Shape and curvature error estimation in polished surfaces of ground glass moulds

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Abstract. In the fabrication process of aspheric glass lens and moulds, shape characterization is a fundamental task to control geometrical errors. Nevertheless, the more significant geometrical functional aspect related to the optical properties is the curvature, that is rarely investigated in the manufacturing process of lenses. In this paper, algorithms for the assessment of shape and curvature errors on aspheric surface profile are presented. The method has been investigated on profiles measured before and at different steps of the membrane polishing process. The results show how surface roughness, shape and curvature, change during the polishing process as a function of the machining time.

Keywords: curvature, shape, glass, polishing, grinding, roughness.

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1 Introduction

Resin based ophthalmic lenses are generally produced by introducing fluid polymer into glass moulds and precisely controlling the thermal treatment responsible for polymerization and curing processes.[1] The quality of the final product is directly related to the micro and macro-geometrical characteristics of the glass moulds, whose aspheric surfaces are generated using CNC controlled contour grinding machines. The next step is polishing process during which a very small amount of material is removed in order to improve the final surface finish and eliminate any surface or sub-surface defects.[2-6] As polishing is a very precise, costly and time consuming operation,[7-10] it is desired that corrections to be done during polishing process are minimum. This can be achieved if the geometric tolerances are reached at the grinding stage itself.[1,11,12]

Currently, the inspection of aspheric surfaces is assessed by shape analysis, using CMM or profilometer[13], or by optical analysis, adopting instruments such as interferometers and focimeters. From shape analysis, information about the mould/lens geometry is obtained, while optical analysis gives properties related to the functional characteristics of the lens/mould. Both shape and optical measurements are of importance to the manufacturing and quality assurance of aspheric surfaces.[14-16] A method allowing the decoupling of the geometrical error in the size (offset) and form components was also proposed.[17] A bridge between geometrical characteristics and optical properties is provided by the curvature, because this geometrical property is related to the lens power.[18,19]

In this study, a method for the investigation of curvature errors on an aspheric surface profile is proposed. This method has been applied to the study of aspheric glass mould surfaces after grinding and at different time span of polishing. Shape error and surface roughness have also been measured, in order to thoroughly assess the fulfillment of the functional requirements of the polishing process. As a result, a relation between roughness, shape/curvature error and polishing time has been obtained.

The knowledge of the nature and variation in shape/curvature error serves two purposes: firstly, it allows the understanding of the grinding and polishing mechanism for the adoption of preventive actions for error compensation, and secondly, it allows the study and optimization of the machining parameters, e.g. polishing time, ensuring better compliance with the functional specifications.

2 Materials and Methods

2.1 Polishing Technology

Membrane polishing process of concave moulds has been carried out using a SPF 80 CNC by OptoTech. The material removal mechanism is a typical example of chemical-mechanical polishing, which occurs between three bodies, i.e. glass workpiece, polyurethane pad tool and a suspension of cerium oxide (CeO_2) in water between the workpiece and the tool.

The polishing machine (Fig. 1(a)) is equipped with two spindles able to rotate with different angular speed, around concurrent axes. At the bottom the mould is mounted on the workpiece spindle, while at the top there is a polishing spindle equipped with the tool, oscillating in the vertical plane (Fig. 1(b)). During the process, this oscillation causes a bending of the bottom lens, which is coupled to the shaft by an elastic rubber joint, favoring a uniform pressure distribution.

The oscillation of the tool, which changes during the process, ensures no preferred orientations of the relative speed between tool and workpiece. This characteristic motion is needed in order to avoid preferred orientation of the surface lay. The polishing tool deserves special attention. It is shown in Fig. 1(c), disassembled into its components, and basically consists of a metal case containing:

- a flexible rubber membrane on which a layer of polyurethane (1), in contact with the workpiece, is anchored;
- a spherical-cylindrical rubber cap (2), which in turn contains a series of thin plastic cylinders immersed in liquid lubricant;
- a cylindrical rubber membrane (3), which covers and presses cylinders.

This complex configuration helps the tool to better follow the lens/mould shape. A single tool can be adopted to a wide range of lenses/moulds.

2.2 Algorithm for Curvature Analysis

In order to estimate the actual local curvature of 2D mould profiles, a dedicated tool has been developed. This tool can evaluate either the local curvature of the mould surface, or the deviations of the local curvature from the nominal one, computed from the explicit form equation of the mould/lens. Surface profile is measured by a contact stylus profilometer at different polishing time spans, obtaining a set of equi-spaced points. To reduce the effects of measurement noise and roughness, a local parabolic fitting is computed (quadratic fitting better approximates the shape of an aspheric profile than a circle). Then, on the local fitting, the curvature is calculated along with the nominal curvature of the mould/lens.

In detail, on each point $P_i(x_i,z_i)$ of the mould/lens profile, a parabolic fitting $z_i(x)$ is computed adopting the points in the interval $[P_{i-k}, P_{i+k}]$ ($k \in \mathrm{N}$):

$$z_i(x) = a_i x^2 + b_i x + c_i \tag{1}$$

where a_i, b_i and c_i are the fitting coefficients of the i^{th} fitting parabola.

The radius of curvature R of the explicit function $z=f(x)$ is given by the well-known equation:

$$R(x) = \frac{\left(1 + \left(\frac{df(x)}{dx}\right)^2\right)^{3/2}}{\frac{d^2 f(x)}{dx^2}} \tag{2}$$

Consequently, the radius of curvature R_i in the i^{th} point, is obtained substituting Eq. 1 in Eq. 2, calculating the derivative and computing $R(x)$ for $x=x_i$:

$$R_i = \frac{(1 + (2a_i x_i + b_i)^2)^{3/2}}{2a_i} \tag{3}$$

2.3 Experimental Plan

An aspheric profile is defined by the equation:

$$z(x) = \frac{1}{R} \cdot \frac{x^2}{1 + \sqrt{1 - p \cdot \frac{x^2}{R^2}}} \tag{4}$$

where p is the aspherical coefficient and R is the curvature radius at the center. In our study, we set p = -0.5 and R = 57.51 mm.

Nine samples of Schott CH-W0991 glass have been ground by OptoTech ASM 100 CNC Twin Cut[1] (spiral pitch 0.7 mm, tool spindle speed 8000 rpm, workpiece spindle speed 2 m/min, max workpiece spindle speed 200 rpm, grain size 35 μm, tool radius ≅ 40 mm). Samples have been then polished for different time spans, according to the Renard series R5 and R10: 100, 160, 250, 315, 400, 500, 630, 800 and 1000 seconds. The kinematics of the machine tool produces a relative velocity between workpiece and tool, which involves tool oscillation (sinusoidal oscillation from 17° to 24°, frequency 10 Hz), tool speed (400 rpm) and lens speed (350 rpm). Due to the tool oscillation, the relative velocity in the center is not zero (see Fig. 1 b). Surface profile and roughness have been measured by a Taylor-Hobson Form Talysurf i-Series profilometer after grinding and at different polishing time spans, with a sampling step of 0.005 mm.

Shape error has then been analyzed by fitting the measured profile to the theoretical one and evaluating the normal distance between the profiles. Curvature error has been calculated by the proposed algorithms using k = 800, that means local fitting in 8 mm portions.

Specific tools have been developed in Rhinoceros® Version 5 environment using IronPython as programming language, ALGLIB (*Source: http://www.alglib.net/*) for the fitting between profiles and Meta.Numerics (*Source: www.meta-numerics.net/*) to solve linear system for quadratic fitting.

3 Results and Discussion

Figure 2 shows the shape and curvature of both the nominal profile (Eq. 4) and the ground profile. It can be observed that the actual profile is very close to the nominal, while the actual curvature differs from the nominal curvature especially at the center of the lens. This is highlighted in Fig. 3 where the difference between the actual profile and the nominal profile is shown along with the curvature error. In the ground profile two error components can be identified. The first one, distributed along the whole profile, is due to the machine structure compliance and grinding forces that deflect the tool.[20,21] Another contribution is related to the tool size and can be evaluated by computing the offset error.[17] The second, is related to the tool wear which modifies the initially spherical shape of the grinding wheel, and consequently on the ground surface appears the typical shape error at the lens center.[1,21] The first type of error could be reduced by tuning the grinding parameters in order to diminish the force needed for the material removal and adjusting the CAM parameter related to the tool diameter, while the second type of error could be avoided regularly performing "truing-dressing" operations.

It can be recognized that a large shape error at the edge does not mean a large deviation in curvature and consequently the functional properties could be retained even if an excessive deviation appears. In contrast, cusps in shape error produce a significant curvature error.

Along the radial distance, shape error represents the deviation of the actual profile from the nominal one. Analogously, curvature error is the difference between the actual and nominal radius of curvature along a lens profile. Nine samples have been polished at different times and observations have been made to evaluate the effects of polishing time on shape error (Fig. 4) and curvature error (Fig. 5).

To better understand the shape error evolution upon increasing the polishing time (Fig. 4), all the actual profiles have been fitted to the nominal ones. The distance between the actual and the nominal profile has then been computed (shape error) and finally all the error profiles have been translated to a common reference: the minimum at 2 mm from the lens center, due to the grinding wheel wear.

It can be noticed that during the polishing process, the error induced by the grinding wheel wear could not be fixed by increasing the polishing time. At the center, due to the tool oscillation, the relative velocity between polishing pad and lens is limited and consequently the material removed is small. Observing experimental results, the material removal in the considered operating conditions is significant around 25 mm from the lens center. These phenomena could be related to the combination of pressure and velocity. Tuning the machining parameters (such as spindle speed, oscillation and frequency) this error could be reduced and/or moved along the radial position.

Figure 5 shows the curvature error as a function of the radial distance. Increasing the polishing time, curvature at the center does not improve enough because of small relative motion at center, while it worsens in the rest of the profile, especially at a distance greater than 25 mm from the center. In detail, curvature shows a central peak and two deep valleys arranged symmetrically with respect to it: this trend describes the flattening of the central area and the cusps of the profile due to the grinding wheel wear.

Excluding the central portion, comparing shape and curvature error, especially until 630 s, it is possible to see that, while the shape error decreases, curvature error increases, more sharply farther than 20 mm from the center (curvature error remains low until 215 s).

In brief, the investigated polishing technology is found adequate when the curvature of the ground profiles is close to the nominal curvature. Curvature and shape errors of the ground profile related to tools wear could not be fixed during the polishing process by increasing the machining time.

To complete the study of functional geometric characteristics, the surface roughness analysis was carried out as a function of the polishing time at 15 mm from the center (Fig. 6 b). Increasing the polishing time, a rapid decrease of the values of Ra in the initial polishing stage is observed. Then, the measured roughness values tend to a constant value, about 5 nm.

Increasing the distance from the center, the time needed to reach a constant value decreases (Fig. 6b). Finally (Fig. 6a), when the cusps appear in the shape error, the roughness does not reach the expected value (about 5 nm) even at 1000 s ($Ra > 0.2$ µm).

As a result, excluding central portion where the polishing cannot be performed, in order to limit shape and curvature error, still ensuring an adequate surface roughness, a polishing time less than 300 s is suggested (guideline value).

4 Conclusion

The assessment of curvature during the lens manufacturing is a fundamental task, due to its close link with the functional properties. In order to investigate this differential property, a method based on the local quadratic fitting has been implemented. The error on radius of curvature has been investigated on the membrane polishing process as a function of the machining time, together with the shape error and the surface roughness, obtaining a complete characterization of the lens surface functional properties.

Based on the results obtained, it is concluded that to limit shape and curvature error while obtaining an adequate surface roughness, a polishing time of less than 300 s is adequate. Moreover, errors due to grinding wheel wear cannot be removed during the membrane polishing process.

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List of Figure Captions

Fig.1 (a) Work volume of the polishing machine, (b) functional scheme, and (c) polishing tool.

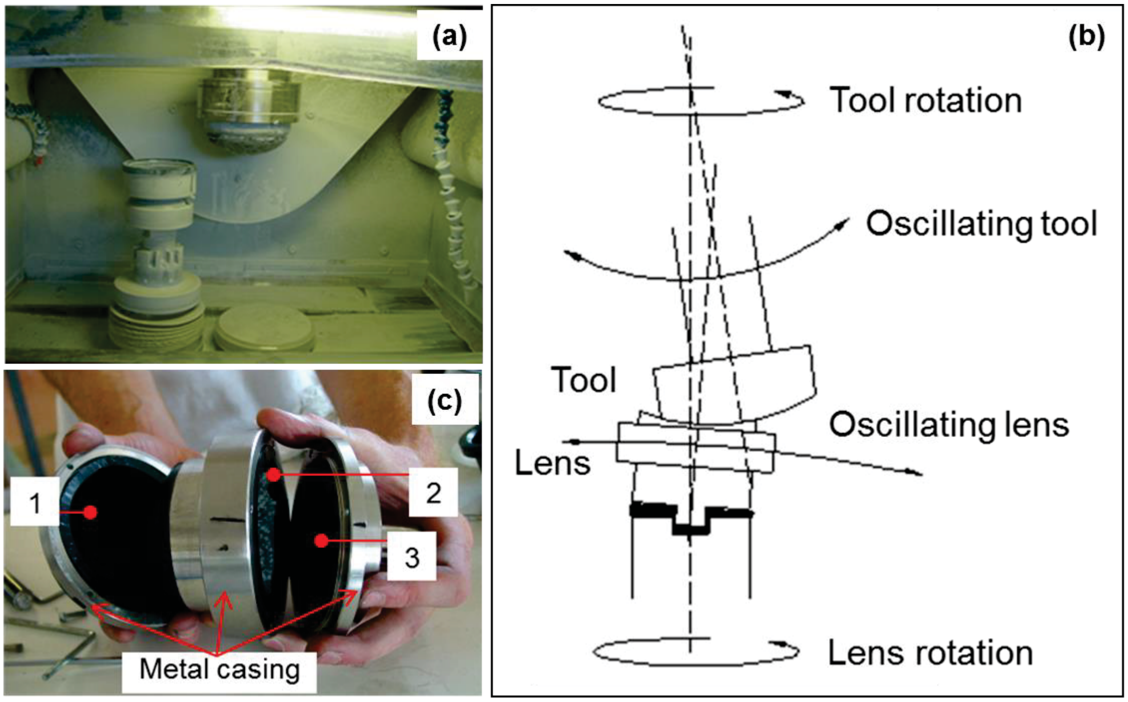
Fig. 2 Lens profile and curvature of the nominal and the actual ground lens mould.

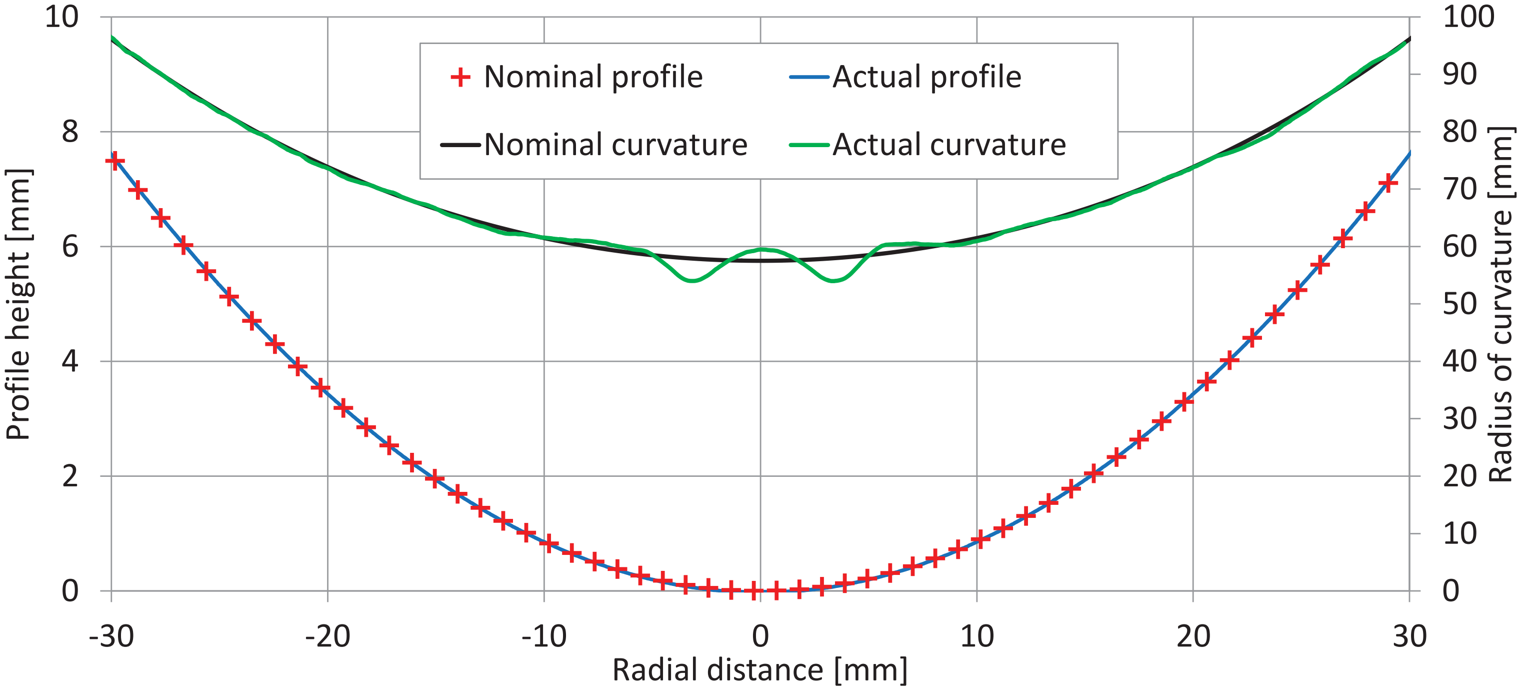
Fig. 3 Shape and radius of curvature error of a ground lens.

Fig. 4 Shape error of the polished lens mould as a function of the machining time.

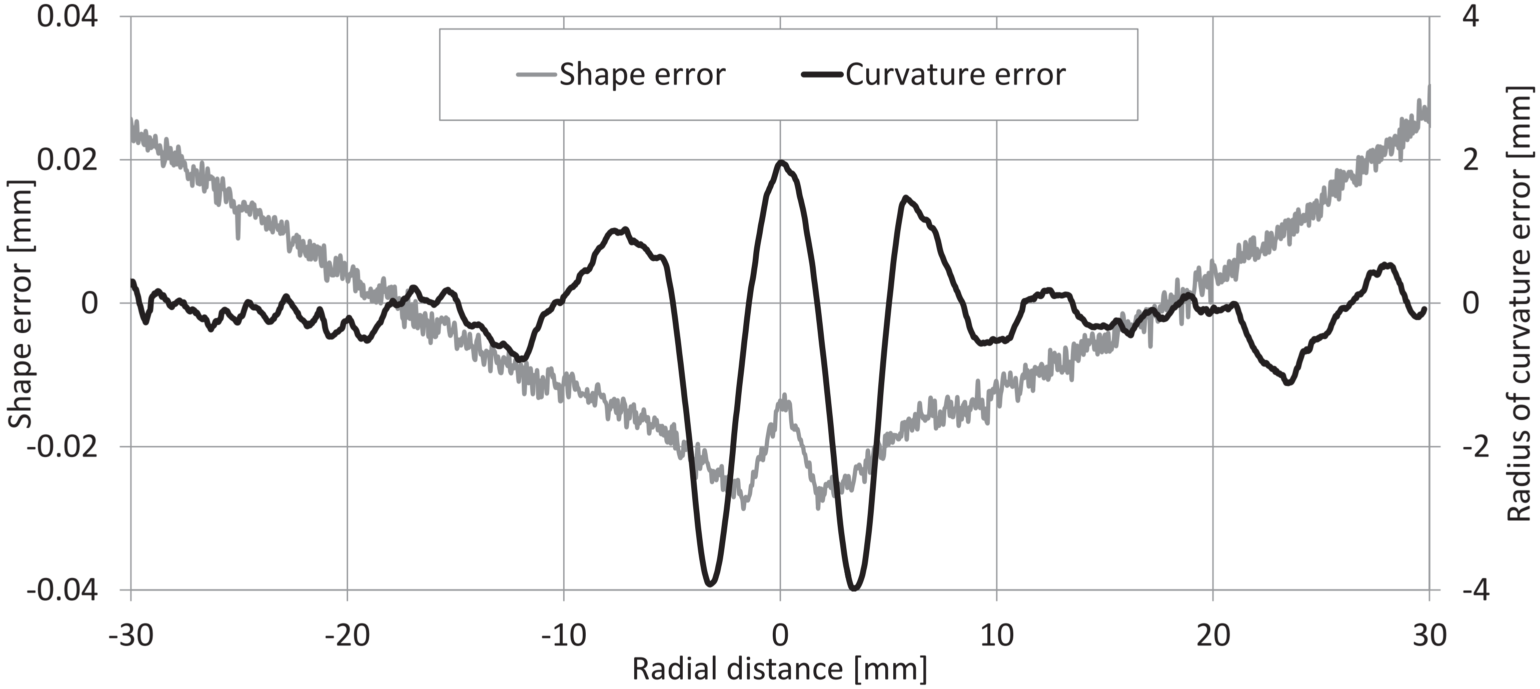
Fig. 5 Radius of curvature error of lens mould as a function of the polishing time.

Fig. 6 (a) *Ra* as a function of the polishing time at 3 mm from the center, and (b) *Ra* as a function of the polishing time at 15 mm, 18 mm and 21 mm from the center.


(a)
(b)
Tool rotation
Oscillating tool
Tool
Oscillating lens
Lens
Lens rotation
(c)
1
2
3
Metal casing



Nominal profile
Actual profile
Nominal curvature
Actual curvature
Profile height [mm]
Radius of curvature [mm]
Radial distance [mm]
10
8
6
4
2
0
100
90
80
70
60
50
40
30
20
10
0
-30
-20
-10
0
10
20
30


Shape error
Curvature error
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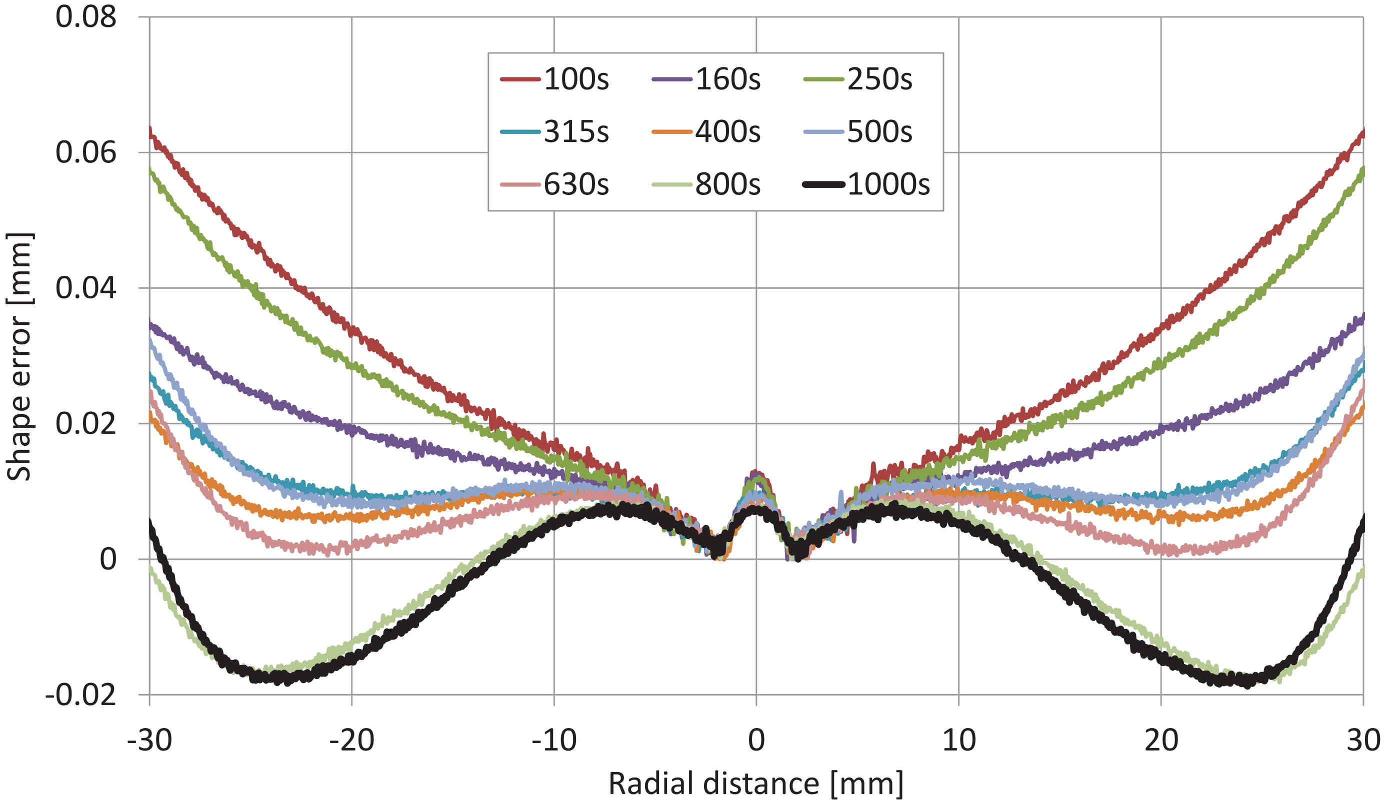
0.02
0
-0.02
-0.04
Shape error [mm]
4
2
0
-2
-4
Radius of curvature error [mm]
-30
-20
-10
0
10
20
30
Radial distance [mm]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0.06
0.04
0.02
0
-0.02
Shape error [mm]
-30
-20
-10
0
10
20
30
Radial distance [mm]
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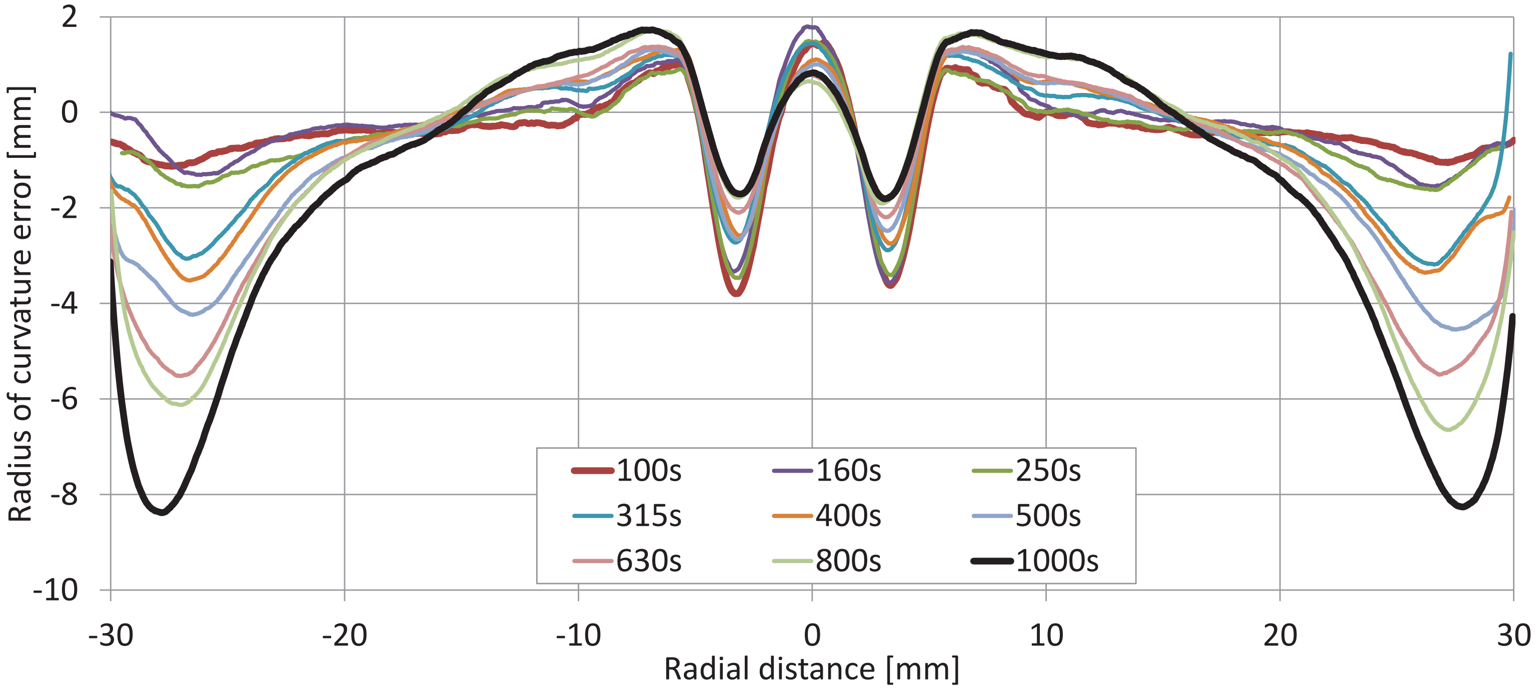
250s
315s
400s
500s
630s
800s
1000s



2
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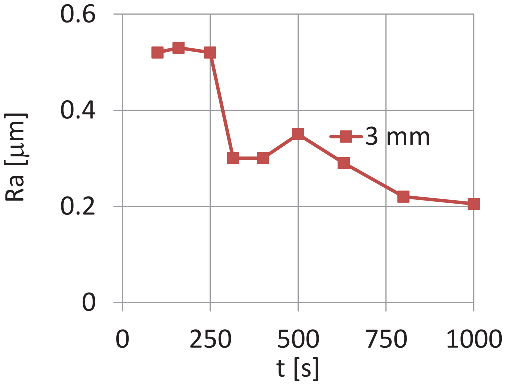
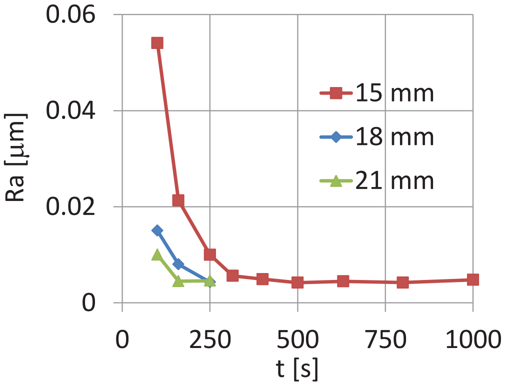
-2
-4
-6
-8
-10
Radius of curvature error [mm]
-30
-20
-10
0
10
20
30
Radial distance [mm]
100s
160s
250s
315s
400s
500s
630s
800s
1000s


0.6
0.4
0.2
0
Ra [µm]
3 mm
0
250
500
750
1000
t [s]

a)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0.04
0.02
0
Ra [µm]
15 mm
18 mm
21 mm
0
250
500
750
1000
t [s]

b)