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LENS MOUNTS IN OPTICAL HIGH PERFORMANCE SYSTEMS WITH SMALL DIAMETERS

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ABSTRACT

Optical high-performance systems with small diameters are a special group of optical systems such as those used in optical systems for mask and wafer inspection, high-resolution microscopy or specific laser applications. These systems are mechanically characterized by an outer diameter between 20 and 80 mm which is common for standard microscope objectives. An optical characterization is given by a high numerical aperture and an optical design for DUV/VUV applications. The optical performance with respect to the Strehl Ratio is well in excess of the diffraction limit (>95%). Future and partly current requirements for such systems cannot be met safely with the existing possibilities of technical realization.

From this follows that there is a growing need for technological and constructive development. As part of the structural design of optical systems, the mounting of optical components with mechanical elements, for instance lens mounts and the connection of mounted optical components to more complex systems, such as objectives, take a central role.

The aim of this paper is to give a short introduction to the current stage of development on the implementation of these mounting applications followed by the propagation of current and future requirements. As an example for a group of new solutions to fulfill the given requirements a kinematic lens mount will be demonstrated. This lens mount is able to connect a lens with a holder under low mechanical stress. An optical surface error given by mechanical stress less than 8 nm will be shown on practical results.

1. CURENT DEVELOPMENT STATUS

The current stage of development producing optical systems of high performance is illustrated by the following chapter.

The process of manufacturing is intended for systems of small diameters. Depending on the field of application of the product this multi-step process may vary in detail. The general succession of essential process stages and steps for manufacturing and use is shown in figure 1.

The fabrication of the optical parts as well as the mechanical parts needs several process steps varying in order and purpose of the element.

The processes of primary shaping and forming are used to create the semi-finished products for high performance optics.

To finish shaping the optical components a chronology of cutting processes as grinding, lapping, polishing, centering and correction polishing like CCP (Computer Controlled Polishing) or IBF (Ion Beam Figuring) is necessary.

Furthermore several processes like cleaning and coating or cementing of lens groups (called cemented lens pairs) are essential.

Lathing is the primary process to fabricate the mechanical components in combination with heat treatment processes like stress free annealing in combination with a material specific surface treatment like anodizing for aluminum materials and passivating for high-grade steels.

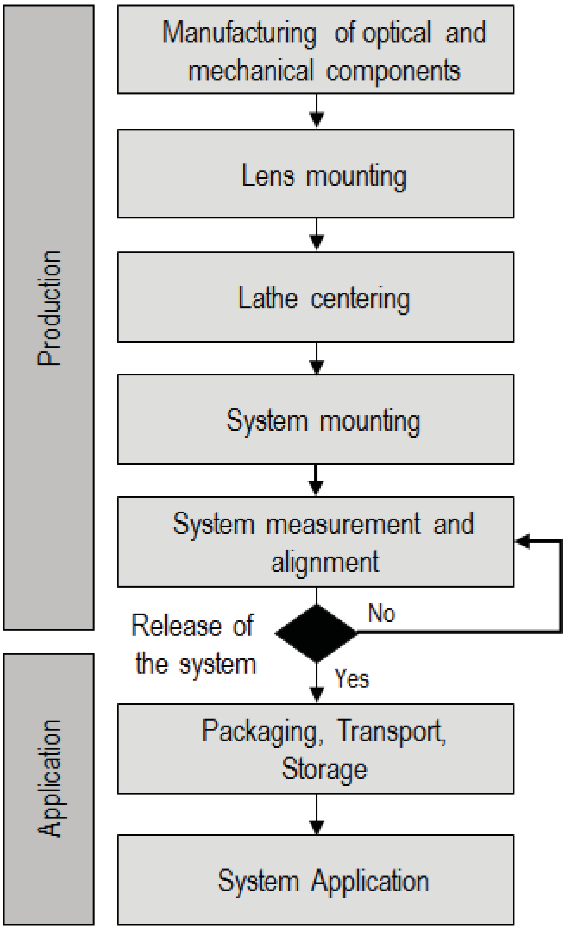

Figure 1 Process chain for manufacturing optical high performance systems with small diameters

Lens mounts for high-performance optics with small diameters are primarily glued mounts. Therefor the optical element is axially situated in a mounting-bore touching the mount itself with its optical active surface or a functional surface (e.g. a chamfer) especially made for. The mechanical part of the mount is distinguished by an axial flat surface or a cup point edge. Hence the optical element and the mechanical mount get glued together circumferential (on the perimeter of the lens) or axial (by applying the adhesive on the opposite surface of the lens) [1]. A schematic illustration shows figure 2. This mounting technology is developing continuously since its innovation in the field of optical high performance systems.

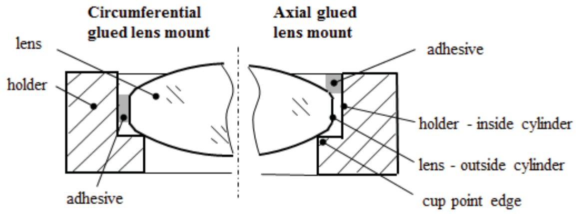

Figure 2 Variants of lens mounting by gluing [1]

The attributes and features of the adhesive have fundamental impact on the performance of the cemented lens mount as well as the process control and the shape of the groove carrying the adhesive. Concerning its applicability in high performance optics the technology of glued mounts is determined.

A systematic analysis performed by [2] shows the discrepancy between high requirements concerning lens mounts with low internal stress and stable positioned lens mounts for high-performance optics. These requirements cannot be met safely with the current technology of circumferential and axial glued lens mounts.

According to the process of lens mounting the optical system gets through a subsequent lathe centering technique. By this the pre-mounted optical system (e.g. a lens or a cemented lens pair) gets machine finished to create proper axial and radial mating surfaces for consecutive processes. The radial mating surfaces get machined receiving a shape concentrical to the optical axis of the optical element and a diameter aligned to the inner diameter of the fill cylinder. Processing the axial mating surfaces, there is a need to place these perpendicular to the optical axis as well as keeping a defined axial distance between the apex of the optical element to the referenced surface. This process step allows a high-precision positioning of the optical element to the mount itself and shortens the tolerance chain about one element (optical element to mechanical mount) as they appear together. This allows to meet the required today's specifications of high performance optics and makes the lathe centering process one of the key technologies in the process of manufacturing high-performance optics with small diameters.

Subsequently all direct mounted components are assembled together to one overall system. A common technique for high-performance optics with small diameters is the serial alignment of all mounted and lathed optical elements in a fill cylinder with spacer rings in-between. Secured with an axial lock the system is complete afterwards. This configuration of optical systems is called subcell assembly and is shown as a schematic in figure 3.

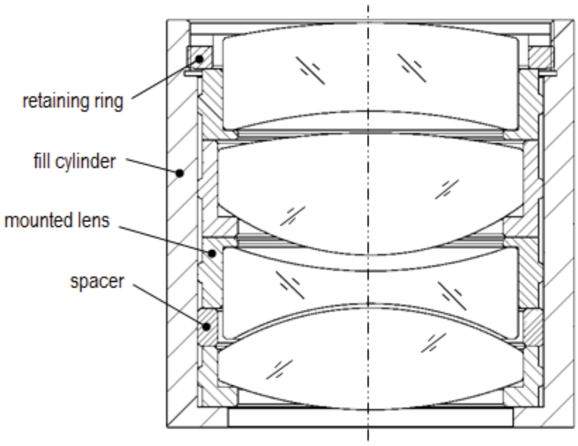

Figure 3 Subcell assembly technique– primarily used in optical high performance systems with small diameters

An extreme close toleration of specific parameters of the optical element (refraction number, center thickness) as well as the mounted optical element (shape deviation, crown height) can lead to running out of technologic and economic efficiencies. This points a need of compensating devices to meet the requirements of the representational function.

Measuring the parameters of the existing optical element as well as the mounting element a subsequent combination calculation based on these parameters creates an individual optical system. [1] pulls up the variation of the air gap to compensate deviations in the refraction number, center thickness and crown height in the combination calculation. The remaining deviations of the processes described as well as the assembling clearance during the installation of the mounted lenses in the fill cylinder cause residual errors with bad influence on the representational function of the optical system.

An iterative process of a system check and system adjustment is used to emend the remaining optical deviations.

Figuring out the aberrations during the system check several methods are state of the art. [3] shows a modified star pattern. [4] uses the image of a point figure to derive from this to the sort of the aberration and to figure out the directions of adjustments required.

Possible spots for adjusting are interfaces that are changing the air gap like swappable spacer rings, the rotation of mounted lenses or the lateral movement of mounted lenses [3]. Also possible and common for microscope lenses is the adjustment by settling the mechanical interface of the lens to its plane of focus.

As all the required specs for the optical system are met, all results get documented and the system gets released afterwards. From there on the optical system can be used in its application.

Operating conditions as well as transportation conditions play a major role causing a need of essential requirements concerning the design of the optical system.

The most important environmental conditions are temperature, external forces like pressure loads, impact loads, vibrations, humidity, contamination and high-energy radiation.

Depending on the spectrum of the application the range of environmental conditions can be strongly constricted (as optical systems for semiconductor applications) or strongly widened (like for military systems and space applications).

Operating conditions are understood as all conditions in which the optical system has to achieve its required optical performance.

Transport conditions are all extreme conditions the system has to survive without any damage. All alterations happening to the optical system under transport conditions have to be reversible to ensure the system achieves its optical performance again under operating conditions.

2. REQUIREMENTS

The function of an optical system strongly depends on the shape and position of the optical elements. Requirements concerning shape and position in high-performance optics are derived by [3] and [5] on concrete optical designs like:

- Optical surface error < 30nm pv[1]
- Decentration of the optical element to the optical axis of the overall system < 2 µm
- Tilt of the optical axis referring to the axis of the overall system < .3’ and
- Air gap deviation between adjacent optical elements < 2 µm

These requirements have to be achieved precisely in the related production process. Furthermore, there is a need to avoid any deviations during the following production steps and over the systems lifetime with its different influencing variables. Thus, for the mounting technology a position stable and stress relieved lens mounting interface is necessary.

Common requirements for stress relieved high-performance lens mounts are derived in [6]. It is presumed that the optical surface error given by mechanical stress should be less than 8nm pv. Another approach is given by the measurement of the optical retardation as an equivalent to the mechanical stress. As the stress birefringence of a single optical element is less then < 1nm/cm, [6] talks about a low stress lens mount for high performance optics.

Without any statements concerning typical environmental conditions this description would be

[1] pv (peak to valley) surface error is a measure for the highest deviation between the real optical surface and the ideal one

imperfect. Furthermore a separation between operation conditions and transport conditions is necessary.
The requirements for optical systems used in the field of wafer inspections the environmental conditions are strongly restricted. These high performance optics are used in insulated measuring chambers preventing the optics from contamination, external forces, vibrations and changes of the humidity. The transportation conditions are mostly defined by special transport specifications like:

- Temperature range 10 -35 °C,
- Maximum relative humidity 50 %,
- Maximum shock rate 100 m/s^2
- Pressure range 500 to 1200 mbar.

3. KINEMATIC LENS MOUNT

The first chapter illustrated that the requirements for high-performance optics cannot be met safely with glued mounts. These circumferential or axial glued mounts cause internal tensions in the optical element and are not stabile concerning their position.

The following chapter shows a solution meeting common requirements of high-performance optics. Concerning the design of a lens mount containing a mechanical part and an optical element a general solution space is given in [2]. Figure 4 shows an exemplary solution to be discussed.

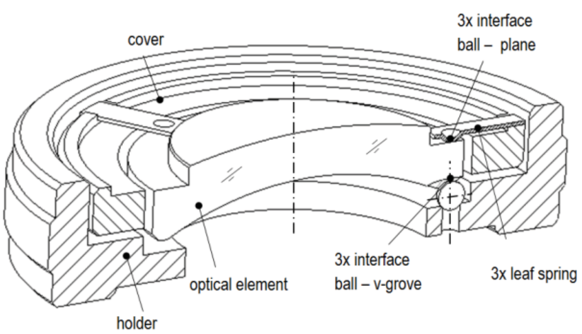

Figure 4 Stress relieved kinematic lens mount [2]

The optical element is connected to the holder by 3 Sphere – V-groove coupling points. This allows an exact constraint position of the optical element referenced to the mechanical part. The V-grooves are placed in the optical element and the spheres are fixed on the lens mount (e.g. laser welded or soldered). Locking the optical element in axial direction a cover keeps the lens down with laser-welded flat springs.

All coupling points are placed symmetrically to the optical axis and are located in a 3x 120° pattern. Having all flat springs fixed a single cover keeps the applied spring force equal on all contact points. This cover is not constraint in its radial position enabling it to arrange itself on the position of the optical element. The necessary spring load can be calculated by an analytic analysis of the temperature range, FEM simulations or experimental investigations.

An easy way to create a sufficient pre load is to apply a defined weight on the cover. Gluing the cover together with the lens mount secures its position. The limited performance of adhesive bonds has no effect on the alignment of the optical element as there is no direct contact between the adhesive and the lens. That means there is no way to implement parasitic forces and the adhesive itself is not in the direct light path which protects the adhesive from direct radiation.

Figure 5 is a showcase demonstration of the internal stress in the optical element and the surface deformation depending on the spring load.

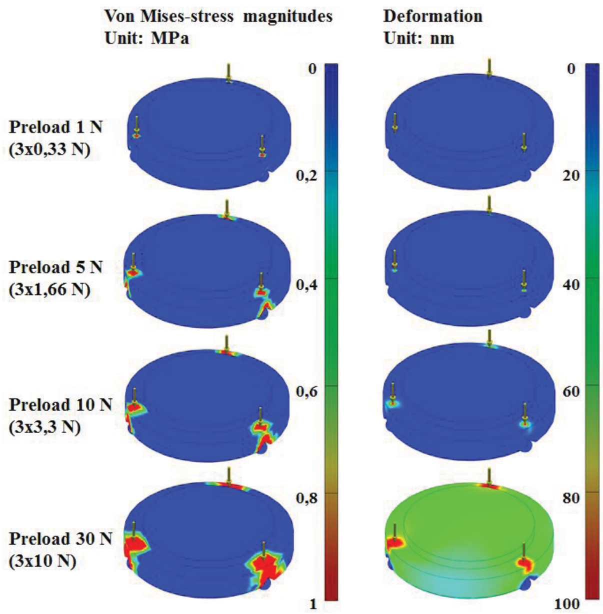

Figure 5 Stress magnitudes and deformation by various preloads showing the advantages of the used design principles [2]

A variation of the spring force shows the advantages of the design principle discussed. A short and direct flow of forces ensures a low and local/punctual internal stress in the optical element.

The principle of the kinematic mount prevents the system from being over-constraint and avoids the optical element being loaded with bending stress. The optical element with a weight of 1.7g shows even with a spring load of 30N no deformation of the optical surface. Only the deformation of the coupling points causes a uniform displacement of the whole optical element.

The practical implementation of the kinematic mount may has no ideal normal forces interacting with the coupling points caused by production tolerances and mounting tolerances. Depending on the displacement between the coupling points on both sides of the optical element preload forces will cause parasitic bending stress inducing deformations of the optical element. Figure 6 shows the impact of the displacement in terms of a rotation between the top and the bottom coupling points on the mechanical stress and the deformation of the lens. Though the spring load is kept constant at 10N (3x 3.3N) while the angle offset increases in several steps. Apparently, small angles have no crucial impact on the internal forces as well as on deformation.

Increasing the angle to noticeable greater values causes perceptible effects on the optical element. An extreme example with a tilt of 60° shows the effect of maximum deformation. In reality this case is not to expect. It can be assumed that the design is insensible against the expected mounting displacements for angles smaller than 10°.

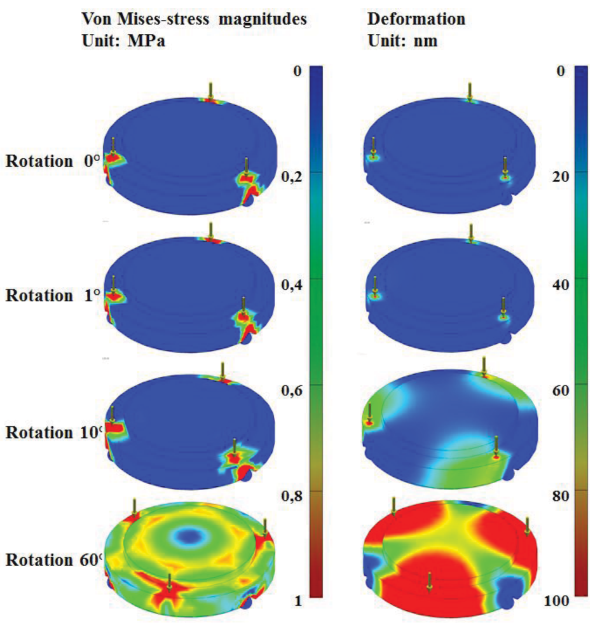

Figure 6: Stress magnitudes and deformation by various force application points with a preload of 10N (3x3.3N) showing the insensibility against mounting errors [2]

The performed FEM analyses are considered as qualitative illustrations showing the effectiveness of the design principles. Downright forecasts by FEM simulations regarding deformations and internal stress in the optical element would need experimental researches verifying the results and maybe a demand of revising parameters.

For experimental studies a spring force of 5N was chosen. The performance verification is oriented on the process chain to produce high performance optics related to figure 1. The requirements should be met safely and guaranteed under operating conditions. Figure 7 shows a general overview of a test scheme. Referring to this schedule the optical surface error, the position of the optical elements in reference to the holder as well as the stress-induced birefringence get measured to detect and verify influencing parameters and variations during the test process.

The following results of experimental researches were made for a concave/convex lens of SiO_2 with an outer diameter measuring 17mm and a center thickness of 3mm. This test object for characterization was chosen as this geometry is known as sensitive to external forces and mounting stress.

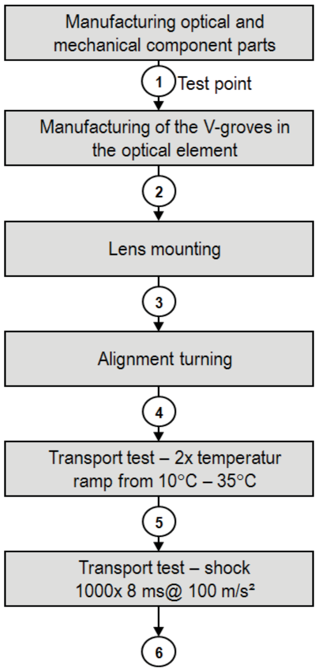

Figure 7: Testing procedure

The given uncertainties of measurements refer to the manufacturer's data and were verified in advance under the specific measuring conditions.

Proofing the stress relieved lens mount several investigations measuring the surface error of the optical element as well as the stress-induced birefringence were accomplished during various process steps referring to the scheme shown in figure 7.

The diagram in figure 8 shows the optical surface error of one test sample during all six steps of the test scheme. This sample exemplary shows the optical surface error caused by the lens mount occurring less than the required 8nm pv and being below the quantification limit of the used interferometric setup.

Furthermore the measured surface deformation as a confirmation of a low internal stress is verified by the low stress-birefringence. Figure 9 shows the stress-birefringence of the mounted optical element over several process steps. The uncertainty of measurement is +/- 0.1nm/cm for the optical path difference. The results show that the stress birefringence caused by the lens mount is in the area of the quantification limit of the polarimeter used and meets the given requirements safely. Both measuring methods demonstrate that the kinematic lens mount described is stress relieving and able to achieve requirements of optical high performance systems.

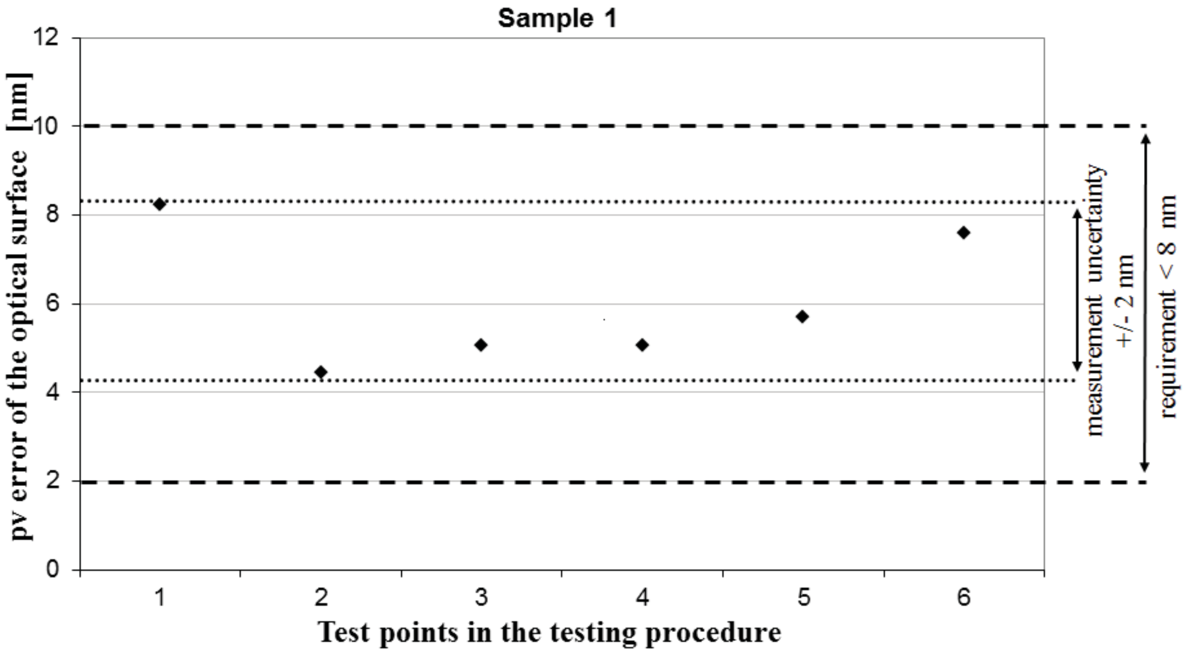

Figure 8 Peak-to-valley error of the optical surface of a test sample shows that the surface deformation caused by the lens mount is below the quantification limit

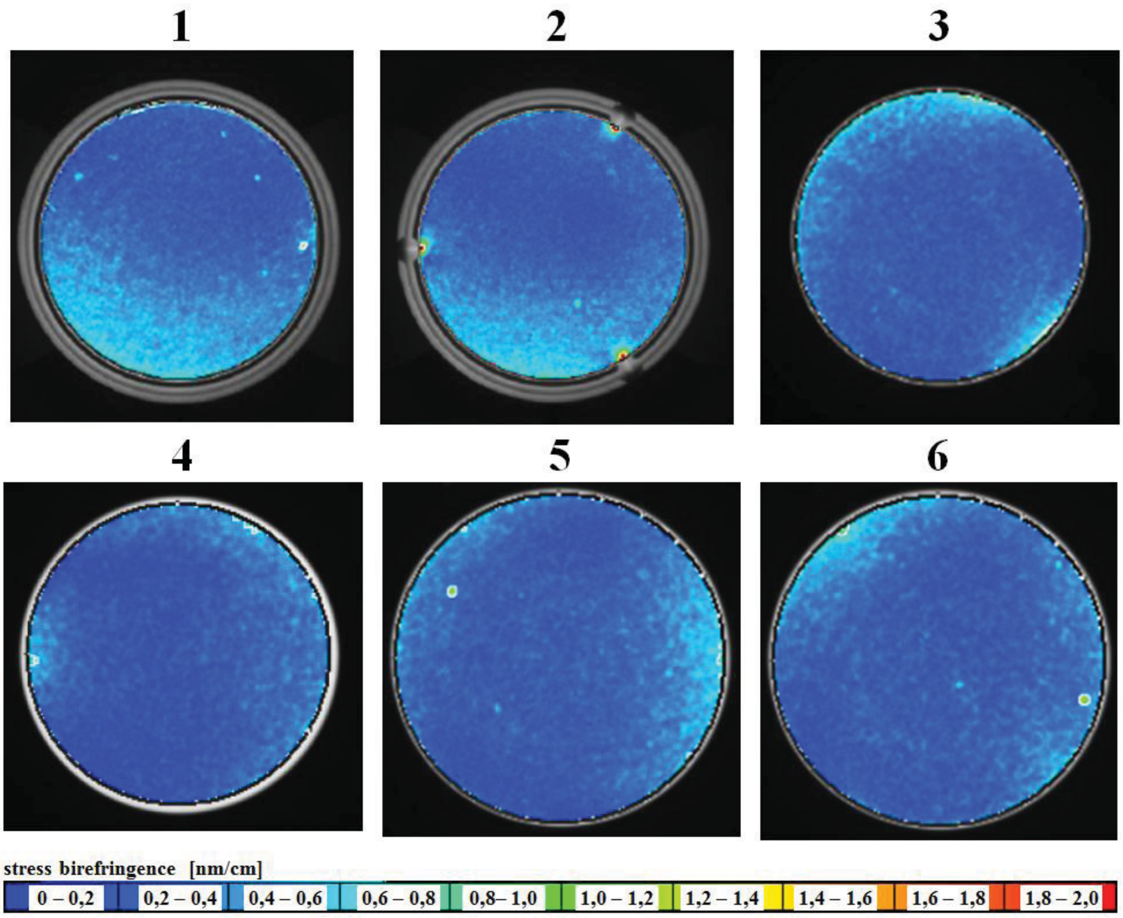

Figure 9 Stress birefringence of a test sample shows that changes in optical retardation caused by the lens mount are below the quantification limit

The evidence for position stability is performed by measuring the centering based on a geometric-optical reflex image method. As a reference for measuring the position of the optical element after the process of lathe centering is used. The results are shown in chart 1. This chart shows that the test samples reach a grade of stability in which the solution of the used measuring devices is not adequate. Nevertheless no relative movement appeared bigger than the requirements for $\Delta_{decentration} < 2\ \mu m$ and $\Delta_{tilt} < 0.3'$.

	Test point			measurement uncertainty
	4	5	6	
Longitudinal positioning error	1,1	1,6	2	± 1
Δ [µm]	-	*0,5*	*0,4*	
Tilt of optical axis [min]	0,07	0,09	0,05	± 0,05
Δ [min]	-	*0,02*	*0,04*	

Chart 1: Measurements of the decentration of a test sample show that the movement of the lens in respect to the holder is in the range of the quantification limit

Summarizing, the kinematic lens mount as shown in figure 4 meets the typical requirements of optical high performance systems during the whole process safely.

Concerning a detailed characterization the quantification limit of the available measuring equipment is the limiting factor. Compared to existing solutions based on glued lens mounts the experimental results of the kinematic mount demonstrate a considerable improvement. At this, it is essential to differentiate between glued lens mounts with adhesives of high stiffness (hard glues) and adhesives of low stiffness (soft glues).

Regarding to the low mechanical stress in the optical element the kinematic lens mount is comparable with mounts using low stiffness adhesives. However, these low stiffness adhesives are determined concerning their position stability caused by their sensitivity to humidity and temperature changes. Hard glues are usually not that sensitive to changing environmental condition. Caused by their high stiffness they cause mechanical stress getting cured which makes them not suitable for glued lens mounts similar to figure 2. As known, all adhesives are not long term durable when being exposed to DUV radiation. Concerning this a big improvement was made. As no organic materials are under direct radiation or hit by scattered light, no limitations exist.

4. SUMMARY

Optical high performance systems with small diameters are a special group of optical systems. A classification of this group with respect to its geometrical requirements as well as its performance was given. An overview shows the aspects of the current stage of development and the future requirements for production and implementation of these systems.

For the problem of bonding optical elements with mechanical lens mounts, a solution meeting the requirements was presented.

According to existing solutions of glued lens mounts, a considerable improvement is shown.

Although the verification of function is limited by the quantification limit of the used measuring devices. This problem especially occurred during the characterization of the position stability. The concept of this solution anticipated sliding friction based on relative movements between the optical element and the holder during temperature changes and shock loads which were expected not to be reproducible. This effect was not detectable with the measuring equipment used but it is predicted to be the limiting factor for applications with required position stabilities in the nanometer range.

Another limiting factor of the demonstrated lens mount is their general applicability. For instance biconvex lenses with sharp-edged design provide no room for the necessary V-Grooves. This group of optical elements shows a major need of developments for new mounting technologies.

A solution space as well as design guidelines for challenging the shown limits and developing new mounting solutions is proposed in [2].

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