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Concept and realisation of a modular alignment turning machine

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Abstract

Exact mounting references manufactured by the alignment turning process are essential in order to effectively assemble high-quality optical systems. In order to extend the capabilities, a concept of a modular alignment turning machine was investigated and realized. The basic approach is a vertical, hydrostatic spindle (C-axis) integrated in a horizontal X-axis. The spindle carries an alignment chuck that manipulates the optical assembly in four degrees of freedom (Tx, Ty, Rx, Ry) according to the on-machine metrology. By moving the X-axis, the spindle-workpiece arrangement can positioned at three vertical Z-axis modules. They can flexible serve as machining or metrology stations.

Keywords: optical systems assembly, reference structures, alignment turning

1. Introduction

Alignment turning machines are core part of a classical assembly philosophy for high quality optics based on ultra-precise manufactured references [1]. Even the alignment turning approach is highly specialized, different machine concepts are commercialized in optics fabrication. Recent developments broaden the technology to aspherical lenses and infrared lenses [2] and the integration of tactile and optical measurement modules are introduced to improve process stability [3]. However, the alignment turning method has been limited to lenses and rotationally symmetrical housing structures so far. The underlying diamond turning process favours housing materials like aluminum, brass, and electroless nickel to achieve manufacturing tolerances of less than 2 µm. The presented modular approach innovates the alignment turning technology towards arbitrary optical elements and housing materials.

1.1 Method of alignment turning

The basic idea of the alignment turning approach is the manufacturing of mounting structures, well referenced to the optical axis of the optical element. Common to all implementations is an on-machine decentration measurement of the lens in respect to the working spindle axis (machining coordinate system) by a focusable autocollimator. Using a servo turning technology or by centering the lens in coincidence to the spindle axis with an alignment chuck, the housing can be machined in relation to the optical axis of the lens. Outcome of the alignment turning process are lens housings with well-defined outer diameters, vertex heights, and highly flat and parallel rims, resulting in a deterministic system assembly [4].

1.2 Enhancement of the method

By using the presented modular machine setup, additional on-machine metrology and cutting techniques can be flexibly adapted to manufacture references and assembly structures in close relation to an optical parameter or function. Thereby, the new approach enables the alignment of an optical assembly or system, not only regarding the centration but also by different optical parameters like surface form, intensity distribution, or beam profile depending on the metrology used. For example, an optical surface or system is aligned by means of an interferometric test setup at one Z-station. The following machining of assembly references at the housing of the optical element uses the flexible application of different cutting processes at the other Z-axis modules. The implementation of a milling spindle or an ultrasonic assisted turning system can expand the approach to non-rotationally symmetrical geometries and alternative housing materials.

2. Machine concept and realization

Figure 1 illustrates the basic concept of the modular alignment turning machine. A vibration isolated horizontal granite basement carries the X-axis with an integrated vertical spindle as well as a vertical granite wall that represents the basis for three vertical Z-axis. Whereas the linear axis are implemented as compact precision roll bearing slides, the workpiece holding spindle is realized as a hydrostatic bearing and can also act in C-axis mode.

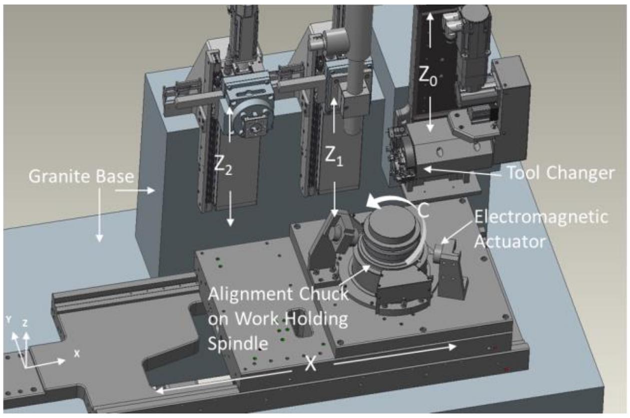

Figure 1. Concept of the modular alignment turning machine.

Thanks to the stiffness of 1000 N/µm axial and 800 N/m radial at a distance of 110 mm from spindle nose, a motion accuracy less than 40 nm axial and radial is provided even if the adjustable workpiece chuck is mounted on top of the spindle. The chuck consists of two adjustment elements (spherical and plano) that are preclamped with a variable force of 300 to 3000 N using permanent and electro magnets. Actuators equipped with an electromagnetic striking mechanism can manipulate the chuck elements by introducing mechanical impulses with a variable strike energy. The stick slip effect used enables positioning steps in the submicrometer range in four degrees of freedom (Tx, Ty, Rx, Ry). The alignment of the optical assembly is performed by analyzing the on-machine metrology and the resulting alignment steps controlled by the actuators. Three working areas below the three Z-axis modules are realized by a total X-axes travel of 600 mm. Depending on the required process step, the workpiece holding spindle can be positioned on the three vertical Z-axes for measuring or cutting processes. Z0 and Z2 provide 300 mm and Z1 250 mm length of travel. Typically, the Z1 axis with a positioning accuracy of 2 µm is holding the traditional decentration measurement system. Z0 and Z2 offer a positioning accuracy of 1 µm and can be equipped with optical or mechanical metrology systems or alternative cutting tools. Exemplary, a customized tool holder is shown in figure 2, which enables the automatic change of up to four tools with a reproducibility less than 1 µm mounted on the Z0 axis.

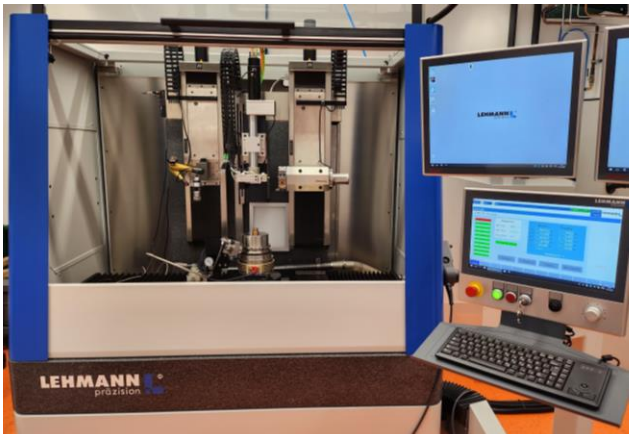

Figure 2. Modular alignment turning machine, developed at Fraunhofer IOF and realized in collaboration with Lehmann Präzision GmbH

3. Exemplary usage of the realized machine setup

For a promising application of the realized machine, the vertical Z2-axis permits the installation of an interferometer that can measure the surface form of an optical surface, mounted on the alignment chuck. By using the spindle as a reference axis, the part under test is investigated at different rotational positions. The optical element can be centered and aligned according to the acquired and analyzed interferometer data set. This method works for rotational symmetrical surfaces like aspheres or off-axis aspheres as well as freeforms. Depending on the shape of the optical element, the interferometric evaluation of the optical element can be done by the examination of:

i. sub-apertures, e.g. surface sections
ii. full aperture
iii. full aperture and reference fiducials.

The approach aims in particular to simplify system integration for brittle material aspheric and freeform optics such as a mirror made of ZERODUR or glass, permanently bonded in a metallic frame [5]. Such elements can be clamped onto the alignment chuck via intermediate plate, whereby the clamping accuracy is not critical since mechanical references are machined after the optical surface has been aligned. Taking an on-axis aspherical mirror (figure 3) as an example, the interferometer equipped with a transmission sphere would lead to the interference of a sub-aperture or surface section, respectively (i). The visible fringe pattern obtained by the spherical reference can be used

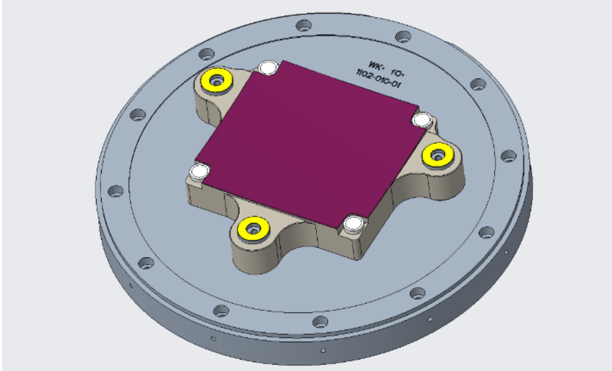

Figure 3: Mechanical design of an on-axis aspherical mirror made of brittle material. Interfaces for system integration (indicated in yellow) must be alignment turned to enable snap-together integration.

very sensitively to align the mirror in the machine coordinate system. As shown in figure 4, a symmetric ring shaped fringe pattern at different spindle positions indicates when proper centering for an on-axis asphere has been achieved. Following, the machining of mounting references on the frame is possible. Method (i) can also be applied to more complex optical shapes: optical simulation provides the fringe pattern of a surface that has to be aligned, even if only sub-apertures can be seen by the spherical reference. Furthermore, the full aperture interferogram can be used for partial alignment (ii) when using

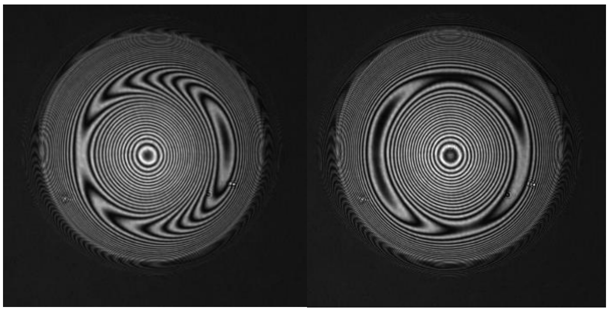

Figure 4: Fringes of an on-axis asphere, left: misaligned, right: alignment improved by adjusting 5 arcsec tilt in Ry

a computer generated hologram (CGH). Reference fiducials implemented on both the optical element and the CGH enable the alignment of even more complex elements (iii).

4. Conclusion

The developed modular machine extends the manufacturing approach of alignment turning. Due to individual utilization of metrology and cutting systems, the machine offers multiple setups, customized to the optical component and the housing material. The essential point is the manufacturing of ultra-precise references that are well defined and exactly related to the optical coordinate system.

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