Aspheres and freeforms

Historically, the disadvantages of poor manufacturability and metrology determined the choice of using classical optics for opto-mechanical instrumentation. Worldwide however, a lot of time and effort is invested in manufacturing aspheres and freeforms, e.g. in advanced manufacturing and metrology machines and also in the improvement of optical design packages. This paper describes the state-of-the-art manufacturing technologies that TNO Science and Industry is using to manufacture these complex optics.

• *Guido Gubbels* •

TNO Science and Industry develops opto-mechanical instrumentation, important markets for which include the semiconductor industry and space and science applications. Besides providing valuable design work on these systems, TNO can also manufacture the optical components for the high-precision instruments involved. An ongoing trend in optical manufacturing is the manufacture of aspherical and freeform optics.

Author

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This paper is an updated version of [1].

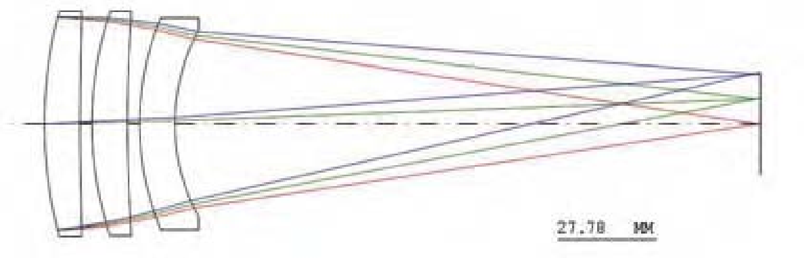

Figure 1. Fraunhofer triplet. The light comes from the left (far field) and is imaged on the right plane.

Aspheres and freeforms

Why?
This is an important question because aspheres and freeforms are difficult to manufacture. The benefits of aspheres and freeforms are as follows:
- Less optics are used in the opto-mechanical system, resulting in a decrease in the number of optical surfaces. Since every surface means a reduction in light intensity (e.g. by scattering), this results in a higher throughput of the optical system.
- Less optics also means a reduction in mass and size.
- An improvement in optical quality (e.g. spherical aberration, coma, distortion).
- A more favourable positioning of the optical components is possible.
- They facilitate chromatic aberration-free optics. When aspherical or freeform mirrors are used, chromatic aberration does not occur.

Optical designers have recognised these advantages for many years. However, for the single production of high-accuracy optics, which are generally needed in the aforementioned markets, the following disadvantages are also very important:
- Optical tolerance analyses are not standard practice yet in optical design packages.
- Aspheres and freeforms are difficult to manufacture with classical production technologies.
- It is difficult to validate the surface shape.
- They are more difficult to align because they have more degrees of freedom.
- They are more expensive because of the above reasons.

Aspheres and freeforms may be an interesting option for mass production because of the major benefits. This is evident from their increasing use in mobile phones and camera objectives, for example. Many of these optics are manufactured using moulding techniques, indicating that one good mould can produce many optics, thus decreasing the cost per element. However, for prototyping and small batch optics, the disadvantages generally result in a choice in favour of classical optics (spheres and flats).

Optical designing
The optimisation of a Fraunhofer objective with an aspherical surface will be shown as a design example. In this case, optimisation was only performed on lens shape and not on lens material. The classical Fraunhofer objective is a triplet as shown in Figure 1. When reducing the number of elements and letting the left surface become aspherical, the transmitted wavefront error of the lens system diminishes from 3.26λ to 0.89λ. This example shows the power of aspheres, i.e. less optical elements and higher accuracy.

The application of aspherical and freeform optics involves new design methodologies. Although a nominal freeform optical design can be made relatively easily these days, the optical tolerance analysis of such a system is more complex. Performing a good tolerance analysis and distributing the error budgets to an opto-mechanical system requires a good knowledge of available machining and metrology capabilities.

Freeform manufacturing

Deterministic machining
Freeform (and asphere) manufacturing is a bit different from classical production technologies in that manufacturing is performed using a so-called sub-aperture tool. This is a tool that is significantly smaller than the area to be machined. Examples of deterministic machining processes include diamond turning, computer-controlled polishing (CCP), ion-beam figuring, plasma jet etching and fluid jet polishing.

In deterministic machining, the workpiece is pre-machined to the rough shape with typical surface shape deviations of 5 µm peak-to-valley (PV). After that, a first precision machining step is applied to decrease the surface roughness. This can be diamond turning or pre-polishing. After this, an iterative process of metrology and corrective machining is applied, as shown in Figure 2. Two techniques are available at TNO, i.e. diamond turning and computer-controlled polishing.

Diamond turning
Diamond turning is a precision machining process that is commonly used in optics manufacturing nowadays. Typical materials for diamond turning include non-ferrous metals such as aluminium and copper, some crystalline materials

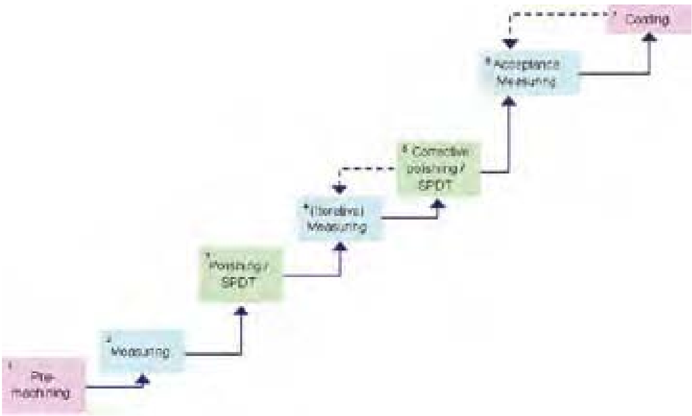

Figure 2. Value chain for freeform machining and metrology.

Figure 4. Diamond turning of a cylindrical mirror, which is a freeform surface, using the machine's slow tool servo.

such as germanium, silicon and calcium fluoride, and some polymeric materials such as polymethylmethacrylate (PMMA). At TNO, most diamond turning is performed on aluminium AA6061. The application of rapidly solidified aluminium grades [2] that have smaller grain sizes and reach better surface roughness values is a new development.
Generally, diamond turnable nickel platings have to be applied to reach 1 nanometer surface roughness levels. However, nickel platings require additional manufacturing steps and post-polishing to remove the diamond turning grooves. In an ESA study, TNO recently improved the achievable results for the rapidly solidified aluminium RSA6061. Figure 3 shows a diamond-turned surface of RSA6061. Diamond turning to 1 nm R_q surface roughness is now possible using this special material. Additional manufacturing steps, such as nickel plating, are no longer needed.

Today's diamond turning machines are very accurate and, as a rule of thumb, an accuracy of 100 nm PV can be achieved with a 100 mm diameter. The accuracy of the

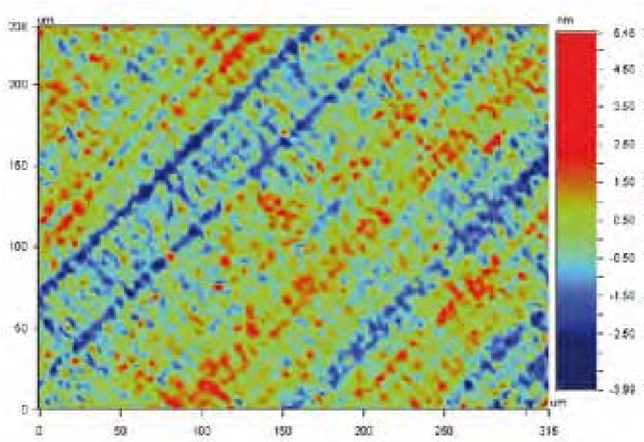

Figure 3. Diamond-turned rapidly solidified aluminium. Surface roughness value as good as diamond-turned nickel plated surfaces.

final product depends on interfacing, balancing and tooling. For freeform optics, the PV is slightly higher, but TNO is proactively working on decreasing the surface shape error to attain values similar to those for on-axis optics.

The reason that the PV error is higher in freeform machining is due to the diamond turning machine's slow-tool-servo action. An example of a freeform optic production is shown in Figure 4, where a cylindrical surface is cut using the slow tool servo. The tool needs to move to and fro per revolution to cut the cylindrical surface. This results in subsequent errors, which directly lead to additional surface errors.

TNO has two diamond-turning machines, a Precitech Nanoform 350 and a recently purchased Precitech 700A. The former is a three-axis machine that can apply slow-tool-servo turning (XZC mode) and the latter is a five-axis machine, not only capable of slow tool servoing, but also capable of fly-cutting (grid) in XYZ mode. Furthermore, this machine has a B-axis that facilitates tool normal machining, for example. It is not only optical components, but also precise mechanical components that can be made on these machines. Both machines can be fitted with a grinding spindle as well, which means that precision grinding aspheres and freeforms is then possible.

Computer-controlled polishing

TNO is able to apply deterministic polishing for producing non-diamond-turnable optics. Computer-controlled polishing (CCP) can produce freeforms and aspheres with high accuracy. Figure 5 shows an example of an asphere being polished using TNO's Zeeko robot polisher (FJP600). Zeeko technology uses an inflatable membrane called the bonnet, which has a spherical surface to which a polishing cloth is glued. As can be seen from Figure 5, polishing slurry is added to the polishing zone.
In contrast to magneto-rheological finishing (MRF), Zeeko technology enables the application of any kind of polishing

cloth to the bonnet. This makes it possible to machine various materials and carry out quick testing with different polishing cloths to optimise the polishing process. This is very important since TNO makes optics from different glasses and many other materials, like stainless steel, molybdenum and silicon carbide.

All deterministic processes use the same principle: they measure the deviation from the theoretical surface and use this error map to calculate the dwell times needed to remove this error. Typical accuracies that can be reached using deterministic polishing techniques are 60 nm PV over 100 mm diameter, but this is largely influenced by mounting, bonnet size and metrology. The difficulty in deterministic polishing of high-accuracy optics is accurately determining the removal function created by the bonnet and the error after each polishing step.

Figure 5. An aspherical surface on TNO's polishing robot.

Metrology

Metrology is very important in the above techniques, since a very accurate 3D error map is needed as input for deterministic machining. In fact, until now only few metrology instruments are available to measure aspheres and freeforms as 3D objects. In industry, a lot of metrology is performed by 2D profilometers (e.g. from Taylor Hobson, Mahr and Mitutoyo). An extra stage has been added to these instruments to enable 3D measurement, but this has a lower accuracy than 2D measurement. For 3D measurements, coordinate measuring machines (CMM) can be used. But high accuracy is only reached for CMMs with small measurement volumes (e.g. ISARA, Zeiss F25, Panasonic UA3P). The disadvantage of these CMMs is that they work in contact mode, which means that optics can be damaged during measurement. An interesting technique that is available commercially and that is non-contact is QED's stitching interferometer. Although stitching may yield high accuracy, its long measurement time is a disadvantage.

The required surface shape errors for infrared applications are less critical (can be a few micrometers), but for visual applications in the high-tech industry shape accuracies better than 150 nm over 100 mm are not uncommon. When dealing with aspheres and freeforms this is an enormous task for metrology instruments. It can therefore be said that the real breakthrough in freeform optics will come when metrology catches up with the current capabilities of machines for manufacturing optics.

TNO has two techniques that can be used in the production of aspheres and freeforms. The first is on-machine metrology, typically suited for infrared optics or optics with less stringent accuracy requirements. The second is the latest development in freeform metrology technology, an instrument called NANOMEFOS.

On-machine metrology

Infrared applications require less stringent surface shape accuracies. It is therefore interesting to apply an on-machine metrology tool. Contact probes are available on current diamond-turning machines, as can be seen in Figure 6. This is not standard technology for polishing machines, although investments are being made for them to become standard. The difficulty with polishing robots is that these machines are not as accurate as diamond turning

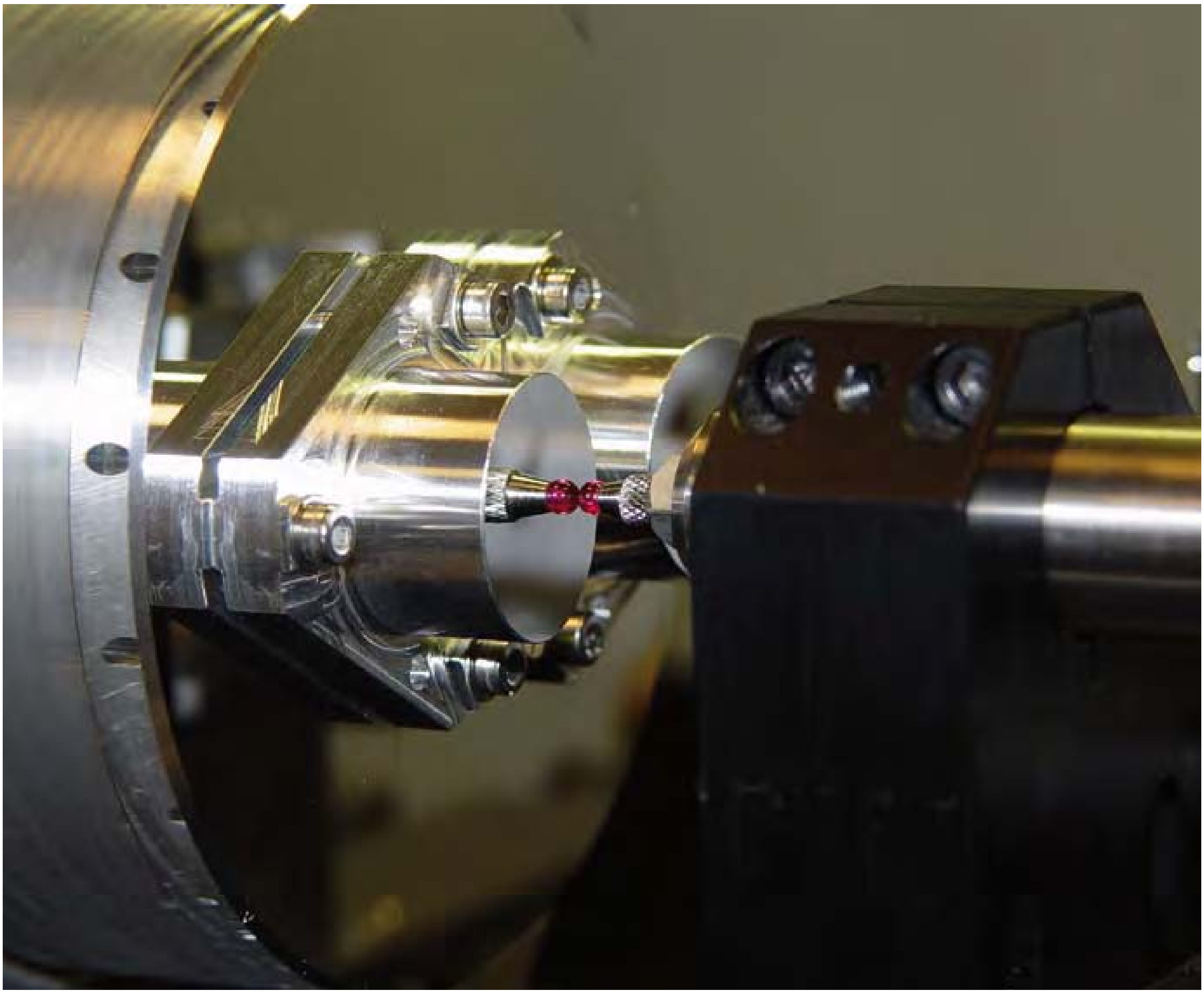

Figure 6. On-machine metrology (the Precitech Nanoform 350's Ultracomp system) to measure an off-axis parabola.

machines, meaning that an on-machine metrology system can only measure to micrometer uncertainty, whereas with a diamond-turning machine this can be well below one micrometer.

Non-contact freeform metrology instrument

When on-machine metrology is not enough to measure an aspherical or freeform optic (which is often the case), TNO employs a new and very promising instrument called NANOMEFOS [3]. This instrument is a non-contact measuring machine for freeform (and aspherical) optics up to 500 mm diameter. It has been developed by TNO Science and Industry, Eindhoven University of Technology and the Dutch metrology institute VSL as part of SenterNovem's Dutch Innovation-oriented Research Programme (IOP). This machine can be used as a measurement machine during deterministic machining processes, and it can be used as an acceptance measuring machine (see also the value chain in Figure 2).

When using NANOMEFOS, the surface to be measured is placed on a continuously rotating air-bearing spindle, while a specially developed optical probe is positioned over it by a motion system (see Figure 7). The optical probe facilitates high scanning speeds (up to 1.5 m/s), and its 5 mm measurement range captures the non-rotational symmetry of the surface. This allows for the stages to be stationary during the measurement of a circular track, reducing the dynamically moving mass to 45 g. This way, a circular track is measured several times to acquire sufficient data for averaging. The position of the probe is measured interferometrically relative to a silicon carbide metrology frame. Capacitive probes measure the product position, also relative to this reference frame. Static as well as dynamic position errors from this short metrology loop are compensated for in data processing.

Reproducibility tests on tilted flats, which are traceable freeforms, have shown that a reproducibility of

Figure 7. Measurement of a strongly curved convex asphere on NANOMEFOS.

approximately 3 nm can be reached. NANOMEFOS has a measurement uncertainty of approximately 30 nm.

The major advantage of NANOMEFOS is its flexibility. Measuring an asphere is difficult and generally requires the use of a computer-generated hologram. However, with NANOMEFOS every asphere can be programmed and measured easily. Custom-made (if at all possible) computer-generated holograms are no longer required. Although high-accuracy freeform measurements are very difficult, NANOMEFOS is very flexible and can be programmed for many freeforms. Another major advantage is the measurement of convex optics. Typically, a highly curved convex optic of > 50 mm diameter cannot be measured on most 4” interferometers (most standard versions) and requires large-aperture interferometers, which is why convex aspheres are frequently not applied. NANOMEFOS can therefore be considered to facilitate convex aspheres.

Conclusions

Historically, the disadvantages of poor manufacturability and metrology determined the choice of using classical optics for opto-mechanical instrumentation. Worldwide however, a lot of time and effort is invested in manufacturing aspheres and freeforms, e.g. in advanced manufacturing and metrology machines and also in improvement of optical design packages. Aspheres are being used, but cheap and high-quality aspheres are still difficult to come by. Freeforms are emerging, but still relatively far off, which is primarily due to difficult metrology.

TNO is actively working on improving freeform optical designing and tolerancing freeform optics. In combination with its advanced manufacturing and metrology technology, TNO will be ready for future optics and optical instruments.

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