New Optical Polishing Techniques for Aspherical and Free-Form Lenses

Executive Summary Report

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1. Introduction

Both the rotationally aspherical and the free-form elements especially are recently considered as main drivers to increase the optical performance of optical systems while keeping the volume and mass at the same or even decreased level. Their manufacturing strategies and final performance, however, are not straightforward to predict and experiences differ from company to company. Hence the main outcome of this project was a final description of the processes for manufacturing and measurement of aspherical and free form elements to achieve given surface form error and surface micro-roughness. The aim was also to identify processes that minimize the number of manufacturing cycles to reduce manufacturing costs and production time.

The final agreed materials and performances of individual elements are summarized in Table 1.

Table 1: Update of project requirement summarization.

	Fused Silica		CaF_2 (crystal orientation <111>)	
Specification	**asphere**	**Free-Form**	**asphere**	**Free-Form**
WFE (nm RMS)	40 (25) *	150 (40)*	40 (25)*	150 (40)*
SaD ISO 10110-7	1x0.1	1x0.1	1x0.1; each ø 25 mm	1x0.1; each ø 25 mm
Microroughness (nm RMS)	0.5 (0.3)*	0.6 (0.3)*	0.7 (0.5)*	1.0 (0.5*)
Diameter (mm)	>= 80	>= 80	>= 80	>= 80
Curvature radius (mm)	<= 80	<= 80	<= 80	<= 80
Slope (mrad)	>1	>1	>1	>1
Deprture from BSF (mm)	> 0.045	> 0.045	> 0.045	> 0.045

( ) represent project target value
**Target value defined in SoW will be retained as long as possible*

The project itself is divided into two main branches. The first one is taken by Toptec and it describes the project solution in order to achieve its goals on free-form elements. The second branch is dedicated to aspherical elements, and it is solved by asphericon s.r.o.

2. Overview of material used

The material of refractive elements plays an important role in the optical system. It is mainly used to beat chromatic aberrations. Other material characteristics enable it to be used in UV spectral regions or enable it to work in a radiant environment. Exactly such materials are in the interest of this project.

The very first material of the project is mandatory to be CaF2. From the optical design point of view, it is the perfect material to beat the chromatic aberration through its abbe number that reaches a value of 95.3 and it is vastly used for this purpose. On the other side, it is a very difficult material from the manufacturing point of view. It is soft so that the cosmetic parameters are always on issue. It is thermally very sensitive so it can crack easily when exposed to thermal shocks. It is vastly more fragile than any other glass so the manipulation of housing must be done with special care. It is a radiation-hard material.

The second material for the purpose of the project was negotiated during the negotiation phase of the project. One of the drivers of material selection is its applicability to the UV and VIS wavelength range. The requirement for the UV-applicable material penalizes most used glass materials for the VIS application as common glass materials drop their transmission capabilities dramatically below 400nm (see Figure 1).

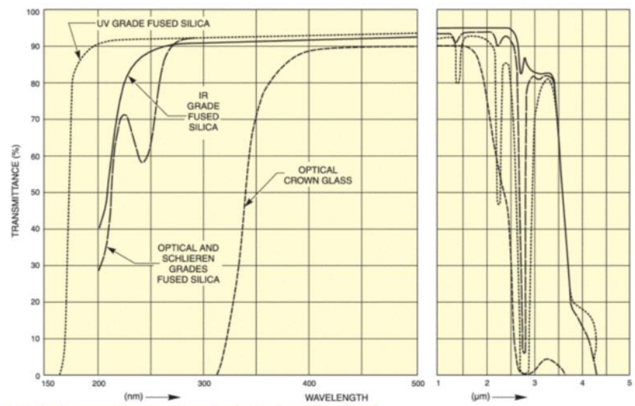

Figure 1: Transmission curves of standard refractive materials (source: https://www.newport.com/n/optical-materials).

Further limitation comes from the assumption for the usage of the results for space applications where there usually is a requirement for radiation-hardened materials usage. There are several rad-hard materials from SCHOTT company as BK7G18, LF5G19, LF5G15, K5G20, LAK9G15, F2G12, and SF6G05 but they all suffer from no transmission for UV application.

For these reasons, the second material was agreed to be Fused Silica which is both radiation-hard and has a high transmission for UV application (see Figure 1).

The fused silica also has some exceptional parameters with respect to the production and handling demands which enable us to focus on the manufacturing process rather than the handling and protection processes.

3. Manufacturing process

3.1. Free-form manufacturing process

3.1.1. Free-Form element made of Fused Silica

Regarding the free-form element, it is important to start a description of the surface employing a free-form design with a parametric f(x,y) equation. The form of the equation needs to be known to all production machines, measurement devices, and especially their users. Very often the equation is transformed to the surface profile called NURBS, a spline surface profile that can be shared between different devices or machines. It needs to be beware to handle all transformations correctly between individual machines, software, and measurement devices. After the surface design is set and well understood we continued with basic grinding, corrective grinding, and further with different techniques of CNC polishing that were necessary to master to successfully handle the surface correctly.

It is necessary to pay special attention to the testing setup and all alignment processes of individual production machines because testing free-form elements is usually non-trivial. Special care must be given to the calibration of measurement setups as one of the most important lessons learned is the necessity of correct interpretation of measurement and precision of matching the simulation with reality. Usually, different measurement techniques for different parameters need to be applied. As the Free-Form surface was designed smartly it enabled us to use stitching interferometry for the evaluation of the surface form – one of the project goals. The second goal was to reach very low microroughness – for that, we use white light interferometry.

The developed process for fused silica enabled us to reach the following values of interest.

Table 2: Summary table of Free-Form FS sample resulting performance parameters.

Free-Form FS	Form deviation ⌀80 mm (ISO 10110-5) [nm]	Surface radius	Microroughness rms [nm]	Cleanliness (ISO)
Tolerances	RMSi < 150	80 +/- 0.015 mm	< 0.6	1x0.1; E0.5
Results	RMSi 77.915	80.0013 mm +0.0016%	0.5	0x0.1

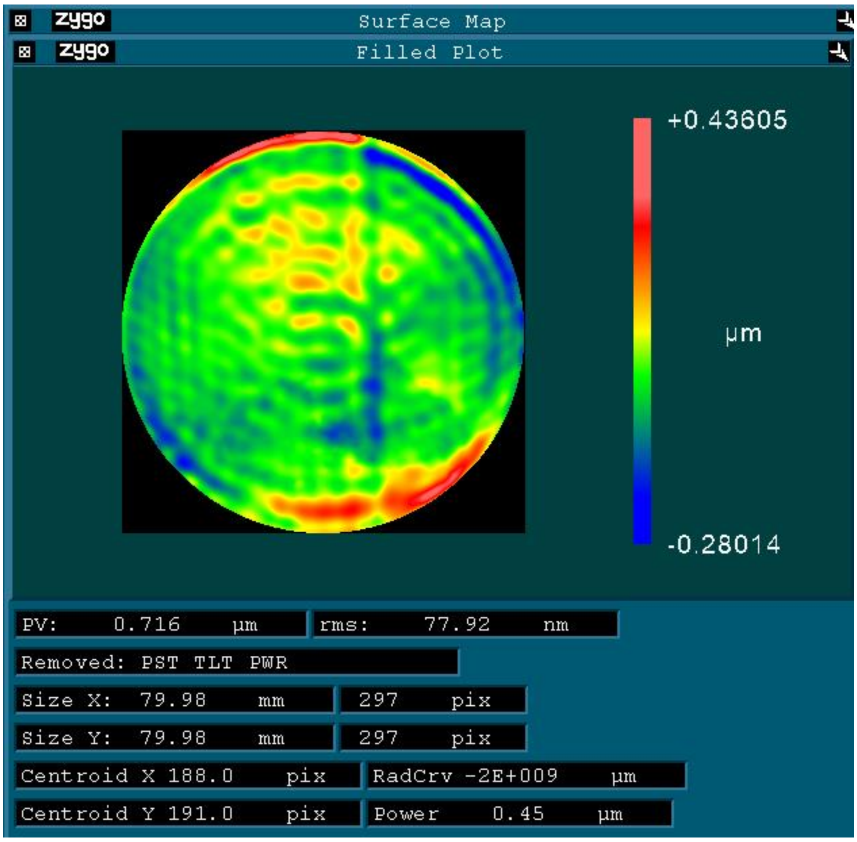

Figure 2: Surface form deviation for Free-Form FS element (80 mm aperture).

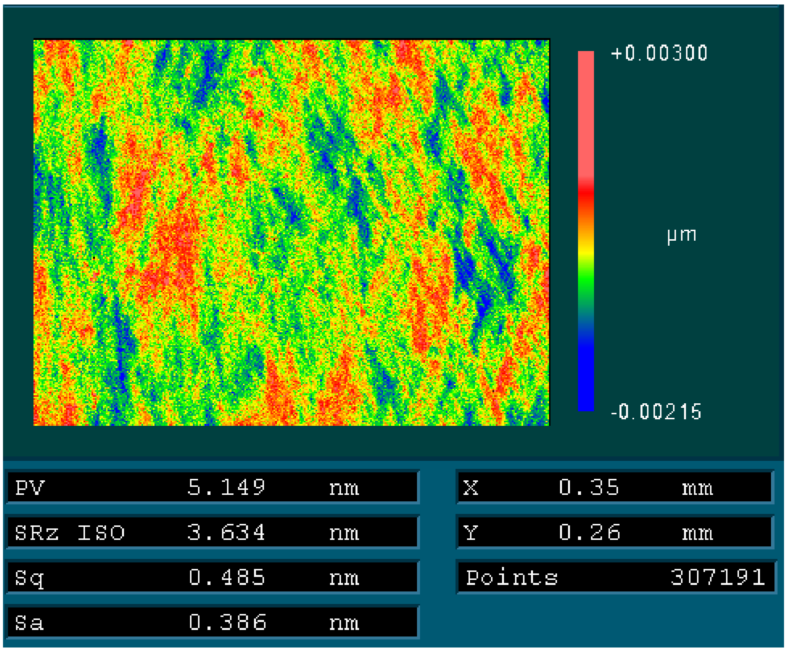

Figure 3: Surface microroughness map for Free-Form FS element (representative center sub-aperture, 20x magnification).

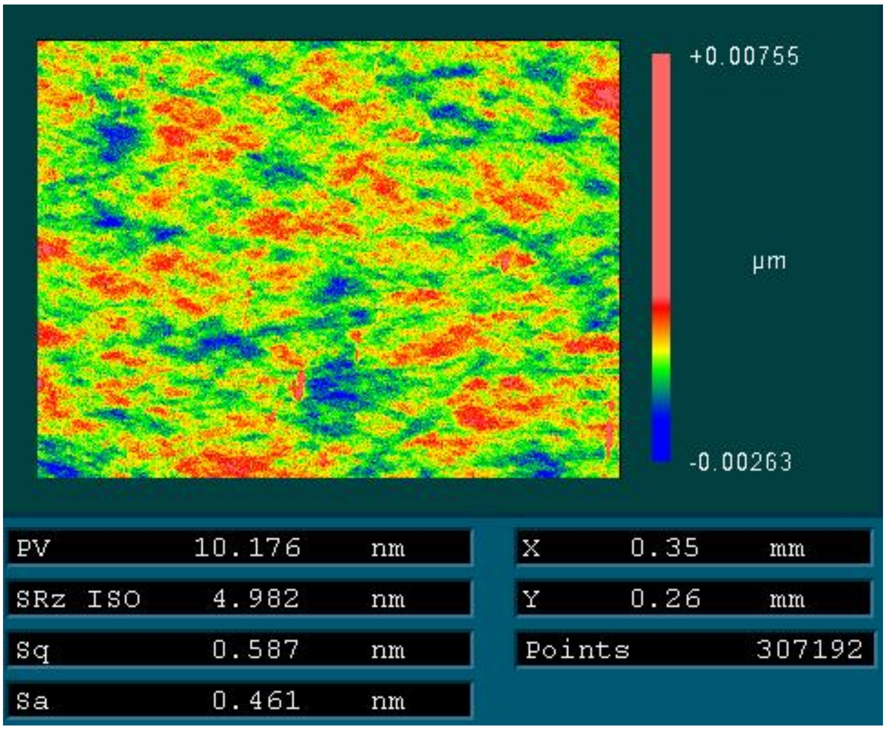

Figure 4: Surface microroughness map for Free-Form FS element (representative annulus subaperture 25 mm from the centre, 20x magnification).

3.1.2. Free-form element made of CaF_2

Regarding the calcium fluoride Free-Form element the manufacturing setup was refined when CNC Free-Form grinding process was substituted by the Single Point Diamond Turning (SPDT) process. The other steps of the production chain were essentially analogous, with the difference of polishing slurry was used for all CaF2 polishing.

The result of the developed process for CaF_2 is as follows.

Table 3: Summary table of Free-Form CaF2 sample resulting performance parameters.

Free-Form CaF2	Form deviation ø80 mm (ISO 10110-5) [nm]	Surface radius	Microroughness rms [nm]	Cleanliness (ISO)
Tolerances	RMSi < 150	80 +/- 0.015 mm	< 1	1 x 0.1 (at each subaperture of ø25 mm); E0.5
Results	RMSi 131.190	79.9963 mm -0.0046%	2.3	0x0.1

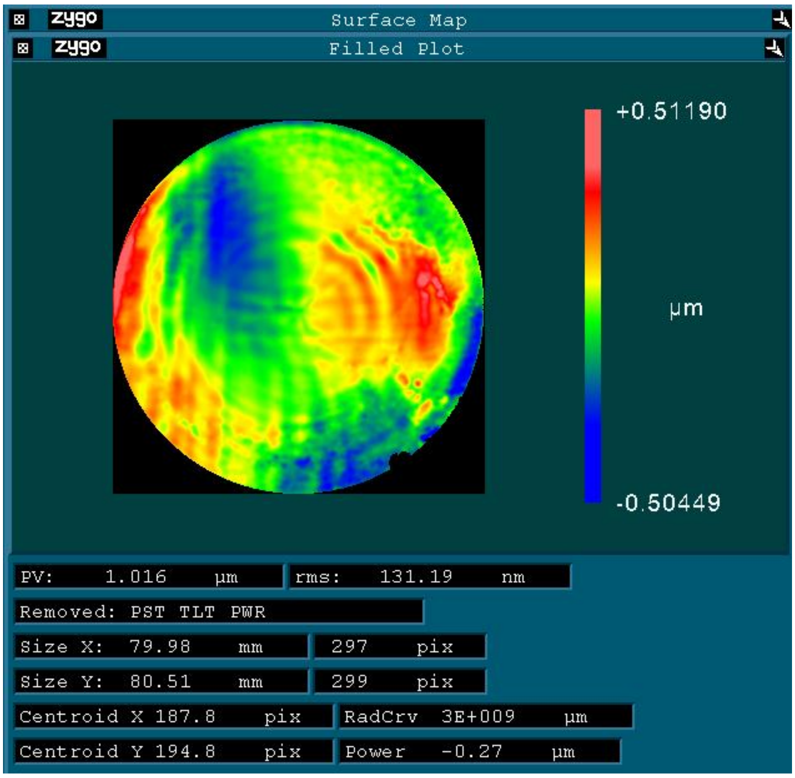

Figure 5: Surface form deviation for Free-Form CaF2 element (80 mm aperture).

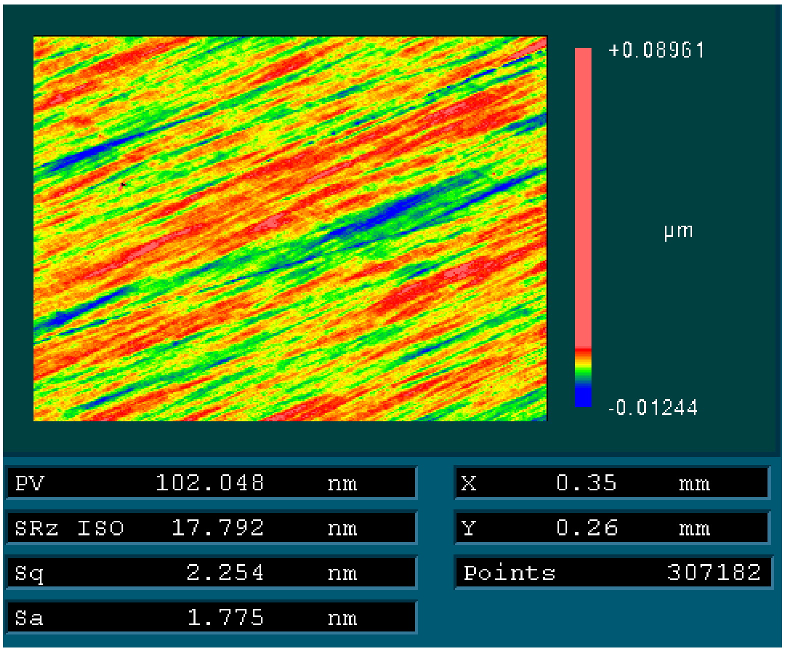

Figure 6: Surface microroughness map for Free-Form CaF2 element (representative centre subaperture, 20x magnification).

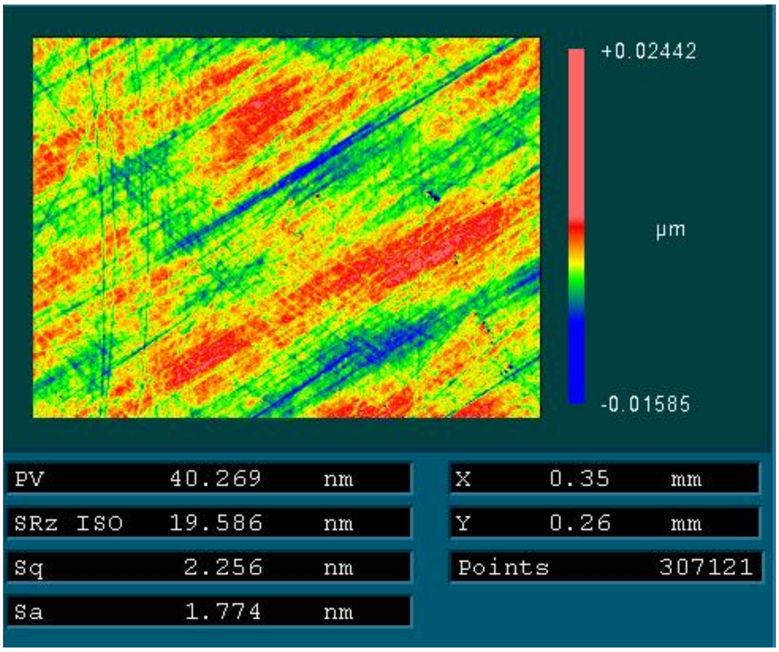

Figure 7: Surface microroughness map for Free-Form CaF2 element (representative annulus subaperture 25 mm from the centre, 20x magnification).

3.2. Aspherical manufacturing process

3.2.1. Aspheres made of Fused Silica

In standard production are the polishing processes used in combination with cerium oxide-based slurry and in experiments it was proven, that it is also the best choice for polishing the Fused Silica. Good chemical reactivity between the slurry and polished surface leads to low microroughness. Against the standardly used slurry, that was used for pre-polishing, finer slurry with a more advanced composition was used for the final polishing process.

The final Angstrom polishing process made us compromise between surface form deviation and microroughness. The Angstrom polishing process is complicated because it is a great approach for reducing the microroughness on the sample surface, however, it is difficult to set proper parameters because it prone to increasing the surface form deviation. Despite that, we were able to find proper parameters and obtained great surface microroughness and preserve the surface form. As the polishing slurry, Hastilite FIN was used.

After multiple runs of the Angstrom polishing surface form deviation was below 40nm as required. Surface microroughness was improved significantly. Measurement was done at four points - on the vertex, at 10 degrees from the vertex, on the position 20 degrees from the vertex, and at position 26 degrees from vertex. In all points was the result in microroughness in tolerance. Surface quality was approved by ISO control and was in limits.

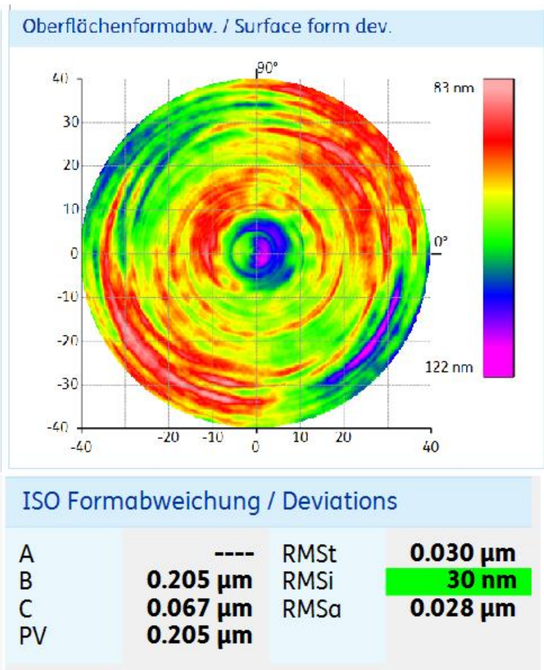

Figure 8: Surface form of the fused silica lens #3 (HW3).

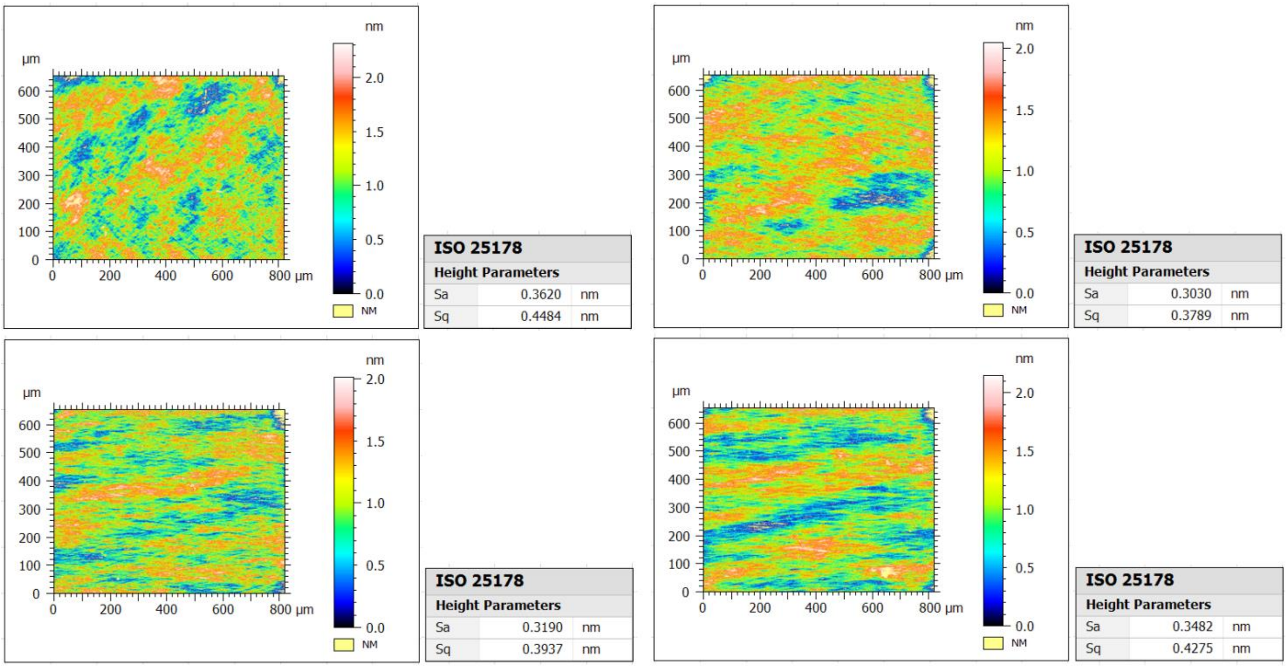

Figure 9: Final microroughness on the HW3, magnification 20x. Measured on the positions 0, 10, 20 and 26 degrees.

Table 4: Summary of the reached parameters on the fused silica aspherical lens #3 (HW3).

	Target / Goal	Result
Surface form error CX (rms)	40 nm	30 nm
Surface radius error CX (rms)	± 15 µm	0.72 µm
Microroughness CX (rms)	0.5 nm	0.4 nm
Cleanlines	1 x 0.1	OK
Edge Chips	0.1 mm	OK
Central thickness	± 0.3 mm	-0.07

3.2.2. Aspheres made of CaF_2

The difference between Fused Silica and CaF2 is its form. Fused silica is an amorphous material, whereas CaF2 is a crystalline material. This aspect brings new complications to the polishing process. During the rotationally symmetric polishing process, that is standardly used, the removal of the tool is periodically changing in one turn. It is visible from the projection of the cubic crystalline structure in the direction (1,1,1), which was used. The lattice shows 3-fold symmetry. Therefore, the removal will also change in three periods in one turn. Due to this fact, trefoil will be generated on the surface.

After pre-polishing, where was the grinded structure polished away, the correction polishing for improving the surface form, started. In this step, the correction of the trefoil structure started with 3D correction. For the whole process, several diamond-based slurries with decreasing mean particle size were used. The residual errors were removed with asphericon's polishing technology Angstrom polishing. With the combination of 3D polishing and Angstrom polishing it was reached the values in specifications. Surface microroughness was not easy to reach at all measured points. But the median value met the required specifications. Measurement was done in four points - at the vertex, at 10 degrees from the vertex, at the position 20 degrees from the vertex and at position 26 degrees from the vertex. On the border was the resulted microroughness slightly over tolerance. Surface quality was approved by ISO control and was within the limits.

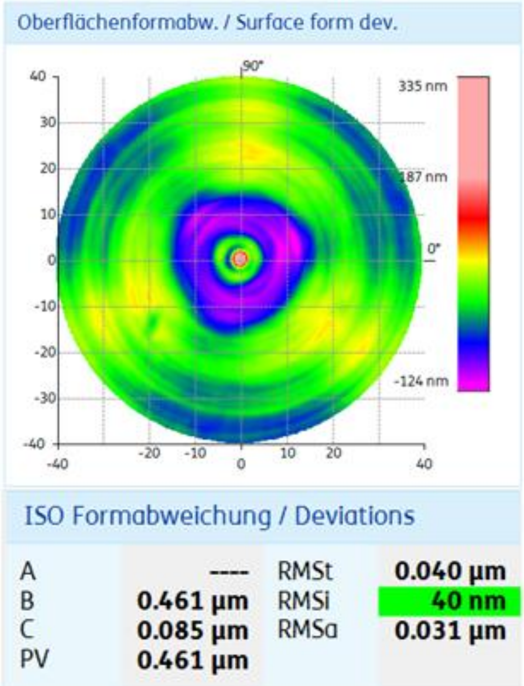

Figure 10: Surface form of the CaF_2 lens #7 (HW4).

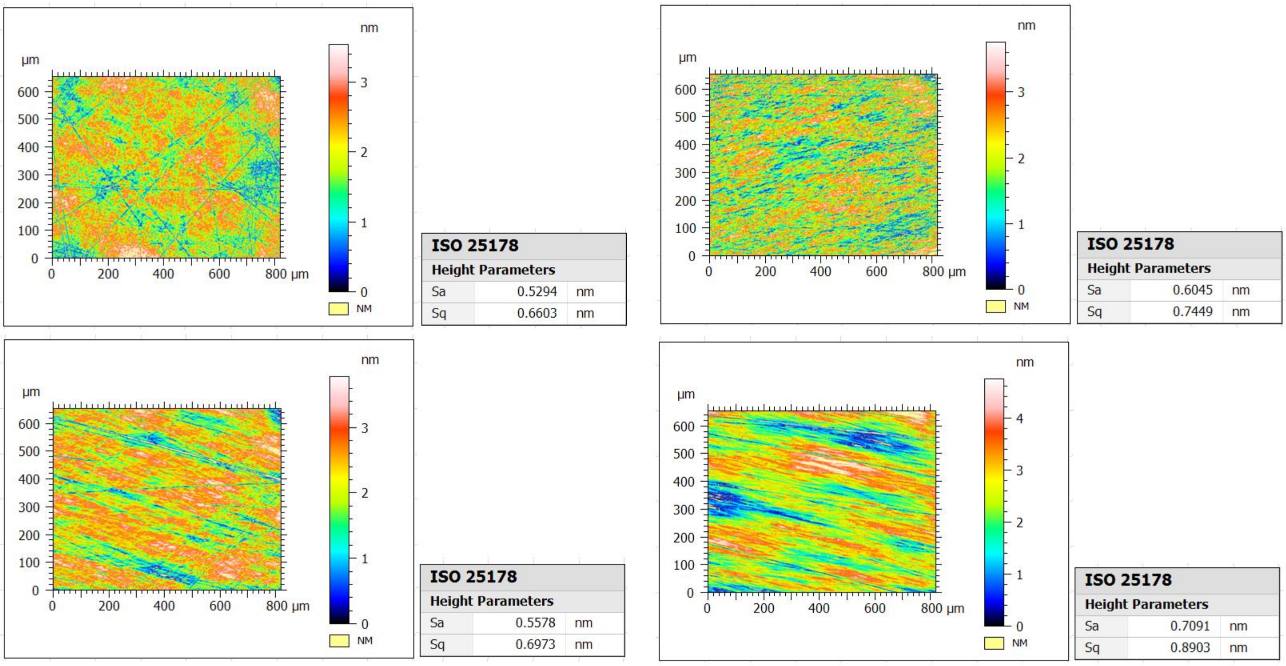

Figure 11: Final microroughness on the HW4, magnification 20x. Measured at the positions 0, 10, 20, and 26 degrees.

Table 5: Summary of the reached parameters on the CaF_2 aspherical lens #7 (HW4).

	Target / Goal	Result
Surface form error CX (rms)	**40 nm**	**40 nm**
Surface radius error CX	**± 15 µm**	**8.22 µm**
Microroughness CX (rms)	**0.7 nm**	**0.7 nm**
Cleanlines	**1 x 0.1 (at each Ø 25 mm)**	**OK**
Edge Chips	**0.1 mm**	**OK**
Central thickness	**± 0.3 mm**	**-0.02**

4. Conclusion

The part of the project focused on free-form elements successfully managed to reach the goal of the project as regards the surface form error to be smaller than 150 nm RMS value for both the CaF_2 material and the Fused Silica. Toptec reached 131 nm of the CaF_2 material and 78 nm on the Fused Silica. Regarding the surface micro-roughness, the goal to reach values smaller than 0.6 nm on Fused Silica was met when Toptec reached 0.5 nm.

Toptec was able to overcome and solve several difficulties to achieve these values. Namely during the CNC grinding phase when overcoming data handling issues in the corrective grinding process. During the data handling when data needs to be transferred correctly between individual manufacturing machines and measurement devices from numerous manufacturers. During the matching of surface form measured data with the real surface and finally during the polishing process when appropriate polishing steps organization and process parameters settings had to be found mainly for both the Fused Silica and CaF_2 materials.

Toptec however was not able to meet the micro-roughness level requirement of the CaF2 to be smaller than 1.0 nm. Toptec was reaching the mean value of 2.3 nm on the free-form CaF_2 element. The main reasons were identified as the forming of fine scratches generated on CaF_2 by the pitch tool and diamond slurry interaction. It could be a result of the polishing raster kinematics when the workpiece without rotation movement restricts the surface smoothing. Another, probably more important reason, could also be the usage of a too primitive extracorporeal polishing slurry delivering system made by Toptec without sufficiently powerful mixing, which could prevent the slurry agglomeration especially when delivering the final polishing slurry with particles under 0.5 µm. Hence, as regards microroughness, the possible way forward could be the usage of a professional slurry delivering system fully integrated into the Zeeko polishing machine system with control of the particle agitation and slurry temperature. This hypothesis, however, would need to be verified. Further improvement of the roughness could come from changing the tool path geometry together with workpiece rotation which leads to the need for a change of Zeeko's original possibilities resulting in closer cooperation with Zeeko software manufacturer.

The development of the polishing process for aspheres made of fused silica was very successful. Asphericon was able to meet all required values with sufficient margins. The final microroughness of 0.4 nm rms is already close to the measurement limit of the white light interferometer WM 100. Therefore, further improvement is conditional on the purchase of new more precise measurement equipment for microroughness measurement. The final form deviation of 30 nm rms is an excellent value. Another improvement could be done by applying a 3D correction process on the amorphous material. This procedure will be tested in asphericon in the next months a potentially could bring new production possibilities of high precision aspherical lenses.

Polishing the CaF_2 was a much more challenging process. In the end, we met all the required values but just very tightly. The form deviation of 40 nm rms seems to be very at the limit of our technology. Significant improvement probably requires more precise technologies such as MRF or Ion beam finishing. The microroughness reduction under approximately 1.5 nm rms was an extreme struggle. To reach the required microroughness 0.7 nm rms was necessary to use three different diamond slurries in a row and days of process adjustment. It makes the process ineffective and expensive. The goal of asphericon is process optimization where one of the ways could be the use of alumina-based slurries which are very cheap compared to diamond slurries. Even if the surface quality would be worse developing a cost-effective process of CaF_2 is for asphericon a very interesting goal.

Thanks to the project asphericon gained great experience with plenty of new polishing slurries and optimized a lot of internal processes. But the biggest benefit of the project is the successful establishment of the 3D correction process. It opens to asphericon s.r.o plenty of new possibilities, which materials can be machined, and also increases the precision level of aspherical lenses on standard materials.