. measured on the maximum allowed area for the used interferometer are presented in table 2.

*Table 2*

**Surface flatness results**

| Property | Piece no. 1 | Piece no. 2 |
|---|---|---|
| Surface form tolerance | 3/0.062 (0.099/0.025) | 3/0.049 (0.131/0.019) |
| Peak-to-valley height | 32 nm | 37 nm |
| RMS | 7 nm | 7 nm |
| Ra | 6 nm | 6 nm |
| Measured area | 159.44 mm x 119.58 mm | 159.44 mm x 119.58 mm |
| Wavelength | 632.80 nm | 632.80 nm |

The most important characteristic that can be observed in table 2 is the peak-to-valley value which is considered the overall surface flatness value of the measured piece.

This value is usually transformed as a function of λ and as a ratio, in this case the calculated value would be around λ/19 for both optical pieces, which is used as per ISO 10110 to indicate, in the technical drawing, the required surface flatness value for the respective optical surface.

## 6. Conclusions

The adaptability and the flexible nature of the design of the used blocking device insures that in the future the same device can be used to generate, grind and polish spherical surfaced mirrors. These mirrors would have a very small decentering error thanks to the fact that the optic piece will have the same position in the blocking chuck throughout the whole processing. Processing spherical mirrors is important as it is a precursor of aspherical surface generation which is done from a closely shaped spherical surface with small radius modifications as to achieve the aspherical curve [7].

Seeing as it has been determined that the optical performance of glass, from the refractive index [12] to the surface absorbance parameters [13] which has a direct dependence on the temperature it is only logical to assume that for the high-energy laser beams of the ELI-NP laser the surface of the mirror as well as the coatings will suffer irreversible destructive changes. This signifies that the laser grade mirror provided have a consumable nature and need to be replaced often which means that the production of such mirrors has to be dependable and consistent.

The reliability of mirror production was achieved by using the above described processing technology.

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