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Optimization of the continuity of the aspherical production processes in asphericon s.r.o based on subsurface damage and microroughness analysis

Ondřej Matoušek[1, 2*], *Karolína* Sedláčková[1], and *Vladislav* Kuryshev[1, 3]

[1]asphericon s.r.o., 463 12 Jeřmanice, Czechia
[2]Technical university of Liberec, Institute of New Technologies and Applied Informatics, 461 17 Liberec, Czechia
[3]Technical university of Liberec, Dept. of Power Engineering Equipment, 461 17 Liberec, Czechia

Abstract In the paper is presented an analysis and optimization of the standardized sub-apertural grinding process used in the serial production in asphericon s.r.o. The monitored parameter was the depth of subsurface damage and surface microroughness. Tested were five grinding processes, which were automatically generated by the internal system, for five different diamond grit sizes (D151, D91, D64, D30, and D15). For evaluation of the depth of the defected layer was used modified wedge polishing method which is suitable for analysis of the rotationally symmetrical sub-apertural grinding processes [1]. For identifying the presence of the subsurface damage two methods were used. Defect detection using an optical microscope, as the broadly used and reliable method, and detection by standard ISO control to get the comparison with the method used in common serial production. The microroughness was measured using a white-light microscope concerning the used grinding tool and the amount of removed material. Within the experiment was found as the most effective two-step process uses D91 for rough grinding and D30 for fine grinding. D91 provides a very good removal characteristic with final subsurface damage of 44 μm which is possible to grind out using the D30 tool in two steps with final subsurface damage 22 μm in a total processing time of 137 minutes. This grinding process is timewise in best balance with 80 minutes long polishing process and therefore minimize the production cost. Result microroughness around 2 nm Sq in the fully polished zone is already limited by the polishing process. Using a finer grinding tool is not bringing improvement in the surface microroughness just shortening polishing time due to lower subsurface damage.

1 Introduction

Serial production of aspherical elements is becoming more widespread but compared to spherical optic is the productivity still way lower and due to that also price higher. In high volume production could even small optimization in the process significantly affect the final price. Extremely important is the proper continuity of every single processing step. These are in aspherical production much more interconnected compared to spherical production. One of the most important parameters to know for the proper planning of the whole production process is the level of the subsurface damage [2] after each machining step and the resulted surface microroughness [3] after applying the production chain.

The layer of the subsurface damage consists of the small cracks which are passing from the surface deeper into the material. In the optical industry is this layer generated mainly during the grinding process, when a glass is removed with a rigid diamond tool. Usually, multiple grinding steps with different diamond grit sizes, from rough to fine, are used in the production process. In the rough grinding step is removed a high amount of the material, but also high subsurface damage is caused. It leads to a very long polishing time. Therefore, the fine grinding step with constant removal is used to grind out the whole defected layer caused by the rough tool. After the fine grinding is the element not free of subsurface damage, but the depth of the damage is reduced which also reduces polishing time [2].

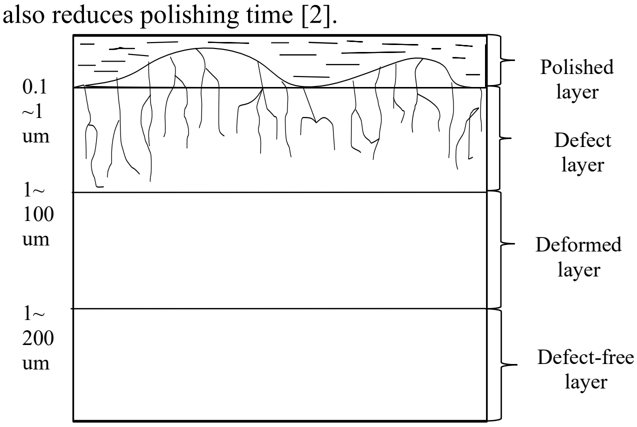

Fig. 1. Schematic view of the subsurface damage in brittal materials.

* Corresponding author: o.matousek@asphericon.cz

During the polishing process, the layer of the subsurface damage must be fully polished out. The necessary removal rate depends mainly on the depth of the defect layer, which must be removed. The deformed layer is in the case of the glass materials almost negligible. There is a lot of room for optimization of the processes. In general, the finer grinding tool is used, lower the subsurface damage is generated. But a fine diamond tool allows to remove only thinner layer of the material and the use a lower feed. It causes a longer processing time. In high volume serial production, as in asphericon s.r.o, is very important to balance polishing and grinding time to reach the most productive process. It requires setting up the grinding process time by choosing a proper tool with a certain diamond grit concerning the necessary time to polish out the defected layer.

The most often used method for subsurface damage identification is wedge polishing [4, 6]. Grinding is performed on a plano sample which is then polished under a certain angle. The angle is selected based on the expected deepness of the defects and the diameter of the sample. For optical materials such as glass, it is usually a few tenths of arc minutes. By the wedge polishing, three zones are formed on the surface. One zone is a ground surface that was not polished at all, the last zone is a fully polished surface. In between is the zone of subsurface damage, where the density of the defects is gradually decreasing from the ground zone to the fully polished zone (Figure 2). The depth position of the last defect is determined as the depth of the subsurface damage. The depth position or rather Z position can be measured using a tactile profilometer. The ground part of the sample is used as a reference and from it, the profile of the wedge, and from the lateral position of the last defect, the depth of subsurface damage is calculated.

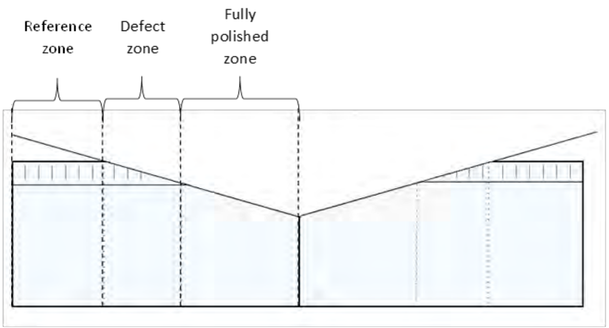

Fig. 2. V-shape polished surface with marked referenc (ground), defected, and fully polished zone.

This method can be modified in a way, to be more suitable for aspherical technology [1]. In this case, the wedge polishing is replaced by the polishing of a V-shaped hole into the surface using standard rotationally symmetrical aspherical polishing. As reference is left a ring of an unpolished surface at the edge of the sample. In this case, the ground and subsurface damage zones have the form of rings the fully polished zone is then the rest of the surface up to the centre of the sample. Because the profile measurement is done from edge to edge the reference part is on both sides. It makes it much easier and more precise to align the date and therefore also to calculate the depth of each defect compared to standard wedge polishing, where the reference is only on one side. The advantage is also that the form of the polished V-profile can be very easily driven and optimized by setting up the process parameters. The greatest benefit of using V-shape polishing is that for subsurface damage identification and the standard serial production is used the same polishing process. Therefore, the obtained values are in direct relation to the manufacturing process.

Fig. 3. Sample of diameter 167 mm polished to the V-shape**.**

The crucial step is the identification of the end of the subsurface damage zone. The most often used method is manual identification of the position of local defects at the edge of the zone using an optical microscope. This method is very time-consuming, but reliable. This method is usually used as a reference for newly developed methods and is used in the experiment as well. The second method used for defected zone localization is a control according to the ISO 14997 standard. In this procedure are used exactly defined illuminations lamps, magnification glasses, and comparison gauges to evaluate the final surface quality. It is worldwide the most common quality control (QC) method for optical elements and asphericon s.r.o uses it as well. An experienced controller can find even a single isolated defect of size close to one micrometer. Therefore, the method was chosen as a possible alternative for localization with a microscope.

But subsurface damage is not the only parameter taken into the account in the optimization. Important is also surface microroughness which is affected not only by the polishing process but also by the previous grinding steps. Too rough grinding increases polishing time not just by the necessity of removing the defected layer but also, because flexible tools are used for polishing, the rough structure is copied into the polished surface and takes a longer time to get rid of it. This effect negatively affects the surface microroughness and increases the total polishing time. Due to that is important to measure after polishing the surface microroughness on several radial positions concerning previous machining steps and the depth of the removed material. As standard for polished surfaces with microroughness deep under 10 nm Sq is used white-light interferometry [5]. The most common and reliable parameters used for 2D evaluation of the microroughness are Sa (1) and Sq (2) described below. Before its calculation, 4th order 2D polynomial is subtracted from the data to suppress the effect of the surface form.

Sa – average roughness:

$$S_a = \iint_a |Z(x,y)|\ dx\,dy \tag{1}$$

Sq – Root mean square roughness

$$S_q = \sqrt{\iint_a (Z(x,y)^2)\ dx\,dy} \tag{2}$$

2 Experiment

For the evaluation of the subsurface damage caused by the standard asphericon's sub-aperture grinding processes was chosen the most common glass Schott N-BK7. The diameter of the samples is 167 mm. The big diameter of the elements allows polishing gradual V-shape with a very low angle which helps to increase the precision of the method. The polishing process was held with standard tooling, polyurethane pad LP-35 from Universal Photonics, and cerium oxide-based polishing slurry AUERPOL PZ 110 with a mean particle size of 0.9 um. The parameters of the polishing process were at the beginning automatically generated by the internal technological system to ensure the relation with standard serial production. After that, the polishing times were linearly modified (shortened at the edge prolonged in the center) to get the required V-shape.

Table 1. Equipment used in the experiment.

Machining	Grinding	OptoTech ASM-100
	Polishing	OptoTech ASP-200b
Form measurement	Tactile form measurement	MarSurf LD 260 Y
	Non-contact form measurement	LuphoScan 260
Inspection	Ground surface roughness measurement	MarSurf LD 260 Y
	WLI for defects detection	MarSurf WM 100
	Optical microscope for defects detection	Zeiss Vario Axioscope

Asphericon s.r.o is mainly focused on serial production therefore all the processes are standardized and automatically generated based on parameters of the successful processes from the last 20 years. Input parameters for the creation of grinding processes are tool diameter, diamond grit size, type of glass, and diameter of the machined element. Based on this are generated tool speed, workpiece speed, feed, and removal in one step. Under the test were standard processes listed in the table below.

Table 2. Parameters of the grinding proceses for each tool.

Tool	Tool speed [u/min]	Lens rotation smooth grinding [mm/min]	Grinding track resolution [mm/point]	Z – removal in one step [mm]	Number of steps	Length of the one grinding step [minutes]
D151	-6131	7200	0,05	0,1	1	27
D91	-6131	7200	0,05	0,1	1	27
D64	-6131	7200	0,05	0,06	2	27
D30	-6131	4800	0,05	0,03	3	55
D15	-6131	4800	0,05	0,015	5	55

The used grinding tools from Lach Diamant have standard wheel construction of a diameter of 100 mm and a thickness of 10 mm. All the tools have the same metal bond and tested were five different diamond grit sizes (D151, D91, D64, D30, and D15). Dimond concentrations are C60 for D151 and D91, C100 for D64, and C50 for D30, and D15. Differences in the diamond grit size are visible in the below-presented microscope photos.

Fig. 4. Grinding tool with grit size D151.

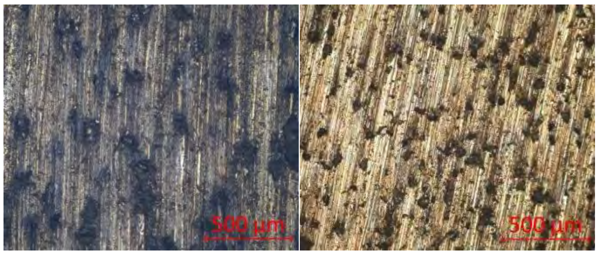

Fig. 5. Grinding tools with grit size D91 on the left and D64 on the right.

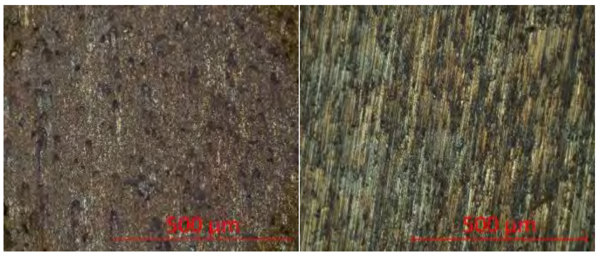

Fig. 6. Grinding tools with grit size D30 on the left and D15 on the right.

For polishing of the proper V-shape into the surface was at first generated standard polishing file for constant removal 30 µm all over the surface. The constant removal was then modified by doubling the polishing time in the center (position 0) of the lens and by shortening it by three at the edge (position 66) (Table 3 column "Position on the curvature"). In between the positions is polishing time linearly interpolated. To change the depth of the V-shaped hole for the different diamond grit sizes the polishing times in each position were simply multiplicated or divided, all by the same number (Table 3 column “Dwell time”). It of course changes the total polishing time (Table 3 column “Time”). All the other parameters were constant to reach the same polishing conditions and are listed in the table below.

Table 3. Parameter of the grinding processes for each tool.

Tool	Tool speed (outer/inner) [1/min]	Lens rotation polishing (outer/inner) [1/min]	Position on the curvature	Dwell time	Position of the tool	Time
D151	2/66	509/1499	0/33/66	60/36/12	5/27/49	2:31:06
D91	2/66	509/1499	0/33/66	20/12/4	5/27/49	0:50:22
D64	2/66	509/1499	0/33/66	18/10.8/3.6	5/27/49	0:45:20
D30	2/66	509/1499	0/28/66	16/9.5/3	5/27/49	0:37:06
D15	2/66	509/1499	0/28/66	9.5/4.5/1.5	5/27/49	0:18:33

Applying the grinding processes listed in the table above (Table 2) for grinding plan surfaces were reached PV form deviations under 5 µm on all test surfaces. It makes a good starting point for V-shape polishing because even without subtracting the form of the ground surface from the form of the polished one can be reached good precision. Despite that fact, the effect of the form deviation after grinding will be considered.

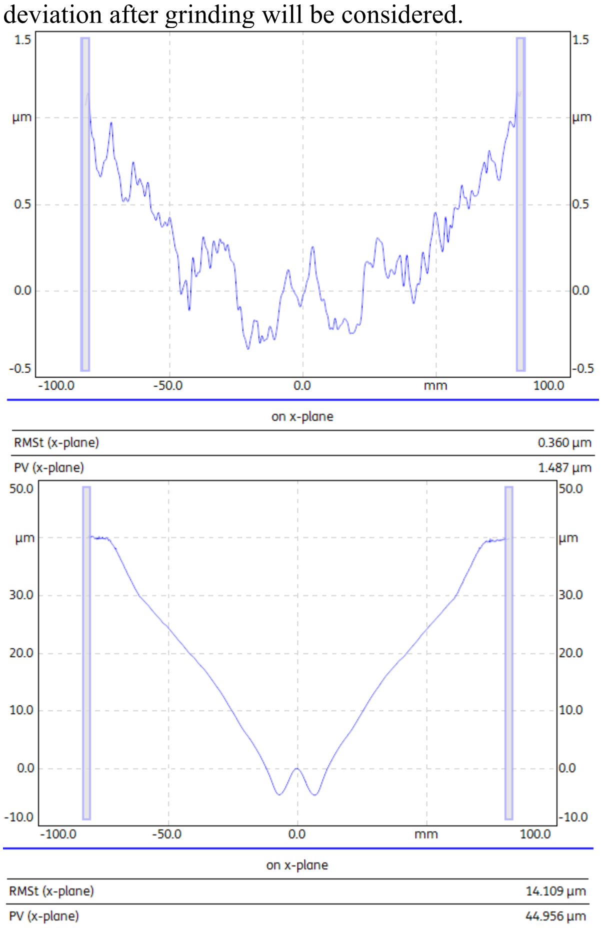

Fig. 7. Surface form deviation after grinding with the D30 tool on the top. On the bottom the same sample after the V-shape polishing.

Polishing with the parameters in the Table 3 led to a V-shaped form deviation on all the test elements. As can be seen in the measured data (Figure 7) in the centre of the elements is a small hill. It is not an issue because the fully polished surface was reached before the hill is rising on the surface. Therefore, the analysis of the subsurface damage is not affected by that. Only in microroughness measurement must be taken as a starting point the lowest point on the surface, not the center of the element. Polished was diameter 140 mm to preserve unpolished reference edges. The depth of the polished V-profiles including subtraction of the form of the ground surface is listed in the table below.

Table 4. Surface form parameters of each smaple after grinding and plolishing.

Tool grit size	PV after grinding [µm]	Depth of the V profile [µm]
D151	3.9	141.2
D91	5.3	53.3
D64	3.9	75.3
D30	1.5	45.0
D15	2.9	41.8

3 Results

After successful polishing it was possible to detect the edge of the subsurface damage using both methods, microscopic detection, and standardized ISO control. In the pictures below is presented the development of the surface quality depending on the amount of the material removed by the polishing process. With the increase of the depth are defects evolving from high density cracks through local defects with long grooves behind to the fully polished surface. The long grooves behind the defects are very typical for rotationally symmetric sub-apertural polishing processes and are given by the direction of the material removal. The major material removal direction is from the crack in the direction of the

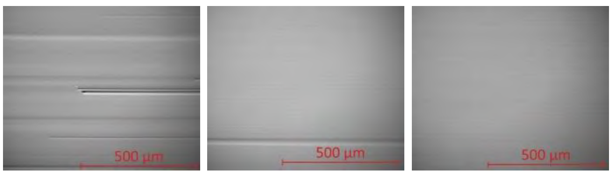

Fig. 8. Microscopic view in depths 25 µm, 50 µm and 75 µm respectively of the V-shape polished surface grinded with the D151 tool.

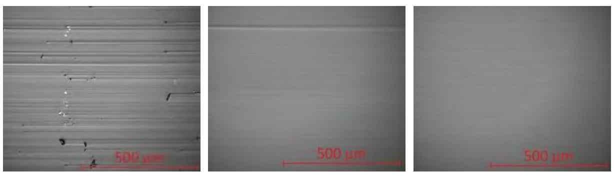

Fig. 9. Microscopic view in depths 12 µm, 24 µm and 36 µm respectively of the V-shape polished surface grinded with the D91 tool.

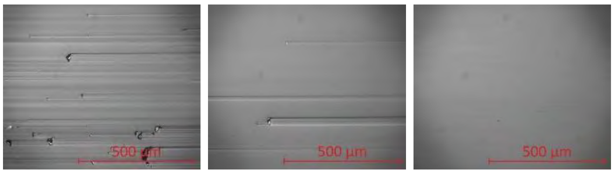

Fig. 10. Microscopic view in depths 10 µm, 20 µm and 30 µm respectively of the V-shape polished surface grinded with the D64 tool.

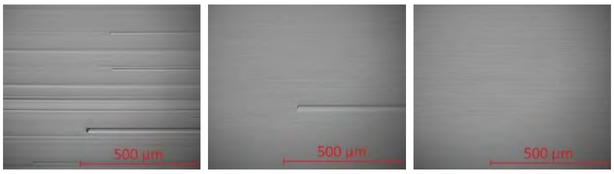

Fig. 11. Microscopic view in depths 7.5 µm, 15 µm and 22.5 µm respectively of the V-shape polished surface grinded with the D30 tool.

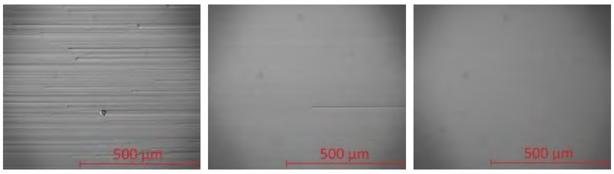

Fig. 12. Microscopic view in depths 4 µm, 8 µm and 12 µm respectively of the V-shape polished surface grinded with the D15 tool.

The depth of the subsurface damage is decreasing with decreasing diamond grit size, as it should be. It is an expected trend because the D number approximately defines the maximum size of the diamond particle in the bond. The ratio between the depth of the subsurface damage and the D number is 51 to 80 percent with an increasing trend from rougher to finer grit size (Table 5). Such dependence is typical for all grinding and even polishing processes of brittle materials using diamond particles. Using finer particles has a generally positive effect on subsurface damage or microroughness but the improvement is limited by any non-zero value. Therefore, is the ratio between quality and particle size more unfavourable for smaller particles.

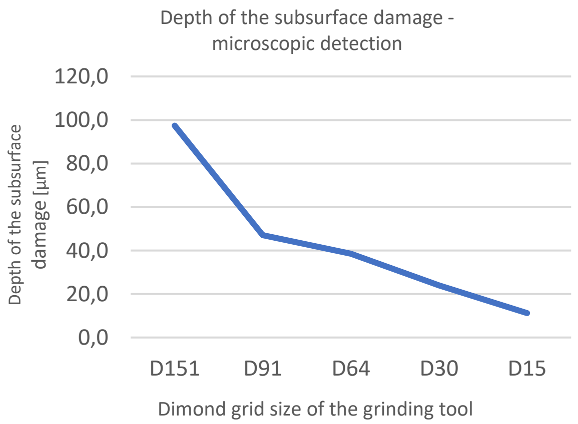

Fig. 13. Depth of the subsurface damage inspected by the referenc microscope based method.

As shown in the graph above and listed in the table below (Table 5), the detected subsurface damage is in the range from 97.4 µm for D151 to 11.2 µm for D15. A very positive result is that the ISO detection by the QC gives very similar results to detection by the microscope. Different values are only for D91 where the ISO control revealed the depth of the subsurface damage smaller by 0.8 µm and for D30 where is the difference 2 µm again smaller for ISO control. It gives us a good picture of that how very precise is experienced quality control. Important is to note that the detection using a microscope is at least ten times more time-consuming.

Table 5. Depths of the subsurface damege inspected by microscope and ISO controle and ration between grit size and subsurface damege.

Tool grit size	Depth of subsurface damage – microscope detection [µm]	Depth of subsurface damage – ISO detection [µm]	Ration D# / Depth of subsurface damage [%]
D151	97.4	97.4	64.5
D91	47.0	46.2	51.6
D64	38.5	38.5	60.2
D30	24.0	22.0	80.0
D15	11.2	11.2	74.7

From the grinding parameters, times and resulting subsurface damage was found the most optimal combination of the processes. The rough grinding using D91 and D30 for fine grinding.

Using D91 for rough grinding gives the best performance to quality ratio. Against the D151 allows removing only a thinner layer of the material. But maximal possible removal of 0.6 mm is suitable for most of the aspheres, which usually have smaller departures from the best-fit sphere. Therefore, can be ground in one step even with D91 with less than half the depth of the subsurface damage. Using D64 does not have many benefits against D91 mainly because is usually necessary to grind the surface in two steps and the benefit of lower subsurface damage does not sufficiently compensate the doubling of the processing time. But in specific cases can be used D64 as the only grinding tool (one level grinding). It is helpful for steep lenses with big diameters. In these cases, sometimes a second tool cannot be used due to the space in the machining chamber. The disadvantage of the one tool solution is worse final microroughness (Table 7). There are also processing issues such as high material removal with one grinding tool of intermediate grit size and long polishing time. Both those aspects cause high tool wear which leads to the lower long-term stability of the processes. Also, in general, is unwanted to have a longer polishing process than the grinding process, because there is no room for optimizing polishing, which is often necessary, without effect to total process time.

The fine tool with a grit size of D30 is the most suitable for serial production because allows reaching a better balance between the grinding and polishing times. The grinding time using the D15 tool is double compared to the D30 if all subsurface damage after rough grinding with D91 must be removed. With the D15 at least three but in real four cycles are needed, because removal 45 µm is too close to subsurface damage 44 µm, compared to two cycles with D30. The polishing time after the D15 is less than half compared to D30 but in high amount production, it only leads to longer standing times of the polishing machine because the total grinding time D91 + D15 247 minutes is at least four times longer compared to polishing. On the other hand, the benefit of the very low subsurface damage reached with the D15 tool can be used in special single-piece production or on very soft and chemically sensitive material in combination with unfavourable concave curvature which typically leads to long polishing times. Typical use is for grinding crystalline materials for example calcium fluoride where is the minimization of the subsurface damage critical for successful polishing.

Table 6. Possible production processes and the optimal process marked in bold.

Tool combination	Grinding time [minutes]	Polishing time [minutes]
D151 + D30	247	80
D151 + D15	412	40
D91 + D30	**137**	**80**
D91 + D15	247	40
D64 + D30	164	80
D64 + D15	219	40
D91	27	180
D64	54	140

Microroughness reached in the fully polished zone was relatively similar for all tested diamond grit sizes respectively only slightly lower for the two-fine tools D30 and D15. For the tool with grit sizes D151, D91 and D64 are final microroughness around 3 nm Sq and for the fine tools, D30 and D15 are microroughness under 2.5 nm Sq (Table 7, values are calculated as an average from three measurements in the fully polished zone). It means that the polishing process can remove quite well the grooves and micro defects and the surface microroughness is given mainly by the polishing process. But the benefit of the use of the fine grit size tools is not negligible and has a positive effect on the polishing time and on the final microroughness which is approximately 20% better too.

Table 7. Microroughness Sq in the fully polished zone.

Tool grit size	Sq microroughness in the fully polished zone [nm]
D151	2.9
D91	2.8
D64	3.1
D30	2.0
D15	2.4

In the measurements, below is showed a comparison of the not fully polished zones after tools D151 and D30 which were captured by the white-light interferometer. A different characteristic of the structure is clearly visible. The tool with grit size D151 creates much bigger local defects and due to that also polishing process produces much wider and deeper grooves on the surface behind them (Figure 14 - left) compared to the tool with the grit size D30 (Figure 14 - right).

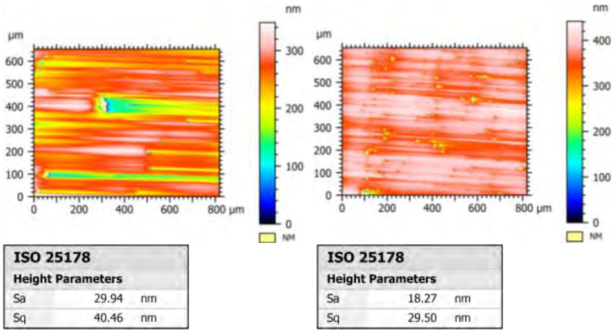

Fig. 14. Comparsion of the partly polished zones of the sample grinded with D151 (left) and D30 (right) tool measured with white light interferometer. Lateral resolution of both mesurement is 1.22 – 780 mm^{-1}.

The wider and deeper grooves tend to be copied by the flexible polishing tool for a longer time and therefore negatively affect the final microroughness. It could be well visible in the comparison below (Figure 15). Both pictures are from the fully polished zones. The left one is after grinding with D151 and the right one after D30. The surface structure after D30 is obviously finer compared to the structure after D151. As was already mentioned that the surface microroughness after fine tools D15 and D30 is approximately 20 % lower than after rough tools D151, D91, and D64. The higher value is coming from the rougher structure at the beginning of the polishing process and its copying by the flexible tool. It is different from the spherical or plano polishing where are used rigid full surface tools which do not tend to follow the waves on the surface. In the full-surface polishing is important to remove the whole defected layer and microroughness is then defined only by the polishing process and material properties.

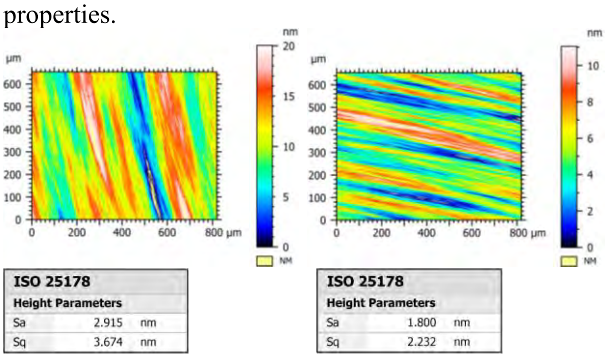

Fig. 15. Comparsion of the fully polished zones of the sample grinded with D151 (left) and D30 (right) tool measured with whitelight interferometer. Lateral resolution of both mesurement is 1.22 – 780 mm^{-1}.

4 Conclusions

In the paper was analysed five standard grinding processes used in asphericon s.r.o and their combinations to find the optimal production process for aspherical surfaces concerning the production time but also the required high surface quality. For analysis of the subsurface damage was used V-polishing method using the standard internal sub-apertural polishing process. It allows the analysis of the subsurface damage and microroughness related directly to the real production processes. For identification of the subsurface damage were used two methods. Localization by the microscope as a reference method and by ISO quality control. For microroughness measurement was used white-light interferometer with lateral resolution 1.22 – 780 mm-1.

In the experimental part was grinded five samples of a diameter of 167 mm with tools with 5 different grit sizes D151, D91, D64, D30, and D15. The resulted subsurface damage was identified very similarly with both mentioned methods with a maximal difference 2 µm which is less than 10%. It is a positive result of this comparison because it shows that the ISO control is precise enough to identify subsurface damage and way faster compared to the microscopic method. The measured depth of the subsurface damage is decreasing with the grit size of the tool from 97.4 µm for D151 to 11.2 µm for D15 (Figure 13). Based on the subsurface damage, removal rate, grinding time, polishing time, and final surface microroughness was chosen the most effective combination of the tools and processes. For rough grinding is the most suitable D91 grit size because allows removal of the required amount of the material in one step, which is beneficial compared to D64, and produces only 44 µm subsurface damage which is less than half compared to D151. For fine grinding, in combination with rough grinding using D91, was evaluated as the best the tool with a grit size of D30. The resulted subsurface damage is 24 µm. The removal of 0.03 µm allows doing only two steps of fine grinding which is the biggest advantage against the D15 tool which needs four cycles on the surface pre-grinded with D91. Even if the use of the D15 tool shortens the polishing time from 80 to 40 minutes is grinding with D30 more effective due to grinding the times of 137 minutes compared to 247 minutes. Also, there is no benefit of better surface microroughness after grinding with the D15 tool because the values show no significant differences. But the use of D15 has a reason for very specific materials, for example, soft crystals such as CaF2, for which machining are used very special and long polishing processes and therefore a limitation of the subsurface damage to the minimum is beneficial. An interesting alternative for D91 and D30 can be only one level grinding with D64. The overall processing time is very favourable. The two-step grinding process takes 54 minutes and the polishing time is 140 minutes (Table 6). The disadvantage of the process compared to two-level grinding is lower stability in grinding and polishing as well. In the grinding is problematic that the high amount of the material is removed by the tool with just intermediate grit size and in polishing very long processing time. It leads in both cases to high tool wear. Also as presented above (Table 7) the final microroughness of the polished surface is already slightly worsened by skipping the fine grinding step. But using only one grinding tool can be very helpful for big lenses with high curvature which often do not allow to have two tools in the processing chamber due to the limited space.

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