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Analysis, tolerancing and diagnosis of diamond machining errors

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ABSTRACT

Diamond machining of aspheric lenses can introduce manufacturing errors which are not found in conventionally finished optics. They have therefore not been addressed by conventional tolerancing and raytracing methods.

This paper will show how some of these errors arise, and their appearance when examined interferometrically. Raytracing and experimental analysis of the effect of these errors on system performance is described, and diagnosis, with or without null test optics, is discussed.

1. INTRODUCTION

We start by reviewing the diamond machining process and briefly describe the occurrence of tool centring (or "ogive") and orthogonality (or "conical") error in diamond machined parts. The effect of these errors on the optical performance of a system is described, along with a raytrace method for analysing the effects which confirms observed results. A limited test procedure for diagnosing these specific errors is then described, and its effectiveness is demonstrated by showing computer generated and real interferograms of defective and perfect parts.

2. THE DIAMOND MACHINING PROCESS

2.1. Why aspherics?

Aspherics are used in optical design to provide extra design variables without introducing more components. Possible payoffs are:

- better transmission
- better optical correction
- less weight
- cheaper raw material and assembly
- a more compact system
- coping with a confined space envelope

2.2. Diamond turning

In diamond turning, a diamond point is used as the cutting tool in a numerically controlled lathe. The workpiece is typically pulled onto a vacuum chuck, whose surface is itself diamond turned to match the rear surface of the lens to within a few fringes. The spindle rotates with extreme precision, typically using air bearings. The tool moves under computer control and its movements are monitored by a laser interferometer.

The surface finish produced by this process is good enough for IR and some visual optics applications. An important advantage of the process is the very high reproducibility attainable in a well controlled process; all lenses produced to a given prescription should be identical.

2.3. The problems

By their nature, aspheric surfaces are difficult to test, since only in certain special cases does the aspheric surface match an easily-generated test wavefront. In addition, a number of errors and artefacts occur in the diamond machining process which are not found in other optical fabrication processes. No less than ten defects that can occur are listed below:

x-centring (or "ogive") error	tool wear
orthogonality (or conical") error	machining grooves
y-centring error	centrifugal distortion
print-through of rear surface defects	faulty jigging
dust under rear surface	air pressure changes (affect laser interferometer)

Most are random "one-offs" particular to one part or one jigging arrangement. Machining grooves cannot be totally eliminated with present technology and have an effect which is hard to quantify on system performance. The first two artefacts, Ogive and conical error, are systematic and reproducible, and can seriously or catastrophically degrade system performance. They are easily detected even using spherical-wavefront interferometry, and should not be encountered in products from a reputable supplier. However, very accurate setting up of the machine is required to eliminate them, and many diamond machining fabricators have only belatedly realised the importance of these effects and the need to control them.

2.4. Ogive and conical error

These errors occur when the co-ordinate system in which the diamond tool is moving is not correctly aligned to the axis of the lathe spindle. A tilted set of co-ordinates leads to, for example, a conical surface being manufactured when a flat one was intended. See fig 1. A decentre of the co-ordinate system relative to the spindle causes the effect shown in fig 2, in which a curved surface has a discontinuity on axis, an effect referred to as "ogive" or "x-centring" error. The resulting surface is a figure of revolution generated by rotating the aspheric profile about a point offset from the axis of the aspheric surface.

It can be shown that on a curved surface the effects of these two errors are mathematically equivalent, so this analysis is restricted to x-centring or ogive error. We can trace rays through (or generate interferograms on) a surface with x-centring error by identifying the ray intercept (or point on the interferogram) and applying a decentre along the vector from the point of interest to the optical axis. Thus we can assess the performance loss due to these errors by means of a simple modification to a raytrace programme incorporating 3-D tilts and decentres.

A similar analysis can be done for y-axis tool centring errors in which case the decentre is applied at right angles to the vector towards the optical axis.

3. EFFECTS OF CENTRING ERRORS

3.1. Practical observations

These errors were brought to our attention during the breadboarding phase of a project using several aspheric elements. The system did not focus with the lenses in or near their nominal positions, and the MTF of the optics seemed to be very poor. Known fabrication errors in other parts at the system could not account for these problems. When the central portions of the aspheric lenses were examined on a laser Fizeau interferometer (with a spherical wavefront) it was found that a straight tilt fringe could not be obtained at the centre of the surface, and measurements using a digital rail showed that the base radius was too short.

Once the interferograms were recognised as being characteristic of x-centring error, two avenues of work were initiated: computer simulation of the interferograms, to quantify the error, and raytrace analysis to assess the degradation due to the error.

3.2. Computer generated interferograms

A short computer programme was written to draw simulated interferograms. A reference sphere is defined with a given radius and decentre. The aspheric surface is described by its base curvature, conic constant and power series coefficients; conical, x- and y- decentre errors can be specified. For each point on the interferogram the centre of the reference sphere is decentred in the appropriate sense to simulate the error in the aspheric (this is a computational convenience which is equivalent to decentring or tilting the axis of the aspheric surface). The distance from the displaced centre of the reference sphere to the point on the aspheric surface is calculated and subtracted from the radius of the reference sphere. The result is converted into a phase difference and determines the "intensity" parameter of the "area colour" function of the HP9020 computer. The computation for approximately 10000 points takes about 230 seconds, or the time is halved if the pattern is known to have mirror symmetry. This is the case with x-centring error, if the tilt fringes are appropriately oriented, but not with vertical or y-centring error of the tool.

Actual and computer-generated interferograms of the faulty surfaces (over the central 17 mm or so of the lens) are shown in fig 3. Simple visual comparison of the fringes was sufficient to determine that about 8±0.5 μm of x-centring error was present.

3.3. Raytracing with x-centring error

Raytracing methodologies will be familiar to most readers. That used by the Kidger Optics "SIGMA" software, used for this work, broadly follows the methods described by Welford in ref. 1. A simple spherical surface is traced in three stages:

1) Transfer to vertex plane;
2) transfer to surface, for which there is an analytic solution;
3) refraction by a vector form of Snell's law.

Raytracing through an aspheric surface is more complicated, because there is no analytic solution for the transfer from the vertex plane to the surface. This transfer is done in a series of iterations. First the ray is propagated from the vertex plane to a plane tangent to the aspheric surface at the x-y co-ordinates of the intercept with the vertex plane. Then another tangent plane is generated, coinciding with the aspheric surface at the x-y co-ordinates of the new intercept, and so on until the error in the approximation of the tangent plane to the aspheric surface is negligible. The ray is then refracted as before.

In order to trace rays through the defective aspheric surface we first trace the ray to the vertex plane of the aspheric. Then, just for this particular ray, we decentre the surface along the vector joining the ray intercept to the axis of the surface. No more is required in the case of a "meridian" ray when this vector does not rotate as the ray propagates. However, in the case of a general or "skew" ray, the vector joining the ray to the axis rotates as the ray propagates; so the decentre required to simulate x-centring error changes direction as we propagate from the vertex plane through the succession of tangent planes to the aspheric surface.

Therefore we recompute the dx and dy components of the decentre in each aspheric iteration, assuring the correct outcome for skew rays. Fig 4 illustrates the geometry, and fig 5 is a flow diagram of the relevant part of the computer code.

3.4. Raytrace results

The raytracing procedure was validated by analysing a paraboloid with x-centring error. As one might expect, the ray spot diagram shows that the point focus on axis is degraded to a ring, whose radius equals the amount of centring error. A better focus (a higher concentration of rays) is obtained by refocussing. This refocus is in the same direction as and of similar magnitude to that indicated by the change in the best fit radius of the base sphere.

The 8µm of x-centring error estimated from the computer-generated interferograms was then applied to the Germanium aspherics in the real system. It was found that the on-axis geometrical MTF was catastrophically degraded at the higher spatial frequencies, as shown by fig 6. These results are obtained with a significant focus adjustment consistent with, though rather less than, that experienced in the breadboard equipment. (This discrepancy may be due to the use of geometrical rather than diffraction analysis. The diffraction OTF software we had at the time did not deal with afocal systems, and in any case most commercial diffraction OTF software has not been written to deal with singularities at the centre of the wavefront and may not, therefore, give reliable results. Alternatively there may be other experimental factors in the breadboard layout contributing to the error.)

3.5. Tolerancing of x- and y- centring errors.

Our work shows that small amounts of x-centring error have a significant effect on system performance and state of focus. The amount that can be tolerated will depend on such factors as operating wavelength, power of the surface, refractive index of the material and the state of correction required. However, for typical systems operating in the 8-12µm region, the required tolerance is likely to be in the range 0.1-1µm for steeply curved surfaces. For shallow surfaces, more centring error can be permitted and a tolerance on conical error may be more appropriate (remember that the two cannot be distinguished experimentally on a single component). Vertical centring error, on the other hand, is much more tolerable, since it mainly affects the centre of the lens, having little effect on the outer part of the component or on most of the area of the transmitted wavefront.

4. DIAGNOSING AND CONTROLLING THE PROBLEM

Most diamond machining houses will have their own methods for controlling the various errors that can occur in the process. This paper is written from the point of view of procuring aspherics from subcontractors. There are two problems. One is to ensure that whatever criterion is applied should be understood and agreed by both supplier and purchaser - and preferably should be sensibly defined on the drawing! The second is to devise a cost-effective test method.

Optical testing has been revolutionised in the last two decades with the advent of laser interferometry, desktop computers and video processing hardware and software. Complex wavefronts can be reproduced with computer generated holograms, and complex interferograms can be analysed by computer. If unlimited resources are available a null test can be created or simulated for almost any aspheric configuration. However, when we are working to tight budgets and timescales, and with small quantities of components, we may have to use a more pragmatic approach, which attempts to extract as much information as possible from simple equipment. As we have indicated, all aspherics can be tested for x-centring (and conical) error by examining an interferogram made with a spherical wavefront of the centre of the aspheric surface. It should be possible obtain a straight fringe across the centre, and measure the correct base radius on a radius slide.

When these test procedures were adopted we were able to specify components which provided substantially the correct system performance (see fig 7).

5. SUMMARY AND CONCLUSIONS

Diamond machined components will not perform correctly if small (0.1-1µm) tool centring errors are present in the setting-up of the diamond machine. These errors cause shift of focus and loss of MTF. A raytrace routine was modified to quantify the effects of centring errors and to allow tolerances to be established, and a computer programme was written to generate interferograms as an aid to testing.

Even if full optical testing is not being carried out, diamond turned aspherics should have their centres interferometrically tested to ensure that these errors are within acceptable limits.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

1. W T Welford, Aberrations of the Symmetrical Optical System, pp. 46-60, Academic Press, London. (1974).

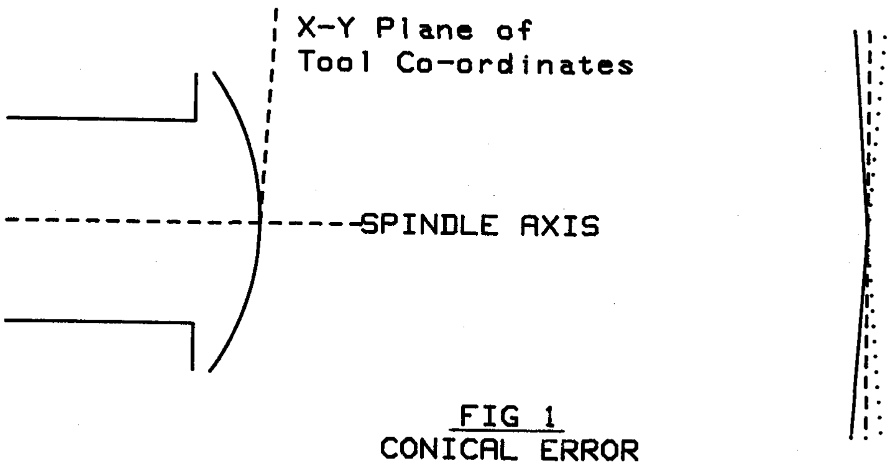


FIG 1
CONICAL ERROR

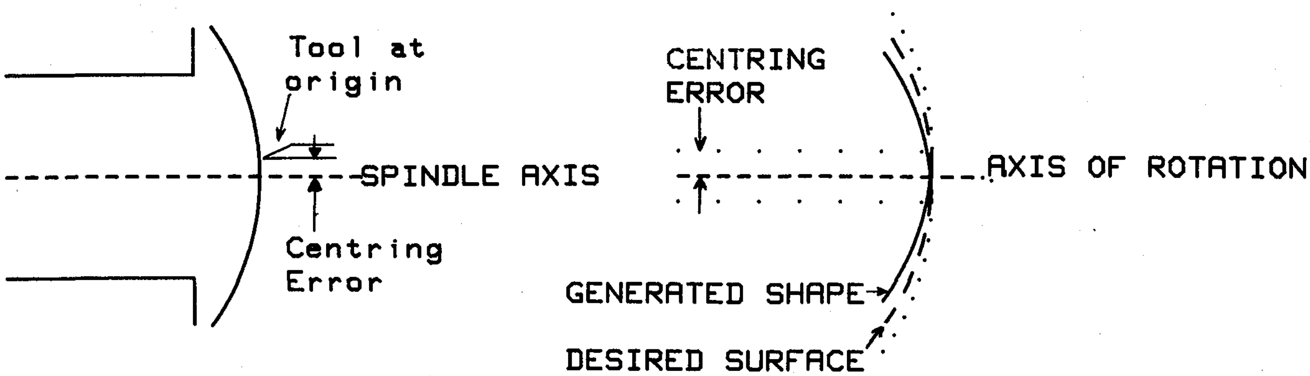
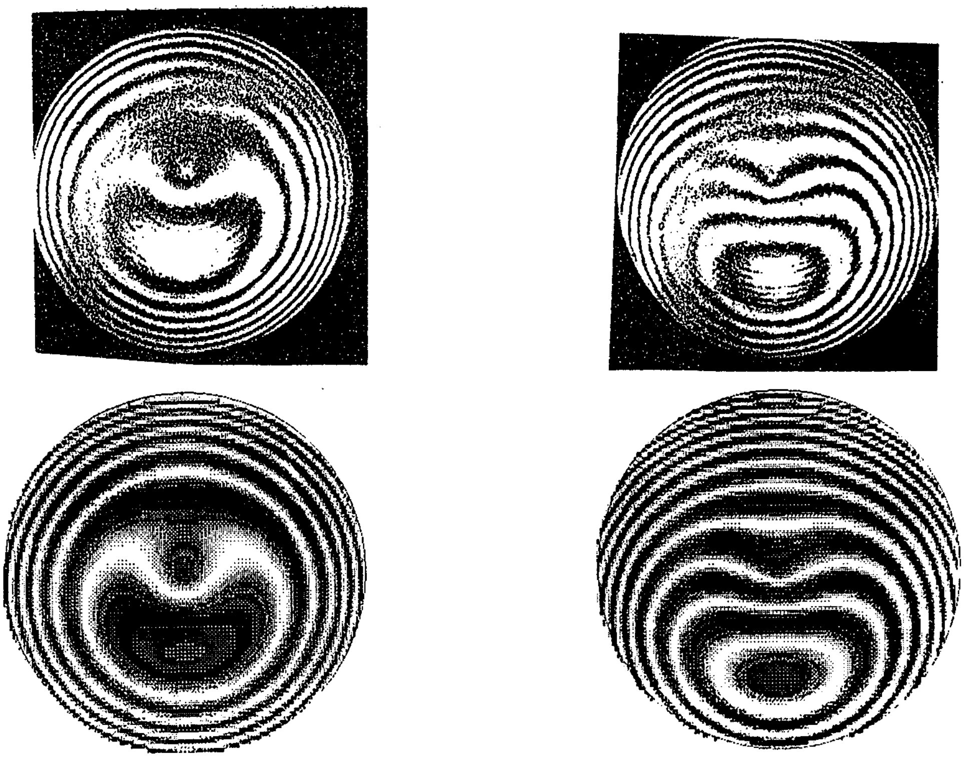


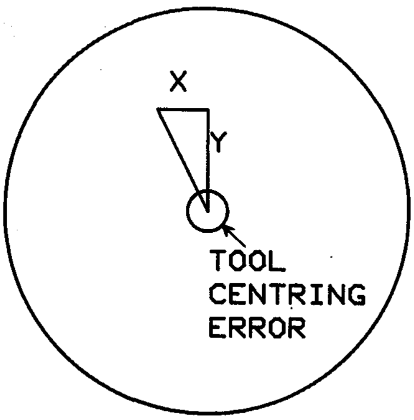
FIG 2
OGIVE ERROR



<u>FIG 3</u>

INTERFEROGRAMS SHOWING OGIVE ERROR

Real at top , computer generated at bottom



$$dx = \text{Ogive error} * \frac{X}{\sqrt{(X^2+Y^2)}}$$

$$dy = \text{Ogive error} * \frac{(\ X}{\sqrt{(X^2+Y^2)}}$$

<u>FIG 4</u>

RAYTRACING GEOMETRY

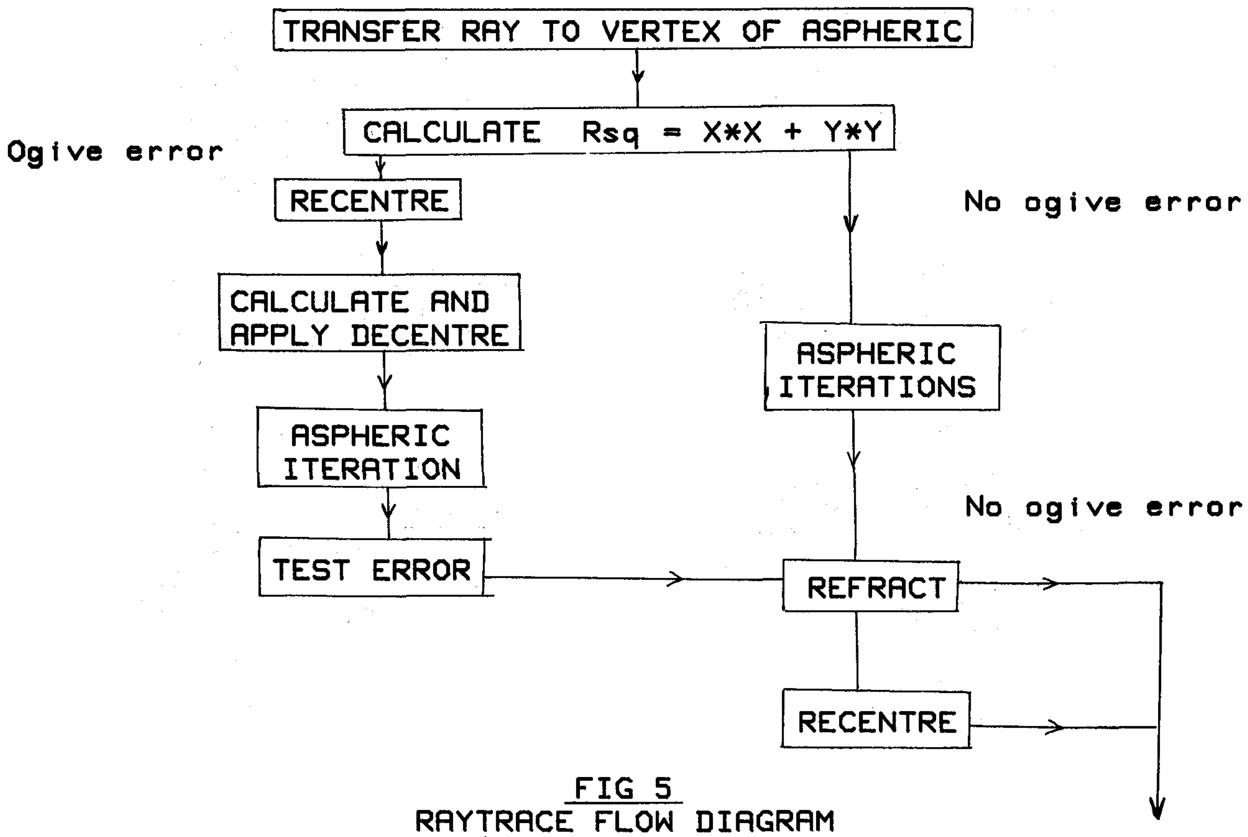


FIG 5
RAYTRACE FLOW DIAGRAM

FIG 6
CALCULATED SYSTEM MTF CURVES
Ideal (left) and with .008mm ogive error (right)

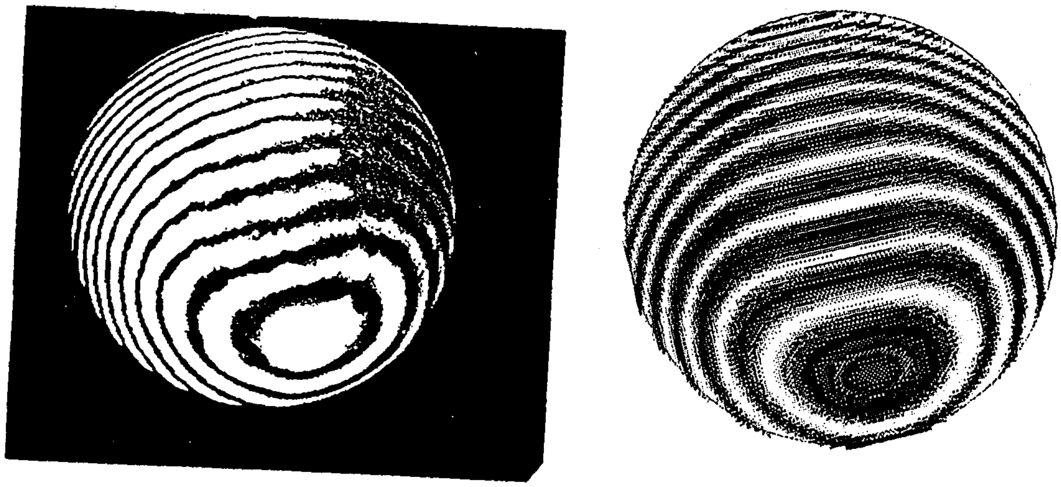


FIG 7
INTERFEROGRAMS FREE OF OGIVE ERROR
Real at left . computer generated at right