APPLICATION OF INTERFEROMETRY FOR TESTING MACRO/MICROGEOMETRY OF OPTICAL SURFACES

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Abstract

New technologies to generate optical surfaces have been introduced recently. Interferometric testing of optical surfaces is widely used in laboratories but has only recently been applied in industry. Interferometric testing of plane, spherical and aspherical surfaces will be described together with the fringe analysis. Electronic phase measurement techniques eliminate photographing the fringe pattern for the analysis of the wavefront. Aspherical surfaces can be tested successfully by using computer generated holograms. Alternatively, aspheric surfaces in production can be tested with a master surface, using a holographic technique to be described. A slightly modified fringe analysis technique can be used for the study of the microgeometry of optical surfaces. For testing surfaces in the grinding stage two wavelength holography will be described.

Introduction

For many years semiquantitative but relatively simple tests such as the Fizeau, Twyman-Green as well as Ronchi and Foucault and Hartmann[1] were used. They still have their place, but precision and time are gained by employing laser sources and photoelectric detectors together with microprocessors for the analysis of the large quantities of data. Testing is no longer necessarily performed by opticians only, but could be by individuals with training to use newer trechniques and equipment. For testing optical systems, the optical transfer function or modulation transfer function measurement is widely used.

The emphasis in this paper is placed on testing of optical surfaces and components rather than on the evaluation of optical systems. Interferometric testing of optical surfaces and components is known for many years. Only recently that interferometry has been widely accepted for industrial applications. For further successful application of interferometry in industry for testing macro- and microgeometry of optical surfaces, fast fringe analysis is desirable.

Interferometric testing

Different interferometric arrangements are used for testing optical components and surfaces. The most commonly utilized interferometers are the Fizeau, Twyman-Green, Mach-Zehnder, Smart point diffraction and the scatterplate interferometer[1].

The Fizeau interferometer measures the departure between a test- and a reference surface. The surface under test can be a flat surface, a spherical - or even an aspheric surface. It can also be placed in contact with a reference surface leading to the well-known Newton fringes, using an extended light source for the measurements. If the separation of the reference and test surface is larger than a few wavelength, a collimated coherent wave is appropriate. Fizeau interference arrangements using a laser source are shown in fig. 1. Fig. 1a shows the nucleus of the well-known Zygo interferometer for testing plane - and spherical surfaces. A well corrected objective L_2 collimates the light of a Laser focused to

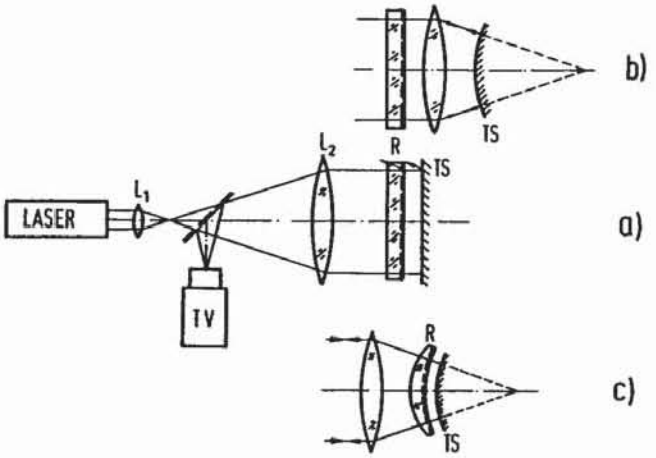


Fig. 1:
Fizeau interference arrangements for testing
a) plane surface
b) spherical surface with a plane reference
c) spherical surface with a spherical reference
R = reference surface
TS = test surface

a pinhole with lens L_1. The wavefront reflected from the test object is compared with the one of the reference surface. For testing spherical surfaces, an additional well corrected collimator lens is needed (Fig. 1b). Alternatively, a spherical reference surface can be used for testing spherical surfaces as shown in fig. 1c. The shape of the wavefront as well as the radius of curvature can be measured by focussing to the vertex and center of the surface under test. The Fizeau configuration employs the least number of components.

A Twyman-Green-Interferometer is shown schematically in fig. 2. The beam splitter separates

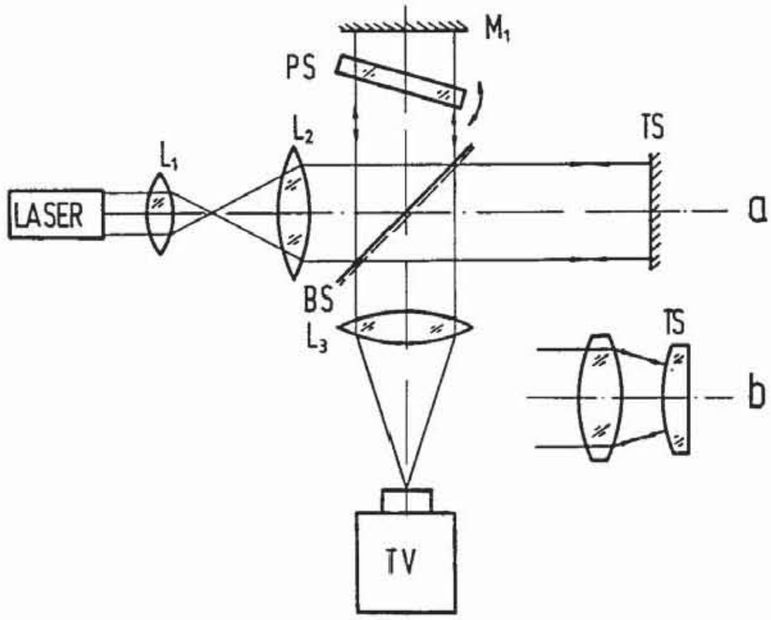


Fig. 2:
Twyman-Green interferometer for testing
a) plane surfaces
b) spherical surfaces
M 1 = reference mirror
PS = plane parallel plate for phase shifting
BS = beam splitter
TS = test surface

the reference wave reflected from mirror M_1 from the test wavefront reflected by the surface under test (TS). The interference pattern, obtained after the recombination of the reference and test wavefronts can be recorded photoelectrically by means of CCD diode arrays or by using TV techniques. For the fringe analysis it can be useful to shift the fringe pattern by changing the phase in the reference beam by $\pi/2$ and π as will be discussed later. Different methods can be used for changing the phase deliberately, two have been used, namely moving the reference mirror by means of a piezo or by tilting a plane parallel plate. The Twyman-Green-interferometer can be used for testing surfaces, optical components, homogenity of optical material as well as for testing lens systems.

Two-wavelength interferometry

In the early fabrication stage of grinded optical surfaces the sensitivity of classical interference arrangements is very often too high. Using a longer wavelength light source such as of a CO_2 laser (λ = 10,6 µm), can lead to experimental difficulties in recording and analysing the interference pattern. Two-wavelength holography provides a mean of using visible light to obtain an interferogram identical to the one that would be obtained for a longer wavelength. Recording a hologram of the surface under test with two wavelength slightly different leads to an interference pattern when reconstructed with one of the recording wavelength. Alternatively, a hologram of the test object recorded with the wavelength λ_1 can be returned after development in exactly the same position, occupied during the exposure. Illuminating the interference arrangement with a different wavelength λ_2, a Moiré pattern is obtained identical to the interferogram that would have been obtained if the optical elements were tested using a wavelength λ_{res}, with

$$\lambda_{res} = \frac{\lambda_1 \lambda_2}{(\lambda_1 - \lambda_2)}$$

An arrangement for real-time two wavelength holography is shown in fig. 3. Two wavelength λ_1 and λ_2 of an Ar-laser for instance are used simultaneously. The two recorded holograms are reconstructed with one of the two recording λ's selected by the Bragg angle of the volume storage device, such as a $Bi_{12}SiO_{20}$ (BSO) crystal. The method has been used for contour line holography in real-time[9].

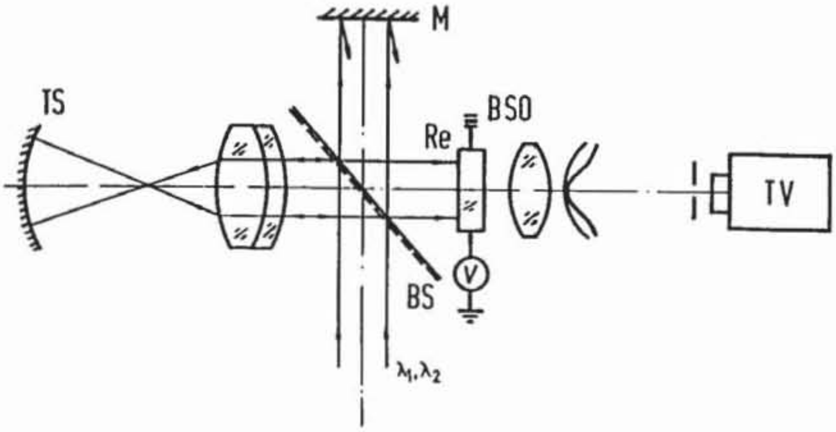


Fig. 3:
Arrangement for real time interferometry, using two wavelengths λ_1 and λ_2 of an Ar-laser, using a BSO-crystal as storage device

BS = beam splitter
M = reference mirror
TS = test surface

Fig. 4 shows the results of a real time contour line hologram of a metallic surface with a contour line separation of 14 µm. Alternatively, thermoplastic material could be used for two-wave-length holography.

Fig. 4:
Real time contour lines of a metallic surface with 14 µm line-separation

Fringe analysis in interferometry

For a two beam interference arrangement the stationary fringe pattern corresponds to a surface variation of $\lambda/2$ in double-pass, where λ is the wavelength. Sharpening fringes with multiple beam techniques improves the location of the fringe position. Increasing the sensitivity further requires either a shorter wavelength or improved means of interpolation between the fringes.

For the fringe analysis different methods are applied:
- Photographing the fringe pattern and determining the position of the fringe centers to feed into a computer which in turn calculates the phase.
- Measuring the fringe position directly by using photoelectric detectors such as diode arrays or television techniques. Simple fringe analysis techniques can be used when closed fringes are avoided by deliberately introducing tilts. A deliberately introduced phase shift in the reference beam can be useful for the analysis of closed fringes and the sign of deformation.

Electronic phase measurement techniques for interferometric applications fall into two general categories, namely
1. Sensors for which the phase difference between the two interfering beams is changed in discrete steps in time; they are often called phase shifting interferometers.
2. Sensors for which the phase difference between the two interfering beams is changed at a constant continuous rate in time producing a frequence difference between the two beams. They are often called heterodyne or AC interferometer.

Phase measurement technique

Different phase-measuring methods exist[3]. In a three step technique for measuring the phase, the phase of the reference beam is changed by $\pi/2$ and π respectively and the detector reading is recorded in turn. The phase measurement is performed at each detector point. The resulting intensities of the two beam interference pattern are

$$E_1 = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left[2kW(x,y)\right]$$

$$E_2 = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left[2kW(x,y) + \pi/2\right]$$

$$E_3 = I_1 + I_2 + 2\sqrt{I_1 I_2}\cos\left[2kW(x,y) + \pi\right]$$

where I_1, I_2 are the intensities of the beam 1 and 2 respectively, leading to

$$C = \frac{E_1 - E_2}{E_1 - E_3} = \frac{\cos[2kW(x,y)] + \sin[2kW(x,y)]}{2\cos[2kW(x,y)]}$$

arriving at the phase of the wavefront $W(x,y)$

$$W(x,y) = \frac{1}{2k}\arctan(2C-1)$$

where $k = \frac{2\pi}{\lambda}$ is the wave number with λ as wavelength.

A Hamamatsu C-100 camera was used for recording the intensities at 64 by 64 and 512 by 512 data points respectively. For the one-dimensional analysis of the wavefront, 1024 data points are used. The irradiance is measured for the three phase shifts 0, $\pi/2$, π. Alternatively, for the integrating technique, the phase of the reference relative to the test beams is varied at constant rates rather than in discrete steps. They integrate from 0 to $\pi/2$, $\pi/2$ to π and π to $3\pi/2$. The wavefront variation between two detector points should not exceed $\lambda/8$. Tilting a plane parallel plate was preferred to a piezo driven mirror (fig. 2) for the stepwise phase shift.

Knowing $W(x,y)$ of the interference pattern at the different detector points, the wavefront needs to be calculated. Zernike polynomials were found to be appropriate for our applications leading to the classical aberration terms[3]. They can be written in polar co-ordinates as a product of two functions depending on the radius r and azimuth Θ. The described technique leads to an automatic wavefront analysis with a sensitivity $\geq\lambda/100$. Examples of the fringe analysis are shown in fig. 6 and fig. 7 for a glass surface and a diamond turned Ge-aspheric lens surface.

Testing aspheric surfaces

Aspheric surfaces could be used more frequently when manufacturing and testing in industrial environments can be improved.

Different methods can be used for testing aspheric surfaces.

1. Testing the performance of the complete optical system.
2. Using a null corrector in the test arm of a two beam interferometer in order to compensate the aspherical wavefront deviation of the surface under test. Special aspherical surfaces like paraboloids could be tested with a modified 2-beam interferometer.
3. Using a computer generated hologram in a two beam interferometer either to transform the aspheric wavefront of the test surface to a stigmatic one or to generate an "ideal" aspheric wavefront for comparison in the reference beam.
4. A point by point analysis, normally with a mechanical taster.

Computer generated holograms are applicable advantageously for testing a widespread range of aspheric surfaces. A number of papers on testing aspheric surfaces by means of computer generated holograms (CGH) have been written, only a few will be mentioned[4-8]. From a practical point of view, a two beam interferometric arrangement in which both beams pass through the CGH is desirable. In this way the inhomogenity of the hologram storage material (usual high quality photographic plates) is nearly compensated. For testing aspheric surfaces with CGH, different holographic configuration can be used. For symmetrical optical systems to be tested, in-line[6-8] (Gabor-Type) and off-axis CGH can be applied; their differences and applications are discussed in reference 6. We use both configurations[6] but prefer very often the off-axis arrangement.

Different methods for generating CGH have been devised or are in the process of being developed. For plotting CGH, a Calcomp plotter is often used. Laser or electron beam scanner can be utilised for larger wavefront compensations i.e. finer grid patterns, leading to an improved accuracy and resolution. A drum scanner guided by the computer (PDP 11/34), used for computing the wavefront satisfies our requirements. The Optronics drum plotter has a maximum spatial resolution of 20.000 pixels by 20.000 pixels and a format of 23 x 23 cm². After an one step reduction on high contrast photographic plates or on photo resist, to improve the diffraction efficiency, the CGH is ready to be used in a two-beam interferometer.

An arrangement with an off-axis hologram for testing aspheric surfaces is shown in fig. 5. In-line holograms described in references 6 and 8 can also be used. Although we use both arrangements, we prefer very often the off-axis configuration, occasionally we apply in-line holograms.

An interference arrangement with an off-axis hologram for testing aspheric surfaces is shown in fig. 5. Simple lenses L_1, L_2, L_3 can be used to illuminate the aperture of the test sur-

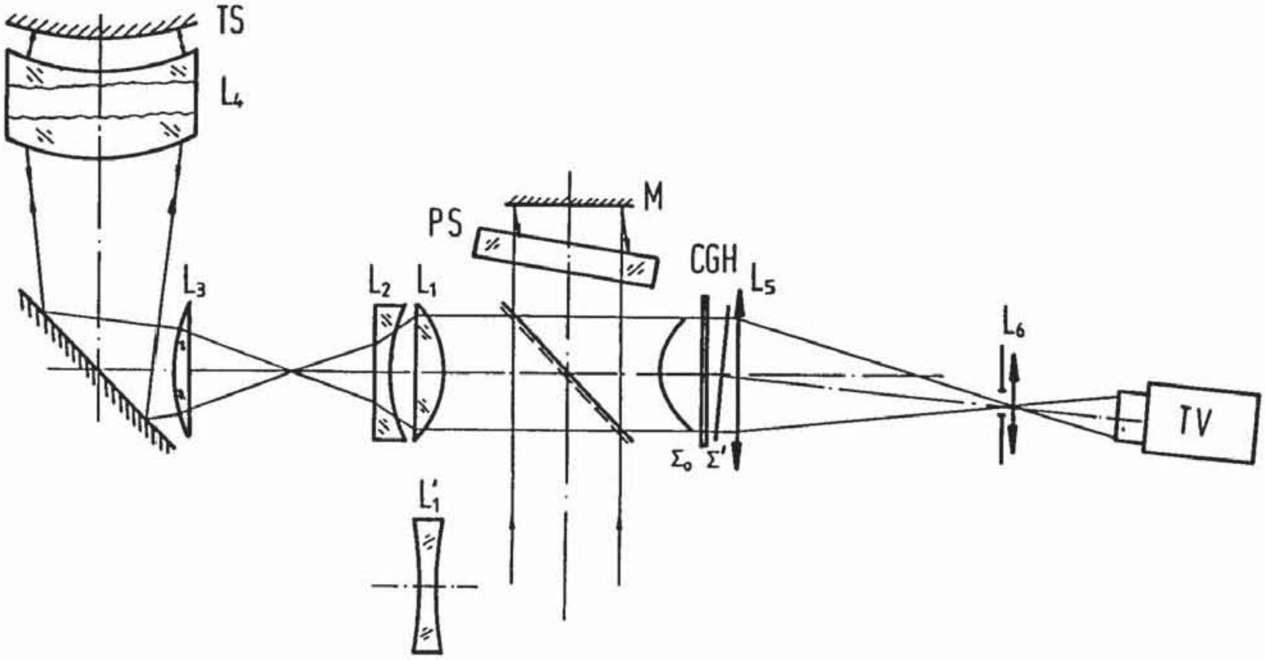


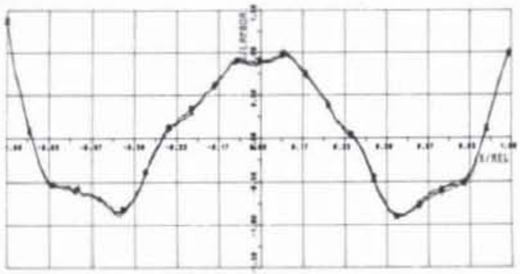
Fig. 5: Experimental set-up for testing spherical and aspherical surfaces. BS = beam splitter, MS = reference mirror, L_1, L_2, L_3 = auxiliary lenses, PS = parallel plate for phase shifting the reference beam, L_4 = high quality lens for testing spherical as well as aspherical surfaces, L_1' = auxiliary lens to be used together with L_4 for testing spherical surfaces as well as for determining the vertex of the aspheric test lens accurately

face[6]. They should also image the test surface onto the CGH, a necessary condition for strong wavefront deviations. In addition, L_1, L_2 and L_3 compensate some of the wavefront deviations produced by the aspherical surface in order to be left with less than 50 λ/mm to be compensated with the CGH. The CGH is computed by ray tracing chosing a number of rays to compute the wavefront at the hologram. The optical path differences for the different rays are inverted to obtain the wavefront polynomial for the CGH. A CGH is manufactured as described previously. The predicted aberrated wavefront will be compensated with the CGH in the first diffraction order and compared with the perfect reference wave reflected from mirror M. Departures from the simulated data of the aspherics will lead to interference fringes. L_4 is a well corrected lens system to be used together with L_1' for testing spherical surfaces, as shown in fig. 1, but it is also needed for focussing on the vertex of the aspherics. The plane parallel plate in the reference beam is used to shift the phase as described earlier. The Hamamatsu C 1000 camera is connected to the computer PDP 11/34, for the fringe analysis.

For testing very different aspheric surfaces, the separation of the lenses L_1 to L_2 or L_2 to L_3 may need to be modified or the lenses may be replaced appropriately. They are, however, not supposed to act as a null corrector i.e. they do need to be perfect to match the aspherical surface under test.

Designing and fabricating a null corrector becomes an iterative process between the designer and shop personnel to insure proper performance. Furthermore, it needs to be tested. Even for the compensating system the lens data are not always known to the required accuracy. For testing it and compensating for the errors a CGH hologram together with an appropriate spherical reference mirror can be generated. No fringes should occur for perfect agreement. Disturbances introduced by the auxiliary lenses as well as by other error sources lead to fringes to be compensated in the CGH for testing the test surfaces. Some of the errors to be compensated result from departure from the lens data and separation used for the computation, centring errors of the components, magnification error and distortion by photo-reduction, errors in generating the hologram.

Results of two aspheric surfaces tested off-axis in reflexion are shown in fig. 6 and fig. 7.



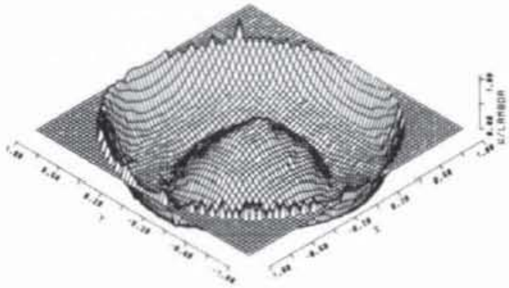
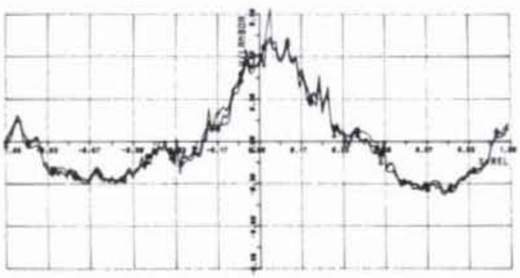


Fig. 6a:
Interferece pattern obtained from an aspheric surface from a glass lens tested with λ = 633 nm

Fig. 6b:
One-dimensional fringe analysis of fig. 6a, using 1024 data points

Fig. 6c:
Result of the two-dimensional automatic fringe analysis of fig. 6a using 64 x 64 data points

Fig. 6a shows the interference fringe pattern of an aspheric glass surface and fig. 7a the result of a diamond-turned aspheric Ge-lens surface. The automatic fringe analysis leads to fig. 6b and 7b for the one-dimensional fringe analysis using 1024 data points and fig. 6c and 7c for two-dimensional fringe analysis using 64 x 64 data points.



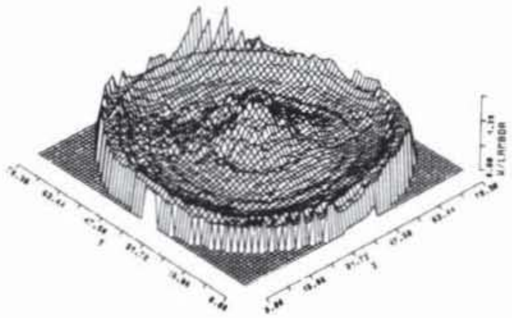


Fig. 7a:
Interference pattern obtained from an aspheric Ge-lens surface manufactured by diamond-turning, tested with λ = 633 nm

Fig. 7b:
Result of the automatic one-dimensional fringe analysis of fig. 7a using 1024 data points

Fig. 7c:
Two-dimensional fringe analysis of fig. 7a

Holographic testing of optical surfaces

Optical surfaces can be tested by holographic techniques, comparing the test surface with a master surface already measured with a CGH, as described previously. Thermoplastic film material can be used for storing the hologram of the master surface. Replacing the master by the test surface leads to a second wavefront to be compared with the wavefront reconstructed from the hologram. Interference fringes occur, indicating the difference between the master surface and the surface under test. Fig. 8 shows the experimental set-up for testing spherical and aspherical surfaces. Macro- and microgeometry changes can be observed when comparing different figuring stages in high quality optics. The results of an application of the method for serial testing of aspherical surfaces is shown in fig. 9a and fig. 9b. In fig. 9a no fringes occur by comparing the master surface with its own, stored, wavefront. For con-

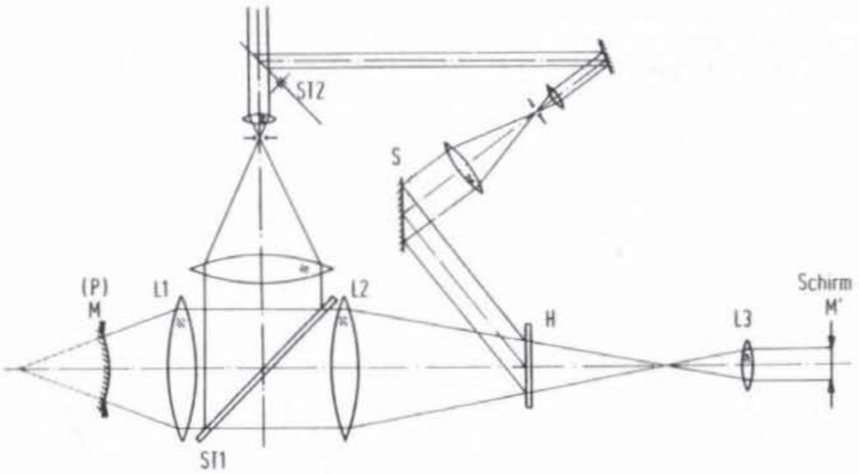
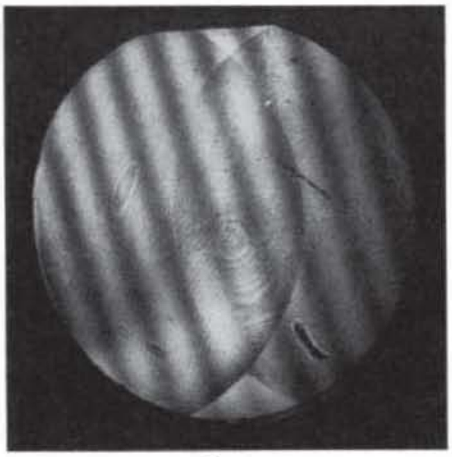


Fig. 8:
Arrangement for comparison of the aspheric surface with a master surface in serial production using a thermoplastic storage material


a


b

Fig. 9a:
Comparison of the master itself with its own reconstructed wavefront; a small tilt was introduced

Fig. 9b:
Comparison of a typical aspheric surface of a serial production with the wavefront of the master hologram

venience, an additional tilt can be introduced. Different test surfaces, however, show fringe patterns like the one in fig. 9b.

Testing fine form errors in optical surfaces

Fine form errors, commonly called surface microroughness, were discussed in details by J.M. Bennett in the previous paper. Different techniques are possible to measure fine form errors of optical surfaces; namely

- with a diamond stylus of a profiling instrument leading to a sensitivity of a few Å[10,11]
- alternatively, by measuring scattered light produced by the fine structure[12]
- interferometric optical phase measurement techniques [13,14,15]
- speckles techniques could be used for an integral measure of the surface roughness[16] (to be applied for rougher surfaces)

A comprehensive report on a computerized stylus instrument for measuring the roughness and statistics of machined and polished surfaces in the micrometer roughness is given in reference[10]. A comparison of the stylus instrument with an interferometric method is described in reference[11]. Microscopic surface structures scatter the incident light leading to a measure of the microstructure. Quantitative measurements can be obtained by detecting the scattered light with a photodetector array, for instance. The sensitivity of the system is 50 Å but could be improved[12].

The most precise methods for measuring surface finish of machined part are the interferometric methods described by Bennett et al[13]. They have demonstrated sub-nanometer accuracies by measuring surface roughness using a FECO interferometer. The method has a high sensitivity but is time consuming and environmental control is required. Bennett uses multiple-beam fringes of equal chromatic order obtained by multiple reflections between two partially silvered surfaces, the extreme smooth reference and the test surface. A conventional heterodyne interferometric measurement technique has been used by Sommargren[14] to obtain surface profiles with accuracies of 1 Å rms. This approach is faster than the FECO interferometer application but requires a rotating air bearing platform for scanning an annular region of a sample. Koliopoulos[15] describes a Mirau interferometric arrangement using a phase measuring technique for the fringe analysis.

Fig. 10 shows results of our improvised microstructure analysis by high pass filtering the fringe pattern shown in fig. 6b and fig. 7b for the glass and the Ge-surface. The sensitivity in depth is better than $\lambda/100$. An improved version will be built with higher sensitivity and spatial resolution.

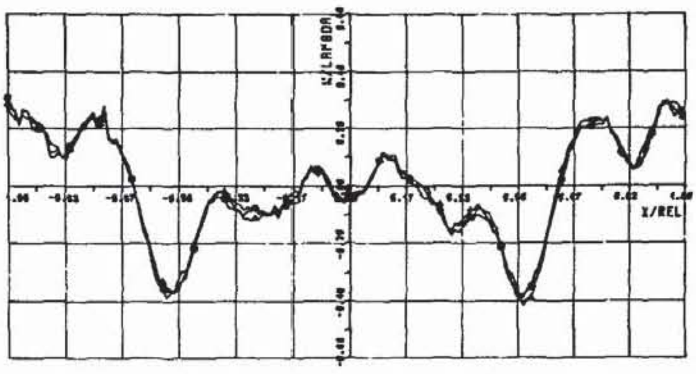


Fig. 10a:
Microstructure analysis of the aspheric glass lens surface, tested in fig. 6

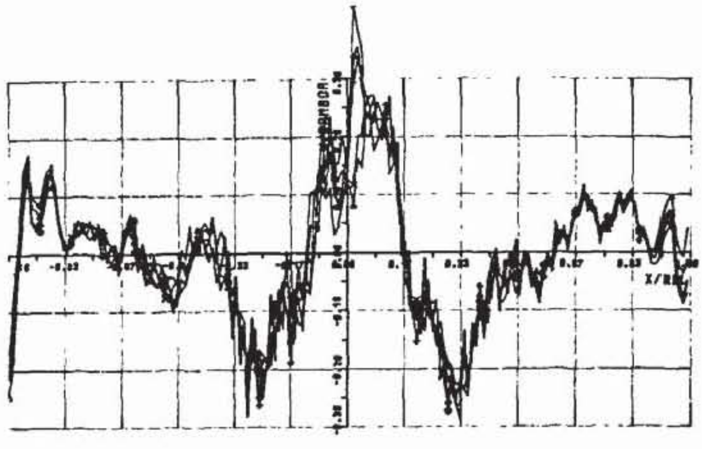


Fig. 10b:
Microstructure analysis of the Ge-surface tested in fig. 7

To summarize the microroughness measurements, the stylus instruments may be more flexible than interferometric techniques and can be adapted to more types of measurements. They give line information only and can lead to surface damage. Dual-beam interferometric methods yield a qualitative, as well as quantitative, assessment of the surface.

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