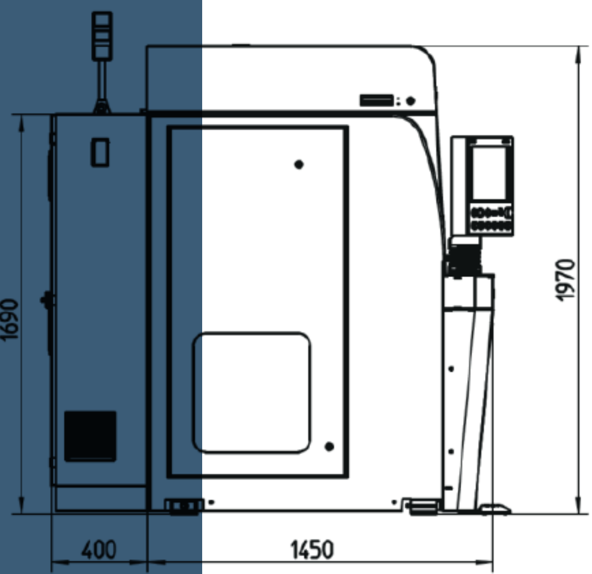
FREEFORM SURFACES

OPPORTUNITIES AND CHALLENGES FOR OPTICAL LENS MANUFACTURING



Optical lenses made of plastic, glass and crystals are traditionally made in manufacturing processes such as milling, turning, grinding and polishing. High-quality lenses are very demanding when it comes to surface quality and dimensional accuracy. A particularly good choice to achieve high surface quality in precision optics is the use of removal mechanisms with an undefined cutting edge, such as grinding and polishing. Using these processes, spherical lenses, with their simple geometry, can be manufactured in high quality with relatively simple kinematics.

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However, lenses with higher degrees of freedom, such as aspheres and especially freeform surfaces, offer great benefits for the design of optical systems.

Typical examples of freeform surfaces are varifocal lenses, head-up displays and earth remote sensing systems. Freely designable surface profiles make it possible to achieve a wide range of new features and improved image quality.

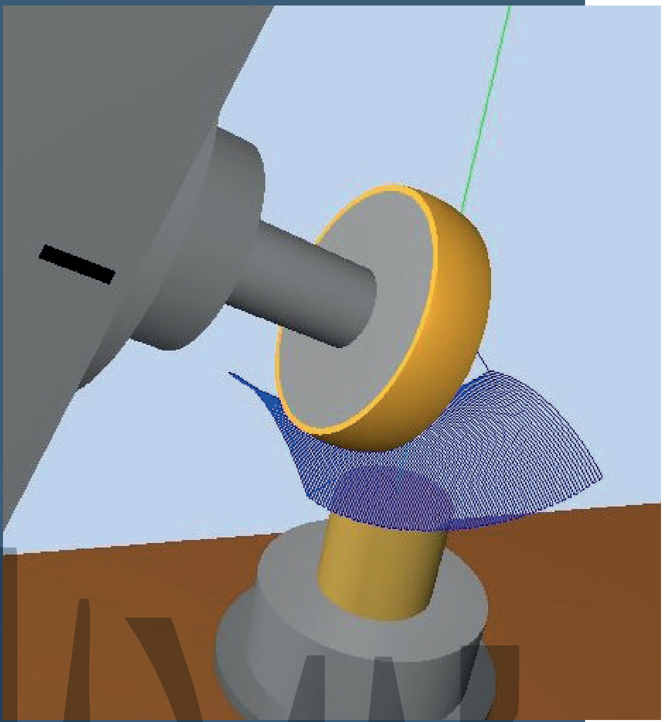
The number of lenses in complex optical systems can be reduced without diminishing performance. Assemblies can thus be developed in much more compact, lighter and thus more practical ways.

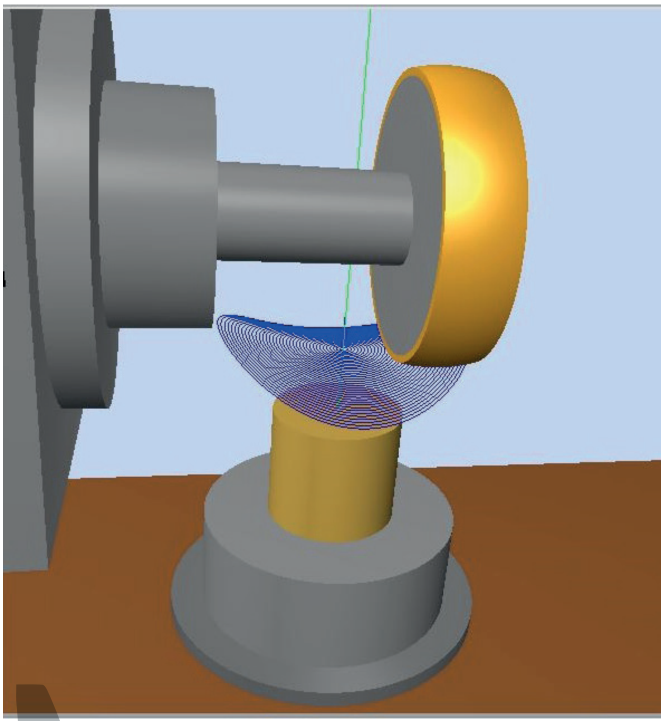
The digital transformation is increasing the demand for such systems – or actually makes them possible in the first place.

However, these freeform surfaces are very challenging for the entire process chain. The required tools with point contact (sub-aperture tools) make the process particularly complex.

This applies not only to the production process itself, but also to the measurement technology that is indispensable for the evaluation and subsequent correction of high-precision optics.

The following article presents and evaluates available technologies for the production of freeform optics.





BENEFITS AND APPLICATIONS OF FREEFORM LENSES

The classic example of a freeform surface in ophthalmic is the varifocal lens. Due to the normal ageing process, typically between the ages of 40 and 50, the eye's ability to adapt between near and far slowly decreases.

This leads to discomfort, especially at close range, although optical aids are not yet required for distance vision. The great advantage of varifocal lenses is that different strengths can be combined in one lens. In contrast to the single-vision lens, it has two different ranges for near and far as well as a transition range.

Compared with simple rotationally symmetrical lenses, however, the description of these freeform surfaces is very complex and the calculation costly, as they are individually adapted to each spectacle wearer and each eye for optimum results.

Freeform surfaces are not only useful in ophthalmic, but also in precision optics.

Especially in optical systems with complex beam paths, the number of lenses can be significantly reduced through the use of freeform surfaces by combining several functions in one lens.

As a result, these optical systems are more compact and the overall weight can be significantly reduced. This is relevant because, in contrast to ophthalmic, lenses in precision optics are usually made of mineral glass, ceramic materials and crystals and not of plastic, which results in a significantly higher weight.

If several classic lenses are replaced by a lens with a freeform surface, the assembly components are reduced. Certain applications, such as head-up displays, can even be produced exclusively with a freeform surface. The task of a head-up display is to project a straight image onto a curved glass surface.

This means that the distortion of the curved projection surface in the lens of the head-up display must be anticipated, so that it is then precisely cancelled out in the addition. Similar to the varifocal lens in ophthalmic, the freeform surface must also be elaborately calculated and designed.

Application example for freeform surfaces: head-up display. Source: GettyImages/Mike Mareen

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In contrast to the often fully automated production of ophthalmic lenses, precision-optic lenses are usually still produced in small batches (up to 20, rarely up to 100 pieces) without the automated linking of processes.

However, the demands on these lenses in terms of accuracy, optical properties and durability are around 10 to 1,000 times greater than for ophthalmic lenses. For this reason, almost exclusively high-quality and partly complex glass materials are used for production.

Some of these brittle and hard materials place high demands on the machining process and the tools used. This applies in particular to precision-optic lenses with freeform surfaces. The complexity, requirements and manufacturing costs of the individual lens increase significantly per optically effective area. Lenses made of plastic can be produced effectively and economically by milling, turning and polishing. In precision optics, diamond turning is rather a niche application and is usually only possible with certain crystalline materials (Ge, ZnSe, CaF2, SI) and metals.

The advantage here is the geometrically defined cutting edge and the possibility of producing freeform surfaces very flexibly and in a short time.

In addition, very good surface qualities can be achieved directly without the need for a subsequent polishing process. However, in most cases and for all other materials the basic geometric shape must be produced by grinding, in which bronze-bonded diamond grinding wheels are usually used. To achieve high geometric accuracy, the dressing of these tools is of vital importance. Here it must be noted that the wear of the grinding wheels means that the shape and contact point are not constant, depending on the kinematics used.

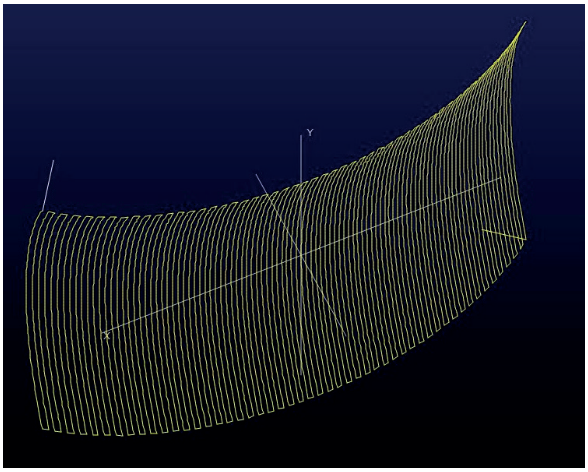
Ultimately, the surface quality and geometric accuracy can only be achieved through the polishing process.

Classic polishing is a very complex process, which cannot yet be modelled with absolute accuracy. Like grinding, it involves removing material with a geometrically undefined cutting edge, but in contrast to grinding it is a dwell time-controlled or time-dependent process.

The material is removed mechanically between the polishing tool and the workpiece as well as the abrasive particles in the polishing medium, whereby the mechanical process is partly overlaid by chemical processes.

The removal of material is very low and strongly dependent on various influencing factors. In addition to the size and number of abrasive particles, the contact pressure, hardness and pore concentration of the tool and even the temperature of the polishing medium determine the amount of material removed.

Therefore, there are countless polishing pads and polishing media of different materials and material properties on the market.



Tool path for raster mode machining

In precision optics, a high degree of accuracy can only be achieved through an iterative manufacturing process.

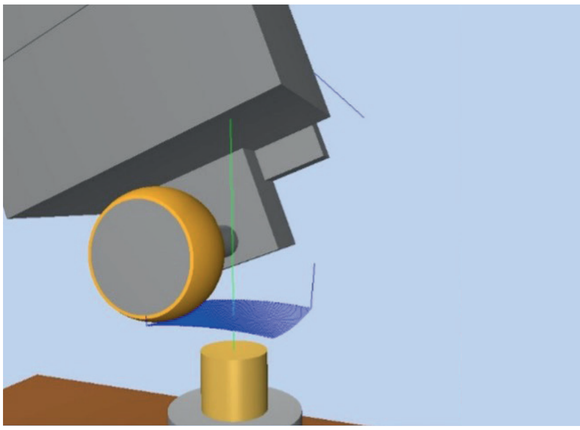
The lens is therefore not only measured to check the quality, but also for correction purposes. Between the individual production steps of pre-grinding, fine grinding and polishing, the lens is measured in order to correct it in the subsequent process step.

Process steps may need to be repeated until the lens is within specification. However, this also means that the lens has to be calibrated anew for each measuring process both on the measuring machine and on the processing machine.

This is problematic because, unlike ophthalmic lenses, these lenses do not all have the same basic shape. To achieve the desired accuracy, a locally resolved deviation is calculated from the measured lens.

From this deviation and an algorithm with a specific material removal simulation model, a dwell time on the tool path is then calculated according to the deviation.

The aim here is to dwell as briefly as possible on surface sections with a small error in order to generate less material removal and, conversely, to dwell longer on sections with larger errors in order to reduce the deviation accordingly. Polishing is carried out as evenly as possible across the lens to avoid transitions.



Machine simulation of raster mode tool path

In contrast to spherical lenses, the production of freeform surfaces is much more complex.

The surface is not rotationally symmetrical and cannot be described by a simple geometric curve. The lens can therefore usually not be created via surface or line contact, but must be produced via a point contact between tool and workpiece (sub-aperture method).

In reality, a certain overlap is always necessary to ensure minimum removal. The more complex the geometry and the smaller the minimum local radius of the lens, the smaller the real point contact must be.

For various reasons, this leads to a significantly more complex manufacturing process and, depending on the process kinematics used, requires between three and six simultaneously moving machining axes.

The movement of the axes is not always uniform, but is subject to strong fluctuations depending on the geometry. The resulting accelerations place significantly higher demands on the processing machine and the necessary dynamics, since surface defects occur more frequently at the points where acceleration parameters change.

The smoother the movements and the greater the overlap between tool and workpiece, the easier it is to achieve optimum surface quality. The machining program is also much more complex. Instead of a simple curve, the geometry is represented by a point cloud.

The finer the point spacing, the more accurately the freeform is reproduced, but the more complex the path calculation or the calculation of correction courses.

The smaller the overlap between workpiece and tool, the more potential transitions will have a negative impact on the surface quality and the accuracy of the geometry. Due to the point contact, the lens must be machined in a raster mode similar to milling or coordinate grinding.

During raster mode grinding, care must be taken to ensure that the machining direction or the individual lines are not reflected in the workpiece. Different movement profiles with different movement sequences are therefore offered. For the highest demands, the remaining structures must be removed in a further polishing step with a greater overlap. With the smallest inner radii, the geometric accuracy can suffer as a result.

The measurement of the freeform surface is also much more complex.

Spherical lenses can be measured quickly and effectively with an interferometer. An alternative to the interferometer is to measure discrete points, for example with a surface profiler with which aspheres can also be measured relatively easily and quickly.

Depending on the required accuracy, only one line on the surface must be measured for rotationally symmetrical surfaces. In the case of a freeform surface, the same processes are sometimes used, but with considerably greater complexity. With a freeform surface, basically the entire lens must be recorded and measured point by point using a suitable procedure.

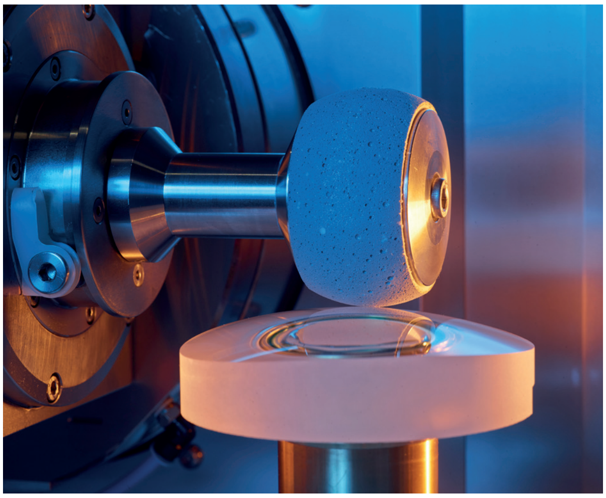
For example, several lines can be scanned in equidistant sections and then merged into a 3D graph. Depending on line spacing and lens size, this can take a long time. Ideally, a 3D measuring machine is used for grinding in order to scan all points of the machining program and thus determine the deviation at each point.

This accuracy is sufficient for grinding; the interferometer provides even more precise results for polishing.

In order to complete the fast measurement by interferometer in spite of the freeform surface, it is possible to use a computer-generated hologram, which generates the desired shape of the wavefront.

However, the hologram can only be used for a specific lens and is only suitable for series production due to the high acquisition costs. Alternatively, the wave deformation can also be determined in the optical system.

Once the surface has been measured, the actual deviation from the target geometry at each point can be calculated by superimposing the original and target geometry. A new machining program can be created from the difference as a correction program.

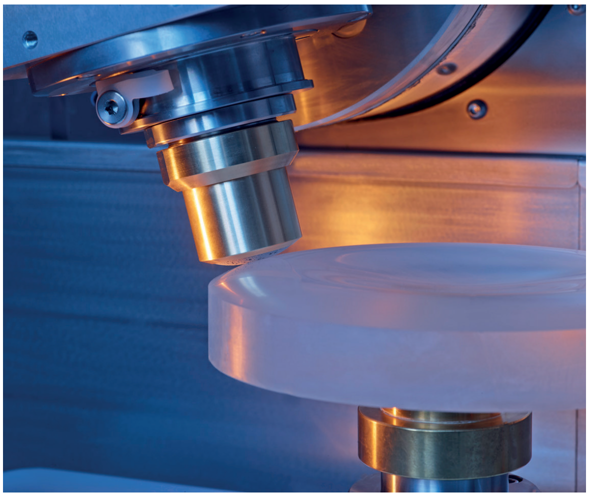


Wheel tool for point-polishing of freeform surfaces

A wheel tool is typically used as a polishing tool with point contact.

This allows a comparatively high removal rate to be achieved. By dressing, the tool shape can be maintained or the spherical shape, which is deformed by wear, can be restored. A major disadvantage, however, is that the pores create linear structures on the lens, which are not acceptable in optical applications. The high removal rate simultaneously limits the achievable surface qualities. The tool is not suitable for the production of micro-optics, as the minimum tool radius is limited. The tool is also unwieldy and can lead to collisions.

A special polishing tool was developed for finest surface qualities and best imaging accuracy.



Point-polishing with ADAPT tool

With it the smallest geometrical deviations can be repaired with pinpoint accuracy. Due to the low and locally limited material removal, the areas that already correspond to the target geometry are removed less, as is the case with other polishing tools.

Another advantage is that the tool can be variably equipped with different polishing medium carriers and different degrees of hardness.
There is no need for a special polishing medium. This allows the tool to be adapted to the individual needs and knowledge of the customer and the specific process and polishing kinematics.

In addition, the tool can be used on a standard machine, which can also produce aspheres and spheres cost-effectively if required. One disadvantage of the tool is the low and unevenly distributed removal.

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For correction, however, knowledge of the exact distribution of the removal is required. Special software has been developed for this purpose, which models this removal with sufficient accuracy.

The ADAPT-Freeform software uses the tool and workpiece geometry, the defect geometry and a system-dependent stock removal coefficient to be determined individually to calculate a dwell-time-controlled NC program with which the optimum surface quality and the smallest deviations from the nominal geometry are achieved.

For the process to be as efficient as possible, it makes sense to first polish as close as possible to the nominal geometry with the wheel tool and then simply correct it with the ADAPT tool.

This results in the following optimised process:

1. Grinding to the target geometry
2. Fast polishing with wheel tool
3. Measurement and lowest possible residual error
4. Elimination of the structures and removal of the remaining error with ADAPT-Freeform and ADAPT tool

SUMMARY

Lenses with freeform surfaces undoubtedly offer a very high potential. Several optical functions can be combined in one lens to create more compact and lighter systems. Complex applications can only be realised with freeform surfaces.

Just as the potential of freeform surfaces increases, so does the complexity of the entire process chain. The description of the freeform surface is much more complex and the demands on the geometric accuracy increase significantly. The more demanding tool path and the necessary dynamics significantly increase the demands on the processing machines. The point contact between tool and lens, the resulting small overlap area and the necessary grid make the conditions for highest surface qualities difficult. Due to the more complex surface topography, the measurement required for the iterative manufacturing process is also more complex and significantly more time-consuming.

For optimal surface quality and highest accuracy, a polishing tool is required that leaves minimal structures and can correct errors as accurately as possible. The combination of ADAPT tool and ADAPT-Freeform software was developed for this task. With the help of the modelled material removal function and the measured geometric deviation, the software calculates a precise trajectory curve with the corresponding dwell time of the tool at each path point.

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