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Technology development for precision optics fabrication

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This article is dedicated to Prof Kehar Singh for his significant contributions to Optics and Photonics

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Fabrication of conventional optics is an old age technology primarily includes flat and spherical surfaces. Usage of rotationally symmetric aspheric surfaces providesmore degree of freedom to an optical designer to control aberrations and improving the performance of the imaging system. Development of CNC based manufacturing technologies has given the opportunity to fabricate complex aspheric and non-rotationally symmetric freeform surfaces. An overview of the manufacturing trends for precision optics is presented with technological transformation from conventional to modern CNC based techniques those are suitable for complex aspheric and freeform fabrication along with suitable metrology feedback.

Keywords: Aspheric and freeform optics, CNC optical manufacturing, Optical tower, SHS based freeform metrology.

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1 Introduction

21^{st} century is an era of optics, which is an enabling multidisciplinary technology that has a significant effect and growing impact in many areas of our day to day life. Being an extraordinarily strong and dynamic field, optics technology has significant contribution and diverse applications in the areas of telecommunications, biomedical applications, solar energy, defense, space, surveillance etc. Due to the advancement in the CNC (Computer Numerical Control) based manufacturing technology, demand of complex asphericsand freeform surfaces has also been made from the optical industries to realize advanced optical systems [1]. Aspheric and freeform surfaces have advantages over conventional spherical surfaces in imaging and non-imaging applications such as day camera, IR camera, compact projection systems, head-up displays, computational imaging, space optics and optical systems for surveillance and terrain mapping. Introduction of aspheric and freeform surfaces in the optical system provides more degrees of freedom to the optical designer for better control of aberrations and allows one to develop compact and light-weight systems [2]. Introduction of new optical materials and advancement in the material processing technology could further enable a better design solution for advanced optical systems in multispectral region. This creates optics technology a rapidly growing field and attractive focus for new businesses in the global market

Aspheric and freeform optics can be machined by a variety of methods, including ultra-precision cutting, grinding and polishing [3]. Due to complex geometry, manufacturing process requires an extensive research on the generation of tool path and proper selection of subaperture tooling based on the geometry of surfaces under fabrication. In case of aspheric and freeform optics, the machining platform requires multiple axes with precision controlled motions. High speed grinding spindles that can reach speed of 20,000 rpm are used for the grinding of brittle materials [3]. Grinding process itself cannot meet the optical surface requirements for a wide variety of optical components. Hence a subsequent smoothing and polishing steps are required after grinding to make surface transparent with stipulated form error tolerances. These techniques are sub aperture polishing tools for local removal of material based on metrology error profile feedback.

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Requirement of super finish optical surfaces with surface finish of the order of sub angstrom order require post polishing process using magnetorhelogical finishing (MRF) [4], ion beam figuring [5] and ion assisted reactive etching methods.

The increased range of complex surfaces offered by the new fabrication techniques is giving opportunities to incorporate them in the optical systems. However, the requirement of precision manufacturing tolerances depends on the suitable metrology techniques to be incorporated with manufacturing process as an off line as well in-situ metrology. A varieties of metrology techniques are available for the measurement of rotationally symmetric aspheric surfaces. However,some of these metrology techniques have also been applied for the measurement of complex asphere and freeform surfaces. These techniques are primarily profilometery, interferometric and slope based measurement techniques. Subaperture stitching interferometery [6] and scanning Shack Hartman Sensor (SHS) [7] have also been reported for the measurement of complex aspheric and freeform surfaces.

2 Trends in the optical design

The aim of an optical designer should be to design an optical system with ease of manufacturing. The tolerance budget analysis of the designed system must be carried out based on the capability of manufacturing platform. The fundamental requirement of designing any optical imaging system is to have high image quality by controlling the aberration. A suitable optimization technique is employed to optimize the design performance by varying certain design constraints by different optical design software [8]. By using the lens maker formula, image quality can be controlled by changing the curvature of the lens. Same power can be maintained in any lens system by different combination of radii of curvature (ROC) of the two surfaces. Study shows that by changing this parameter only, we can minimize two third order aberrations, namely third order spherical aberration and coma. By using suitable power combination of two different glass materials having different refractive indices and dispersive powers, chromatic defects of the optical imaging system can be minimized.

Conventional optical design comprises of optical components in plano and spherical geometry. Conventional optics based systems are more bulky and involve more number of optical components to meet the performance criterion. Usage of rotationally symmetric aspheric surfaces provides more degrees of freedom to an optical designer to design a system with lesser number of optical components to meet the targeted specifications.

The typical sag equation of an aspheric surface used in most of the design approaches can be given by

$$z = \frac{c(r^2)}{1 + \sqrt{(1-(1+k)c^2\,(x^2 + y^2)}} + \sum_{n=1}^{N} A_i\, r^n \tag{1}$$

The first part of the equation is conic part where c is the curvature, r is the radial distance from the centre, k is the conic constant. The conic constant is shown in Table 1.

Table 1. Values of conic constants for type of surfaces

Conic constant (k)	Surface type
= 0.0	sphere
= –1.0	parabola
< –1.0	hyperbola
> 0	oblate ellipsoid (ellipsoid rotated about minor axis)
–1< k <0	prolate ellipsoid (ellipsoid rotated about major axis)

Comparison of spherical and aspherical surfaces is shown in Fig 1.

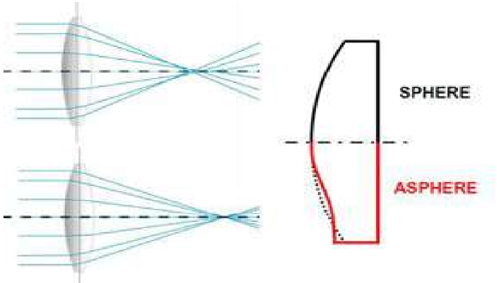


Fig 1. Comparison of spherical and aspherical lenses.

Advancement in the single point diamond turning machines using slow tool servo (STS) [9] and fast tool servo (FTS) [10] make it possible to manufacture aspheric and asphero-diffractive surfaces in non-ferrous metals, crystals and polymers with nanometer finish. This benefits an optical designer to design the infrared optical systems using these geometries to control monochromatic and chromatic aberrations. The scheme of chromatic aberration correction is depicted in Fig 2.

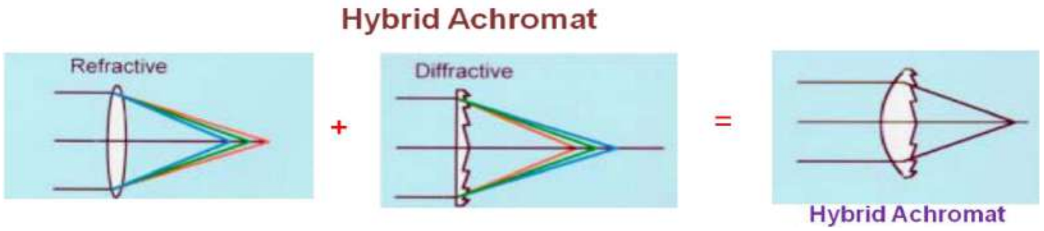


Fig 2. Chromatic correction by diffractive surface.

The sag equation for an asphero-diffractive surface can be defined as

$$z = \frac{c(r^2)}{1 + \sqrt{(1-(1+k)c^2 r^2}} + Ar^4 + Br^6 + Cr^8 \ldots\ldots\ldots + \frac{c_1 r^2 + c_2 r^4 + c_3 r^6 + \cdots\cdots\cdots\cdots}{N-1} - d_{max} * Integer \left| \frac{c_2 r^4 + c_3 r^6 + \cdots}{\lambda} \right| \tag{2}$$

The first term of the equation is conic part where c is the curvature, r is the radial distance from the centre, k is the conic constant. A, B, C…etc are the aspheric coefficients used in the second term. Third and fourth terms are diffractive terms with c_1, c_2, c_3…diffractive coefficients and λ is the operating wavelength.

Freeform surface is non-symmetrical surface and provides more advantages as compared to aspheric surfaces for designing compact and light weight optical systems. Based on the specific applications and profile, freeform surfaces are represented using orthogonal and non-orthogonal polynomials. Orthogonal polynomials includes Zernike circular polynomials [11], Q type polynomials [12], Zernike polynomials over a regularly non circular aperture [13], 2D Chebyshev polynomials [14] and 2D Legendre polynomials [15]. Non orthogonal polynomials to describe freeform surfaces include XY polynomials [16], Spline [17] and radial basis functions [18].

The sag equation based on XY polynomials to represent a freeform surface is given as,

$$Z = \frac{c(x^2 + y^2)}{1 + \sqrt{(1-(1+k)c^2 (x^2 + y^2)}} + \sum_{i=1}^{N} \sum_{j=1}^{N-1} A_i (N) x^{i-1} y^{j-1} \tag{3}$$

Here N is the total number of polynomials terms. A_i's are the polynomial coefficients. A cubic phase profile is shown in Fig 3.

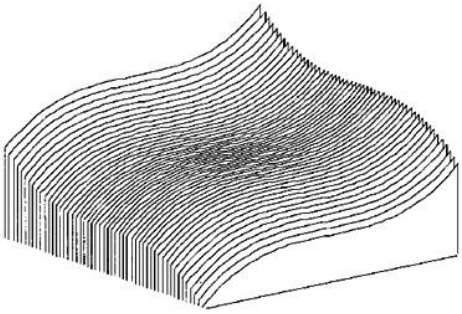


Fig 3. Freeform surface (cubic phase plate)

Complexity for fabrication of an optical surface is generally increased from spherical convex to freeform shape based on the surface shape. The geometry of optical surfaces, i.e.,convex, concave, aspheric, and asphero-diffractive, gull wing and freeform shown in Fig 4 poses challenges in the manufacturing and metrology. Spherical and aspherical surfaces have manufacturability advantage due to their rotational symmetry. However, freeform surfaces, due to non-rotational symmetry and increased complexity demands more special manufacturing and metrology tools. Usage of freeform surfaces to design advance optical systems may be a paradigm shift in the field of optical design by considering its fabricability and measurement aspect.

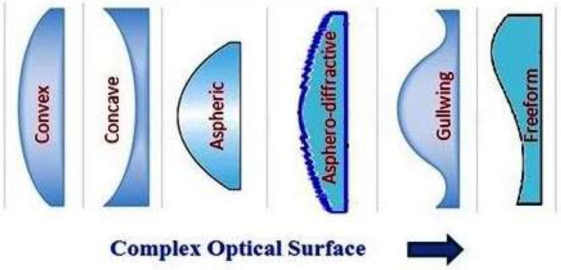


Fig 4. Evolution of optical surfaces.

3 Trends in the optical manufacturing

Present optical fabrication methods are blend of conventional and contemporary CNC based manufacturing technologies. Pitch polishing with metal oxide polishing compound developed centuries ago is still in the use. On the other hand, modern practices are more efficient with computer-controlled machines, deterministic, more precise, and capable to process variety of optical materials in diverse shape and geometries with suitable metrology tools [19]. A conventional manufacturing technique demands a skilled manpower along with the machines to deliver a precision optics. However, the advanced CNC machines are capable to fabricate more complex optical surface by ensuring high repeatability and precision in the manufacturing process. Diamond-turning and grinding technology, in combination with CNC machines, has had a large impact on fabrication technology. Following sections describe the manufacturing trends in conventional and CNC based machines.

3.1 Conventional optics fabrication

Fabrication of conventional optics is an old age technology. In the conventional manufacturing process, optics is being manufactured by grinding and polishing using full aperture tooling which makes the process limited to spherical and plano surfaces. Optical materials including various glass, metals, crystals and polymers are used for fabricating theses optics based on their optical characteristics viz refractive indices, Abbe numbers, transmission etc for various applications from UV to infra-red region of electromagnetic spectrum. The typical fabrication steps in the conventional optical manufacturing include trepanning, curve generation, grinding, smoothing, polishing and centering & edging operations.

In the trepanning, required glass disc is cut from the glass blank using diamond particle impregnated trepanning tools. A designed geometrical form is given to the secular disc in the curve generation stage. Thereafter, grinding and smoothing is done to make surface smooth and removing any tool marks during curve generation process. The polishing operation is carried out to make surface transparent and to maintain optical parameters that include surface accuracy of sub micrometer order and surface finish of nanometer order. For most of the glasses, cerium oxide based polishing materials are being used. For crystalline materials such as infrared materials, aluminum oxide or diamond based slurries as polishing materials are used. After polishing process, the optical components are centered and edged to maintain centering error and final diameter as per design tolerances. Surface form error can be measured using interferometric methods. Various machines/ equipment used in the whole process are shown in Fig 5.


Trepanning
Curve Generation
Smoothing
Polishing
Centering & edging
Laser Interferometer

Fig 5. Conventional trepanning, curve generation,grinding/ smoothing machine, polishing, centering/edging machine and laser interferometer for metrology.

3.2 Computer controlled fabrication process

The usage of aspheric and freeform surfaces has become increasingly popular over the last decade [1,2]. The fabrication of the components for precision optical applications requires submicrometer form accuracy and nanometer surface finish.

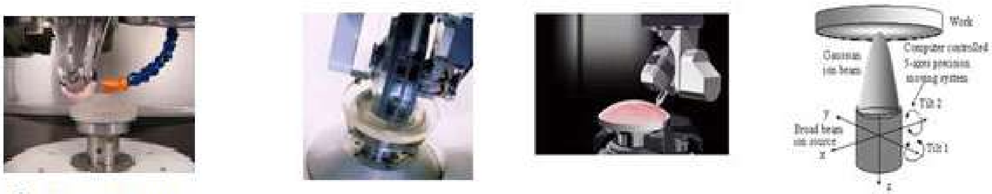
To achieve such a high precision tolerance on the surface, grinding machine should generate the surface of the order of 1-2 micrometer (rms). This can only be achieved by using CNC grinding machines. For the polishing process, various technologies are available including bonnet polishing [20], wheel polishing [21] magnetorhelogical finishing (MRF) [4], fluid jet polishing [22] and ion beam figuring [5]. Single point diamond turning (SPDT) [23] is capable for precision manufacturing of aspheric and freeform surfaces in non- ferrous metal, polymers and crystals.

Twin turret optical grinders (TTOG) based CNC grinding machine (Model-M/s Cranfield precision, UK) is shown in Fig 6. This is a five axes CNC grinder based on deterministic micro grinding that utilizes latest advances in axis positioning. These grinders using two rotary axes are rigidly mounted on a fixed center distance and provide relative motion between the component and cutting tool, with the linear axis used to provide profile of the component and also control the depth of cut. In-situ measurement probe is used for alignment of optics and to provide measurement feedback for corrective grinding. Aspheric surfaces can be generated on these machines with form error < 2µm and surface roughness < 200 nm.

Fig 6. CNC grinding machine and on-machine metrology probe.

Bonnet polishing is one of the advantageous methods, where bonnet is used as a sub-aperture polishing tool. Bonnet can be moved from different directions of the surface and averaging out tooling marks to produce smooth surface. It further eliminates the mid spatial frequencies from the polished surface. Bonnet tool comprises inflated, bulged rubber membrane covered with polishing cloth. The bonnet tool traverses a predetermined tool path based on the geometrical properties of aspheric surface in the presence of polishing slurry. Bonnet tool can directly be used on the grinded aspheric surface for pre and corrective polishing process in contrast to other sub-aperture polishing approaches. This type of polishing can be implemented for all types of optical materials i.e. different types of glasses and IR materials. Further less tool wear and tear cost make this process more economical even for less number of components. Surface form of the order of 60 nm and surface roughness of 3-5 nm is possible by using this technique.

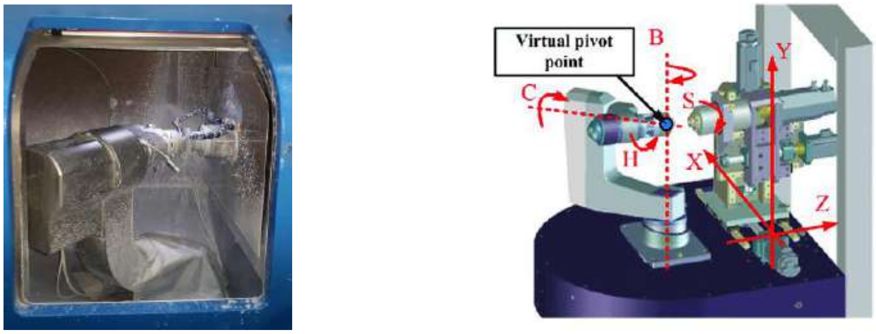
(a)CNC grinding (b) CNC Polishing (c) Polishing Tool (d) Bonnet tool (e) SPDT



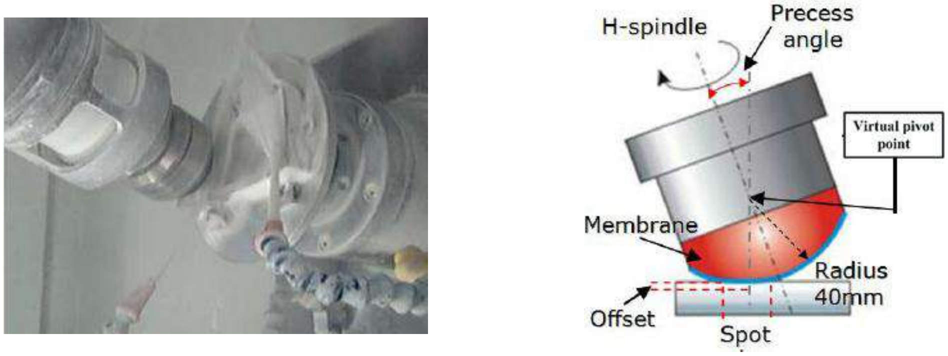
(f) Wheel polishing (g) MRF finishing (h) Fluid jet polishing (i) ion beam polishing

Fig 7. Various CNC grinding/polishing and super finish polishing machines.

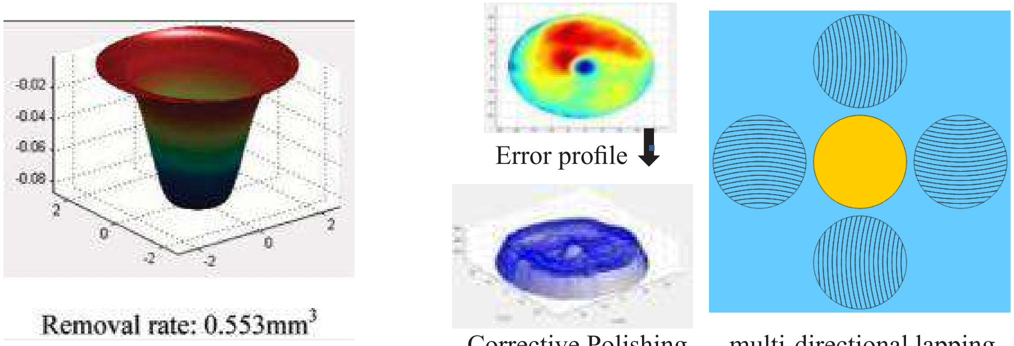
The key features of the polishing machine are; (i) an adaptive pressure bonnet tool which can be tuned for corrective polishing, and (ii) precession position ability allows multi-directional lapping for excellent texture. The footprint of this tool on the optical surface is known as spot, which can be altered by changing the tool offset. The footprint of the spot in terms of material removed is known as influence function and is used for generating dwell time tool path map based on form error. Measurement feedback obtained from various measuring instruments is used for the corrective polishing. This polishing process follows a deterministic approach and with correct set of parameters accuracies of the order of λ/4 (λ = 633nm) are achieved without much difficulty.



CNC polishing machine Axis configuration



Polishing of optics Bonnet polishing



Profile of material removal Corrective Polishing multi-directional lapping

Fig 8. 7 axes CNC polishing machines and polishing process.

In addition to bonnet polishing, other polishing techniques include SPDT, which is prudently used for fabricating infrared optics, metals and other nonferrous and non-silicate materials in aspheric and diffractive shapes. Fluid jet polishing is used to improvise the surface texture of the surface in the presence of high-pressure jet of fluid. To achieve high surface accuracy and low roughness, MRF can be used as a post polishing process after SPDT and bonnet polishing. The polishing slurry coagulated in the presence of electromagnet takes the local shape of aspheric or freeform surface for perfect matching and controlled material removal rate during subaperture correction. In the ion beam figuring process, a directed and controlled beam precisely remove the material using feedback metrology. Using this technology, very high surface accuracy with super finish surface can be achieved.

High removal rate is obtained by rotating the tool rapidly. The simplest geometry would be a circular tool, rotating about the perpendicular to the work-piece surface. The rotational surface speed is zero at the centre and rises linearly to a maximum at the edge of the contact area rotating tool. This action will remove material in a 'V'-shaped profile across cross-section. The size of the contact area and pressure between tool and work piece can clearly governs the range of surface profiles that the tool can produce. The contact pressure and the surface speed at the contact area affect both the removal rate and the surface texture. Control of these variables in the process gives the maximum flexibility and the ability to optimize the cycle-time. The axis configuration and polishing process are depicted in Fig 8.

The following Fig 9 explains the computer controlled polishing process. First, the part is pre-polished and optically measured. Then error profile obtained by measured data is provided as feedback to the machine. Using metrology feedback data, the part is polished again and in two or more iterations, the part is polished as per the required tolerances. Higher the tolerance more will be the iterations.

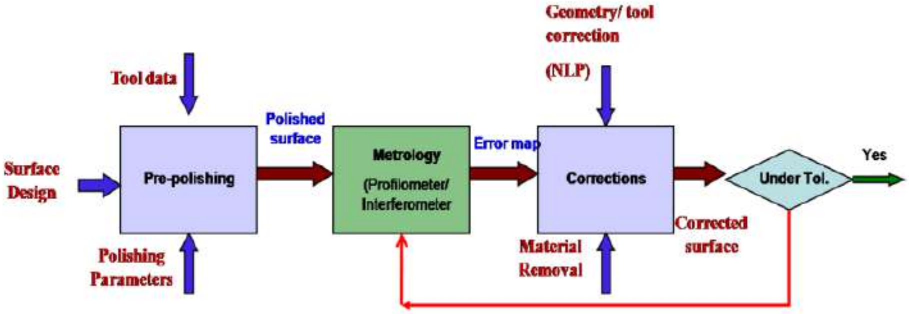
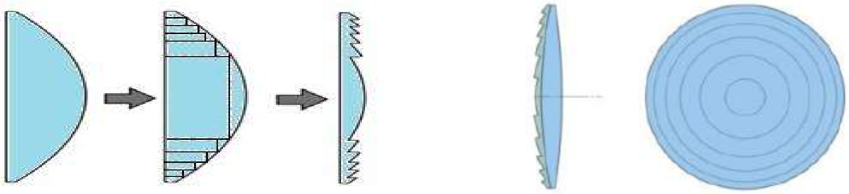


Fig 9. Polishing process flow.

The metrology feedback can be given by contact profilometery, laser interferometer with null optics or non-null based laser interferometer to CNC polishing machine for corrective polishing. Use of CNC based manufacturing technology for aspheric and freeform makes process deterministic in nature and less operator dependent.

Diffractive optical elements (DOE) provide an additional degree of freedom to optical designer for various applications in electro-optical instrumentation. Diffractive optical elements are used independently or with other optical components for making compact optical system and for colour correction, especially for infrared system as due to non-availability of material, colour correction by using doublet is not possible. In many situations, where size or weight reduction is critical, diffractive lenses can provide substantial advantages. Diffractive optical elements are widely used in infrared cameras for correction of aberrated wavefront generated by optical systems [24].

The hybrid lens consists of a conventional refractive lens with a diffractive structure generated into one of its surfaces as shown in Fig 10(a). The diffractive surface can be used to correct image aberrations and colour aberrations in a lens in a manner similar to the use of aspheric surfaces and additional refractive components. A diffractive lens has a negative value of dispersion. When designing broadband systems this property is used to provide chromatic aberration correction. An achromatic diffractive is very useful for thermal imaging camera applications that span over regions of infrared part (3-12 µm) of electromagnetic spectrum. The schematic diagram of asphero-diffractive lens is shown in Fig 10(b). Diffractive structures can be generated using lithographic techniques or diamond turning methods. For infrared region of electromagnetic spectrum, single point diamond turning (SPDT) is best suited technique to generate diffractive structure on germanium and silicon lenses. Figure 11 shows single point diamond turning machine (Model Nanoform 250, Make Precitech, USA).



(a) (b)

Fig 10. (a) Plano-convex lens and its Fresnel lens counterpart (b) Asphero diffractive lens surface.

Fig 11. Single Point Diamond Turning Machine -Nanoform 250(M/s Precitech USA) also tested by digital fringe analysis using the Fizeau interferometer or Twyman Green interferometer.

In recent years, high accuracy machines have been produced that use single point diamond tools to turn optical surfaces directly to finished tolerances. These machines use accurate motions and rigid mounts to generate the optical surface with a single diamond point, just as the part is machined on a lathe. This has the main advantage that aspheric surfaces can be directly generated into the designed surface, without the need for special lapping and metrology. In fact, some optical surfaces, such as axicons, are impossible to fabricate with conventional fabrication methods. Single-point diamond turning (SPDT), in recent years has become economical for production parts. A variety of materials can be fabricated using SPDT. The best results are obtained for ductile metals like aluminum, copper, nickel, and gold. Crystalline materials used for infrared applications such as ZnSe, ZnS, and germanium can also be diamond turned with required results. Glass materials are not suitable for diamond turning because they are brittle, however under carefully controlled conditions, glass can be cut in a ductile mode. The surface structure obtained from diamond turning is different from conventional processes. Polished optical surface has no systematic structure in them, and they can be made perfect to a few angstroms. Diamond-turned surfaces always have residual symmetric pattern from the diamond tool. A final light cut with fine pitch can substantially reduce the tool marks. The scattering from diffractive structure is the limitations of most diamond-turned optics in visible; however for infrared applications such surface effects are not sensitive.

Complex surfaces such as aspheric, diffractive and freeform have advantages over conventional spherical surfaces in imaging and non imaging optics applications. In the last decade, technological advances in machines and tools have made it possible to produce aspheric and freeform surface of reasonable quality. But the success of fabricating these surface depends on the capabilities of characterization procedures and metrology feedback mechanism for optimizing the freeform manufacturing process. Modern optical manufacturing processes are deterministic in nature and streamlined the optics manufacturing processes of more complex freeform surfaces [9,25].

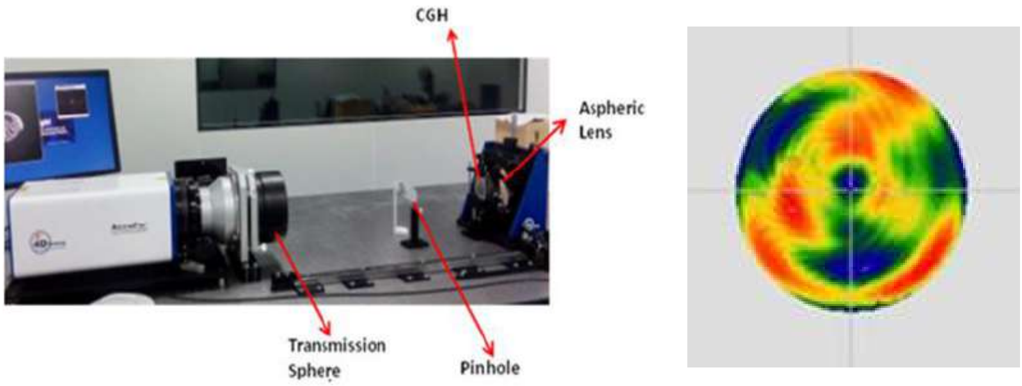
The present CNC based ultra-precision manufacturing technologies include CNC grinding and polishing and single point diamond turning (SPDT) along with fast tool servo and slow tool servo that are capable to fabricate such complex surfaces along with suitable metrology feedback. Both the methods can generate a freeform surface with nano-metric surface finish and sub-micrometer form accuracies if supported by an appropriate metrology and feedback mechanism. Due to the stringent profile tolerances of imaging optics, it is still challenging to fabricate the freeform optics for their applications. Contact metrology i.e. coordinate measuring machines, profilometery and non-contact metrology i.e. interferometry are not capable to directly measure the freeform surfaces and are still topics of interest for researchers [26-29]. Computer generated hologram(CGH) based interferometric measurement is capable to measure freeform surface. However, design and fabrication of CGH for freeform is difficult and challenging [30]. The CGH based test setup for aspheric testing is shown in Fig 12.

The SPDT process is very similar to CNC fabrication for generating the optical surface. However, the diamond-turning machine is having a point contact, hence more sophisticated technology for achieving the final surface. In CNC polishing sport size in 2 to 3 mm restrict accuracy. The surface quality especially surface roughness produced by the diamond turning is much higher than from conventional or CNC polishing practice which restrict the use in visible optics. This limitation of diamond turning can be removed by combining it with post polishing to improve surface finish and reduce scatter. After diamond turning sub aperture processing with small polishing tools, fluid jet polishing or magneto rheological finishing (MRF) are generally used to improve surface figure.

4 Metrology for precision optical surface

The optical surfaces whose production processes include grinding, lapping and polishing, or micromachining has to undergo the stage wise evaluation and correction during production. Besides the physical properties, the measurement of departures from the designed curvature or flatness is a common parameter in optical surface evaluation. The important factor here to be considered is that, whatever is the manufacturing process, the accuracy and efficiency of fabrication depends on the available metrology tools and techniques. Without it, there is no reasonable way to assess the fabricated precision of optical components. For geometrical evaluation, autocollimator based focal length measurement and spherometer based radius of curvature (ROC) are the common methods of testing.

For fabrication of spherical or plano surface, conventional grinding and polishing techniques are used to obtain predefined radius of curvature by using a spherical pitch polishing tool of matching radius of curvature. During the process spherical irregularity and cosmic quality such as scratch, dig etc., are maintained within specified values. The surface accuracy of the lens is measured by contact to a test plate using Newton’s fringes or using contact profiler and it is Shack Hartman sensor (SHS) which is another potential candidate for measurement of complex freeform wavefront [31]. SHS comprises of a micro lenslet arrays and focal plane array placed at the focal plane of micro-lenslet arrays. The measurement principle of SHS is shown in Fig 13.



(a) (b)

Fig 12. (a) Test set up for testing aspheric using CGH with 4D interferometer, USA (b) Phase profile of aspheric surface.

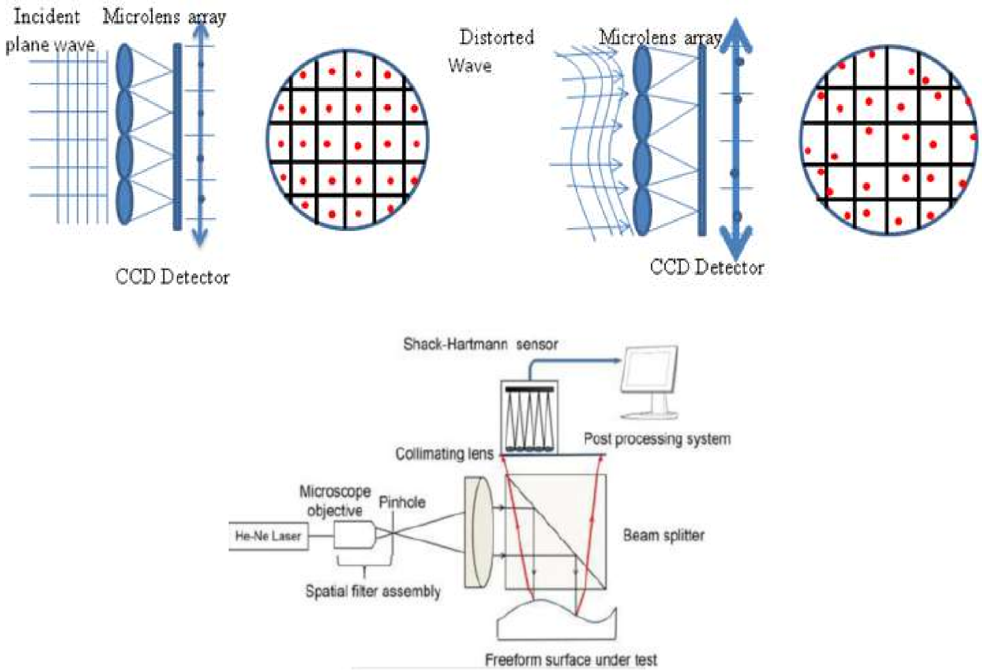
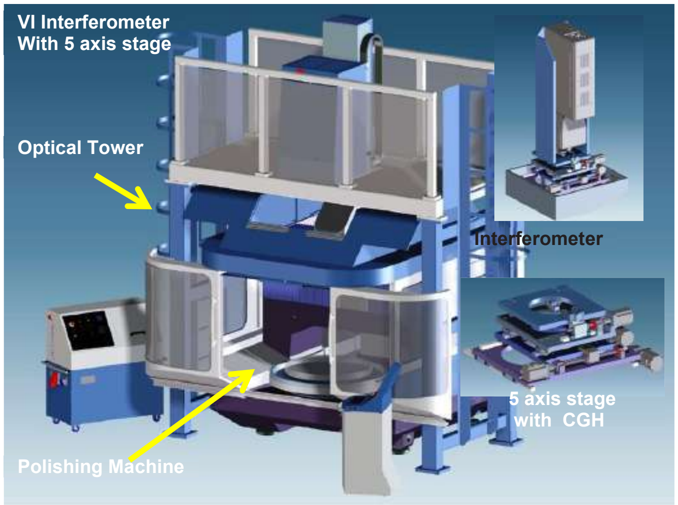


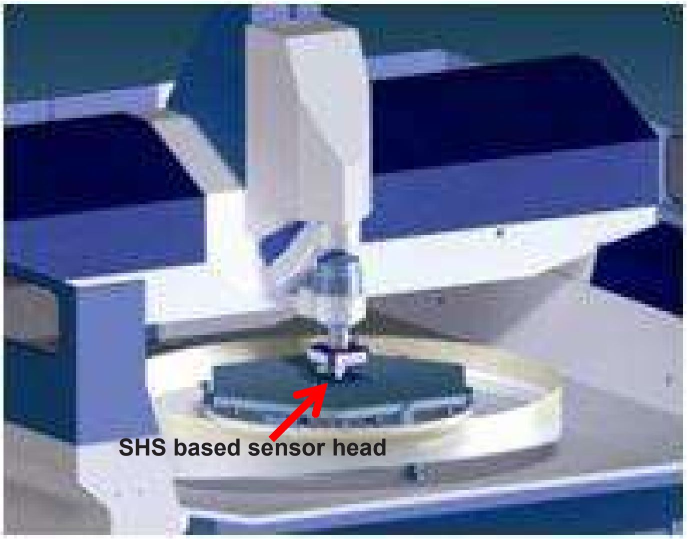
Fig 13. Measurement principle of Shack Hartman sensor and setup for freeform testing.

All the advanced optical polishing methods are iterative in nature and require feedback of optical metrologyfor corrective polishing. Off-line measurement schemes require extensive calibration of metrology before part measurement and prone to various misalignment. Generally an iterative process is followed for such manufacturing requirements, where the component is removed from the machine and transported for measurement to the lab. The measured data is given as a feedback to the machine for further correction. Such an iterative process is time consuming and prone to indexing or position errors. For accurate feedback and reliable results the alignment issues and the accurate indexing challenges have to be taken care of so that the feedback process is efficient and fabrication converges to desired surface.

To save time and cost and overcome the challenges as described earlier, it is desirable to measure the surface "on-machine" where the vibration insensitive (VI) interferometer is integrated into the same polishing machine, either through an optical tower arrangement or by directly coupling the interferometer/wavefront sensor to the polishing spindle. In these applications, it is necessary to employ compact interferometers that are insensitive to vibration and motion. For measurement of roughness, a compact white light interference microscope can be attached to the polishing spindle. For, on machine measurement, the sensor /interferometer should be vibration insensitive, compact and easy to mount. The interferometer should be installed vertically above polishing machine using a tower looking towards polishing area. For mounting and alignment of CGH in the interferometer for aspheric and freeform testing, a 5-axis adjustable mount should be incorporated in the interferometer. For incorporating of SHS on polishing machine, first the polishing tool is removed and then SHS is fitted with same mounting. "On Machine" metrology schemes are shown in Fig 14.



(a)



(b)

Fig 14.(a) In situ metrology with optical tower (b) Schematic of SHS based Metrology attached with polishing spindle.

5 Conclusion

An overview of conventional and advance computer-controlled fabrication techniques is presented for spherical, aspherical and complex freeform optics. Transformation of technological development trends from conventional to aspheric and freeform fabrication is presented. Various CNC fabrication techniques are compared based on their process and requirement of fabrication tolerances. With regards to precision optics testing, a large dynamic range as well as high accuracy can be extremely useful for in-situmetrology (on-machine metrology) manufacturing process.

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