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James J. Kumler, Christian Buss

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James J. Kumler, Jenoptik Optical Systems, LLC, Jupiter, Florida
Christian Buss, TRIOPTICS GmbH, Wedel, Germany

ABSTRACT

Higher performance expectations for complex optical systems demand tighter alignment requirements for lens assembly alignment. In order to meet diffraction limited imaging performance over wide spectral bands across the UV and visible wavebands, new manufacturing approaches and tools must be developed if the optical systems will be produced consistently in volume production.

This is especially applicable in the field of precision microscope objectives for life science, semiconductor inspection and laser material processing systems. We observe a rising need for the improvement in the optical imaging performance of objective lenses. The key challenge lies in the micron-level decentration and tilt of each lens element.

One solution for the production of high quality lens systems is sub-cell assembly with alignment turning. This process relies on an automatic alignment chuck to align the optical axis of a mounted lens to the spindle axis of the machine. Subsequently, the mount is cut with diamond tools on a lathe with respect to the optical axis of the mount. Software controlled integrated measurement technology ensures highest precision. In addition to traditional production processes, further dimensions can be controlled in a very precise manner, e.g. the air gaps between the lenses. Using alignment turning simplifies further alignment steps and reduces the risk of errors.

This paper describes new challenges in microscope objective design and manufacturing, and addresses difficulties with standard production processes. A new measurement and alignment technique is described, and strengths and limitations are outlined.

1. INTRODUCTION

Precision lenses have been mounted the same way for many years. In valuable reference books such as Rudolph Kingslake's "A History of the Photographic Lens"[i], there are examples of lens barrels of portrait lenses from the 1830's which looks as if they could be in production today.

The most frequently used technique for mounting individual lens elements is to clamp the lens near the outer diameter between a shoulder or spacer and a threaded retainer ring. These so-called "Drop-in" Assemblies are low cost, easy to assemble and simple to dis-assemble if needed. This approach requires careful tolerancing of the metal and glass diameters. Few adjustments are feasible.[ii] Other designs use

More demanding applications frequently have optomechanical designs which require an outer barrel which are populated with inner cells. This approach, which is sometimes referred to as a "poker chip assembly" results in high accuracies, like in this projection lens assembly example[iii]Jenoptik employs both of these approaches, as well as other housing design forms for cryogenic temperatures. The selection of the appropriate mounting technique is driven by the tolerance analysis, the size and weight requirements for the assembly, the environmental conditions, the production quantities and the cost targets.

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2. Special Challenges in Microscope Objective Design and Manufacturing

Microscope objectives present special challenges for optomechanical designers. These objectives frequently have elements which are too small (diameters less than 5 mm) to successfully employ threaded retainers.

Life science applications are driving optical designs to faster numerical apertures. Life science applications like 2-photon microscopy, spinning-disk and non-spinning disk super resolution microscopy, and structured illumination (lightsheet) microscope require diffraction limited objectives operating at or near NA 1.0. The high numerical aperture requires micron-level tilt and decentration tolerances.

In some cases like flow cytometers and fluorescence microscopes, it is desirable to be able to adjust the microscope objective to allow it to accommodate different cover glass thicknesses. The most effective way to accomplish this flexibility is with an axial air spacing which can be adjusted. Potted lens elements or lens cells do not lend themselves to this axial adjustment.

In semiconductor inspection equipment, tighter tolerances are required for diffraction limited performance if the objectives are also used at operating wavelengths in the ultraviolet spectrum.

Finally, in laser material processing like laser hole drilling and laser annealing, customers require a well behaved and symmetric uniform spot through focus for laser material processing. This demands more complex objectives with tighter tolerances.

3. Solution: Alignment turning

Alignment turning is the only method by which all relevant parameters of a mounted lens can be aligned, in particular the optical axis between the two centers of curvature and the cell mechanical surfaces. In addition, a large number of different cell sizes can be processed with excellent production accuracies of up to 0.5 micron.

Figure 1 - Alignment turning station ATS 200 by TRIOPTICS GmbH

In alignment turning, the lens is already fixed in a sub-cell in advance. This means that low-stress adhesives with very long curing times can be used for highly precise optics. Similarly, the lenses can be crimped or held by screw rings when the available adhesives are not suitable for the intended application as it is the case in high-power UV applications.

The alignment turning process starts with fixing the cell in an adjustable alignment chuck with the lens in place. Then the position of the optical axis of the lens to the spindle axis is measured with the OptiCentric® system. Using this alignment chuck, the lens is then aligned so that its two centers of curvature are located as closely as possible to the axis of rotation of the spindle.

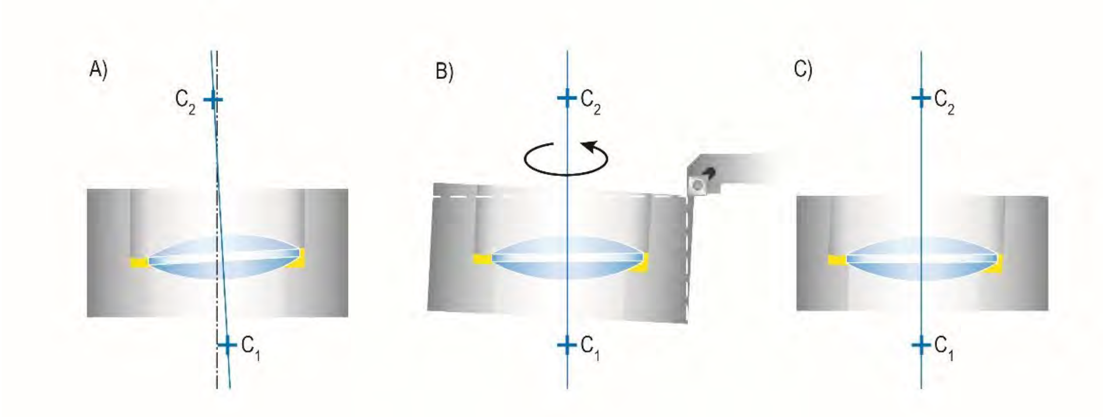

Figure 2 - The alignment process: A) optical axis C1-C2 is determined; C) cell is tilted and decentered so optical axis C1-C2 is coaxial with the mechanical spindle axis, and then the outer cell surfaces are machined; B) after machining the outer cell surfaces run true with the optical and mechanical axes

Then the spindle spins and the contact surfaces of the cell are machined with a sharp (diamond) turning tool, resulting in precisely machined surfaces of the cell. In addition to the outer diameter surface of the cell, it is also possible to machine the front and rear contact surface during the turning process. To do this the turning tool is moved exactly parallel or perpendicular to the spindle axis.

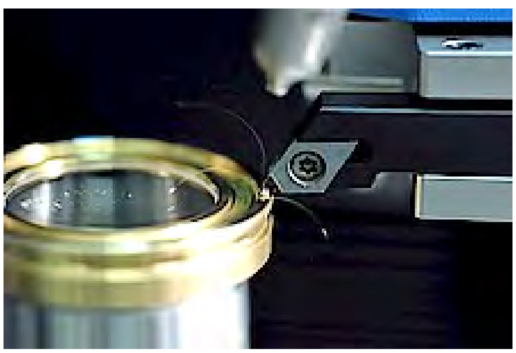

Figure 3 - ATS 200 machining a mounted lens

3.1 Measurement technology for lens centration

For the optical measurement an autocollimator is focused at the center of curvature of the surface (Reflection Mode). The images reflected from the lens surfaces are observed through a CCD camera. The entire measurement process is software controlled.

When a centration error is present, the observed image describes a circle while the sample rotates on the spindle. The rotation of the center of curvature can be followed directly on the monitor. The radius of the circle is proportional to the size of the centering errors. The result of the measurement can be given as radius of the runout circle or as tilt of the surface.

A centering error is present if the axis of symmetry of an optical element does not coincide with the rotation axis of the spindle. Software algorithms use the directly measured angle of decentration of the centers of curvature to calculate the tilt and shift information for a given lens prescription.

The centering error of a spherical surface is defined by the distance "a" of its center of curvature "C_1" to a reference axis. The surface tilt error χ may also be used. The following correlation applies:

$$\chi = \sin\frac{a}{r}$$

r = radius of the surface under test
χ = angle of the centering error in arcminutes

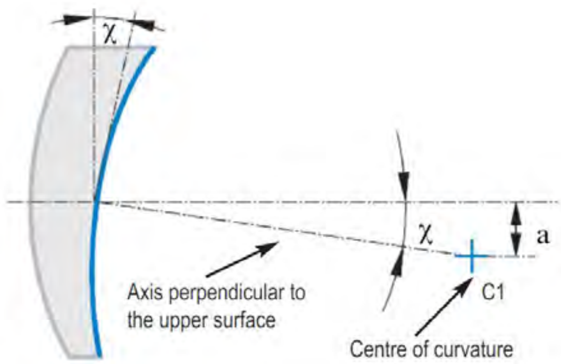

Figure 4 - Schematic diagram of the surface tilt error

It is also possible to provide the measured surface tilt error as eccentricity S at the lens edge if required. (Figure 5)

$$S = D * \tan\ \chi$$

D = lens diameter

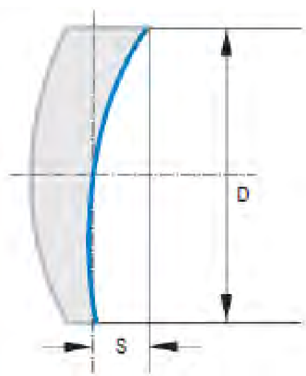

Figure 5 - Surface tilt error given as eccentricity

The measurement technology OptiCentric® features capabilities for measuring single lenses as well as complete objectives. The so-called MultiLens® procedure enables the measurement of the centering error of all single surfaces of a fully assembled objective without the need to dismantle it. Building on this comprehensive measurement function, systems like the alignment turning machines have been developed to carry out the precise assembly of optical systems as an extension of the OptiCentric® system.

3.2 Measurement technology for dimensional accuracy

In order to achieve high accuracy additional measurement technology is integrated into alignment turning stations, alongside the high-resolution autocollimators. These include tactile and optical distance sensors that ensure a highly accurate measurement of the relevant mechanical parameters. This means the highest precision is achieved by a gradual machining process, in which the cell accuracy is checked after each machining step. The cells used in alignment turning do not need to meet exceptionally tight tolerances before machining. The cell offset only needs to be large enough to meet the required tolerance after machining.

Figure 6 - The integrated gauges of the ATS 200 measure the diameter of the mounted lens

3.3 Operator software for alignment turning

The Windows-based graphical user interface of the ATS 200 combines the operation of all machine functions with the routines used to measure the centration. A graphical editor is used to first enter the relevant dimensions of the cell that are to be machined by the system. In addition, the optical data of the lens can be entered so as to be able to measure the centration of the lens. From these data, the software calculates all the movements of the axes, both for the measurement as well as for the subsequent machining of the cell. The software actively alerts the operator to the next steps to be taken and in particular monitors the result of the adjustment and production. At the end of the whole process the software can issue a certificate with the achieved tolerances. This allows subsequent retracing of individual mounted lenses back into production.

The ATS 200 can populate data in a quality management system which can then be managed and shared with other metrology equipment, ERP software and quality management software.

4. Advantages of the TRIOPTICS ATS 200

ATS 200 stands out through its sophisticated centration measurement technology. Combined with the robust tooling process highest precision can be reached. The integrated software that handles both processes supports the station's ease of use and fast operation. This makes it suitable for high volume production. Nonetheless the setup for different types of lenses enables manufacturing in smaller production quantities.

5. Design Implications – How to design lens assemblies for Alignment turning

5.1 Optical Design

The optical designer needs to understand the strengths and limitations of the alignment turning equipment in order to properly utilize the tool in high volume production. Jenoptik has developed macros (scripts) within Code V and ZEMAX which ensure that the optical design stays within operating parameters of the ATS 200 during the optimization phase. These macros set boundaries which prevent the design from wandering into conditions which are ill suited for the tool.

All alignment equipment has difficulty resolving two different surfaces if the centers of curvature are nearly coincident along the optical axis. Our macros make sure that all centers of curvature within an alignment group are separated by a minimum separation distance. This allows the ATS 200 to resolve the two surfaces and properly align.

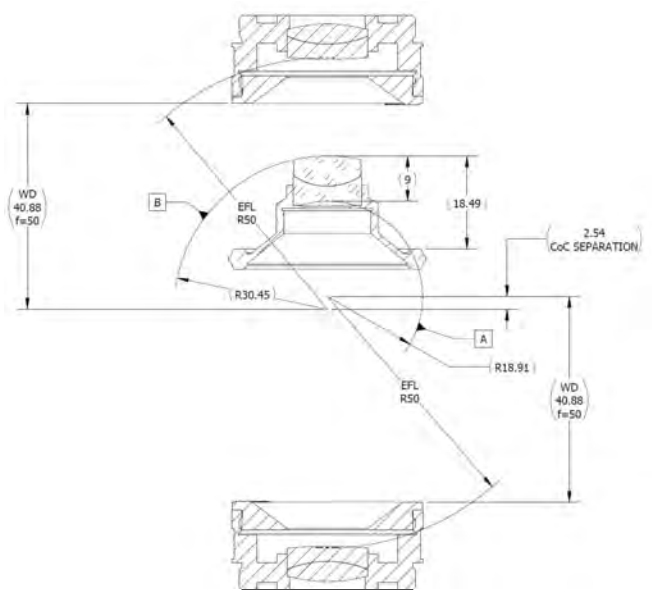

Figure 7 - Illustration of problematic case where the center of curvature of two different optical surfaces are nearly coincident (within less than 3 mm)

The macros also restrict the optical design to radii of curvature which can be captured by the autocollimator head lens selection. There are several head lens selections to maximize precision when aligning the chuck to the work piece optics. The center of curvature of each surface of the optic determines the proximity of the head lens with respect to its working distance. The working distance of the head lens must be sized such that it minimizes the distance to the optic without exceeding the autocollimator height constraints.

Jenoptik's production facility has a family of positive and negative autocollimator head lenses which allow us to cover any radius of curvature less than 2000 mm. The working distance of the head lenses also must be well understood in order to properly design the objectives.

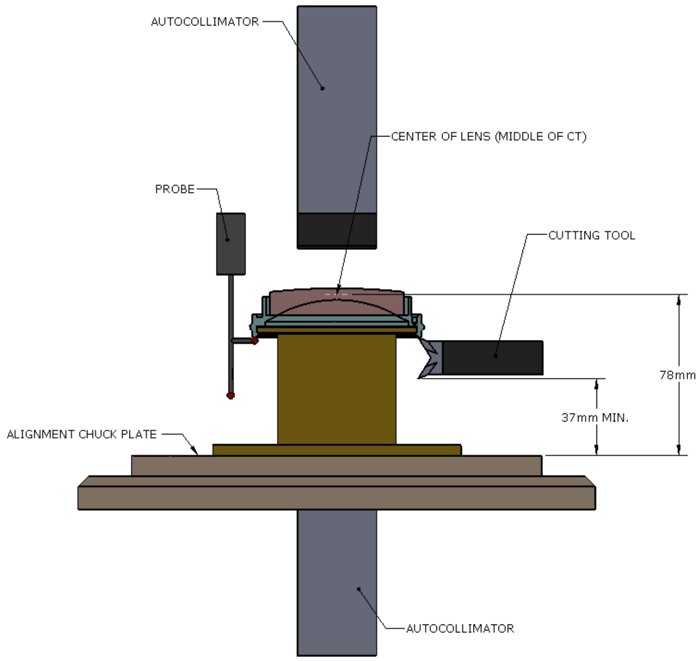

Figure 8 - Illustration of typical workpiece setup showing geometric design constraints

5.2 Mechanical Design

The mechanical design of the lens objectives also need to consider the capabilities of the ATS 200 tool. Brass and aluminum are preferred materials for the housing due to the limitations of tools speeds and feeds.

Typically, the sub-cells are threaded onto an adaptor for the cutting process. In order to avoid making custom adaptors for each product, the Jenoptik opto-mechanical designers design the lens mechanics so that the hardware uses one of a series of "standard" work thread sizes.

lower half of the cutting tool is best for cutting the outer diameter and top surface, and take this into consideration during the design process.

The coefficient of thermal expansion of the housing materials (outer barrel and inner cells) must be included when determining final diameters to be cut. Larger diameter housings may fluctuate more than the tolerance of the desired cut (depending on material).

6. Example #1 – Microscope objective for Life Science Application

Jenoptik designed and build a custom microscope objective which takes advantage of the capabilities of the ATS 200. The 9 mm NA 0.45 (22.5x) objective has demanding requirements for RMS wavefront error over the full field of view and requires advanced assembly and active alignment in order to meet the full specifications.

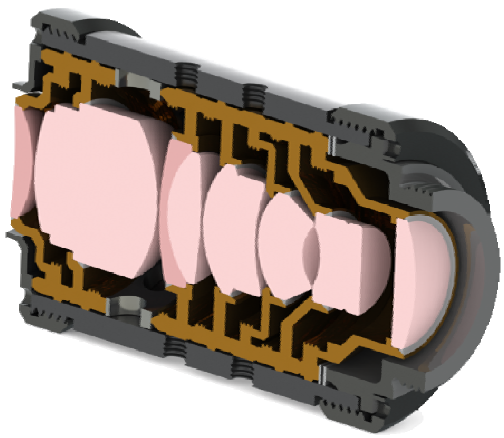

Figure 9- Jenoptik Microscope Objective for life science application

In this objective, the mechanical design chose to set the airspaces without spacers. The ATS 200 is capable of cutting the sub-cells directly to an absolute accuracy of less than 2 microns, which eliminates the need for discrete spacers in high volume production. This reduces the number of metal parts in the bill of materials, lowers costs and eliminates the stack up of tilt tolerances that comes from a discrete spacer. The drawback that any rework or troubleshooting becomes more expensive since the airspaces have been set and material cannot be added back onto the cells. Jenoptik has developed production-ready software tools to facilitate the cell turning cuts to set the airspace. These software tools build in automatic recomputations and calculate the target cell turn vertex to flange distance directly. This streamlines the process and eliminates possible errors in manual build sheets.

In order to meet the performance requirements, the individual elements need to be aligned to less than 10 microns of tilt on all elements (total indicator runout) and less than 3 microns of decenter. The tilt tolerances obviously need to take into consideration the worst case stack up of many cells, so the total indicator runout of any one cell was controlled to within less than 2 microns.

The modulation transfer function (MTF), axial color, distortion and RMS wavefront quality of the objective was measured on the pilot production units. All performance specifications were met on the first nine assemblies. The RMS wavefront quality of the objective are provided in the table below.

Test Parameter	9mm 0.45 NA Objective (22.5x)									Ave
	SN1	SN2	SN3	SN4	SN5	SN6	SN7	SN8	SN10	
On-Axis (waves RMS)	0.024	0.062	0.023	0.037	0.031	0.049	0.05	0.021	0.043	0.038
Off-Axis (0 deg)	0.056	0.051	0.054	0.049	0.04	0.07	0.064	0.026	0.051	0.051
Off-Axis (90 deg)	0.036	0.066	0.032	0.05	0.048	0.057	0.078	0.046	0.041	0.050
Off-Axis (180 deg)	0.042	0.066	0.04	0.054	0.046	0.068	0.095	0.058	0.048	0.057
Off-Axis (270 deg)	0.043	0.051	0.051	0.067	0.028	0.064	0.074	0.038	0.044	0.051

The on-axis RMS wavefront of the objective (0.038 wave RMS on average across the pilot production) compared well with the predicted RMS wavefront as shown in Figure 10 below.

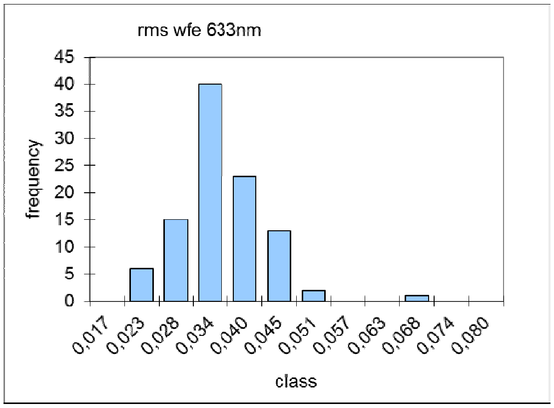

Figure 10 – RMS wavefront performance at 632.8 nm predicted by Monte Carlo analysis

7. Example case study #2 – Microscope Objective for Flat Panel Display inspection

There are examples where the microscope objective housing is severely constrained and there is very little room for a barrel around the elements. In the case below, the nose of the objective had to be as small as possible, forcing the opto-mechanical design to take a much different form. Sometimes this is because the off-axis illumination needs to surround the objective lens. One example is shown in the figure below.

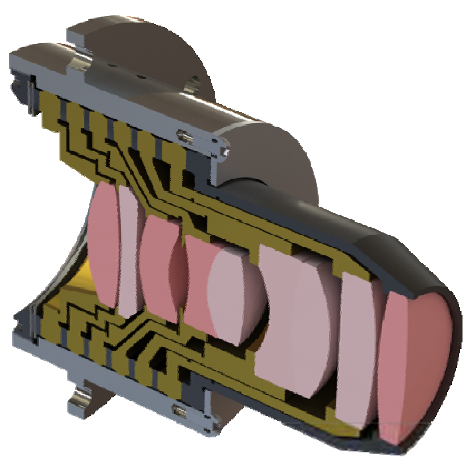

Figure 11 - Jenoptik Microscope for Display Inspection

This objective uses discrete spacers to set the precision airspaces between sub-assemblies. This approach is more flexible in a high volume production in the case where it may be helpful to have a recovery path if the airspaces need to be adjusted. The disadvantage in discrete spacers is the increase in part count and the accumulated tilt error. Discrete spacers can typically be lapped to 1 micron parallelism if required, and a family of spacers (stock spacer kits) can be used to provide a range of airspaces.

8. Conclusions

Alignment turning is a proven technology which allows micron-level alignments in a consistent and deterministic process. Until recently, commercially available equipment has been limited, so adoption of this technologies has been limited. Jenoptik has shown that alignment turning is production ready, and suitable for both small scale production and high rate serial production. The software on the tool is robust, and user friendly.

We have shown examples which demonstrate that the hardware produced with this technology meet or exceed performance requirements. The MTF and the wavefront quality of the objective and the optical system demonstrate that the process predictably produces micron-level alignment.

The technology has been adopted in Jupiter, and the full potential of the alignment turning technology will be realized once we integrate the alignment turning into a complete production line, with data exchanges between the optical design codes (for recomputations), the alignment stations, and the alignment turning machine.

9. Acknowledgement

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Jenoptik would also like to acknowledge the contributions of Paul R. Yoder, opto-mechanical engineer, pioneer and inventor, holder of 14 US patents in opto-mechanical design and lens mounting.

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[i] Kingslake, R. "A history of the Photographic Lens," Academic Press, 1989.
[ii] Yoder, P. R., Jr., "Lens mounting techniques," SPIE Proceedings Vol. 389, 2, 1983.
[iii] Fischer, R. E., "Case Study of Elastomeric lens mounts," SPIE Proceedings Vol. 1533, 27, 1991.