Accuracy of freeform manufacturing processes

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ABSTRACT

The breakthrough of freeform optics is limited by manufacturing and metrology technology. However, today's manufacturing machines like polishing robots and diamond turning machines are accurate enough to produce good surface quality, so the question is how accurate can a freeform be produced. To investigate how accurate freeform optics can be diamond turned, measurable freeforms (e.g. an "off-axis" sphere) were diamond turned and they were compared to there on-axis equivalents. The results of this study are described in this paper. Furthermore, an overview of the accuracies of freeform optics that TNO diamond turned are presented. An indication of freeform accuracy for diamond turned optics is derived from this, which can be used for optical designers as a guideline in their design work.

Keywords: diamond turning, freeform optics, accuracy, aluminium

1. INTRODUCTION

This paper discusses the achievable accuracy of the diamond turning process for freeform optics. Before starting this discussion we will first take a look at some surfaces. Figure 1 on the left shows an aspherical surface. That means that this surface has a rotational symmetry. In this case an axi-symmetry around the vertical axis in the centre of the part. Notice that the spherical surface is a special case of an aspherical surface. When the rotation symmetry is gone, we define the surface as a freeform surface. An example is shown in Figure 1 on the right. Notice that freeforms can have mirror symmetries.

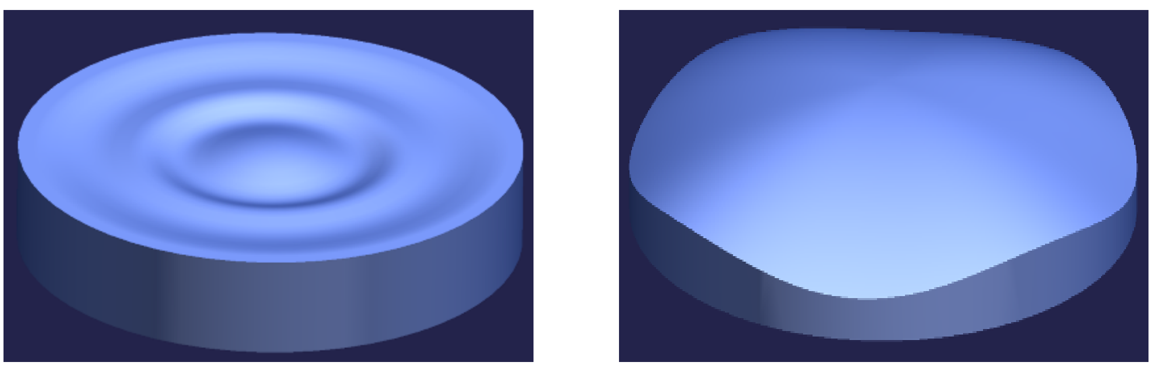

Figure 1: On the left an aspherical surface with an axi-symmetry and on the right a freeform surface having no rotational symmetry.

The question is: why do we want to use freeform optics? The reasons for that can be:

1. Reduction of aberrations, like spherical aberration, coma and distortion;
2. Beam shaping, e.g. for laser beams;
3. Reduction of the amount of components, which leads to:
    a. Size reduction;

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   b. Mass reduction;
   c. Stray-light reduction;
   d. Transmission improvement;
4. Favourable positioning of elements, which gives some design freedom;
5. Prevention of chromatic aberrations, when only freeform reflective optics are used [1].

Despite the large benefits of freeforms, the application is currently mostly limited to lighting systems. In imaging systems the application of freeform optics is still limited. The main reason for this is that optical designers are not satisfied yet with the quality of produced freeforms. This can mainly be attributed to the manufacturing and metrology difficulties of freeforms. Currently it can be said that the quality of freeform techniques is capable of generating accurately enough surfaces. However, the metrology techniques are not yet fully up to date for the production of freeform optics for visual applications.

This paper describes some results of the freeform fabrication and metrology program of TNO Science and Industry and it will show what is achievable with respect to freeform diamond turning, and more specific the slow tool servo machining.

2. DIAMOND TURNING

2.1 Process description

In single-point diamond turning (SPDT) a mono-crystalline diamond tool is penetrated into a rotating workpiece. This is done with a certain feed rate and depth of cut and a rotational speed of the workpiece. When the tool penetrates the workpiece material, a chip is formed that is being removed, see Figure 2. Typical materials for diamond turning are non-ferrous metals, like aluminium and copper, some crystalline materials, like germanium and silicon, and some polymeric materials, like polymethylmethacrylate (PMMA). At TNO most of the work is performed on aluminium AA6061, and most of the examples shown later are derived from diamond turning aluminium.

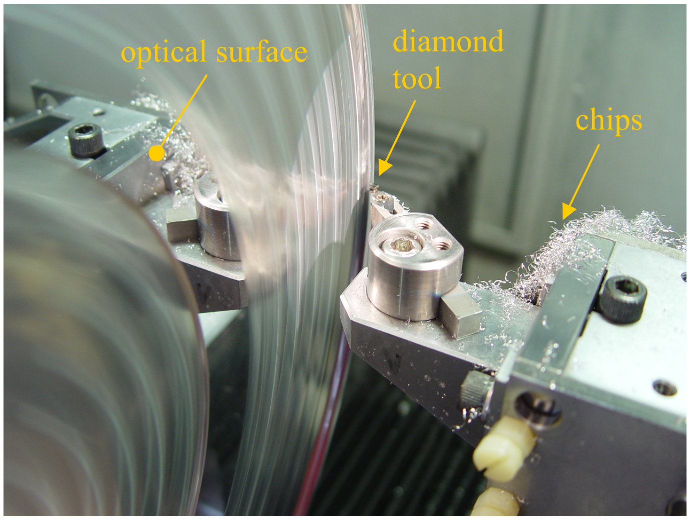
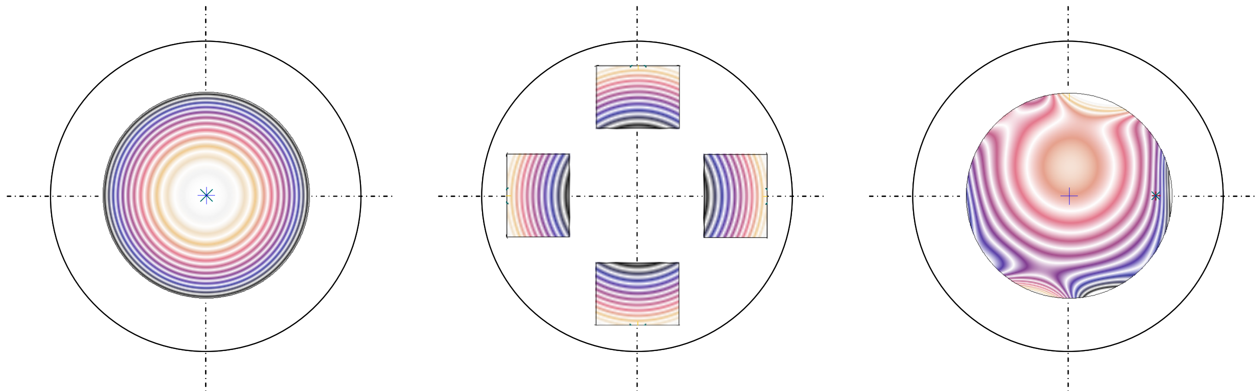


Figure 2: An example of a diamond turning process. The diamond tool cuts the aluminium surface to optical quality. Chips are being removed from the surface.

In classical machining a workpiece is machined while the tool follows an XZ path, typically this is used for generating flat, spherical or aspherical surfaces. Figure 3(a) shows how such a surface is generated. When off-axis elements are produced this can be done by placing (in general multiple) workpieces at the required off-axis distance from the rotation axis of the machine. This way the optical axis of the workpiece(s) coincides with the rotational axis of the diamond turning machine. The production of off-axis elements is typically performed in standard XZ machining, see Figure 3(b).

It becomes different when one wants to machine a freeform surface on a rotating spindle, see Figure 3(c). In that case it will be necessary to have an encoder on the C-axis (the rotational axis of the diamond turning machine).



(a) (b) (c)

Figure 3: (a) On-axis machining of an on-axis surface, (b) on-axis machining of (four equal) off-axis surfaces and (c) on-axis machining of a freeform surface.

During machining it will be necessary to control the X- and Z-axis position in relation to the C-axis position. This process is known as slow tool servo (STS) or slow slide servo (SSS) machining. In this case machining is performed in XZC-mode.

2.2 Diamond turning machine

Diamond turning machines are high precision machines. Typically the X- and Z-slides are made on hydrostatic bearings, while the workpiece spindle, the C-axis, is an air-bearing spindle. Looking at the specifications of the current diamond machine suppliers it can be seen that no large differences exist in the specifications. Small differences in resolution, slide stiffness, radial run-out, swing capacity etc. can be found. For most applications these differences are not significant, since it is not only the machine that determines the outcome of the diamond turning process. Mostly it will be the operator skill, tool wear, workpiece material, coolant/lubrication, environment etc. that determine the quality of the final product.

2.3 Corrective machining

In order to diamond turn accurate freeform surfaces it may be needed to use corrective diamond machining. shows the value chain how it is applied at TNO. First the workpiece blank will be pre-machined to its rough freeform shape (step 1). For aluminium this typically will be a milling process. Then it will be measured for validation (step 2). After this a surface smoothing machining step is performed (step 3). For diamond turning this will be a slow tool servo process with CNC code based on the original freeform surface description. If high accuracy is needed, the surface needs to be measured to obtain the error map (step 4), i.e. the deviation from the theoretical surface. Next, the error map is input for an iterative corrective machining (step 5) and measuring sequence. For acceptance it will be necessary to have an acceptance measurement (step 6), and finally the optic will be coated (step 7).

Currently, TNO has two diamond turning machines for diamond turning freeforms: a Precitech 350 with slow tool servo (shown in the upper left corner of Figure 4) and a Precitech 700A with slow tool servo and additional B- and Y-axis. At TNO the metrology can be performed with on-machine metrology, and also with a dedicated off-line freeform measurement machine, called NANOMEFOS (lower right corner of Figure 4) [2]. An example of successful corrective diamond turning can be found in [3].

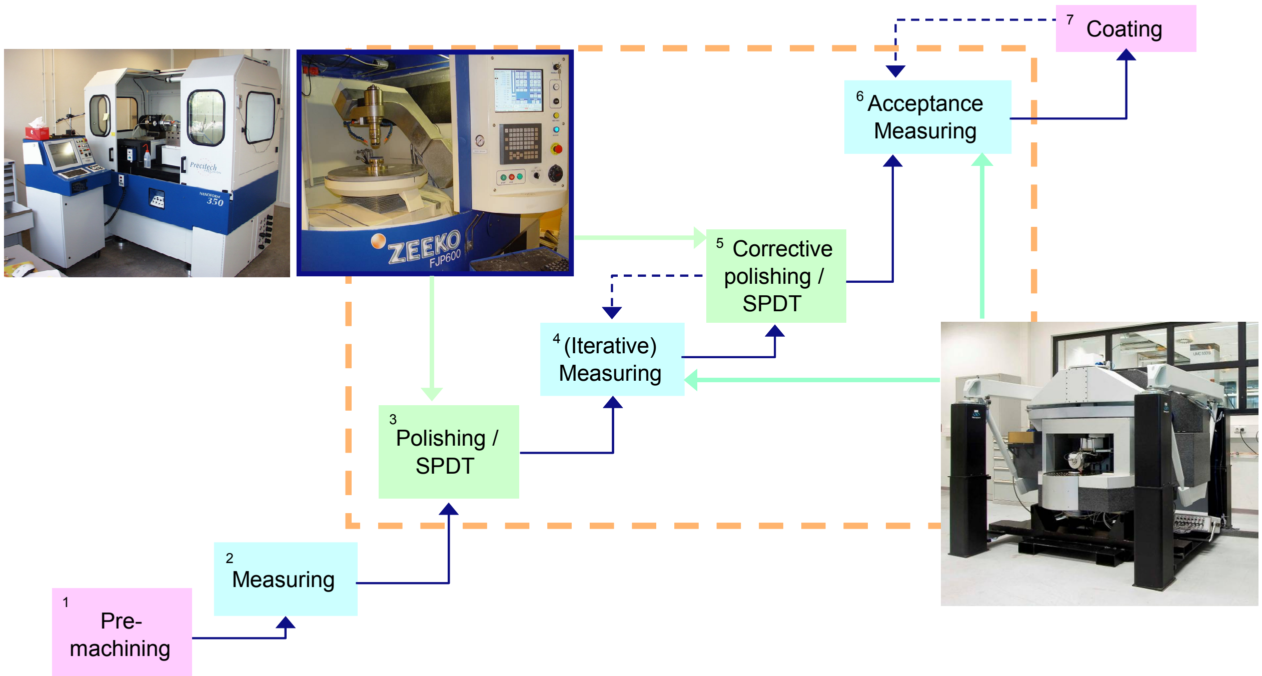


Figure 4: Value chain for freeform fabrication and metrology. After pre-machining the blank, the workpiece will be measured (steps 1&2). After this a surface smoothing machining step is performed (step 3) after which the surface will be measured (step 4). This data, the so-called error map is input for an iterative corrective machining (step 5) and measuring sequence. For acceptance it will be necessary to have an acceptance measurement (step 6), and finally the optic will be coated (step 7).

2.4 Surface roughness

Diamond turning is quite a lot being applied for infrared optics, and in fact there are only little infrared systems that do not contain diamond turned aspheres these days [4]. The main reason for this is that the infrared wavelength is long enough and not scatter too much on the diamond turned surface. To be applicable for the visual spectrum, surface roughness Rq needs to be in the order of 2 nm or less [5] to have less than 1% scattering. Looking at the mostly applied diamond turnable materials, these values only seem attainable in phosphorus nickel platings and special electrodeposited high purity aluminiums like Alumiplate [6]. Commercially available aluminium typically results in Rq roughness values >5 nm. New developments are rapidly solidified aluminium grades that result in surface roughness values Rq < 3 nm [5],[7],[8]. An example of such a diamond turned surface is shown in Figure 5. These aluminium grades open new chances for diamond turned optics without the necessity of additional plated coatings, like nickel or high purity aluminium.

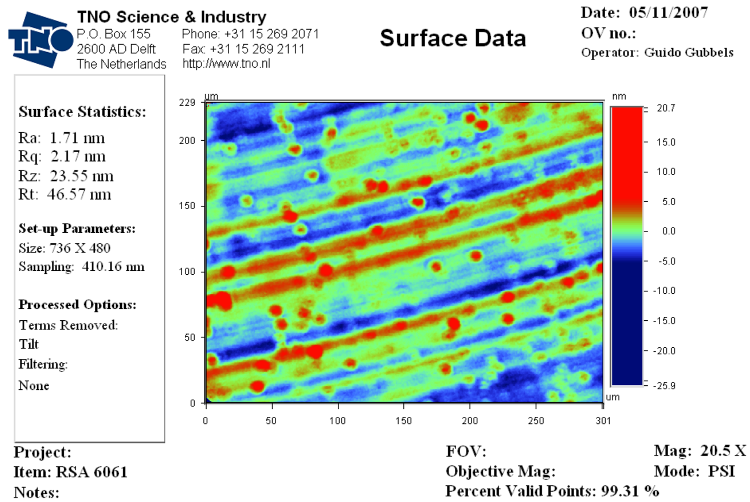


Figure 5: Diamond turned rapidly solidified aluminium (RSA 6061), showing a very low surface roughness value; approaching surface roughness values achievable in nickel plated optics.

3. CASE STUDY: CLASSICAL VS. FREEFORM

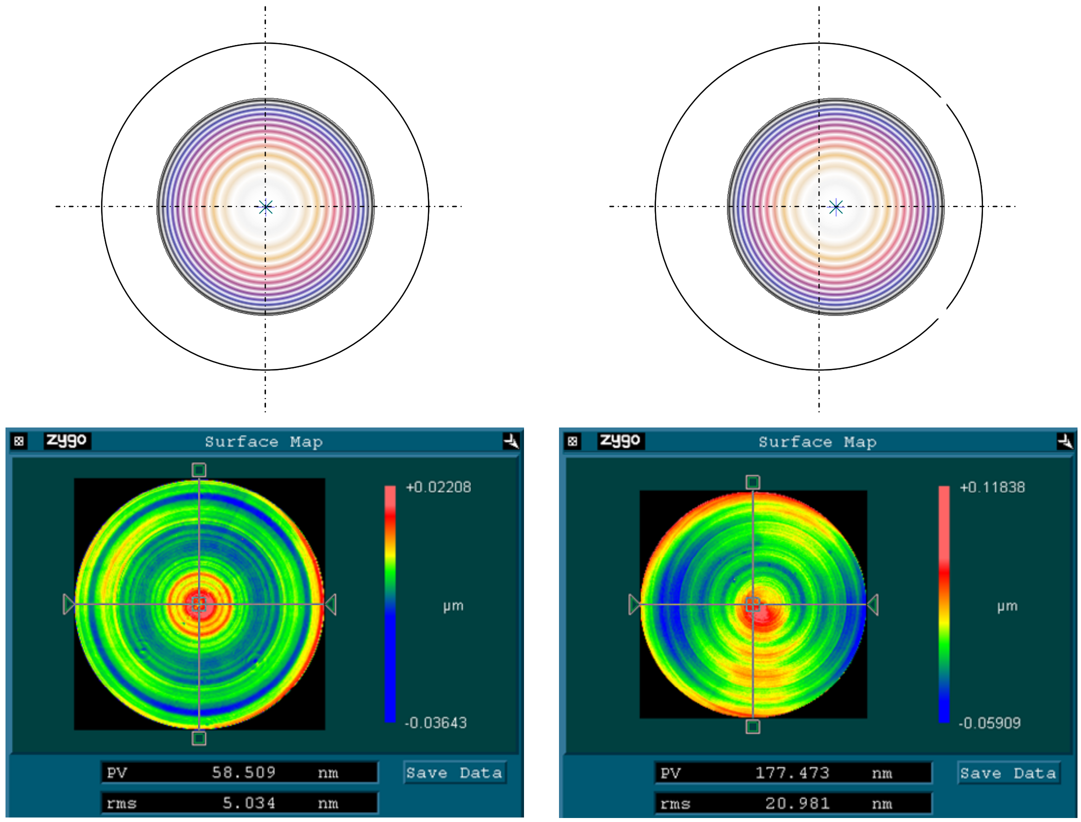
An important question that optical designers have is: "How accurately can you manufacture a freeform surface?" For that purpose we made a comparison between several measureable freeforms. The first case is a comparison between a classically diamond turned sphere and a "freeform" sphere. The second case is that for a classically produced off-axis parabola and a "freeform" off-axis parabola. The classical production means that the surface is diamond turned with the optical axis of the workpiece on the rotation axis of the workpiece spindle of the diamond turning machine.

3.1 Freeform sphere

This case describes the difference between a classically diamond turned spherical surface and a freeform surface spherical surface. The reason for a spherical surface is that the error of a spherical surface is easily measured by an interferometer. The first one was done on-axis, as shown in Figure 6(a), i.e. as an on-axis sphere in XZ-mode. The freeform sphere was done by moving the spherical surface in order to have the optical axis off-axis with the rotation axis of the diamond turning machine, see Figure 6(b). The workpiece was a concave sphere with radius of curvature 158 mm and an aperture of 60 mm. For the freeform case, the off-axis distance was chosen to get a maximum edge sag variation of approximately 1 mm.

Looking at the results in Figure 6(a) and (b), it can be seen that the on-axis sphere is much better than the freeform case: 59 nm PV error versus 177 nm PV error. Looking at the freeform result it can be seen that a small astigmatic error is present, and more clearly a regular pattern can be found that is most likely coming from waviness of the used tool. Also a large error comes from the centre defect, which can be attributed to tool misalignment and may be improved.

Almost trivial to conclude, but based on these results one can say that for on-axis optics it is the best to machine them in normal way, i.e. as a normal on-axis object.



(a) (b)

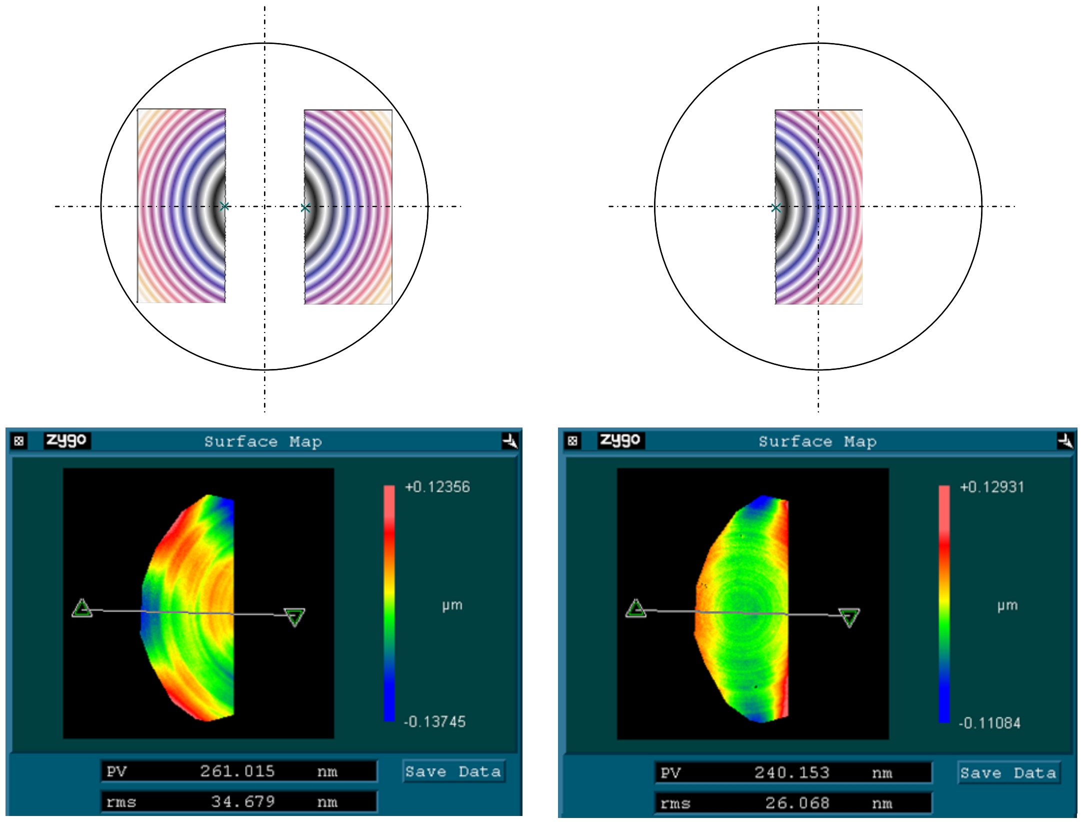
Figure 6: (a) Diamond turned on-axis sphere, and (b) the same sphere, but now diamond turned as a freeform surface. The sphere was concave with radius of curvature 158 mm, aperture 60 mm.

3.2 Freeform off-axis parabola

Coming back to the definition of aspheres and freeforms as described in Section 1, it is important to notice that in general off-axis optics, e.g. an off-axis parabola is considered as an asphere. The reason for this is that it can be produced by placing the optical element in such a way that the optical axis is positioned on the rotation axis of the workpiece spindle, as shown in Figure 3(b). However, when the off-axis distance becomes too large, the off-axis parabola needs to be placed on the rotation axis of the workpiece spindle, making it now a freeform optic.

This case makes a comparison between an off-axis parabolic mirror diamond turned in the classical way as shown in Figure 7(a) and the same off-axis parabola diamond turned as a freeform optic, see Figure 7(b). In that case the slow tool servo is used. The off-axis parabola has a radius of curvature of 250 mm (conic constant k = -1) and an aperture of approximately 90 mm length and 40 mm width. The off-axis distance was 37.5 mm. For the freeform off-axis parabola, the off-axis parabola was tilted to minimize the edge sag variation.

It can be seen in the interferometric measurements in Figure 7 that the off-axis parabola that was diamond turned as a freeform optic has an equivalent shape error as the classically diamond turned parabola, indicating that freeforms can reach a significantly high accuracy in diamond turning compared to the classical production method.



(a) (b)

Figure 7: Comparison between (a) a classically diamond turned off-axis parabola and (b) an off-axis parabola diamond turned as freeform optic. The results are equivalent.

3.3 Summary

Table 1 shows a summary of the two cases. From this table it becomes clear that the off-axis freeform might as well be diamond turned in the freeform manner. The PV and RMS error are nearly the same. The following conclusions can be drawn from this table: on-axis (a)spherical surfaces can best be diamond turned in the classical way, i.e. on-axis. For off-axis surfaces it may be interesting to produce it in a freeform way, unless more optics are needed, then the benefit of multiple workpieces on a large interface prevails. The question arises if a general rule can be found for the production of freeform optics that tells optical designers what to expect on accuracy of freeform optics. A first initiative is presented in the next section.

Table 1: Comparison of classically diamond turned workpieces and the equivalent surfaces produced in a freeform way

		Classical	Freeform
Sphere	**PV** **RMS**	59 nm 5 nm	177 nm 21 nm
Off-axis parabola	**PV** **RMS**	261 nm 35 nm	240 nm 26 nm

4. ACCURACY OF FREEFORM MANUFACTURING

Based on the results of the previous section it becomes interesting to find out if there is a general rule that optical designers can use in their design work. An internet search for achieved accuracies of diamond turned freeform optics gives no specific results that an optical designer can use. Therefore, as a start we investigated the freeforms that we diamond turned over the last few years. The results include relatively small measurable freeforms, or better said off-axis spheres and aspheres that were produced in a freeform sence and that could be measured by interferometer, and the results of the large mirrors that TNO diamond turned for the SCUBA-2 project [3]. In general the smaller optics were not correctively machined. However, the large mirrors were diamond turned using corrective machining as described in Section 2.3.

Figure 8 shows the achieved accuracy of the freeform optics that TNO has made. When plotting the results it was chosen that the criterion of the product of maximum dimension and maximum edge sag variation was a good way for representing the results. The reasoning is simple: it is more difficult to get a good surface shape over a larger optic than over a smaller optic. Furthermore, larger edge sag variation needs more slow tool servo action, leading to more inaccuracies as well.

As a first indication we decided to make a first order fit through the data. For the smaller optics with relatively small edge sag this yields a good fit. As can be seen in Figure 8, the larger optics with larger edge sag stroke result in a larger spread around the fitted line. Especially the point indicated by the arrow is a large “faulty” spot. The main reason for this can be found in the fact that this was the first large mirror that TNO ever made using corrective machining.

The linear fit of the achievable accuracy of diamond turned freeform optics can now be given by the expression:

$$PV = 1.5 \cdot 10^{-6} \cdot L_{\max} \cdot \Delta s \qquad (1)$$

With PV the peak-to-valley error in mm, L_{max} the maximum dimension of the optic in mm and Δs the maximum edge sag stroke in mm. We think that this expression can be used as a guideline for optical designers when designing freeform optics. TNO will work further in getting more values that will improve the quality of the fitted line. Also, TNO will work on further improvement of the accuracy of diamond turned freeforms in order to get the fitted line in Figure 8 further down.

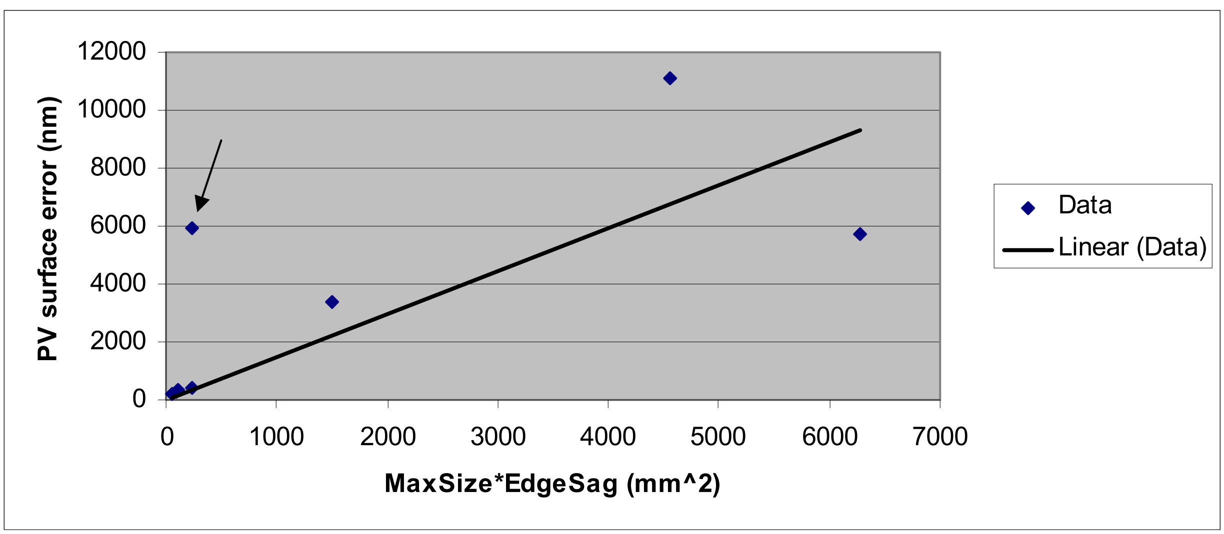


Figure 8: Graph showing the collected TNO data of achievable accuracy of diamond turned freeform optics. The product of maximum size of the optic and the maximum edge sag is a good criterion for the indication of the expected accuracy of a freeform optic.

5. SUMMARY AND CONCLUSIONS

This paper described the accuracy that is currently reached in diamond turning of freeform optics. It has made a comparison of classically turned optics and their freeform equivalents. Depending on the type of geometry it was shown that freeform optics can be produced with an accuracy equivalent to the classical production method.

Furthermore, an initiative was started to capture all of TNO's freeform data to start with a design guide for optical designers to know what is feasible in today's diamond turning accuracy.

ACKNOWLEDGMENTS

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