TRUE TO THE OPTICAL AXIS

The demand for high-precision optical manufacturing technologies is increasing. This includes the need to align passive optical elements such as single lenses and lens systems as well as active optical elements such as laser diodes. For passive and active optical components, alignment turning meets the increasing industrial requirements for precision, freedom of design, automation, and competitive production times. Often, the use of alignment turning is a robust and more efficient alternative to the active alignment of optical systems.

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Introduction

The key principles of alignment turning have been known for about 50 years now. Instead of trying to manually align optical elements (mostly lenses) to increasingly high accuracy requirements using traditional shimming methods, an ultra-precision machine takes the mounted lenses and cuts precision reference surfaces onto the mount. The lenses are then assembled with little to no further adjustment. In effect, ultra-precision diamond cutting replaces manual, error-prone labour, resulting in both shorter assembly time and higher accuracy for high-precision objective lenses.

In earlier days, only large corporations with substantial budgets have developed their own solutions based on these concepts. However, in the past 10 to 15 years, with the ongoing improvement of measurement technology and industrial control systems, the underlying technology has evolved significantly. This has led to the emergence of specialised alignment turning machines suitable for all fields of optics assembly. Whether for small microscope optics or large semiconductor lenses, there are solutions available to meet the specific needs and challenges of nearly all industries.

TRIOPTICS has played a significant role in this field in the past years, with an installed base of more than seventy alignment turning machines in different market segments. With these machines, it actively enables customers worldwide to produce high-precision objective lenses more efficiently and cost-effectively than ever before.

Alignment turning for mounted lenses

There are many challenges in the creation of high-precision objective lenses. These start with developing a good optics design and a suitable opto-mechanical concept. Assuming that the individual (glass) parts are made well, the main challenge is to minimise centration errors and control the air spacings between the lenses.

It has been known for over a hundred years that the best way of achieving this is to glue (or pot) the lenses into individual mounts that can then be put into a barrel with spacer shims between the mounts to account for any deviating centre thicknesses of the lenses. This approach, which is similar to a "poker chip assembly", results in high levels of accuracy. The selection of the appropriate mounting technique is based on the tolerance analysis, the size and weight requirements for the assembly, the environmental conditions of the final use of the objective lens, the production quantities, and the cost targets.

Today, the target accuracies for an assembled, high-precision objective lens are often lower than 1 to 2 µm of decentration of the optical axis along the objective lens and 1 to 2 µm of error of the air gaps between the lenses. In order to achieve these levels of accuracy in the final objective lens, the target accuracies of an individual mounted lens must be even smaller. Here, a maximum

About TRIOPTICS

TRIOPTICS supplied the first systems for alignment turning over 20 years ago and has been building its own complete alignment turning machines for the past 15 years. The expertise ranges from specialised know-ledge about tools, materials, fixtures, and process parameters to the overall process of optics assembly for a wide range of industries. With the centration measurement device and the cementing, bonding, and gluing stations, the company's extensive experience can be leveraged to solve specific challenges for its customers – whether it is for a small company entering the market or for a large corporation seeking to increase the efficiency of their production.

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AUTHOR'S NOTE

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of 1 μm of decentration and an accuracy of 1 μm of the flange-to-vertex distance of the lens is required. Any shim-based assembly method will require disproportionately greater effort on the part of the operator to achieve good accuracy. The unique advantage of alignment turning is its ability to produce accurate centration and flange-to-vertex distances in just one automated step.

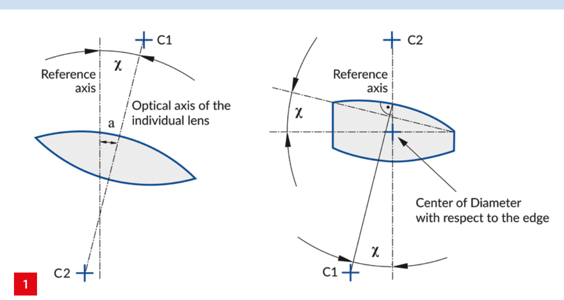
The principle of alignment turning

Traditionally, a lens is aligned to its mount and then glued in place with the highest possible precision (cf. OptiCentric® Bonding). Then, the mount is fitted into a barrel. Since the mount is made before the lens is glued to it, the mount cannot accommodate any (thickness) deviation of the actual lens from the nominal design. That is why shims must be used during the assembly process. Also, to achieve a reasonable production rate, fast UV-curing adhesives have to be used for this technique, resulting in relatively high stress on the lens.

Alignment turning works "the other way round" (see the box on the right). A lens is glued to a mount, which is slightly larger than necessary. Then this mount is loaded onto the alignment turning machine and cut to size, considering the concentricity of the optical axis, the cell axis, and the lens thickness. Since the gluing and alignment are two separate process steps, the choice of adhesive is no longer a determining factor for the process time. Slow-curing RTV-glues and even designs with threaded retainer rings (as often seen in high-power laser applications) are suitable for alignment turning.

Centration measurement, alignment, cementing and bonding

The precise centration and alignment of a lens is crucial for the image quality of the optical system. According to ISO 10110, a centration error is given when the optical axis of a lens does not coincide with a reference axis due to a difference in position and direction. Centration errors occur during the cementing, aligning, and fixing of lenses. Therefore, the precise requirements of optical systems can be best met if all manufacturing steps are uniformly designed and incorporated into a single measurement and manufacturing system. The centration error of a single lens is defined as shown in Figure 1.

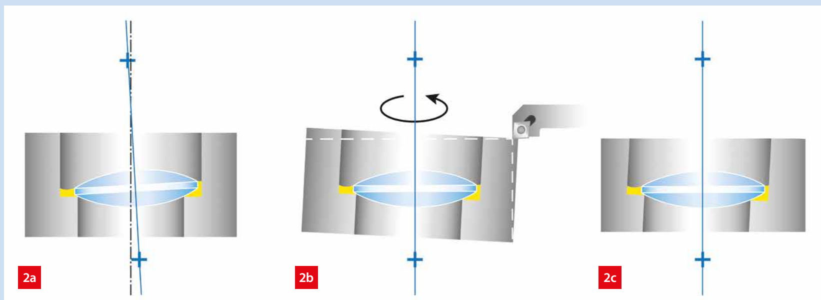


The optical axis of a single lens is the line connecting the centres of curvature of the two spherical surfaces (C1 and C2). The centration error is then defined by the angle χ and the distance 'a' to a given reference axis.

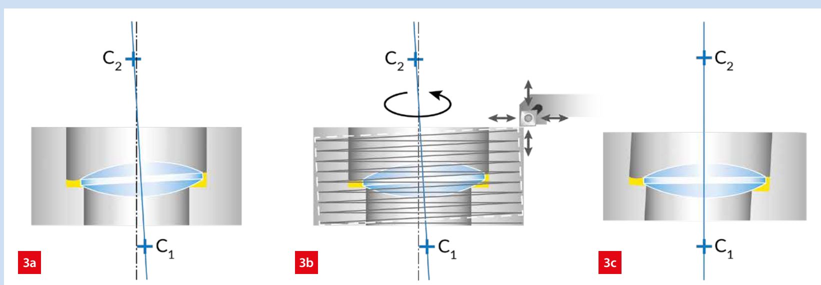
What is alignment turning?

In the alignment turning process, reference surfaces on a mount (diameter and flange) are machined true to the optical axis of a lens. Two methods exist for the alignment turning of mounted lenses: chuck-based alignment turning and CNC-based alignment turning. Both processes have specific advantages and disadvantages, such as greater or less flexibility and process time. After machining, the alignment-turned mounts typically have no relevant differences, irrespective of the process used.

Schematic representations of the chuck-based and the CNC-based alignment turning process are shown in Figures 2 and 3, respectively.



Chuck-based alignment turning process.
(a) The centration of the optical axis of the lens with respect to the spindle axis is determined.
(b) The chuck is aligned so that the optical axis of the lens corresponds to the spindle axis of the alignment turning machine. Then the reference surfaces of the mount are turned.
(c) The reference surfaces are then aligned to the optical axis.



CNC-based alignment turning process.
(a) The centration of the optical axis of the lens with respect to the spindle axis is determined.
(b) The linear axes of the machine move in coordinated motion with the rotating spindle offset by the centration error. At the same time, the machine axes cut the tilted diameter and flange surfaces according to the centration measurement.
(c) The reference surfaces are then aligned to the optical axis.

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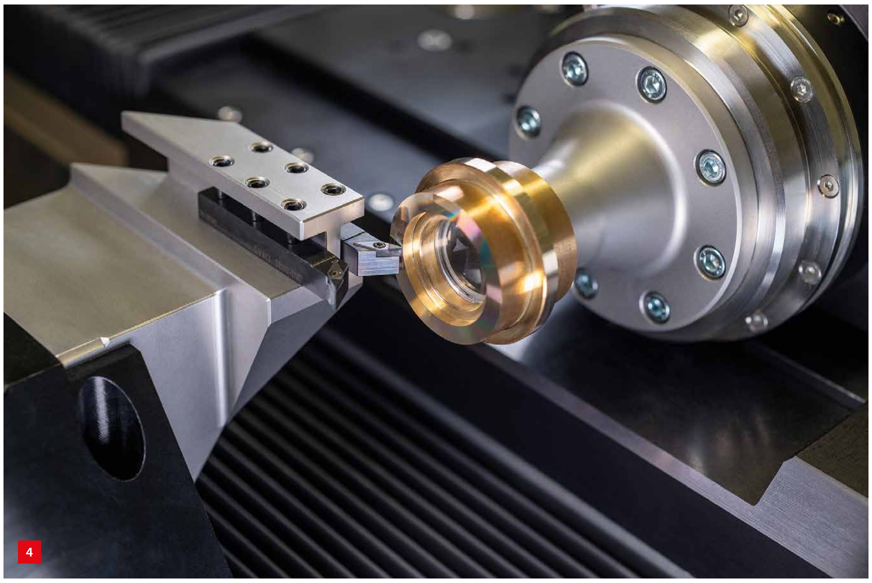

Flange turning with the CNC-based ATS-C from TRIOPTICS.

The cylindricity of the mount, the concentricity of the diameter reference surfaces, and the planarity of the plane reference surfaces depend on the machining technology used. Available aerostatic and hydrostatic spindles have residual run-out errors of less than 0.1 µm and allow for an accuracy in the 0.1 µm range. Provided the mounts are made from non-ferrous metals and diamond tools are used for alignment machining, tight dimensional tolerances of the reference surfaces can be achieved with highly repeatable precision. To minimise the effect of errors on the machine system, the machines are equipped with granite bases, vibration damping elements, and high-precision drive systems, thereby following the design rules for ultra-precision machines (Figure 4).

Applications and design guidelines

The benefits of alignment turning can be maximised if the unique manufacturing capabilities the method has to offer are considered during all stages of the design process for an objective lens. In particular, the optics designer has the advantage of configuring a few parameters in advance that enable the machine to align well. For example, at least several millimeters should be allowed for the distance between the (two) centres of curvature of a lens to improve the accuracy of the tilt measurement. Also, the ranges of the lenses' radii of curvature can be chosen to maximise the measurement accuracy.

Alignment turning works for all lens materials. Typically, the measurement of the centration is done in reflection. This means, that even lenses that are not transparent for the illumination wavelength of the centration measurement system can easily be measured. The system is designed to work with Fresnel reflection of the outer surfaces, even if they are coated with broadband anti-reflection coating. Reflectivities down to below 0.25% pose no problem for the measurement system. If needed, the operating wavelength of the centration measurement system can be chosen, ranging from various LEDs in the visible spectrum to medium- and long-wave infrared lasers.

For standard lens materials, the machine measures the vertex of the lens with a low-force tactile touch probe. This poses a potential problem for softer materials or even coatings that must not be touched during the process. In these cases, non-contact options for the measurement of the lens vertex are available. A preferred non-contact measurement system is a short-coherent interferometer, which is also capable of measuring the lens thickness. It can be used to measure the vertex and the centre thickness, after which the top and bottom flange surfaces are cut to the actual thickness of the lens. This happens in one step and on one machine.

The opto-mechanical design is also important. The mount of the lens must be designed to withstand the cutting forces, although diamond tools impose only very little force. Nevertheless, wall thicknesses below 1 millimeter are possible. However, they should only be chosen if size and weight restrictions call for very thin mounts. The functional integration of aligning and fixing features in one surface can help to reduce the size and weight of mounts. Therefore, a recent measure is to include threads as part of the reference surfaces. Chuck-based machines are ideally equipped for cutting precise threads to the diameter surfaces.

The preferred materials for mounts are brass and aluminium. These materials are used in more than 80% of all applications and have the specific advantage that they can be machined with diamond tools. Of these two materials, brass is most widely used because of the tighter fits that can be achieved during assembly. Of course, specific solutions for steel, stainless steel, and other materials such as titanium, NiP-coated steel, and Invar exist if these are the materials of choice.

The fixtures to hold the mounted lenses on the chuck typically employ either clamping or threading features. While clamping features need to be more sophisticatedly designed, they can typically be made smaller and thus allow for smaller mounts.

Special lenses

While most lenses are of a spherical nature, a lot of current lens designs also include cylindrical lenses or aspherical lenses. Aspherical lenses have higher requirements with regard to the measurement, as the optical axis is more difficult to measure. The outer (off-centre) region of the lens surface needs to be measured for obtaining accurate and complete centration information from the asphere. This problem can be overcome by measuring with an additional probe, for example a chromatic confocal probe. Centration information from the outer areas of the aspheric surfaces allows for an alignment according to the optical design.

Cylindrical surfaces, on the other hand, are very distinctive in that the surface is plane in one direction (infinite radius) and curved in the direction perpendicular to it (finite radius). The reflection of a cylindrical surface depends on the azimuthal orientation of the lens. A spherical surface, however, is rotationally symmetric and its reflection is independent of the azimuthal orientation. With a specific illumination (pin-hole reticle), the cylindrical lens can be measured and the centration measurement can be calculated with an accuracy similar to that for a spherical lens.

Another case is that of cemented lenses. Here, two (doublet), three (triplet), or more lenses are cemented together and glued to a single mount. These are frequently used for achromatic and apochromatic designs. If the alignment should take the inner surfaces into account, a mathematically ideal alignment cannot be achieved (three or more centres of curvature generally do not lie on one single line). Still, a best-fit alignment is feasible if acceptable by the optical design. TRIOPTICS alignment turning machines can measure inner surfaces with the same accuracy as that of outer surfaces by taking the effect of the optical glass and the centration error of the outer surfaces into account.

Large lenses
For large and very large lenses with mount diameters ranging from 200 mm to over 400 mm, the principle of putting the mounted lenses into a barrel becomes less attractive from a manufacturing point of view. The cost of making a barrel with the required accuracy and the challenge of precisely fitting the mounts into large barrels outweighs the advantages offered by this method of assembly. Nevertheless, the alignment turning process can be used to improve large objective lens assemblies. The overall process of assembly changes slightly in this case. While the mounted lenses still get machined, they are subsequently assembled in a different way.

The alignment turning machine cuts only the flange surfaces to size without machining the diameter. Once all mounts are cut, workers stack the individual mounts together on a centration test system (such as OptiCentric®); see Figure 5. Since the flange surfaces are accurately cut, the optical axis is rectangular to the flange surfaces and needs no further adjustment in tilt. The air gaps are correct because the flange surfaces are accurate with respect to the vertices of the lens. The assembly step on the centration

5

Centration measurement system.

measurement system ensures that the lateral position of the optical axes of the mounts is within sub-micron accuracy – all without the need for a barrel.

Conclusion

Alignment turning has a versatile range of applications and can be applied in microscope-sized up to stepper-sized optics. The overall assembly flow may differ accordingly, however. The advantages are manifold. The parts are mechanically more robust, since the cells share full surface contact with each other. The time it takes to achieve micron accuracy is reduced as compared to traditional manual methods. This results in cost savings for the overall process of objective lens assembly. Additionally, since the mechanical alignment tolerances are very small, it may be possible to slightly loosen the tolerances of the glass. Designs exist that have been transferred to the offshore manufacturing of lenses because the mechanical alignment process was more than compensating for the tolerances in the glass.

Alignment turning for active components

The principle of cutting lens mounts to the desired dimensions can also be applied to mounts of active optical components. With a set-up capable of measuring both the tilt and shift of the laser beam, the alignment machine can align the beam to the mechanical rotation axis. Achievable accuracies are in the range of a few arcseconds in tilt and a few micrometers in shift from the mechanical axis. The result is a sub-system aligned with high accuracy that allows efficient drop-in assembly in the next production step.

Active optical components pose various challenges for the metrology system. Typically, the lasers have different wavelengths, vastly different source powers, and different beam qualities. At the same time, tilt and shift decoupling is more demanding. The uncertainties of the measurement increase with higher tilts and shifts of the laser beam. The challenge is to measure correctly without tuning the measurement system to a specific beam profile and wavelength. This makes the absolute measurement of the alignment errors more difficult.

TRIOPTICS uses a specific optical system to optically decouple tilt and displacement. This set-up is robust enough to work over a long wavelength band. This affords great versatility and usability for a variety of laser sources and applications, be it laser range finders or laser coupling applications.

The traditional, chuck-based method of alignment turning is the method of choice for the alignment of laser beams with varying wavelengths and beam profiles. The requirement of measuring absolute decentration values with micron precision is less relevant if the laser spot does not visibly rotate on the measurement systems for both shift and tilt in its aligned state. Therefore, even if the absolute measurement is difficult or not precise enough, the accuracy of the final aligned beam can still be measured with high precision. Machining parameters can then be flexibly chosen like in the alignment turning of mounted lenses.