A Technique to Control Global Figure Using Acid Immersion and Zernike Decomposition

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Abstract: Introduction of a technique to control the global figure of an optical substrate that leverages the bulk removal efficiency of a full aperture process but has the determinism of a sub aperture figuring approach.
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1. Introduction

The fabrication of an optical component is primarily about establishing a (very specific) global profile on one or more surfaces. In modern manufacturing environments, this is usually done by a mix of full aperture and sub aperture grinding and polishing processes to converge on a desired result and will usually involve some level of figure error, micro-roughness, and surface quality requirement [1]. Beyond the expectation of convergence on the surface requirements, an optimal technology or process will have deterministic figure control, a high volumetric removal rate, and accommodate any reference surface geometry (planar, spherical, aspherical, or freeform). In an endeavor to converge towards this ideal, an alternative surface figuring technique has been developed based on wet etching and the decomposition of Zernike polynomials [2] into angular components [3].

2. Profile Etching

In describing this technique, it is appropriate to begin with the fundamental elements involved and build up to the ultimate implementation. Consider the wet etching [4] of an optical component for stock removal using an acid bath. In practice, the etch rate will be stable and isotropic such that, by fully submerging the substrate in the acid, a uniform removal of material will be performed. The change in height (**h**) of the surface will be defined by $\mathbf{\Delta h} = \boldsymbol{ER} \cdot \boldsymbol{\Delta t}$, where $\boldsymbol{ER}$ represents the removal rate of the acid and $\boldsymbol{\Delta t}$ is the elapsed time. Technically, the etching described above qualifies as a deterministic full aperture process in the most basic form of uniform removal but as yet, there is no basis for figure control. The scenario can be adjusted slightly by introducing the concept of a partially submerged substrate. By approximating a step function defined by the interface between the air and the acid bath, the system can be re-expressed by the following equation (1).

$$\Delta \mathrm{h}(\Delta t, \mathrm{y}) = \begin{cases} ER \cdot \Delta t\ , & \mathrm{y} = in\ acid \\ 0, & \mathrm{y} = in\ air \end{cases} \tag{1}$$

There is now a positional dependence of the removal defined by the location (**y**) of a point on the substrate and it becomes more appropriate to describe the system as having a removal function instead of a removal rate. Defining the setup this way suggests that by introducing kinematics into the system it is possible to obtain controlled non-uniformity of the etching in a similar fashion as that employed in many sub aperture processes. This is exactly the case, and the initial implementation will be that of a controlled immersion of a substrate into the acid at a fixed velocity in order to correct wedge.

Wedge is simply a linear amplitude gradient that exists about a given length (**L)** of a substrate. To correct a wedge, it is necessary to preferentially etch the thicker portion of the substrate by lowering the substrate into the acid bath in a controlled fashion. Since there is freedom to choose the substrate orientation, the amplitude gradient is defined to have a maximum deviation ($\mathbf{\Delta h}=\boldsymbol{h_{max}}$) at the bottom of the substrate and ($\mathbf{\Delta h}= 0$) at the top. From equation (1), the time ($\boldsymbol{\Delta t}$) required to remove $\boldsymbol{h_{max}}$ is simply $\boldsymbol{h_{max}}$ / $\boldsymbol{ER}$. Therefore, the immersion velocity ($\boldsymbol{v_y}$) is equal to **L** / $\boldsymbol{\Delta t}$. Substituting for $\boldsymbol{\Delta t}$ and noting that **L** / $\boldsymbol{h_{max}}$ can be defined as the inverse of the surface slope ($\mathbf{m}_{wedge}$), the final velocity required to correct (or impart) the wedge is defined in equation (2).

$$v_y = \frac{ER}{\mathrm{m}_{wedge}} \tag{2}$$

There is an implicit requirement that the slope (**m**) must be positive (**m**>0), which would prove restricting when expanding the figure correction beyond wedge. Fortunately, there is an easy solution that was hinted at by the selection of orientation in the example above. Given that the removal is independent of any position (**x**) along the width, the rotation of the substrate by 180° simply serves to invert the target profile. Therefore, negative slopes (**m**<0) will become positive in what will be a mirrored version of the profile. Thus $\mathbf{m_{180}} = -\mathbf{m}$ and the correction again becomes possible. The importance of this relation will become apparent when expanding the concept to arbitrary profiles.

Now assume there exists a function **h(y)** that represents an arbitrary amplitude variation about **y**. Traversing along the profile **h(y)** by an arbitrary distance $\mathbf{\Delta y}$ will have an associated change in profile amplitude $\mathbf{\Delta h}$, thereby the concept of wedge ($\mathbf{\Delta h/\Delta y}$) is reintroduced on a *local* scale, and a new velocity function ***v***(**y**) can be established to perform the *local* correction. As the limit of $\Delta \mathbf{y} \to 0$, the slope **m(y)** is the derivative of the surface profile at location **y**, thus **m(y)** = ***dh/dy*** and ***v***(**y**) = ***ER*** **/ m(y)**. Given the arbitrary nature of **h**(**y**), the sign of the slope will also be arbitrary. It has been established that the immersion process can only correct positive slopes but it has also been demonstrated that a rotation of the substrate by 180° will convert negative slopes to positive ones. Thus, a complete change to the surface profile will be performed in rotated pairs and the final correction equation is as follows, where the subscripts dictate the separate 0° and 180° increments.

$$v(y)_{0,180} = \begin{cases} \dfrac{ER}{\left(\frac{dh_{0,180}}{dy}\right)}, & \left(\frac{dh_{0,180}}{dy}\right) > 0 \\ \infty, & \left(\frac{dh_{0,180}}{dy}\right) \leq 0 \end{cases} \tag{3}$$

It should be noted that in the situation where the slopes are negative and the velocity equates to infinity, there would be no removal in theory. In practice, the velocity is maximized to the constraints of the system and some minimal removal is unavoidable.

There now exists a means to impart any general profile **h(y)** onto the surface(s) of an optical component using a wet acid bath. However, the dependence on **y** only is limiting, and it will be demonstrated in the following section that the removal function can be expanded beyond this limitation. In fact, the concept of decomposing Zernike polynomials (which are functions of **x** and **y**) into angular components that are dependent on **y** and immersion angle **ϴ** is introduced, and it will be shown that the acid etch process can be used to recreate these polynomials.

3. Zernike Decomposition

Zernike polynomials [2] are commonly used in optics to describe a surface or the figure error associated with a surface. They are most familiarly recognized by the descriptions of the early terms (*power*, *coma*, *astigmatism*, *trefoil*, *etc…*) but consist of an infinite series of orthogonal functions of increasing complexity. The expressions of these polynomials become cumbersome when fully expanded, and so will the expressions associated with the decomposition into angular components. Therefore, it will be practical to switch to a graphical representation and it will be understood that the descriptions that follow can be demonstrated (and proven) computationally.

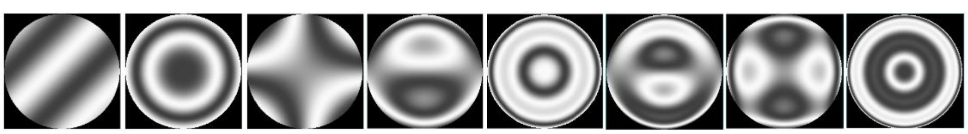

Figure 1. Representative Zernike polynomials up to 4th order spherical.

In order to recreate the first series of Zernike profiles (Figure 1.) using the etching method described above, it will be necessary to repeatedly immerse the substrate into the acid at varying discrete angles. These angles will be confined to 45° increments for further discussion since this will be all that is needed to describe the terms in Figure 1. Additionally, since profiling must be done in pairs (0° and 180° apart), reference to future immersion angles will be described by the first orientation only and the repeated 180° etch will be implied. Therefore, the immersion angles will be designated as $\boldsymbol{\Theta_i}$ and $\boldsymbol{i}$ will assume the values 0,45,…,315.

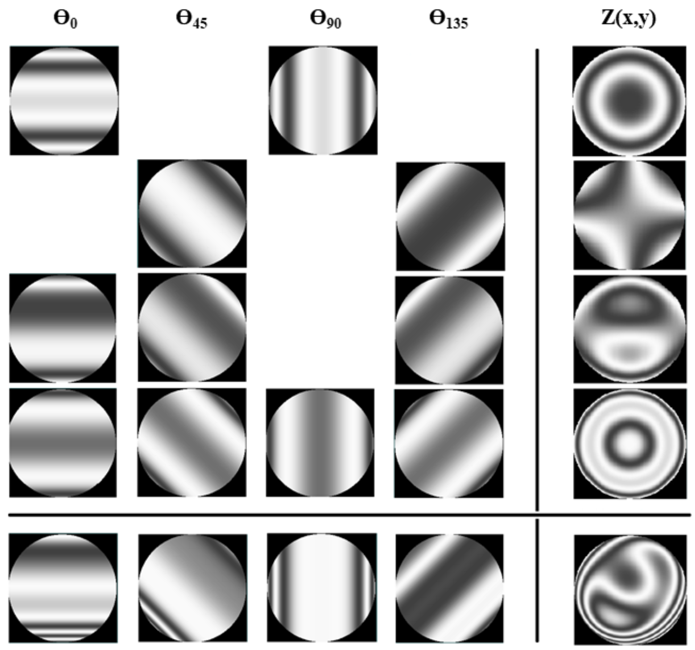

Figure 2. Recreation of Zernike polynomials from angular decomposition (0°,45°,90°,135°)

The images on the top left in Figure 2. demonstrate how the Zernike polynomials can be split into angular components that are merely functions of one variable (**y**) if properly oriented, and can therefore be corrected using the etch profiling method. Each individual immersion will act to linearly recombine the individual profiles to recreate the appropriate Zernike (the summation of each profile from left to right in Figure 2). In the cases shown for *power*, *astigmatism*, *coma*, and *3rd order spherical*, a complete recreation can be performed by as few as 4 discrete angles. Although it will not be presented here, it can be shown that the first 16 terms can be recreated as above in as few as 8 rotations. Higher order terms will require more rotations.

It is not necessary that each individual polynomial used to describe the surface be imparted sequentially. Each discrete angle will have contributions from each Zernike term and can be profiled concurrently based upon the sums of the profiles at each angle (the summation of each profile from top to bottom in Figure 2). Returning back to the mathematical model, a slight modification can be made to equation (3) to include the angular rotation and a new function $\mathbf{Z_n}(\mathbf{y})$ is created for each immersion angle (**Θ**), where $\mathbf{Z_n}$ represents the angular profile associated with the n^{th} Zernike term. The complete picture is represented in equations (4) and (5) where **Θ** will assume the values 0,45,…,315.

$$h(y)_{\Theta} = \sum_{n=1}^{n=16} Z(y)_{\boldsymbol{n},\Theta} \tag{4}$$

$$v(y)_{\Theta} = \begin{cases} \dfrac{ER}{\left(\frac{dh(y)_{\Theta}}{dy}\right)}, & \left(\dfrac{dh(y)_{\Theta}}{dy}\right) > 0 \\ \infty, & \left(\dfrac{dh(y)_{\Theta}}{dy}\right) \le 0 \end{cases} \tag{5}$$

4. Application & Results

In this section, examples of two components that have been processed will be described. Additionally, there are some unique advantages of the process that will be highlighted concerning optical window manufacturing, minimization of edge effects, aspherization, scalability towards large substrates, and bulk processing. In regards to the practical process implementation, the optics referenced below were fused silica (SiO_2) and etched using a buffered hydrofluoric acid solution (BOE).

In the first example, the transmitted wavefront error (TWE) of a fused silica window was measured before and after profile etching. A comparison was made between the Zernike coefficients used to describe the wavefront error and a very high convergence was achieved and is demonstrated in Figure 3. and Table 1.

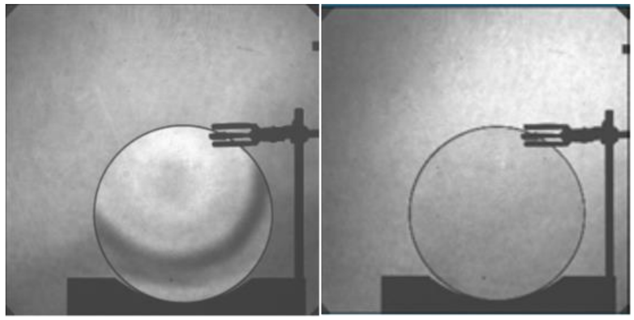

Figure 3. Before (left) and after (right) TWE measurement.

Table 1. Zernike coefficient comparison

Zernike Description	Initial (waves)	Post-Etch (waves)
Tilt X	-0.069	0.000
Tilt Y	0.275	0.001
Focus	-0.151	0.000
Astig 0,90	0.017	0.001
Astig +- 45	-0.014	0.012
X Coma	0.005	-0.003
Y Coma	-0.008	0.005
Sphere	0.010	0.005

Given that the component was an optical window and the requirement was specified in TWE, both surfaces could be processed at the same time. The double sided application of the process highlights a potential advantage in a production environment since this will effectively double the removal rate of the correction. Another benefit is shown in the fidelity of the data out to the very edge of the substrate. The edge effect from processing is too small to be quantified from the associated data taken and this demonstrates another advantage of the process.

In the second example, the process was utilized to aspherize the surface of a curved geometry as oppose to correcting the figure error of the planar geometry of a window. The aspheric departure was characterized by the conic (k) only and the deviation was completely described by Zernike polynomials up to 3^{rd} order spherical. For visualization purposes, a synthetic fringe overlay of a scaled version of the aspheric departure is shown in Figure 4. In this application, the process was implemented for bulk convergence towards the final surface profile and used in a complementary fashion with other deterministic finishing techniques to fully fabricate the optic. Two significant advantages of the process are highlighted in this example. The first is the demonstration of the independence of the etching on the surface geometry. The acid will always contour to the geometry of the surface and by (mathematically) projecting the desired profile onto a virtual plane, the process can be readily applied. The second is a less apparent benefit from the double-sided nature of the process. Since the etching was performed simultaneously on both surfaces of the optic, the profile change on the planar surface was equal to the change on the curved geometry of the aspheric surface. In this situation, it was possible to leverage existing interferometric capability for planar surfaces in order to characterize the opposing surface profile where the equivalent capability was unavailable.

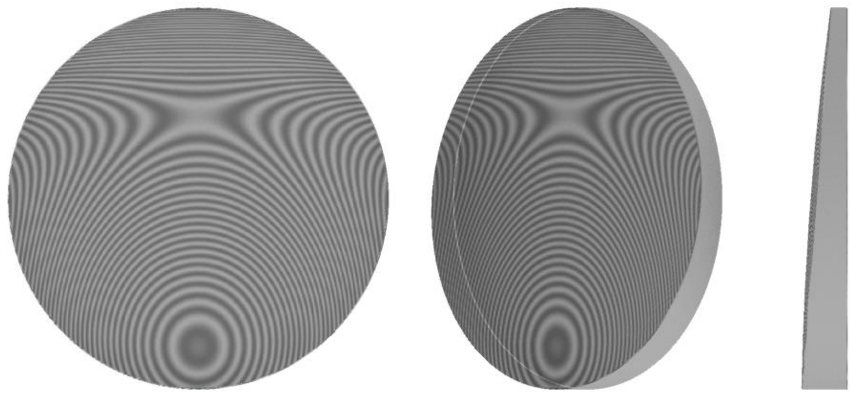

Figure 4. Plane-Convex lens with aspheric *fringe* overlay

So far, there has been little reference to removal rates of the process. In part, this is due to the fact that the etch rates can vary dramatically based on concentration and temperature. However, there is also the notion of an effective removal rate in the etch process that must be highlighted. Although the etch rate is stable at a fixed temperature (and concentration), the ultimate volumetric removal rate on the substrate will vary with the size of the substrate and this is subtly implied from equation (2) regarding wedge correction. It can be noted that, for a given amplitude of correction, if the length of the substrate gets larger, then the velocity will scale proportionately. In other words, the processing time is the same independent of the size of the substrate and the volumetric removal rate of the system is not a constant.

As an example, consider a typical etch rate of ~80 nm/min and a 100mm diameter circular substrate. In order to correct 1um of wedge the associated velocity will be 8 mm/min and the correction will take 12.5 minutes. If the diameter is increased to 1000mm, the velocity goes to 80 mm/min and the correction time remains the same. Of course, the amount of material removed has increased by a factor of a hundred and the effective removal rate jumps from ~0.3 mm^3/min to ~30 mm^3/min. Thus, one of the primary advantages of the etch profiling technique is exemplified by the drastic increase in removal efficiency as the substrates grow in size.

The implementation so far has centered around the idea of processing a single optical substrate. However, given that there is no real concept of a processing tool that must be oriented to the surface, it is appropriate to consider the bulk processing of more than one substrate. If the substrates have like geometries and the desired removal is consistent across each substrate, there is nothing that would prevent concurrent processing if given the appropriate tooling.

5. Conclusion

The acid profiling approach has proven to be very useful for establishing an efficient deterministic process that satisfies the process time (high removal rate) and geometry restraints involved in optics manufacturing,. The stability of the acid etch rate contributes to the high level of determinism and provides some freedom of use for many different sizes and geometries of a substrate. Combined with the kinematics of orientation and velocity, this mix between a full and sub aperture approach has also demonstrated some desirable volumetric removal rate efficiencies, especially when applied to increasingly larger substrates.

In this paper, the examples were limited to polished substrates nearing completion. However, there are many processes and technologies involved in the manufacturing of an optical substrate and the acid profiling technique should serve in a complementary fashion in support of many of them. There are some interesting possibilities for bulk shaping in the early fabrication stages, expansion to complex freeform surfaces to leverage the geometry independence, or perhaps some other unique implementation that has yet to be considered.

6. References

[1] Tayyab I. Suratwala, Materials Science and Technology of Optical Fabrication (Wiley, 2018), Chap. 1.

[2] Zernike, F., "Beugungstheorie des schneidenver-fahrens und seiner verbesserten form, der phasenkontrastmethode," Physica 1(7-12), 689–704 (1934).

[3] US and Foreign patents pending, Zygo Corporation.

[4] Spierings, G.A.C.M, “Wet chemical etching of silicate-glasses in hydrofluoric-acid based solutions’ *J. Mater. Sci. 28 (23):6261-6273*