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8884-1, Session 1

Cost effective fabrication method for large sapphire sensor windows

Mark Walters, Alan R. Gould, Kevin Bartlett, Matthew R. Brophy, Jessica DeGroot Nelson, Optimax Systems, Inc. (United States)

Sapphire poses very difficult challenges to optical manufacturers due to its high hardness and anisotropic properties. These challenges can result in long lead times and high prices, even for transparent armor components such as windshields. Large sensor windows demand much higher precision surfaces compared to transparent armor to achieve acceptable image quality. Transmitted wave front error tolerances of a quarter wave or less over a 12-15 inch aperture is typical for sensor windows. The combination of very hard IR transmitting materials with the precision optical tolerances only further pushes out lead times and causes the cost of these components to be even higher. Traditional sapphire window manufacturing methods are typically a three-step process consisting of fixed abrasive grinding, loose abrasive lapping and polishing. The total time required to perform these steps equate to the high cost associated with traditional sapphire window manufacturing. Optimax is developing a high speed, cost effective process to produce high precision sapphire sensor windows. The Optimax high speed process is a two-step process that combines precision fixed abrasive grinding and high speed polishing. The precision fixed abrasive grinding step produces surfaces that require minimal material removal during the polishing operation. The polishing step combines a high speed process with custom slurry that yields high removal rates and good surface quality. In-house studies have demonstrated cycle time reduction of up to 6X as compared to conventional processing. In addition to cost savings from reduced cycle time, this process also produces less waste through elimination of the loose abrasive lapping step and the associated consumables.

8884-2, Session 1

Effects of varying machine stiffness and contact area in UltraForm Finishing

Dennis E. Briggs, Samantha Echaves, Brendan Pidgeon, Nathan Travis, Jonathan D. Ellis, Univ. of Rochester (United States)

UltraForm Finishing (UFF) is a deterministic, subaperture, computer numerically controlled, grinding and polishing platform designed by OptiPro Systems. UFF is used to grind and polish a variety of optics from simple spherical to fully freeform, and numerous materials from glasses to optical ceramics. The UFF system consists of an abrasive belt around a compliant wheel that rotates and contacts the part to remove material. This work aims to measure the stiffness variations in the system and how it can affect material removal rates. The stiffness of the entire system is evaluated using a triaxial load cell and a capacitance sensor. Because the wheel is conformal and elastic, the shapes of contact areas are observed for variations in applied force. The combination of these two properties helps characterize the pressure distribution over the contact area and thus, directly relate them to material removal rate via Preston's equation. Using our current testing apparatus, we will demonstrate stiffness measurements and contact areas for multiple UFF belts during different states of their lifecycle and assess the material removal function from spot diagrams as a function of wear. This ultimately allows us to make better estimates of Preston's coefficient and develop spot-morphing models to better predict instantaneous material removal functions.

8884-3, Session 1

Determination of a suitable parameter field for the active fluid jet polishing process

Roland Maurer, Heiko Biskup, Christian Trum, Rolf Rascher, Christine Wünsche, Hochschule Deggendorf (Germany)

In 2012 a well-known company in the field of high precision optics assigned the University of Applied Sciences Deggendorf to determine a suitable parameter field for the Active Fluid Jet Polishing (AFJP) process in order to reach a surface accuracy of at least $\lambda / 5$. The active fluid jet polishing is a relatively new and an affordable sub-aperture polishing process. For a fast and precise identification of the parameter field a considered design of experiment is necessary. The available control variables were the rotational speed of the nozzle, the distance between the test object and the jet, the feed rate, the material of the pin inside the nozzle and the material of the test object itself. In order to reach a significant data density on the one hand and to minimize the number of test runs on the other hand a meander shaped tool path was chosen. At each blank nine paths had been driven whereby at each path another parameter combination was picked. Thus with only one test object nine parameter settings may be evaluated. For the automatized analysis of the tracks a software tool was developed. The software evaluates ten sections which orthogonally intersect the nine tracks on the test-lens. The significant measurement parameters per section are the width and the height of each path as well as the surface roughness within the polished tracks. With the aid of these parameters and further statistical evaluations a suitable parameter field for the goal to find a constant and predictable removal spot was determined. Furthermore up to now over 60 test runs have been successfully finished with nine parameter combinations in each case. As a consequence a test evaluation by hand would be very time-consuming and the software facilitates it dramatically.

8884-4, Session 1

Magnetorheological finishing with chemically modified fluids for studying material removal of single-crystal ZnS

Sivan Salzman, Henry J. Romanofsky, Yoem I. Clara, Luccas J. Giannechini, Garrett J. West, John C. Lambropoulos, Stephen D. Jacobs, Univ. of Rochester (United States)

Magnetorheological finishing (MRF) of polycrystalline CVD zinc sulfide (ZnS) and zinc selenide (ZnSe) can leave millimeter-size artifacts on the part surface. These pebble-like features come from the anisotropic mechanical and chemical properties of the ceramic material, and from the CVD growth process itself. The resulting surface texture limits the use of MRF for polishing aspheric and other complex shapes with these important IR materials.

An investigation of the individual contributions of chemistry and mechanics to polishing of other polycrystalline ceramics has overcome this material anisotropy problem. The approach taken was to study the removal process for the different single crystal orientations that comprise the ceramic, making adjustments to mechanics (polishing abrasive type and concentration) and polishing slurry chemistry (primarily pH) to equalize the removal rate for all crystal orientations. Polishing with the modified slurry was shown to remove surface texture.

Here we present chemical (acid etching) and mechanical (micro-hardness testing) studies performed on the four single crystal orientations of ZnS: 100, 110, 111 and 311. We found a relatively high degree of variation in these properties that can help to explain the surface texture developed from MRF of the polycrystalline material.

Theoretical calculations of micro-hardness, planar and bond density are presented and compared with the experimental data. For the first time, surface characterization of these single crystal orientations of ZnS for material removal and roughness with chemically-modified MR fluids at various pH levels at and below pH 6 are presented.

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8884-5, Session 1

Dressing of fine grained diamond grinding wheels for ultra precision grinding of structured molds in brittle hard materials

Thomas Bletek, Fritz Klocke, Martin Hüntten, Olaf Dambon, Fraunhofer-Institut für Produktionstechnologie (Germany)

The manufacturing of structured molds calls for alternatives in terms of grinding wheel geometry and dressing. To manufacture geometric features in the micron range on molds, sharp edged fine grained grinding wheels can be used. A dressing procedure with metal alloy blocks is used to create sharp edged grinding wheels. This paper presents results and achieved tip radii of dressed resin bonded and metal bonded grinding wheels. Furthermore, a grinding test on a tungsten carbide mold is carried out to create a diffractive structure and the achieved form accuracy and surface roughness are presented.

8884-6, Session 2

The removal of mid-spatial frequency (MSF) errors using stress-polishing

Peter C. Hill, Peter N. Blake, Carl R. Strojny, Shahram Shiri, Jason G. Budinoff, NASA Goddard Space Flight Ctr. (United States); Gregory J. Michels, Sigmadyne, Inc. (United States)

The impact of MSF errors is well understood within the optics community. As a result there are a number of organizations that have developed techniques to reduce MSF errors. We evaluate how stress polishing can be used to remove MSF errors and other sub-aperture tool marks.

Stress polishing is used in a slightly different manner than it has traditionally been used. Instead of using stress to generate an equal but opposite departure from a best fit sphere prior to grinding, the aspheric surface is generated using a small tool CNC machining process. This technique provides both high removal rates and deterministic removal of material, both of which lead to cost savings during this stage of the manufacturing process. After the asphere is generated, a mechanical load is placed onto the optic to deform the asphere into a sphere. The sub-aperture tool marks are removed by post-polishing the optical surface with a loose abrasive and large aperture lapping process.

Because stress harness designs can usually only be verified after the final polishing step, these fixtures can be difficult and unpredictable to design, often requiring multiple grinding/polishing iterations before an adequate design is realized. Stressing an optical surface from an asphere to a sphere, however, allows the use of in-situ optical metrology to verify the fixture design and, if necessary, optimize the fixture design prior to grinding/polishing the optical surface. These techniques reduce the lead time and cost typically required to manufacture stress harnesses.

8884-7, Session 2

Efficiency of magnetorheological fluid finishing on the elimination of defects in fused silica optics

Rodolphe Catrin, Commissariat à l'Énergie Atomique (France); Daniel Taroux, Philippe Cormont, Cédric Maunier, Thomas Corbineau, Gérard Razé, Jérôme Néauport, CEA (France)

The MegaJoule laser being constructed at the CEA near Bordeaux (France) is designed to focus more than 1 MJ of energy of UV light, on a millimeter scale target in the centre of an experiment chamber. After amplification and transport at the wavelength of 1053 nm, frequency conversion at 351 nm is done with KH₂PO₄ crystals. The final optic assembly of this system is made up of large fused silica optics, working in transmission, that are used to convey, focus or shape the laser beam. When exposed to fluences of some joules per centimetre square at 351 nm within nanosecond pulse duration, fused silica optics can exhibit localized damage. Damage sites grow exponentially after further laser exposition and therefore dramatically limit the optic lifetime. The nature of the surface finishing process has been established to determine the lifetime of these components under high UV fluences (i.e. more than 5 J/cm² for 3 ns pulses). Being able to reduce or eliminate the damage initiators such as subsurface cracks present in subsurface damage layer (SSD) of conventionally polished optical components aims this study.

Magneto-rheological fluid finishing (MRF) is chosen as a final polishing tool to remove layers of material without inducing further damages. MRF enables to process optics with very small normal stresses applied to the surface during material removal and thus permits the elimination of the residual subsurface cracks. This study offers a better understanding of the efficiency of MRF polishing on the elimination of subsurface cracks in SSD layers.

8884-8, Session 2

Optical surfacing process optimization using parametric smoothing model for mid-to-high spatial frequency error control

Dae Wook Kim, College of Optical Sciences, The Univ. of Arizona (United States); Hubert M. Martin, The Univ. of Arizona (United States); James H. Burge, College of Optical Sciences, The Univ. of Arizona (United States)

High performance optical systems aiming very low background noise from scattering or sharp point spread function with high encircled energy often specify their beam wavefront quality in terms of structure function or power spectral density function, which requires a control of mid-to-high spatial frequency surface errors during the optics manufacturing process. Especially, for large aspheric optics fabrication, achieving the required surface figure irregularities over the mid-to-high spatial frequency range becomes a challenging task as the polishing lap needs to be compliant enough to conform to the varying local surface shapes under the lap. The compliance degrades the lap's smoothing capability which is mainly relying on its rigidity. The smoothing effect corrects the mid-to-high spatial frequency errors as a polishing lap removes low spatial frequency (i.e. larger than the lap size) errors on the optical surface. Using a parametric smoothing model developed to quantitatively describe the smoothing effects during Computer Controlled Optical Surfacing (CCOS) processes, actual CCOS data from large aspheric optics fabrication projects have been analyzed and studied. The measured surface error maps were processed with the model to compare different polishing runs using various polishing parameters such as lap stroke speed and polishing interface material. The results showing the improvements of surface irregularity as a function of spatial frequency will be presented to optimize the CCOS process for higher smoothing efficiency.

8884-9, Session 2

Relationships between subsurface damage depth and surface roughness of grinded glass optics

Pierre Blaineau, Raynald Laheurte, Philippe Darnis, Univ. Bordeaux 1 (France); Nathalie Ferriou-Daurios, Commissariat à l'Énergie Atomique (France); Olivier Cahuc, Univ. Bordeaux 1 (France); Jérôme Néauport, Commissariat à l'Énergie Atomique (France)

Subsurface damages (SSD), which are introduced during grinding process of optical components for high power lasers applications, act as initiator for laser damage and are responsible of the low lifetime of these components. The knowledge of the SSD depth is essential to remove the damaged layer of the optical component during the last finishing step of grinding. However, existing methods to measure the SSD depth are either destructive or costly and complicated. Thus these methods are hardly useable industrially. That is why many studies have been made on the relation between the SSD and the surface roughness of grinded glasses. These studies founded several relations between the SSD depth and the peak to valley roughness (R_t), but the observed relations between these two parameters change with the grinding mode used and with the surface roughness measurement methods.

In our study, the relations between SSD and surface roughness are widely explored to find a better and easier way to assess the SSD depth. For that purpose other surface roughness parameters are measured, especially the one from Abbott Firestone curve. Several grinding modes are tested, from rough grinding to finishing, with loose or bound abrasives. Finally, the accuracy of the relations between SSD and surface roughness is also studied.

The results show that the 100-Mr2 parameter from the Abbott Firestone curve is more accurate than R_t for an assessment of the SSD depth.

8884-10, Session 2

Fabrication of optical surfaces of fused silica with ultralow subsurface damage

Junlin Wang, Changchun Institute of Optics, Fine Mechanics and Physics (China)

Modern optical applications, such as X-ray optics, UV optics, semiconductor applications, require optical components with ultrahigh reflectivity and ultralow scattering. The level of subsurface damage is proportional to the surface scatter and related to the laser damage threshold of the optic. In this paper, Numerical controlled micro-jetting fluid (MJF) polishing technology is applied to eliminate subsurface damage of fused silica. Both of the theory and the techniques about MJF technology are introduced in detail. When the surface was polished, white-light interferometer (WLI) was used to measure the changing of waviness during the fabricating process. Results show that no new scratches were produced by MJF when the nanoparticles removed the atoms away from the surface, and subsurface damage leaved by traditional methods was well removed. The roughness decreased monotonously with the removal of subsurface damage layer. And ideal supersmooth surface without subsurface damage was achieved with waviness less than 0.2nmRMS.

8884-11, Session 2

Multiwavelength digital holography for polishing tool shape measurement

Vit Ledl, Institute of Plasma Physics of the ASCR, v.v.i. (Czech Republic); Pavel Psota, Technical Univ. of Liberec (Czech Republic); Jan Vaclavik, Institute of Plasma Physics of the ASCR, v.v.i. (Czech Republic); Roman Dolecek, Technical Univ. of Liberec (Czech Republic); Petr Vojtisek, Institute of Plasma Physics of the ASCR, v.v.i. (Czech Republic)

Classical chemical mechanical polishing is still a valuable technique, which gives unbeatable results for some types of optical surfaces. For example, optics for high power lasers requires minimized subsurface damage, very high cosmetic quality, and low mid spatial frequency error. One can hardly achieve this with use of subaperture polishing. The shape of the polishing tool plays a crucial role in achieving the required form of the optical surface. Often the shape of the polishing tool or pad is not known precisely enough during the manufacturing process. The tool shape is usually premachined and later is changed during the polishing procedure. An experienced worker could estimate the shape of the tool indirectly from the shape of the polished element, and that is why he can achieve the required shape in few reasonably long iterative steps. Therefore the lack of the exact tool shape knowledge is tolerated. Sometimes, this indirect method is not feasible even if small parts are considered. Moreover, if processes on machines like planetary (continuous) polishers are considered, the incorrect shape of the polishing pad could extend the polishing times extremely. Every iteration step takes hours. Even worse, polished piece could be wasted if the pad has a poor shape. The ability of the tool shape determination would be very valuable in those types of lengthy processes. It was our primary motivation to develop a contactless measurement method for large diffusive surfaces and demonstrate its usability. The proposed method is based on application of multiwavelength digital holographic interferometry with phase shift.

8884-12, Session 3

Innovations within the process chain for ultraprecise optics fabrication

Sebastian Stoebenau, Sebastian Stahringer, Roland Mandler, Matthias Pfaff, OptoTech Optikmaschinen GmbH (Germany)

Manufacturers are faced with the recent trend towards middle and large scale optics providing highest levels of shape accuracy and surface finish. This leads to increasing demands with respect to the manufacturing equipment and processes. Not only a single step but the whole process chain needs to be addressed during optimization. It starts with the reduction of MSF errors during grinding and ends with well converging correction cycles during polishing. The very consequent design of high stiffness grinding machines comprises hydrostatic bearings and a gantry-type machine base made from granite. The reliability and convergence of the correction cycles during polishing strongly depends on stable and predictable removal functions. Both issues are covered using active fluid jet polishing (A-FJP) as the last mechanical machining process. The final shape accuracy is achieved by ion beam figuring (IBF). Besides the fabrication processes another hot topic throughout the complete production chain is related to metrology issues. We present the latest results for the fabrication of spheres and aspheres using all above mentioned technologies on state-of-the-art machines and metrology equipment in our workshop. For each step we identify the key challenges and introduce ways how to meet them.

8884-13, Session 3

Deterministic polishing process for aspheric lenses in a production environment

G. Stach, F. Schwalb, Satisloh GmbH (Germany)

Grinding, polishing and finishing with ultra-precise form correction from one supplier. Satisloh provides machines, peripheral equipment, training, service, consumables, tools and process-support. All the equipment is made for industrial environment. Together with exclusive, experienced partners, aspheric lenses will be manufactured more efficiently.

Since the market release in 2011 and more than 15 units in the field, the ADAPT process has been improved and the calculation speed has been increased drastically by utilizing the 64bit operating system with extended memory allocation. The polishing tool design has been optimized in order to increase accuracy and productivity even on steep concave lens shapes.

Additional metrology interfaces were added and the distortion correction for interferograms based on CGH (computer generated hologram) measurements has been integrated.

The characteristics of this process with only one pre-polishing run and typically only two correction cycles minimizes the generation of mid-spatial frequencies drastically. This fact improves the processing times of the following finishing process considerably and reduces machine time and polishing slurry consumption, respectively other consumables.

8884-14, Session 3

Deterministic finishing of aspheric optical components

Teddy J. Lambropoulos, Ed Fess, Scott DeFisher, OptiPro Systems (United States)

Manufacturing aspheric optics can present challenges depending on the complexity of their shape. This is especially true during the finishing stage. To tackle this challenge, OptiPro Systems has developed two technologies for deterministic optical polishing: UltraForm Finishing (UFF) and UltraSmooth Finishing (USF). UFF is a deterministic sub aperture polishing process that polishes spherical, aspheric, and free form surface geometries. In contrast, the USF process is a deterministic mid to large size aperture polishing process that works with a conforming lap. These two technologies have the ability to tackle a wide range of optical shapes by removing sub-surface damage, removing various mid-spatial frequency artifacts that might be left from a grinding process, and correct the optic's figure error in a controlled fashion. This presentation will describe these technologies, present performance information as to their capabilities, and show how OptiPro is developing these technologies to push the state of the art in manufacturing.

8884-15, Session 3

Efficient grinding and polishing processes for asphere manufacturing

Markus Hinn, Schneider GmbH & Co. KG (Germany); Alex Pisarski, Schneider Optical Machines Inc. (United States)

The increasing use of aspheres in a variety of optical systems has pushed the industry to become more efficient at its manufacturing processes. Precision aspheres for imaging applications often require high form accuracy and smooth surfaces. Traditional grinding techniques are effective at achieving the correct aspheric prescription. However, the process often results in significant sub-surface damage and mid-spatial frequency errors which can be difficult and time consuming to correct during polishing. Optimizing the kinematics of the grinding platform can reduce these errors and simplify the polishing process allowing for improved manufacturing of aspheres.

The SCGa 100 grinder and SCPa 100 polisher provide unique platforms for manufacturing aspherical optics. The SCGa 100 combines cup-wheel and peripheral wheel grinding options onto a single, flexible platform for manufacturing both spheres and aspheres. Optimized kinematics enables grinding of convex aspheres using only two axes of motion (X and Z). Stiff spindles and in situ balancing suppress vibrations and enable the use of small grain diamond tools for a semi-transparent surface after grinding. This setup ensures an accurate tool path for high form accuracy of the aspheric shape while minimizing sub-surface damage and mid-spatial frequency errors. Subsequently, polishing time on the SCPa 100 is significantly diminished. Using an off-axis polishing process with high removal rates, remaining sub-surface damage is efficiently removed without distorting the aspheric prescription. A sub-aperture corrective polishing is then performed to further improve the final surface figure. The combination of optimized grinding and efficient polishing creates an effective process for manufacturing high quality aspheres.

8884-16, Session 3

Getting the most out of your cerium oxide glass polishing slurry: reducing risk and improving performance with plasma produced particles

Patrick G. Murray, Abigail Hooper, Nanophase Technologies Corp. (United States); Jason Keleher, Jordan Kaiser, Meghan Nichol, Lewis Univ. (United States)

Recent dramatic price volatility and assurance of supply concerns with cerium oxide have left many users of this material in an uncertain and vulnerable position. Since few viable alternatives to ceria for precision glass polishing exist, and much of the supply is very concentrated geographically, technology which conserves ceria, improves absolute removal rate and promotes slurry longevity becomes extremely attractive under these circumstances.

Using a plasma-based process to produce cerium oxide confers some unique attributes to the particles which make them particularly well suited for precision glass polishing operations. Many of those same particle characteristics, such as full crystallinity, near theoretical density, very high surface and bulk purity and extremely high zeta potentials in water can also be useful in mitigating the risks associated with a limited and costly ceria supply. This paper will explore how plasma-derived particles, in combination with a high performance chemistry package, can together constitute a fully formulated precision glass polishing slurry with very high activity, extended slurry lifetime, recyclability, and excellent overall process economics. Results showing the effect of particle longevity and chemical additives on removal rate and process stability will be discussed in detail, and selected examples

which distinguish the benefits of a fully formulated, plasma-derived cerium oxide polishing slurry over conventional milled ceria will be shown.

8884-17, Session 3

New developments in fixed abrasive grinding and their potential for the production of optical components

Marcel Patraschkov, dopa diamond tools (Germany)

Fixed abrasive grinding is a process that is known and applied by most optical component manufacturers. dopa has developed a new generation of grinding tools that by far exceeds the performance of currently known technologies. Using those you are not only able to cut down your grinding time, you will also save a lot of time and consumables in polishing.

The unique diamond-resin-matrix can be used in most different fixed abrasive tools as for example:

- plano grinding tools for the manufacturing of prisms or wedges,
- double sided grinding tools for the production of wafers or windows
- or generators and wheels for curved shapes.

8884-18, Session 4

Developments in precision optical grinding technology

Edward M. Fess, Michael J. Bechtold, Franciscus Wolfs, Rob Bechtold, OptiPro Systems (United States)

Optical systems that utilize complex optical geometries such as aspheres and freeform optics require precise control through the manufacturing process. As the preparatory stage for polishing, this is especially true for grinding. The quality of the grinding process can greatly influence the polishing process and the resultant finished product.

OptiPro has performed extensive development work in evaluating components of a precision grinding machine to determine how they influence the overall manufacturing process. For example, spindle technology has a strong effect on how a grinding machine will perform. Through metrology techniques that measure the vibration characteristics of a machine and measurements of grinding forces with a dynamometer, OptiPro has also developed a detailed knowledge of how the machine can influence the grinding process. One of the outcomes of this work has led OptiPro to develop an ultrasonic head for their grinding platform to aid in reducing grinding forces. Initial results show a reduction in force by ~50%.

This presentation will detail three main areas in grinding technology. The first will be to outline grinding challenges faced today, and describe how they are influenced by the grinding process. The second will be to detail how ultrasonic can aid in reducing tool wear and increase production rates. The third will be to present surface information on several challenging optical components.

8884-19, Session 4

Additive manufacturing of tools for lapping glass

Wesley B. Williams, The Univ. of North Carolina at Charlotte (United States)

Additive manufacturing technologies have the ability to directly produce parts with complex geometries without the need for secondary processes or fixturing. This ability was used to produce concave lapping tools with a VFlash 3D printer from 3D Systems. The lapping tools were first designed in ProEngineer with two varieties, one defined by a constant radius and the second a parabolic curve. The models were converted to STL files which the VFlash used in building the parts, layer by layer, from a UV curable resin.

The tools were rotated at 45 rpm and used with 220 grit silicon carbide lapping paste to lap 0.50" diameter fused silica workpieces. The samples developed a matte appearance on the lapped surface that started as a ring at the edge of the workpiece and expanded to the center. This indicated that as material was removed, the workpiece radius was beginning to match the tool radius. The workpieces were then cleaned and lapped on a second tool (with equivalent geometry) using a 3000 grit corundum aluminum oxide lapping paste, until a near specular surface was achieved.

By using lapping tools that have been additively manufactured, fused silica workpieces can be lapped to achieve a specified convex geometry. This approach may enable more rapid lapping of near net shape workpieces that minimize the material removal required by subsequent polishing. This research may also enable development of new lapping tool geometry and groove patterns for improved loose abrasive finishing.

8884-20, Session 4

Freeform polishing with UltraForm Finishing

Franciscus Wolfs, Edward M. Fess, Scott DeFisher, OptiPro Systems (United States)

Recently, the desire to use freeform optics has been increasing. Freeform optics can be used to expand the capabilities of optical systems. These same traits that give freeform optics the ability to improve optical systems, also makes them more challenging to manufacture. This holds true for grinding, polishing, and metrology, and as freeform optics become more prevalent in the industry, tolerances will become more stringent.

OptiPro Systems has developed a method of deterministic freeform polishing to be used with its UltraForm Finishing (UFF) process. This method uses the error map of the surface to determine the appropriate feed rates for removing a portion of the error from the surface of the optic. The material removed varies across the surface of the optic to allow for the error to decrease across the surface at a uniform rate. The flexibility of this method allows for the deterministic polishing of surfaces that can be mathematically modeled.

In addition to deterministic polishing, OptiPro is also developing a software package for generating freeform tool paths. This software can be used for both grinding and polishing freeform optics. It has the ability to generate the freeform tool paths for deterministic polishing. This software will make it easier to manufacture and polish complex freeform surfaces.

8884-21, Session 4

Fabricating freeform multispectral-ZnS corrector lenses

Matthew R. Brophy, Nathan Smith, Thomas J. Hordin, Alan R. Gould, Optimax Systems, Inc. (United States); Kate Medicus, Optimax Systems (United States); Mark Walters, Jessica DeGroot Nelson, Optimax Systems, Inc. (United States)

For over 100 years, optical imaging systems were restricted to rotationally symmetric lens elements, due to limitations in processing optics. However, the present rapid development and application of CNC machines has made fabrication of non-rotationally symmetric lenses, i.e. freeform surfaces, economical. The benefit of using freeform surfaces is that the lens designer has more flexibility to create innovative 3D imaging packages, while correcting for aberrations. This report details capabilities at Optimax for manufacturing freeform surfaces, with a specific example towards creation of freeform multispectral-ZnS surfaces for application as a corrector lens. In addition to fabricating freeform optics, advances have been made in producing smooth surfaces on polycrystalline materials. In the past, achieving a smooth surface on polycrystalline materials during sub-aperture polishing has proven challenging, because of a phenomenon called grain decoration or "orange peel". Significant progress has been made at Optimax in this field through utilization of proprietary pads, slurries, and processes.

8884-22, Session 4

Efficient machining of ultra precise steel moulds with freeform surfaces

Benjamin Bulla, son-x GmbH (Germany); David J. Robertson, Durham Univ. (United Kingdom); Olaf Dambon, Fritz Klocke, Fraunhofer-Institut für Produktionstechnologie (Germany)

Ultra precision diamond turning of hardened steel to produce optical quality surfaces can be realized by applying an ultrasonic assisted process. With this technology optical moulds used typically for injection moulding can be machined directly from steel without the requirement to overcoat the mould with a diamond machinable material such as Nickel Phosphor. This has both the advantage of increasing the mould tool lifetime and also reducing manufacture costs by dispensing with the relatively expensive plating process. This publication will present results we have obtained for generating free form moulds in hardened steel by means of ultrasonic assisted diamond turning with a vibration frequency of 80 kHz.

To provide a baseline with which to characterize the system performance we perform plane cutting experiments on different steel alloys with different compositions. The baseline machining results provides us information on the surface roughness and on tool wear caused during machining and we relate these to material composition.

Moving on to freeform surfaces, we will present a theoretical background to define the machine program parameters for generating free forms by applying slow slide servo machining techniques. A solution for optimal part generation is introduced which forms the basis for the freeform machining experiments. The entire process chain, from the raw material through to ultra precision machining is presented, with emphasis on maintaining surface alignment when moving a component from CNC pre-machining to final machining using ultrasonic assisted diamond turning. The free form moulds are qualified on the basis of the surface roughness measurements and a form error map comparing the machined surface with the originally defined surface.

These experiments demonstrate the feasibility of efficient free form machining applying ultrasonic assisted diamond turning of hardened steel.

8884-23, Session 4

Integrated manufacturing of complex freeform surfaces

Frank Niehaus, Stephan Huttenhuis, Schneider GmbH & Co. KG (Germany); Alex Pisarski, Schneider Optical Machines Inc. (United States)

Innovative freeform optical systems such as head-up displays or LED headlights often require high quality and high volume optics. Injection molded polymer optics are a cost effective solution. However, mold manufacturing is extremely challenging due to tight slope and surface quality tolerances.

Currently, mold manufacturing requires multiple iterations and several production steps using different equipment for manufacturing and metrology. Switching between manufacturing and metrology equipment can cause re-clamping errors which limits the accuracy of the measurement and of the corrective program. As a result, the accuracy of the freeform surface is severely limited and the production time is increased. Thus, a single platform machining center for freeform surfaces is required.

The UPC 400 can manufacture ultra precision freeform surfaces up to 400 mm in diameter by integrating diamond turning, milling, and metrology onto a single platform. This approach removes the time consuming re-clamping process and errors associated with alignment and data conversions. In contrast to other commercially available machinery, the UPC 400 utilizes a linear arrangement with the Fast Tool Servo system (FTS), the milling spindle, and the measurement tool on a single X-axis slide. This increases surface accuracy as it eliminates the need for a rotary axis with limited positioning accuracy in order to change between process steps. An advanced software package supports data handling of NURBS data for both machining and measurement. Combining machining processes and data handling onto a single platform makes the UPC 400 efficient for both prototyping free-form optics and manufacturing high precision molds.

8884-24, Session 4

Conformal window manufacturing process development and demonstration for polycrystalline materials

Nathan Smith, Alan R. Gould, Thomas J. Hordin, Kate Medicus, Mark Walters, Matthew R. Brophy, Jessica DeGroot Nelson, Optimax Systems, Inc. (United States)

Conformal windows pose new and unique challenges to manufacturing due to the shape, measurement of, and requested hard polycrystalline materials. Their non-rotationally symmetric shape and high departure surfaces do not lend themselves to traditional optical fabrication processes. The hard crystalline materials are another challenge due to increased processing time and possibility of grain decoration. We have developed a process and have manufactured various conformal windows out of fused silica, glass, zinc-sulfide multispectral, and spinel. The current process involves CNC generation/grinding, VIBE polishing, and sub-aperture figure correction. The CNC generation step incorporates an ultrasonic assisted grinding machine; the machine settings and tool are being continuously optimized for minimal sub-surface damage and surface form error. In VIBE, polishing to less than 5 nm rms surface roughness while maintaining overall form error is accomplished with a full aperture conformal polish

8884-91, Session 4

Fabrication of high precision metallic freeform mirrors with magnetorheological finishing (MRF)

Matthias Beier, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Sebastian Scheiding, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany) and Friedrich Schiller Univ. Jena (Germany); Andreas Gebhardt, Roman Loose, Stefan Risse, Ramona Eberhardt, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Andreas Tünnermann, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany) and Friedrich-Schiller-Univ. Jena (Germany)

The fabrication of complex shaped metal mirrors for optical imaging is a classical application area of diamond machining techniques. Aspherical and freeform shaped optical components up to several 100 mm in diameter can be manufactured with high precision in an acceptable amount of time. However, applications are naturally limited to the infrared spectral region due to scattering losses for shorter wavelengths as a result of the remaining periodic diamond turning structure. Achieving diffraction limited performance in the visible spectrum demands for the application of additional polishing steps. Magnetorheological Finishing (MRF) is a powerful tool to improve figure and finish of complex shaped optics at the same time in a single processing step.

The application of MRF as a figuring tool for precise metal mirrors is a nontrivial task since the technology was primarily developed for figuring and finishing a variety of other optical materials, such as glasses or glass ceramics. In the presented work, MRF is used as a figuring tool for diamond turned aluminum lightweight mirrors with electroless nickel plating. It is applied as a direct follow-up process after diamond machining of the mirrors. A high precision measurement setup, composed of an interferometer and an advanced Computer Generated Hologram with additional alignment features, allows for precise metrology of the freeform shaped optics in short measuring cycles. Shape deviations less than 150 nm PV / 20 nm rms are achieved reliably for freeform mirrors with apertures of more than 300 mm. Characterization of removable and induced spatial frequencies is carried out by investigating the power spectral density.

8884-25, Session 5

Comparison of alignment errors in asphere metrology between an interferometric null-test measurement and a non-null measurement with the tilted-wave-interferometer

Goran B. Baer, Johannes Schindler, Christof Pruss, Wolfgang Osten, Univ. Stuttgart (Germany)

between surface and alignment errors. This leads to lower requirements for the alignment accuracy of the surface under test as weA common method for the measurement of aspheres and freeform surfaces is the adaption of the wavefront to the surface under test with compensation optics, for example CGH's. Here the alignment can be achieved by additional alignment structures in the CGH. However the alignment is never perfect which introduces errors to the measurement. Usually these errors like tilt defocus and koma are simply subtracted from the measurement result, since the exact retrace errors introduced due to the misalignment are unknown. Here the misalignment leads to errors in the measurement that cannot be removed. In the case of

the tilted-wave-interferometer these retrace errors can be calculated using the calibration information of the setup, which allows a more sophisticated method for the distinction II as a more accurate way of removing the alignment errors from the measurement. In the presentation the method for the alignment of the surface under test, as well as the removal of the alignment errors will be compared between a measurement with a CGH and a measurement with the tilted-wave-interferometer. Further measurement results of an aspheric surface obtained by both methods will be shown and the influence of the alignment will be compared.

8884-26, Session 5

Comparison of contact and non-contact asphere surface metrology devices

Scott DeFisher, Edward M Fess, OptiPro Systems (United States)

Metrology of asphere surfaces is critical in the precision optics industry. Surface metrology serves as feedback into deterministic grinding and polishing platforms. Many different techniques and devices are used to qualify an asphere surface during fabrication.

A contact profilometer is one of the most common measurement technologies used in asphere manufacturing. A profilometer uses a fine stylus to drag a diamond or ruby tip over the surface, resulting in a high resolution curved profile. Coordinate measuring machines (CMM) apply a similar concept by touching the optic with a ruby or silicon carbide sphere. A CMM is able to move in three dimensions while collecting data points along the asphere surface. Optical interferometers use a helium-neon laser with transmission spheres to compare a reflected wavefront from an asphere surface to a reference spherical wavefront. Large departure aspheres can be measured when a computer generated hologram (CGH) is introduced between the interferometer and the optic. OptiPro Systems has developed a non-contact CMM called UltraSurf. It utilizes a single point non-contact sensor, and high accuracy air bearings. Several different commercial non-contact sensors have been integrated, allowing for the flexibility to measure a variety of surfaces and materials.

Metrology of a sphere and an asphere using a profilometer, CMM, Interferometer with a CGH, and the UltraSurf will be presented. Cross-correlation of the measured surface error magnitude and shape will be demonstrated. Comparisons between the techniques and devices will be also presented with attention to accuracy, repeatability, and overall measurement time.

8884-27, Session 5

Non-contact metrology of aspheric surfaces based on MWLI technology

Gernot Berger, Juergen Petter, Lufos GmbH (Germany)

Today's machines for the production of optical surfaces achieve form accuracies in the range of a few nanometers and are able to make increasingly complex shapes. This trend puts more and more extreme demands on the employed measurement technology. Besides the absolute form measurement accuracy, which must be significantly better than ± 100 nm, crucial requirements include high flexibility in terms of the asphericity (i.e. large spherical departures), base form (e.g. segmented optics), and surface texture (different materials, material mixes, ground, polished). On top of this, measurement times need to be always short and measuring also large optics should be possible. In this contribution a unique and highly flexible approach is presented that enables non-contact profiling of rotational symmetric optics with diameters from 2 mm up to 420 mm. By means of a scanning point interferometer (based on MWLI) the technology meets the above demands. It combines the precision and speed of optical

interferometers with the form flexibility of classical tactile scanning profilometers. The system layout and the concept enabling the high overall system accuracy are explained. Measurement results of various optics (including annular, segmented, and ground optics, optics with diffractive steps, and smart phone lenses) and measurement limits are discussed in detail.

8884-28, Session 5

Vertical interferometer workstation for testing large spherical optics

Bruce E. Truax, Zygo Corp. (United States)

There is a need in precision optics fabrication to measure the radius of curvature and surface quality of large spherical optics. To address this need Zygo designed a interferometer workstation and optical accessories capable of testing optics up to 425mm in diameter with masses of up to 40kg in a downward looking configuration. To measure both spherical and plano surfaces the system incorporates a part stage with 6 axes of adjustment. A unique method for the implementation of focus, roll and pitch was used allowing for extremely precise adjustment. Very high system stiffness to minimize the effects of environmental disturbance is achieved by supporting the metrology loop in a rigid box structure utilizing polymer granite filled fabricated steel columns. The completed system includes a 300mm diameter transmission flat and 300mm input aperture transmission spheres with f-numbers from f/1.6 to f/0.82 with reference surface diameters of up to 300mm and surface accuracies of better than 63nm PV. These large test optics use a new kinematic accessory mount capable of supporting up to 150kg with a fine adjustment mechanism allowing precision alignment to the optical axis of the interferometer. The design challenges and resulting solutions are discussed. System performance results are presented.

8884-29, Session 5

Retrace error: interferometry's dark little secret

Cody B. Kreischer, Kreischer Optics, Ltd. (United States)

Fizeau type phase measuring interferometers are widely used in the optics industry for surface metrology. Measurement of spherical surfaces requires the use of transmission spheres which are commercially available in various F-numbers. A basic assumption of Fizeau interferometry is that the light reflected off the reference surface, called the reference beam, and the light reflected off the surface being tested, called the test beam, follow a common path back through the optics. For this to be strictly true, we would need the surface being tested to be perfectly spherical and positioned exactly concentric with the reference surface. Measurement inaccuracy that results from failure to meet this condition is referred to as retrace error. Retrace error has been largely ignored with regard to testing nominally spherical surfaces, yet it can be significant when high test accuracy is needed. In this paper, the author identifies two types of retrace error resulting from the test setup: Axial; induced spherical aberration resulting from defocus, and Transverse; induced coma as a result of tilt. The magnitude and exact form of retrace error is shown to be a function of the optical design of the transmission sphere. It is shown that, for the most part, measurement accuracy is independent of the transmitted wavefront error of the transmission sphere. It is shown that retrace error can be modeled in a lens design program with excellent agreement to measurement data. Specific design examples will be presented, including improvements to minimize retrace error. The significance of retrace error to the test accuracy of both spherical and aspheric surfaces will be discussed.

8884-30, Session 5

Round-robin measurements of toroidal window

Kate Medicus, Optimax Systems, Inc. (United States); Scott DeFisher, OptiPro Systems (United States); Marcin Bauza, Carl Zeiss Industrial Metrology LLC (United States); Paul Dumas, QED Technologies, Inc. (United States)

Free-form surfaces are quickly becoming a desired and necessary shape for many refractive and reflective optical systems. Some examples of free-form shapes are toroids, ogives, and other conformational windows. It is clear that the manufacturing of these shapes is limited by accurate metrology, which is required for deterministic polishing, the final manufacturing step of these surfaces.

To address this concern, we have performed several measurements of a toroidal window (with millimeters of departure from a best-fit sphere) using different techniques with a goal of producing a surface map. The toroid is a window 110 mm square with concave and convex surfaces. All measurements were done blind; no participant knew the others' measurement results before completing their own measurement.

We will present the results of each of our measurements along with a description of the measurement method. The various methods are: multiple commercially available bridge type coordinate measuring machines with a touch trigger probe, a specialty built (non-bridge) coordinate measuring machine with a non-contact probe, a high-resolution subaperture stitching interferometer, an extremely accurate coordinate measuring machine with a micro-force probe, a metrological computed tomography machine, a new interferometric tomography technique, and phase shifted deflectometry system designed to look for surface defects. We will present 5 to 8 measurements each surface of the toroid window. In addition, three of the methods measured the thickness variation of the window.

The results illustrate the current capabilities of each measurement technology, highlighting their strengths and pointing to areas of improvement.

8884-31, Session 5

Improved averaging for non-null interferometry

Jon F. Fleig, Paul E. Murphy, QED Technologies, Inc. (United States)

Arithmetic averaging of interferometric phase measurements is a well-established method for reducing the effects of time varying disturbances, such as air turbulence and vibration. Calculating a map of the standard deviation for each pixel in the average map can provide a useful estimate of its variability. However, phase maps of complex and/or high-density fringe fields frequently contain defects that severely impair the effectiveness of simple phase averaging and bias the variability estimate. These defects include large or small-area phase unwrapping artifacts, large alignment components, and voids that change in number, location, or size. Inclusion of a single phase map with a large area defect into the average is usually sufficient to spoil the entire result. Small-area phase unwrapping and void defects may not render the average map metrologically useless, but they pessimistically bias the variance estimate for the overwhelming majority of the data. We present an algorithm that obtains phase average and variance estimates that are robust against both large and small-area phase defects. It identifies and rejects phase maps containing large area voids or unwrapping artifacts. It also identifies and prunes the unreliable areas of otherwise useful phase maps, and removes the effect of alignment drift from the variance estimate. The algorithm has

several run-time adjustable parameters to adjust the rejection criteria for bad data. However, a single nominal setting has been effective over a wide range of conditions. This enhanced averaging algorithm can be efficiently integrated with the phase map acquisition process to minimize the number of phase samples required to approach the practical noise floor of the metrology environment.

8884-32, Session 5

Development of a high-speed nanoprofiler using normal vector tracing method for high-accuracy mirrors

Kohei Okuda, Takao Kitayama, Koji Usuki, Takuya Kojima, Kenya Okita, Junichi Uchikoshi, Osaka Univ. (Japan); Yasuo Higashi, High Energy Accelerator Research Organization (Japan); Katsuyoshi Endo, Osaka Univ. (Japan)

Recently, high precise optical elements are used in various fields. Ultraprecise aspherical mirrors which offer nano-focusing and high coherence are used to concentrate high brightness X-rays in developing third-generation synchrotron radiation institutions. In industry, the extreme ultraviolet (wavelength: 13.5 nm) lithography which contributes to fabricating semiconductor devices uses high-accuracy asymmetric mirrors for its projection optical systems. A request of large progress of the nano measurement and processing technologies is increasing, because it is difficult for such next-generation ultraprecise mirrors to achieve required precision by the normal processing. As for the measuring method in particular, ultra-precision is required, and we developed innovative nanoprofiler that can directly measure the figure of high accuracy mirrors without using a reference surface. The principle of our measuring method is to determine the normal vectors by making the optical paths of incident and reflected light at the measurement point coincident, which is based on the straightness of laser light and the accuracy of rotational goniometers. From the acquired normal vectors and their coordinates, the three-dimensional shape is calculated by a reconstruction algorithm. We calibrated this nano-profiler by considering the system error resulting from assembly error, and evaluated the performance of the nanometer. We measured concave spherical and flat mirrors, and compared the results with those using a phase-shift Fizeau interferometer. The mirror profiles measured by both the instruments were consistent within the range of systematic errors, respectively.

8884-500, Session 6

Disruptive innovation: the story of the first digital camera (*Plenary Paper*)

Steven Sasson, Retired, Eastman Kodak Co. (United States)

The creation of the first digital camera prototype in 1975 at the Eastman Kodak Company will be discussed as well as how the concept was demonstrated within Kodak during the following year. Subsequent technical innovations with megapixel imagers, image compression products in the mid 1980's, and the early commercialization of professional and consumer digital still cameras in the early 1990's will be discussed. The internal Kodak reaction to these developments will be highlighted as well as some of the learned observations about how to deal with disruptive innovation within an established corporate environment will be shared.

8884-34, Session 7

Fabrication and metrology of high-precision freeform surfaces

Chris Supranowitz, QED Technologies Inc (United States); Paul Dumas, QED Technologies, Inc. (United States); Tobias Nitzsche, QED Technologies Inc (United States); Jessica D. DeGroot Nelson, Brandon B. Light, Optimax Systems, Inc. (United States); Kate Medicus, Optimax Systems Inc. (United States); Nathan Smith, Optimax Systems, Inc. (United States)

The need for freeform optical surfaces is being driven by a range of applications. These applications include the desire to package an optical system into smaller spaces, such as helmet-mounted displays. The extreme wavelength and precision of EUV lithography requires all-mirror systems that traditional rotationally symmetric designs cannot achieve. Conformal optics, such as windows integrated into airplane wings, drive freeform designs that must satisfy both optical and mechanical performance specifications. These non-rotationally symmetric optical surfaces pose challenges to the optical fabrication process, mostly in the areas of polishing and metrology. Single point contour grinding and diamond turning processes are well suited to extend to freeform shapes. The same is true for single-point metrology processes like coordinate measuring machines (CMM). Polishing and interferometry processes, however, inherently interact with the optical surface over the full aperture, or at least a subaperture. The varying curvature of freeform surfaces poses significant challenges and drives the need for smaller, more "conformal", tools for polishing and stitching processes for interferometry. In this paper, we present fabrication results for a high-precision freeform surface. We discuss the total manufacturing process, including grinding, pre-polishing, finishing, and metrology, highlighting the capabilities available in today's optical fabrication companies. Results from technologies such as ultrasonic generation, VIBE polishing, Magnetorheological Finishing (MRF), Subaperture Stitching Interferometry (SSI), and CMM metrology will be discussed to illustrate a complete manufacturing solution for high-precision freeform surfaces.

8884-35, Session 7

A simple procedure to include a free-form measurement capability to standard coordinate measurement machines

Florian Schneider, Rolf Rascher, Hochschule Deggendorf (Germany); Richard J. Stamp, Gordon Smith, Univ. of the West of England (United Kingdom)

The modern optical industry requires objects with complex topographical structures. Free-form shaped objects are of large interest in many branches, especially for size reduced, modern lifestyle products like digital cameras. State of the art multi-axes-coordinate measurement machines (CMM), like the topographical measurement machine TII-3D, are by principle suitable to measure free-form shaped objects. The only limitation is the software package. This paper may illustrate a simple way to enhance coordinate measurement machines and add a free-form function.

Next to a coordinate measurement machine, only a state of the art CAD system and a simple piece of software are necessary. For this paper, the CAD software CREO had been used. CREO enables the user to design a 3D object in two different ways. First, the user might design the shape by drawing one or more 2D sketches and put an envelope around. Second, the user could use the formula editor to define one or more mathematical formula which describes the favoured surface. Both procedures lead to the required three-dimensional shape. However,

further features of CREO enable the user to export the XYZ-coordinates of the created surface.

A special designed software tool, engineered with Matlab, converts the XYZ-file into a measurement matrix which can be used as a reference file. Finally the result of the free-form measurement, carried out with a CMM, has to be loaded into the software tool and both files will be computed. The result is an error profile which provides the deviation between the measurement and the target-geometry.

8884-36, Session 7

3D-form metrology of arbitrary optical surfaces by absorption in fluids

Juan Carlos Martinez-Anton, Juan Manuel Plaza Ortega, Jose Alonso Fernandez, Univ. Complutense de Madrid (Spain)

Precision complex optical surfaces are increasingly produced thanks to the advancements in optical fabrication. However, the metrology of these surfaces still lacks some integration in the production line or it is cost prohibitive for small batches. We present a new technique in optical metrology (TOPAF) conceptually distant from the classical approaches. It has significant potential to reduce costs in the production of aspheric, freeform lenses, arrays and other complex shapes on transparent substrates (UV-Vis-IR). It may be applied in all production steps: from grinded to polished parts. It is based on the optical absorption of a water-soluble dye situated between the surface to measure and a reference surface. We take few images of this setup illuminated by a bi-chromatic diffuse light. Under this simple scheme, we may get a detailed topographic map fast and reliably, no matter the surface form, slope and finish. A height resolution below $\lambda/20$ and a sag departure of millimetres are achievable as we will show with analytical and experimental results that support these assertions. Results on aspheric lenses, spherical arrays, rough surfaces and a Rx ophthalmic lens are provided.

8884-37, Session 7

Worthwhile optical method for free-form mirrors qualification

Giorgia Sironi, Rodolfo Canestrari, INAF - Osservatorio Astronomico di Brera (Italy); Giorgio Toso, INAF - IASF Milano (Italy); Giovanni Pareschi, INAF - Osservatorio Astronomico di Brera (Italy)

We present a method developed by INAF (Italian National Institute for Astrophysics) for the qualification of free-form concave mirrors with few microns accuracy required on the shape error. The developed technique is a Ronchi-like optical test based on the comparison of the image generated by the under-study reflecting surface and the image the completely compliant optic should generate in the same configuration. By means of the acquired images it is indeed possible to reconstruct a slope error map of the surface useable both for the mirror shape error reconstruction and for the optical performance evaluation obtained by means of a proprietary ray-tracing code. The advantages of the proposed method is that it offers accuracy comparable to the 3D coordinates measuring machine one but it can be performed on-site using commercial tools, reducing production time and costs.

In this paper we report the measuring concept and compare the obtained results to the analogues obtained by means of a 3D coordinates measuring machine measure. We will discuss the resolution and accuracy limits of the method and their correlation to the different possible measuring configurations and adopted masks. As example, the qualification of the ASTRI (Astrofisica con Specchi a Tecnologia Replicante Italiana) primary mirror segments, realized at INAF in the context of the IACT (Imaging Atmospheric Cherenkov Telescope) project is reported.

8884-93, Session 7

Ex and in situ metrology based on (Shack) Hartmann technique for sub-nanometric metrology

Mourad Idir, Brookhaven National Lab. (United States); Guillaume Dovillaire, Imagine Optic SA (France); Pascal Mercère, Synchrotron SOLEIL (France)

The recent development of third and fourth generation synchrotron radiation facilities has led to unprecedented progresses in X-ray applications such as microscopy, imaging, diffraction and photolithography. To optimize performance in these research areas, metrology tools with capabilities in the nanometre and even the sub-nanometre range are mandatory, in order to characterize the surface figure errors of the optics used to focus or collimate the X-ray beams, to align them on the beam lines and to perform diagnostics of the beam spatial profile. To answer these needs, we have developed two families of instruments for Ex and In Situ Metrology: a Stitching Shack-Hartmann Optical Head (SSH-OH) which performs bidimensional surface figure measurement of X-ray mirrors with nanometer precision and a X-ray Hartmann wavefront sensors (HWS) to measure and control the spatial quality of X-ray beams, to perform in situ alignment and characterisation of optical components.

8884-38, Session 8

Characterization of structural relaxation in As₂Se₃ for analysis of lens shape change in glass press mold cooling and post-process annealing

Erick Koontz, Peter Wachtel, J. David Musgraves, Kathleen Richardson, Univ. of Central Florida (United States) and Clemson Univ. (United States)

This study explores the structural relaxation behavior of As₂Se₃ by thermo mechanical analysis in order to characterize and eventually predict volume change in As₂Se₃ upon relaxation during cooling after precision glass molding (PGM) and annealing. A vertical beam of As₂Se₃ was placed in a thermo mechanical analyzer and fully relaxed at a given temperature. The temperature was then quickly changed a given amount and the 1-D relaxation of the beam was measured until it reached equilibrium at the new temperature. The resultant curve was then fit with a Prony series which captured the relaxation data. The mathematical representation of the relaxation is then analyzed as a function of time, temperature, and quench rate and can be used to predict 1-D length change upon relaxation. A maximum of 3 terms is needed to describe the relaxation behavior and that number declines with an increase in temperature. This decay of the number of Prony terms needed to describe relaxation points to a structure that relaxes with less complexity as it approaches T_g. These trends can be converted to 3-D due to the amorphous and therefore typically isotropic nature of As₂Se₃ glass. This volume change information as a function of vital processing parameters can then be used to predict the change in shape of a work piece during cooling or post process annealing within a precision molding cycle. The mathematical representation of volume relaxation can then be applied to finite element models (FEM) of As₂Se₃ lenses or other optical elements.

8884-39, Session 8

Compositional-tailoring of optical properties in IR transparent chalcogenide glasses for precision glass molding

Benn H. Gleason, Peter Wachtel, J. David Musgraves, Clemson Univ. (United States); Amy Qiao, Norman Anheier, Pacific Northwest National Laboratory (United States); Kathleen Richardson, Clemson Univ. (United States) and CREOL, The College of Optics and Photonics, Univ. of Central Florida (United States)

Five chalcogenide glasses in the GeAsSe ternary glass system were melted, fabricated into polished flats, and molded using a laboratory-scale precision glass molding (PGM) machine. Using binary arsenic triselenide, As₄₀Se₆₀, a commonly available industrial glass as a starting point, this effort examined the effect of adding 5 mol% of either Ge or Se to the composition which is known to influence structural as well as optical properties. The bulk glass density, refractive index, and thermo-optic coefficient (dn/dT) were measured for all compositions, as well as the refractive index after PGM. For the bulk glasses examined, both the refractive index and dn/dT decreased as the molecular percentage of either Ge or Se is increased. After the PGM process, glasses demonstrated an "index drop" consistent with oxide glasses noted in literature [1]. This index drop was also found to be compositionally dependent, again decreasing as the molecular percentage of either Ge or Se is increased and loosely correlated to the starting index of the bulk glasses. Both the Ge-containing and Ge-free tie-lines show potential for a composition with a zero "index drop" after molding, allowing for a novel series of compositions which could be machine for prototyping and later molded for production.

[1]"Refractive index and dispersion variation in precision optical glass molding by computed tomography" W. Zhao et al. App Optics. 48 19 3588-3595 (2009)

8884-40, Session 8

Aqueous cleaning of precision optics parts

Henry P. Ederle, Borer Chemie AG (Switzerland)

The presentation covers different aspects of aqueous ultra-sonic cleaning of precision optics parts by explaining the effects and significance of each cleaning and rinsing step.

The removal of the following contaminants will be described:

- protective lacquers,
- resins,
- putties,
- pitch,
- wax
- polishing compounds
- colour markings
- fingerprints, dust
- storage residues

The suitability (material compatibility) of the different cleaning chemicals for use with the different glass types and different resistance classes such as:

- Water resistance RW(p)
- Acid resistance RA(p)
- Weathering resistance W(s)
- Acid resistance (SR), ISO 8424
- Phosphate resistance (PR), ISO 9689

Major focus of this presentation will be on the importance of rinsing and water quality for the last cleaning steps.

8884-41, Session 8

SP-100 the fast and reliable machine for coating application in precision optics

Gianni G. Monaco, Satisloh Italy S.p.A. (Italy); Marc Peter, Satisloh IPhotonics (Italy) and Satisloh Photonics (Switzerland); Arturo Colautti, Satisloh Italy S.r.l. (Italy); Tom Godin, Satisloh North America Inc. (United States); Steffan Gold, Satisloh Wetzlar (Italy); Michael Witzany, Satisloh Italy (Italy) and Satisloh Italy S.r.l. (Italy); Frank Breme, Satisloh AG (Switzerland)

SP-100 from Satisloh is the perfect coating machine for application in precision optics. Thanks to its innovative concept SP-100 can coat materials in a range of refraction indexes from 1.47 up to 2.05 in the visible (with all the intermediate indexes in between) and up to n=3.5 in the infrared by using only one target material. SP-100 is well suitable for application in the field of microscopy, laser optics, watches, optical filters, endoscopy, semiconductors and more. By replacing the target material the application range of the machine can be further extended.

SP-100 is based on the reliable reactive bipolar Direct Current (DC) pulsed magnetron sputtering technology which guarantees high density of the deposited species, low stress of the deposited multilayer film, high reproducibility, very high hardness (up to 1200 Vickers hardness) with unbeatable high rates ideal for industrial applications. DC-pulsed sputtering assure less arc events and a lower heat load than Radio Frequency (RF) sputtering making SP-100 suitable for different substrates material and for cemented lenses. The small chamber of the SP-100 ensure very fast processes and a broadband AR can be coated in less than 15 minutes process time door to door. Thanks to its flexible substrate holder SP-100 can hold lenses of different sizes and shapes: from small size optics up to 100 mm diameter lenses, rod lenses up to 50 mm length or even glass fibers.

8884-42, Session 8

Development of a high specification coating

Peter E. MacKay, Gooch & Housego Plc (United Kingdom); Mike Wilde, Gooch & Housego (UK) Ltd (United Kingdom)

For many years Gooch and Housego have been supplying very high laser induced damage threshold coated parts to projects such as the National Ignition Facility. We have optimised our substrate preparation and coating processes to achieve repeatable performance well in excess of 10Jcm⁻², 1064nm 3ns pulses. This has used electron beam deposition technology. While this has performed well in the controlled environments of the science labs, it is well known that the coatings produced are porous and therefore susceptible to absorbing water and other chemicals from the atmosphere, modifying the coating performance. The traditional solution has been to select ion beam sputtering deposition techniques, but these are typically expensive, with smaller capacity chambers and produce high stress coatings. Therefore they are not optimal for higher volume components and thin substrates. We present the results of our development to optimise an ion-assisted deposition technique offering the possibility of trading off various design parameters including coating porosity and laser damage threshold, to optimise the coating performance of optics located where they can suffer contamination and outgassing. Such coatings include the challenging design of a dual band visible and 1064nm optimised for both visible transmission range and LIDT performance at 1064nm.

8884-43, Session 8

Refractive index of thin films realized by Satisloh SP reactive sputtering system

Gianni G. Monaco, Satisloh Italy S.p.A. (Italy); Arturo Colautti, Cristina Allegro, Satisloh Italy S.r.l. (Italy); Tom Godin, Satisloh North America Inc. (United States); Steffan Gold, Satisloh GmbH (Germany); Michael Witzany, Satisloh Italy S.r.l. (Italy)

Pulsed DC reactive sputtering is a very interesting technique for coating applications. Reactive sputtering can give very dense layers, low stress of the deposited multilayer film, high reproducibility, very high hardness (up to 1200 Vickers hardness) with unbeatable high rates ideal for industrial applications.

SP-100 is Satisloh reactive sputtering systems with only one target material but can deposit various film materials simply by using different gases such as argon, as well as the reactive gases nitrogen and oxygen. Silicon-oxides, silicon-nitrides and all kinds of siliconoxy-nitrides ($\text{SiO}_x\text{-Si}_x\text{O}_y\text{N}_z\text{-Si}_x\text{N}_y$) with a refractive index range of 1.44-2.05 in the visible range can be obtained.

In the reactive sputtering the material it is usually deposited in the so called "transition mode" where it must be found the correct equilibrium point between the target voltage and the reactive gas flow. The transition mode assure a dense film with a stable rate. Condition to find such equilibrium point is given by the so called "material hysteresis" in which the target voltage is depicted in function of the reactive gas voltage. The hysteresis and the consequent equilibrium point are strongly depended by the power supplied to the target and the inert gas (argon) flow which could affect the optical characteristics and the deposition rate. We checked the refractive indexes of the SiO_x and Si_yN_z of very thin (1 QW Optical thickness at 520 nm) and thicker (3, 5 and 9 QW @520 nm) reporting how the different conditions can affect the refractive index and the deposition rate of the different materials.

8884-44, Session 9

Optical design with orthogonal surface descriptions

Gregory W. Forbes, QED Technologies, Inc. (United States); Christoph Menke, Carl Zeiss AG (Germany)

Slope-orthogonal representations of aspheric shapes were initially introduced to give a more effective and intuitive characterization as well as to deliver the ability to cope with shapes of increasing complexity. We have found, however, that standard design codes (including CodeV and Zemax) can in some cases find systems with better optical performance when optimized in this new representation. After a brief overview of the new convention, a few simple rotationally symmetric examples are presented. We also show some striking results within the realm of freeform design. In that case, systems designed in terms of a gradient-orthogonal representation significantly outperform those found by using either Cartesian or Zernike polynomials. In all of the examples, the end results can be retro-fitted in terms of conventional representations, but the optimizers are unable to find the superior solutions unless the orthogonal bases are employed during the design process. Now that these tools are available in the commercial codes, and that the communication of shape is so much more effective in these terms, our results give added support for a movement across the communities of design, fabrication, and testing to this gradient-orthogonal description of shape.

8884-45, Session 9

Design of systems involving easily measurable aspheres

Paul E. Murphy, QED Technologies, Inc. (United States); Dave Stephenson, JENOPTIK Optical Systems, LLC (United States); Andrew E. W. Jones, QED Technologies, Inc. (United States); Gregory W. Forbes, QED Technologies, Inc. (Australia)

Aspheric surfaces provide significant benefits to an optical design. Unfortunately, aspheres are usually more difficult to fabricate than a spherical surface, making the choice of whether and when to use aspheres in a design less obvious. Much of the difficulty comes from obtaining aspheric measurements with comparable quality and simplicity to spherical measurements. Subaperture stitching can provide a flexible and effective test for many aspheric shapes, enabling more cost-effective manufacture of high-precision aspheres. To take full advantage of this flexible testing capability, however, the designer must know what the limitations of the measurement are, so that the asphere designs can be optimized for both performance and manufacturability. In practice, this can be quite difficult, as instrument capabilities are difficult to quantify absolutely, and standard asphere polynomial coefficients are difficult to interpret.

The slope-orthogonal "Q" polynomial representation for an aspheric surface is ideal for constraining the slope departure of aspheres. We present a method of estimating whether an asphere described by Q polynomials is measurable by QED Technologies' SSI-A system. This estimation function quickly computes the testability from the asphere's prescription (Q polynomial coefficients, radius of curvature, and aperture size), and is thus suitable for employing in lens design merit functions. We compare the estimates against actual SSI-A lattices. Finally, we explore the speed and utility of the method in some lens design studies.

8884-46, Session 9

Using Microsoft Excel as a pre-processor for CODE V optimization of air spaces when building camera lenses

Dave Stephenson, JENOPTIK Optical Systems, LLC (United States)

When building high-performance camera lenses, it is often preferable to tailor element-to-element airspaces instead of tightening the fabrication tolerances sufficiently so that random assembly is possible. A tailored airspace solution is usually unique for each serial number camera lens and results in nearly nominal performance for each. When these airspaces are computed based on as-measured data rather than as-built test data, this can put a strain on the Design Engineering department to deal with all the data in a timely fashion. Excel may be used by the Assembly technician as a pre-processor tool to facilitate data entry and organization, and to perform the optimization using CODE V (or equivalent) without any training or experience in using CODE V. This makes it unnecessary to involve Design Engineering for each lens or wait in their queue. In addition, Excel can be programmed to run CODE V in such a way that discrete shim thicknesses are utilized. This makes it possible for each tailored airspace solution to be achieved using a finite number of shims that differ in thickness by a reasonable amount, like 0.05 mm. It is generally not necessary to tailor the airspaces in each lens to the micron level to achieve nearly nominal performance.

8884-47, Session 9

Integration of measurement data in the comprehensive modelling approach

Ingo Sieber, Karlsruher Institut für Technologie (Germany); Olaf Ruebenach, INGENERIC GmbH (Germany)

Efficient and reliable optical design requires knowledge of the production chain, the materials used, and the environmental circumstances in the field of operation. This is realized in the comprehensive modelling approach consisting of three steps:

1. Design for manufacturing, i.e. the model must be adjusted to the process chain. Knowledge of design rules is required.
2. Robust design, i.e. optimization of the functional design with the objective of a compensation of the tolerance influences on the system's performance. Knowledge of the tolerances of the individual process steps is required.
3. Reliable design with respect to environmental and operational effects, respectively. Coupling of an optical and mechanical simulation tool is required to form the optical simulation environment.

The availability of process knowledge such as e.g. design rules and manufacturing tolerances is ensured by coupling of the optical simulation environment with a process knowledge database.

Integration of measured surface data in this simulation environment enables a realistic simulation and analysis of real, manufactured optics. This approach allows e.g. for the evaluation of replication methods such as precision molding or injection molding against high-precision manufacturing methods, e.g. diamond turning.

After introducing the concept and implementation of the comprehensive modeling approach, the concept of integration of the measured surface data in the model will be presented along with its application to the tuneable optics of the Artificial Accommodation system currently under development in the KD Optimi programme funded by the German Federal Ministry of Education and Research.

8884-48, Session 9

Rapid design of LED optical elements with two free-form surfaces generating uniformly illuminated rectangular area

Mikhail A. Moiseev, Leonid L. Doskolovich, Sergey V. Kravchenko, Image Processing Systems Institute (Russian Federation)

Design of LED optical elements producing uniform illumination in rectangular regions is one of the most actual and challenging problems in the development of lighting devices. Even in case of the single free-form refracting surface the general analytical solution does not exist and various iterative or feedback methods are usually used. As a rule, the LED optical element has at least two surfaces (inner and outer) that provides a large computational complexity of the design process. In this case the only well-known and working solution consists in the optimization of the shape of optical element using standard techniques implemented in commercial lighting software (e.g. TracePro®, LightTools®). Such approach has high computational cost and does not guarantee the obtaining of the appropriate solution.

We propose a new rapid computational method for automatic design of optical elements with two free-form surfaces generating uniform irradiance distribution in the rectangular region. The method includes three stages: analytical computation of the initial approach, parameterization of the surfaces by the bicubic splines and optimization of the spline parameters. For acceleration of the optimization process we derived an analytical expression which allows to estimate the generated irradiance distribution and to evaluate the

merit function in a split of a second. Usage of this analytical expression reduces the time of optimization to few minutes. As an example, the optical element producing uniformly illuminated area with size of 2 m by 3 m is designed. The lighting efficiency of the obtained solution is more than 91%.

8884-49, Session 9

Design of freeform optical elements generating a line-shaped directivity diagram

Leonid L. Doskolovich, Anton Y. Dmitriev, Mikhail A. Moiseev, Image Processing Systems Institute (Russian Federation)

We propose a novel method of designing a refractive surface to generate a directivity diagram (DD) represented as a vector function of one argument. A general relationship for the refractive surface is derived as an envelope of a parametric family of ellipsoids or hyperboloids of revolution (depending on the relative refractive index of the media separated by the surface). Each surface in the family transforms the incident spherical beam from a point (compact) light source into a beam with plane wavefront of desired direction. Several alternative representations for the envelope surface are obtained. In particular, the envelope is represented as a family of curves given by the intersections of ellipsoids (hyperboloids) of revolution with circular cones of rays from the point source. The most important practical problem of generating a line-segment DD is specially studied. This problem can be considered as a standard problem of generating complex DDs composed of a set of line-segments. Indeed, to generate such a DD one can use segmented refractive surface (i.e. the surface constructed from segments, each of them generating corresponding line-segment of the composite DD). A great number of complex geometrical shapes can be approximated by set of line-segments with feasible accuracy. In the case of line-segment DD the calculation of the ellipsoid (hyperboloid) parameters providing required intensity distribution along the DD is reduced to the solution of an explicit first order differential equation. Optical element (LED lens) generating line-segment directivity diagram is designed. The simulation results demonstrate generation of high-quality DD.

8884-50, Session 10

Optical characterization of window materials for aerospace applications

Ken K. Tedjojuwono, Natalie Clark, William M. Humphreys Jr., NASA Langley Research Ctr. (United States)

An enduring need has been identified in the aerospace community to develop transparent window materials that meet or exceed the optical, mechanical, and structural properties of current windows in such applications as crewed spacecraft, crewed habitats and high performance aircraft. Traditionally, fused silica glass has been the material of choice for NASA space missions (e.g., Apollo, Shuttle, and ISS) but this material entails an unacceptable weight penalty. Because it is a brittle material, glass is highly unreliable for use as a primary structure, and therefore designs are penalized by the requirement of providing window pane redundancies. Alternate materials from glass are available, but their use is predicated on the materials allowing high resolution imagery to be conducted through them. For these reasons, the former NASA Exploration Technology Development Program (ETDP) tasked the Advanced Sensing and Optical Measurement Branch at NASA Langley (as part of a wider effort involving the Johnson Space Center and the Glenn Research Center) to commission an optical metrology laboratory capable of quantitatively measuring a number of optical parameters for candidate lightweight window materials for future aerospace use.

The Langley optical metrology laboratory is equipped with a suite of instruments and systems to perform the measurements of: optical transmittance, haze, clarity, birefringence, homogeneity, interferometric wavefront quality, wedge, image quality, and color balance. To date the laboratory has conducted extensive testing on a range of candidate materials from optical polymers (polycarbonate, acrylics, polyurethane) to transparent ceramics (aluminum oxinitride and Spinel).

The full paper will describe in detail the rationale for the laboratory, a description of laboratory capabilities, and an overview and impact of the optical property data that has been acquired to date for use in the aerospace community.

8884-51, Session 10

Development of a calibration standard for spherical aberration

David C. Compertore, Filipp V. Ignatovich, Matthew E. Herbrand, Michael A. Marcus, Lumetrics, Inc. (United States)

Currently, no standard is available for metrology equipment used to measure spherical aberration. As an example, Intraocular lenses (IOL) used in cataract surgery have various levels of spherical aberration designed into them to optimize a patient's post-surgery vision. IOL manufacturers will benefit from an SA certification method using SA certified plano-convex lenses to maintain the accuracy of test equipment used in the building and design of intraocular lenses.

We have selected a set of plano-convex lenses that can be used as SA calibration standards with a NIST-traceable EFL component. The off-the-shelf lenses are tested on a NIST-traceable optical nodal bench, by Optical Testing Laboratory in Corvallis, Oregon to measure the lenses effective focal length (EFL). The central thicknesses of the lenses are measured using the low-coherence interferometer OptiGauge™. The lenses are modeled in optical modeling software (Zemax), where the spherical curvature of the lenses are adjusted to match the EFL, the center thicknesses adjusted to the measured reading, and the theoretical spherical aberrations calculated for different diameters of apertures. Spherical aberrations of the lenses are measured using a commercially available aberrometer CrystalWave™, based on a Shack-Hartmann wavefront sensor. The measured SA's are compared to the calculated theoretical values. For certain lenses we obtained better than 2% agreement between the measured and theoretical values. A tolerance analysis investigates sources of remaining errors including positioning errors, and residual asphericity of the convex lens surface.

8884-52, Session 10

Metrology for multilayer Laue lenses

Nathalie Bouet, Raymond Conley Jr., Juan Zhou, Hanfei Yan, Xiaojing Huang, Yong S. Chu, Brookhaven National Lab. (United States)

The rapid growth of nanoscience requires X-ray microscopy tools with probing capability at the nanometer scale. The multilayer Laue lenses (MLL), a type of volume diffractive optics, have been shown in theory to be able to focus X-rays to 1 nm with high efficiency. Multi-gas reactive sputtering has been used to achieve stress and interfacial roughness reduction. This technique was found to produce WSi₂/Si multilayers with an accumulated film stress significantly lower than Ar-only deposition with identical growth conditions. In the case of fabrication of Multilayer Laue lenses, the growth thickness may reach tens of microns which require different types of metrology to provide adequate information about interfacial roughness, long-term growth rate changes, and film stress in addition to X-ray reflectivity measurements.

Proper layer thickness and placement throughout the stack presents a major obstacle to the fabrication of high-quality nanofocusing MLLs. New metrology strategy involving marker layers, scanning electron and transmission X-ray microscopies will be presented.

8884-53, Session 10

Precision interferometric measurements of refractive index of polymers in air and liquid

Michael A. Marcus, Kyle Hadcock, Don Gibson, Matthew E Herbrand, Filipp V. Ignatovich, Lumetrics, Inc. (United States)

Recently, non-contact metrology methods have become increasingly popular in the field of industrial production of various devices. Most of these methods rely on optical properties of the material measured. For example, the OptiGauge™ uses fast low-coherence interferometry to precisely measure optical thickness of the materials of interest. In order to obtain the physical thickness of the devices, the refractive index of the material needs to be known. Precise knowledge of the refractive index is essential to obtain precise thickness of the devices. Since the index of refraction of many plastic materials tend to change batch to batch and is also a function of temperature and wavelength the index of refraction needs to be measured accurately in order to certify the physical thickness of the device.

We have developed a procedure using a low coherence interferometer for precise measurement of the refractive index in air, as well as in liquid environments. For example, in manufacturing of contact lenses, the lenses are always kept hydrated. In addition to thickness, optical performance of the lenses also depends on the refractive index. The small difference between the index of refraction of the liquid and that of the lens makes the measurements of the refractive index of contact lenses especially challenging. The developed procedure allows us to obtain measurement repeatability of better than 1×10^{-3} in refractive index measurements for materials of thicknesses less than 100 microns thick measured in liquid.

8884-54, Session 10

Optical test bench for high precision metrology and alignment of zoom sub-assembly components

Francois Lepretre, Eric Levillain, Thales Angénieux S.A. (France); Benoit F. Wattellier, Pascal Delage, Djamel Brahmi, Antoine Gascon, PHASICS S.A. (France)

Thales Angénieux (TAGX) designs and manufactures zoom lens assemblies for cinema applications. These objectives are made of mobile lens assemblies. These need to be precisely characterized to detect alignment, polishing or glass index homogeneity errors, which amplitude may range to a few hundreds of nanometers. However these assemblies are highly aberrated with mainly spherical aberration (>30 μm PV).

PHASICS and TAGX developed a solution based on the use of a PHASICS SID4HR wave front sensor. This is based on quadri-wave lateral shearing interferometry, a technology known for its high dynamic range. A 100-mm diameter He:Ne source illuminates the lens assembly entrance pupil. The transmitted wave front is then directly measured by the SID4-HR.

The measured wave front (WF_{meas}) is then compared to a simulation from the lens sub-assembly optical design (WF_{design}). We obtain a residual wave front error (WF_{manufactured}), which reveals lens imperfections due to its manufacturing.

$WF_{meas} = WF_{design} + (WF_{radius} + WF_{glass} + WF_{polish}) = WF_{design} + WF_{manufactured}$

The optical test bench was designed so that this residual wave front is measured with a precision below 100 nm PV. The measurement of fast F-Number lenses (F/2) with aberrations up to 30 μm , with a precision of 100 nm PV was demonstrated.

This bench detects mismatches in sub-assemblies before the final integration step in the zoom. Pre-alignment is also performed in order to overpass the mechanical tolerances. This facilitates the completed zoom alignment. In final, productivity gains are expected due to alignment and mounting time savings.

8884-501, Session 11

NASA funding opportunities for optical fabrication and testing technology development (*Plenary Paper*)

H. Philip Stahl, NASA Marshall Space Flight Ctr. (United States)

Technologies to fabricate and test optical components are required for NASA to accomplish its highest priority science missions. For example, the NRC ASTRO2010 Decadal Survey states that an advanced large-aperture UVOIR telescope is required to enable the next generation of compelling astrophysics and exo-planet science; and that present technology is not mature enough to affordably build and launch any potential UVOIR mission concept. The NRC 2012 NASA Space Technology Roadmaps and Priorities report states that the highest priority technology in which NASA should invest to 'Expand our understanding of Earth and the universe' is a new generation of astronomical telescopes. And, each of the Astrophysics division Program Office Annual Technology Reports (PATR), identifies specific technology needs. NASA has a variety of programs to fund enabling technology development: SBIR (Small Business Innovative Research); the ROSES APRA and SAT programs (Research Opportunities in Space and Earth Science; Astrophysics Research and Analysis program; Strategic Astrophysics Technology program); and several Office of the Chief Technologist (OCT) technology development programs.

8884-67, Poster Session

Position determination of disturbance along a modified Sagnac interferometer

Pang Bian, Yuan Wu, Bo Jia, Qian Xiao, Fudan Univ. (China)

Distributed sensing is one of the most attractive features of optical fiber sensors. The disturbance on the fiber can cause the change of the length and index of the fiber which can lead to a phase shift of the light wave traveling in the fiber. In this case, interferometer offers a economical and an effective measurement.

However, all the interferometers based on the sagnac loop or M-Z interferometer is sensitive to the noise caused by the polarization change or the sensing element of the system must be annular, which limits the use of the distributed sensor.

We present another type of interferometer sensor for the detection and location of the disturbances on different sensing fibers. This system is based on the sagnac interferometer and modified by a faraday rotator mirror, changing the traditional sagnac loop into a linear structure.

The interferometer has two different sensing fibers (fiber A and B), which can detect and locate disturbance along them at the same time. With a piezoelectric ring with optical fiber wound around it placed at the end of sensing fibers B to perform as the phase-modulator, disturbance signal along fiber B is modulated to a higher frequency while the disturbance signal along Fiber A is at lower frequency. With the technique of the frequency-division-multiplexing, the disturbances from the two different fibers can be detected at the same time and then be separated by a multiplier and low-pass filters. And the cross-talk of

the interferometer can be minimized by adjusting the amplitude of the signal which excites the piezoelectric ring.

With the signals from the different areas and the position determination theory, the location of the disturbances along the fiber can be figured out.

To verify the concept and result of the interferometer, a set of ten disturbances was applied at ten equally spaced locations on the two sensing fibers sequentially.

The result of the experiment shows that the disturbances on the two sensing fibers can be detected independently without cross-talk. The system is insensitive to slowly varying disturbance such as the change of the temperature and by using the faraday mirror, the noise caused by polarization change can be reduced. The error of the location is less than 500m.

8884-69, Poster Session

Properties of Kummer beams in the structure of metamaterials

Marco Marin, Univ. EAFIT (Colombia)

The properties of Kummer beams propagation and transformation in optical metamaterials are studied. The possibility is established and conditions are determined for unidirectional and opposite directional propagation of Kummer light beams phase and the longitudinal component of its energy flux in metamaterials. The reflection and refraction coefficients of arbitrary Kummer beam are represented as superposition of linear combinations of reflection and refraction ones of TM- and TE- polarized Kummer beams. These properties are studied in the LG (Laguerre-Gaussian) beams and in Bessel beams. The main goal is to compare these three beams and to show the Kummer's advantage. To use these mathematical functions a Computer Algebra Software has been used, specifically Maple.

8884-70, Poster Session

Dewar-cooler-integrated high sensitivity MWIR wave front sensor

Sabrina Velghe, William Boucher, PHASICS S.A. (France); Serge Magli, SOFRADIR (France); Gilles Aubry, HGH Systèmes Infrarouges (France); Nicolas Guérineau, Sylvain Rommeluère, Julien Jaeck, ONERA (France); Benoit F. Wattellier, PHASICS S.A. (France)

Recent developments in the Mid Wave InfraRed (MWIR) optical domain were made on materials, optical design and manufacturing. They answer increasing demands for more compact, less temperature dependent optical systems with increased optical performances and complexity (multi- or hyper- spectral imagery). At the same time, the characterization of these components has become strategic and requires solutions with higher performance.

The optical quality of such devices is measured by wavefront sensing techniques. PHASICS previously developed wavefront sensors based on Quadri-Wave Lateral Shearing Interferometry (QWLSI) using broadband microbolometers cameras for infrared measurements. However they suffer from reduced light sensitivity in the MWIR domain, which limits their use with broadband sources such as black bodies. To meet metrology demands, we developed an innovative wavefront sensor. This instrument combines the metrological qualities of QWLSI with the radiometric performances of a last generation detection block (Infrared Detector Dewar Cooler Assembly, IDDCA) with a quantum infrared focal plane array (IRFPA) of HgCdTe technology.

The key component of QWLSI is a specific diffractive grating placed a few millimeters from the focal plane array. This requirement implies that

this optics should be integrated inside the IDCCA. To achieve this, we take advantage of the experience acquired from recent developments with optics integrated in IDCCA. Thanks to this approach, we developed a high spatial resolution MWIR wavefront sensor (160x128 points) with a high sensitivity for accurate measurements under low-flux conditions.

This paper will present the instrument technological solutions, the development key steps and experimental results on various metrology applications.

8884-71, Poster Session

Simulations and first manufacturing steps of a fully integrated WDM-element in the visible spectrum

Sebastian Höll, Matthias Haupt, Ulrich H. P. Fischer, Hochschule Harz (Germany)

Due to their economical and easy-manageable advantages, POFs (polymer optical fiber) are going to replace traditional communication media such as copper and glass step by step within short distance communication systems. POFs are already used in various fields of optical communication, e.g. the automotive sector or in-house communication. Though single channel communication systems are state of the art technology, using of only one channel/wavelength for communication limits the bandwidth. For future scenarios this traditional technology is the bottleneck of bandwidth, particularly for HDTV with IP-TV. One solution to breakthrough this limitation is to use more than one wavelength over one single fiber, this is called WDM (wavelength division multiplexing) and is well-established for GOF communication. This technique will be adapted for the visible spectrum for POF. However this multiplexing technology requires two more key-elements: a multiplexer, which combines the multiple wavelengths signals into one fiber, and a demultiplexer at the end of the network to separate the colored signals. In this paper, the development of this key-element based on a Rowland spectrometer will be shown. It starts with the simulation, this is done by means of raytracing. Also the next process steps and solutions for injection molding are described.

8884-72, Poster Session

Off-axis mirror fabrication from spherical surfaces under mechanical stress

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The preliminary results in the fabrication of off-axis optical surfaces are presented. The propose using the traditional polishing method and with the surface under mechanical stress at its edges. It starts fabricating a spherical surface using ZERODUR® optical glass with the traditional polishing method, the surface is deformed by applying tension and/or compression at the surface edges using a specially designed mechanical mount. To know the necessary deformation, the interferogram of the deformed surface is analyzed in real time with a ZYGO® Mark II Fizeau type interferometer, the mechanical stress is applied until obtain the inverse interferogram associated to the off-axis surface that we need to fabricate. Polishing process is carried out again until obtain a spherical surface, then mechanical stress in the edges are removed and compares the actual interferogram with the theoretical associated to the off-axis surface. To analyze the resulting interferograms of the surface we used the phase shifting analysis method by using a piezoelectric phase-shifter and Durango® interferometry software from Diffraction International M.R.

8884-73, Poster Session

Current status of the prototype development of the fast steering mirror for Giant Magellan Telescope

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GMT is to have two secondary mirror systems i.e. Fast Steering Mirror (FSM) and Adaptive Secondary Mirror. FSM is a conventional secondary mirror system with an added functionality of tip-tilt control in order to compensate wind effects and the telescope structure jitter. KASI is currently leading a consortium of several R&D institutes in Korea and in USA for development of the FSM prototype. It is to acquire the key technologies, fabrication and test of highly aspheric off-axis mirror and of the tip-tilt control. A full-size off-axis aspheric mirror segment of 1 m in diameter has been fabricated and its testing methods have been developed. The mirror surface figuring is in process. The tip-tilt test-bed has been constructed to demonstrate the performance tip-tilt mechanism. We report the current status of the program and summarize the technical achievements including early trial performance results.

8884-74, Poster Session

Actuators delay analysis of active lap manufacturing

Hongshen Zhao, Bin Fan, Xiaojin Li, Zhige Zeng, Institute of Optics and Electronics (China)

Active lap technology is one of the most efficient solutions in the manufacturing of large aspheric mirrors. During the processing, the deformation accuracy of the lap which is under active force applied by the actuators on the lap is crucial to fit between the lap and the mirror. The control system can keep the lap maintain an accurate fit with the mirror surface. So the large rigid lap is highly efficient in the manufacturing of large aspheric mirrors just like spheres with a high accuracy.

In out model, the shape of active lap can be controlled by 18 actuators, which can be adjusted manually and tested by the surface detect system which is set up by 60 displacement sensors.

The accuracy of actuators is under stringent requirement. Because of the mechanical and electrical characteristics of the actuators and the force transmission system, delay is inevitable between the control signal and the response of the lap. The shape of active lap deforms under the combination of all the actuators, so any delay brings surface error.

Using the frequency response analyzer, we can get the delay time of every actuator, then surface error can be calculated in our model, corresponding compensation of the control system is put forward too. Finally, the lap surface detected shows that the surface accuracy gets improved after compensation.

8884-75, Poster Session

Metrology of arbitrary optical surfaces by TOPAF

Juan Carlos Martínez-Anton, Juan Manuel Plaza Ortega, Jose Alonso Fernandez, Univ. Complutense de Madrid (Spain)

Precision complex optical surfaces are increasingly produced thanks to the advancements in optical fabrication. However, the metrology of these surfaces still lacks some integration in the production line or it is cost prohibitive for small batches. We present a new technique in optical metrology (TOPAF) conceptually distant from the classical approaches. It has significant potential to reduce costs in the production of aspheric, freeform lenses, arrays and other complex shapes on transparent substrates (UV-Vis-IR). It may be applied in all production steps: from grinded to polished parts. It is based on the optical absorption of a water-soluble dye situated between the surface to measure and a reference surface. We take few images of this setup illuminated by a bi-chromatic diffuse light. Under this simple scheme, we may get a detailed topographic map fast and reliably, no matter the surface form, slope and finish. Some experimental results are given: a collimator lens with aspherical profile, a spherical lens array, a progressive ophthalmic lens, and a ground sphere. We achieve form accuracies from tens of a nanometer to few lambdas. Typically, the height resolution per single imaged pixel is about $\sim 1/1000$ of the maximum sag departure from a reference surface. Uncertainties sources are identified and controlled to approach the figure accuracy to the resolution.

8884-77, Poster Session

4D phase profile measurements using a single-shot phase shifting technique

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In this paper, we propose a quasi common path interferometer using polarizing phase shifting interferometry techniques. The use of phase shifting modulated by polarization has the advantage of not requiring mechanical components, such as PZT, to obtain the desired phase shifts, decreasing the sensibility of the system against external vibrations. The developed system is capable of obtain two beams with adjustable separation, this allowing the two beams move in the x-axis or y-axis, for convenience; it can be used to implement a quasi-common path interferometer that allows the measurement of phase profiles of transparent samples. The optical setup proposed use conventional linear polarizers placed at conventional angles presenting the advantage of not require micro-polarizer's arrays, the interferometer is stable to external vibrations. Unlike previously proposed interferometers, this system does not use a conventional double window; it generates two beams whose separation can be varied according to the characteristics of the phase grid used for generated 2-D interference patterns.

8884-80, Poster Session

Wavefront measurements through optical diffraction interpretation

Stéphane Bouillet, Sandrine Chico, Laure Eupherte, Claude Rouyer, Jérôme Daurios, Commissariat à l'Énergie Atomique (France)

The Laser MégaJoule (LMJ) is a French high power laser dedicated to fusion and plasma experiments. This facility will include 176 square beams involving hundreds of large optical components (the clear aperture being 40x40 cm?). Wavefront performances of all these components are critical to achieve the desired focal spot shape and to limit hot spots that could damage the components. These specifications are usually checked with interferometric setups. This can be uneasy to achieve for specific components such as multi-dielectric mirrors or gratings because one has to use the exact nominal configuration (wavelength, incidence, geometry of the incident beam) to perform the measurement. For the smallest spatial periods, classical techniques like interferometric microscopes fail to measure the wavefront and propose a "surface" measurement that can lead to misinterpretations. We present in this paper measurement methods based on a laser beam diffraction interpretation that can efficiently replace the usual techniques. The first technique consists in measuring intensity level of the dim scattered "corona" around the focal spot. The second one is based upon image processing of near-field acquisitions by the means of Fourier analysis and the Talbot effect theory. Those techniques do not lead to a phase map as classical techniques do but they give access to the Power Spectral Density of wavefront defects over a large spatial frequency bandwidth. For many applications, this is enough information to estimate the component performance. We present results obtained by this way on LMJ components and a comparison with Fizeau interferometer measurement.

8884-81, Poster Session

Absolute testing of freeform lens

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Result of the surface testing contain the reference surface errors and test surface errors in the high-accuracy Phase shifting interferometric which test the relative phase between the two surface. The test accuracy can be achieved by removing the error of reference surface. In this case, one of body of so-called absolute tests must be used which can test the systematic errors, including the reference surface, of the instrument to be used to improve the test accuracy. We review traditional absolute testing of flats methods and use the method to test the freeform lens. The flat can be expressed as the sum of even-odd, odd-even, even-even and odd-odd functions. Through six measurements the profile of the flat can be calculated. The freeform surface is created by 66th Zernike polynomials. The freeform lens is based on the flat lens. Firstly, we use a flat with the surface is around $1/20$ and then use the ion figuring machine of NTG to polish the surface to create the freeform lens. The Zygo interferometer with the absolute method is used to improved the polish accuracy.

8884-83, Poster Session

The influence of calculating compensation force based on different response functions

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Active support technique was widely used in the large base-ground telescope system. It can compensate the tiny distortion caused by fabrication, assembly, temperature or wind. This technique can be applied in processing of large-reflecting mirror. It's easy for fabrication if the mirror's deformation can be control. Three-dimensional coordinate and Zernike polynomial coefficients are two important parameters in describing the mirror's surface. During the processing of large-reflecting mirror, both of them can be used in the response functions in the support system. Propose to separately describe the response function by three-dimensional coordinate and Zernike polynomial coefficients. Calculate the compensation forces which is used in compensating the low-frequency Zernike polynomials surface by both of response functions. Analyze the residual error between the ideal surface and the mirror's surface after deformation. Study the convergence of the residual error when employ different amount of sampling point and Zernike polynomial coefficients. Separately gain the curves about the different amount of sampling point and the residual surface RMS, the different amount of Zernike polynomial coefficients and the residual surface RMS. Finally obtain the optimum response function in large-reflecting mirror fabrication.

8884-84, Poster Session

Fabrication of solid immersion lens applied to infrared microscopy to improve the spatial resolution over its diffraction limit

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Infra-Red (IR) objective achieves a few micrometers of spatial resolution with high Numerical Aperture (NA) of about 0.75, for example, in mid-IR. However, submicron resolution is hard to achieve in Mid- IR because of the long wavelength compared to the visible limit. To overcome the limitation, a solid immersion lens (SIL) is incorporated into the conventional objective so that the high refractive index of SIL contributes to obtain the high spatial resolution image of sample immersed in SIL. Germanium is a typical material of SIL in the infrared wavelengths because of the high refractive index and the high transmittance. In our study, we fabricated a Germanium-SIL using the quantified parameters of the ultra precision machining. The parameters are tool rake angle, cutting speed, feed rate, and depth of cut. The surface shape of the fabricated SIL was measured with the accuracy of 0.0376 μm in RMS and 0.3159 μm in P-V. We applied the fabricated SIL to a custom IR objective to investigate the improvement of its spatial resolution. Optical performance of the IR objective was evaluated with and without SIL. As results, the IR objective with SIL achieved 1.38 μm of the spatial resolution compared with the 5 μm of IR objective without SIL.

8884-85, Poster Session

Slope-sensitive optical probe for freeform optics metrology

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Freeform and conformal optics represent the next generation of optical systems where their utilization leads to more compact, lighter, and higher performance systems for solar collectors, consumer optics, and defense applications. Presently, many metrology systems lack the ability to measure steep deviations from spherical, cylindrical, or plano surfaces due to unresolvable fringes in the recorded interferogram. Optical probing, conversely, using a 5-axis optical coordinate measuring machine is a possible non-contact solution for high accuracy metrology. Optical coordinate measuring machines have two main limitations: inaccuracies in the global positioning and insufficient resolution and local surface slope knowledge. In this work, we address the latter of the two by demonstrating a compact optical probe capable of fiber delivery and fiber detection to remove potential heat sources away from measured optic. A benchtop demonstrator has yielded a displacement resolution below 50 nm and has a noise floor of ~ 2 μrad for surface slope in two orthogonal directions. In this Proceedings, we will detail our probe design, operating principle, and the adaption from a benchtop proof-of-concept to a demonstrator system. The goal of this work is to ultimately integrate this probe into OptiPro's UltraSurf, a 5-axis optical coordinate measuring machine for measuring freeform and conformal optics.

8884-87, Poster Session

Crosstalk-immune fiber optic sensor based on wavelength-division-multiple for disturbance detection and location

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A distributed fiber-optic sensor system based on phase generated carrier for the elimination of the crosstalk of wavelength-division-multiple is proposed and demonstrated to detection and location of disturbance employing time delay estimation. The sensor employs a hybrid configuration of Mach-Zehnder and Sagnac interferometer as interfering unit. A broadband, low-coherence source is spectrally sliced into two wavelength bands using wavelength division multiplexer. Therefore, the sensor consists of two different wavelength interferometers, multiplexing with the broadband light source, interfering unit and sensing loop. Two piezoelectric transducer (PZT) phase modulators, modulated at frequencies, are connected at the two end of the sensing loop and hence four detected signals with two different wavelengths are obtained. Based on the phase generated carrier demodulation, two phase change signals with fixed time delay are achieved and the location of the disturbance gained by time delay estimation enables the localization comparably accurate. Theory analysis and experiment results show that the proposed technology has great potential to be applied the intrusion detecting.

8884-88, Poster Session

Smart and precise alignment of optical systems

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For the assembly of any kind of optical systems the precise centration of every single element is of particular importance. Classically the precise alignment of optical components is based on the precise centering of all components to an external axis (usually a high-precision rotary spindle axis). Main drawback of this time-consuming process is that it is significantly sensitive to misalignments of the reference (e.g. the housing) axis.

In order to facilitate process in this contribution we present a novel alignment strategy for the TRIOPTICS OptiCentric® instrument family that directly aligns two elements with respect to each other by measuring the first element's axis and using this axis as alignment reference without the detour of considering an external reference.

According to the optical design any axis in the system can be chosen as target axis. In case of the alignment to a barrel this axis is measured by using a distance sensor (e.g., the classically used dial indicator). Instead of fine alignment the obtained data is used for the calculation of its orientation within the setup. Alternatively, the axis of an optical element (single lens or group of lenses) whose orientation is measured with the standard OptiCentric MultiLens concept can be used as a reference.

In the instrument's software the decentering of the adjusting element to the calculated axis is displayed in real-time and indicated by a target mark that can be used for the manual alignment. In addition, the obtained information can also be applied for active and fully automated alignment of lens assemblies with the help of motorized actuators.

8884-89, Poster Session

OptiCentric lathe centering machine

Christian Buss, Josef Heinisch, TRIOPTICS GmbH (Germany)

The precise alignment of optical surfaces and elements in the final assembly of an optical system has a strong influence on the imaging quality of the system. In addition to the shift and tilt of individual lenses, the air gap between the lenses has to be controlled precisely. However, the lens thickness is typically only controlled within a few microns or less. Also the shift and tilt errors of lenses with respect to the lens housing is often not sufficient for final assembly. Lathe centering can be used to machine the mount with respect to the measured optical axis. This allows for alignment tolerances in the micron regime which are necessary to reach the demands of critical applications. We describe the general method of lens centering and show a dedicated machine for diamond turning of non-ferrous metal mounts. The machine includes sophisticated contact and non-contact measurement solutions to measure all relevant mechanic-optical properties of mounted lenses. The machine is designed to correct all relevant errors of single mounted lenses in one set-up. Especially the use of the OptiSurf® lens thickness sensor is shown. Using this sensor the lathe centering machine is able to perform the machining and in-situ control of the top to bottom flange surface distance with an accuracy of about one micron. The described machine can use the full range of OptiCentric® measurement devices making it ideal for a wide range of applications, including the centering of infrared lenses. We describe the setup and show specific design steps that were made to achieve the desired accuracy.

8884-92, Poster Session

Experimental study on SPDT machining of Gallium Phosphide

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Gallium Phosphide (GaP) is widely used semiconductor material, but can be also used as a material for visible and infrared optical elements. Combination of its optical and mechanical properties such as high mechanical durability, transparency from visible to infrared wavelengths and high refractive index makes it very interesting material for design of high performance optical systems.

Manufacturing of optical elements for infrared application shifts from traditional grinding and polishing techniques to a more versatile SPDT machining. It is therefore useful to employ SPDT in production of optical surfaces on GaP. As the GaP is hard and brittle material all the problems already known for glasses and other brittle materials are present - such as critical depth of cut and sensitivity to tool rake angle. Here we report results of experiments with SPDT machining of optical surfaces on GaP substrates and comparison with classical machining methods.

8884-94, Poster Session

Improved MRF spot characterization with QIS metrology

Sandi Westover, Christopher A. Hall, Michael A. DeMarco, QED Technologies, Inc. (United States)

Careful characterization of the removal function of subaperture polishing tools is critical for optimum polishing results. Magnetorheological finishing (MRF®) creates a polishing tool, or "spot", that is unique both for its locally high removal rate and high slope content. For a variety of reasons, which will be discussed, longer duration spots are beneficial to improving MRF performance, but longer spots yield higher slopes rendering them difficult to measure with adequate fidelity. QED's Interferometer for Stitching (QIS®) was designed to measure the high slope content inherent to non-null subaperture stitching interferometry of aspheres. Based on this unique capability the QIS was recently used to measure various MRF spots in an attempt to see if there was a corresponding improvement in MRF performance as a result of improved knowledge of these longer duration spots. The results of these tests will be presented and compared with those of a standard general purpose interferometer.

8884-95, Poster Session

Hexapods with fieldbus interfaces for automated manufacturing of opto-mechanical components

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The adjustment of opto-mechanical components in manufacturing processes often requires precise motion in all six degrees of freedom with nanometer range resolution and absence of hysteresis. Parallel kinematic systems are predestined for such tasks due to their compact design, low inertia and high stiffness resulting in rapid settling behavior.

To achieve adequate system performance, specialized motion controllers are required to handle the complex kinematic models for the different types of Hexapods and the associated extensive calculations of inverse kinematics. These controllers often rely on proprietary command languages, a fact that demands a high level of familiarization.

This paper describes how the integration of fieldbus interfaces into Hexapod controllers simplifies the communication while providing higher flexibility. By using standardized communication protocols with cycle times down to 12.5 μ s it is straightforward to control multiple Hexapods and other devices by superordinate PLCs of different manufacturers. The paper also illustrates how to simplify adjustment and alignment processes by combining scanning algorithms with user defined coordinate systems.

8884-55, Session 12

Low weight mirror substrates

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Large mirrors are required for a wide variety of applications. Two key constraints are mirror stability and mirror mass. Low expansion glass ceramics remain a useful material because of its excellent thermal stability, relative ease of processing and lower cost compared to alternatives. However there is room for the improvement of the manufacturing techniques over the traditional methods of milling and etching, which are high risk, expensive and time consuming. A solid blank is milled out using high speed diamond tooling to leave fragile webs of supporting material. The final process steps are the highest risk, when it is possible for catastrophic flaws to appear. We present a novel method of producing a monolithic structure from component pieces that provide a lower risk, lower cost method of producing stable and light-weighted mirrors. Individual smaller components are machined and then bonded together. The bonding process results in near substrate strength components without compromising the very low thermal expansion of the glass ceramic. It also allows the creation of novel designs with hollow cavities embedded within the structure. Prior to commencing the fabrication, the mechanical design was modelled to predict the stability of candidate designs. Tests were carried out on witness pieces to prove the relative strength of the bonds. Prototypes were then fabricated and tested for thermal stability.

8884-56, Session 12

New processing equipment for ASTRO optics

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The next generation of extremely large telescopes comprises several hundred or even thousand single adaptive mirrors with a diameter of up to two meters each. Enabling their fabrication within a reasonable time span was the major motivation to create the world's largest optical processing machine – the UPG 2000 CNC.

It is a gantry-type 8-axis ultraprecision machining center with a weight of more than 80 tons. The machine base made from granite in combination with hydrostatic bearings guarantee for the stiffness and vibration damping needed during grinding. Two slides running on both sides of the same granite gantry are carrying spindles for grinding or polishing, respectively. For prepolishing and correction operations different processes can be applied based on the multitool concept. Together with on-machine metrology equipment for shape accuracy determination, the whole process chain for the fabrication of highest quality level asteroptics is integrated.

We are giving a detailed description of its realization – starting with the fundamental machine concept and ending with the latest fabrication results.

8884-57, Session 12

Model-based polishing of meter size optics

Jan-Claas Tiedemann, Marcel Achtsnick, Elisabeth Becker, Berliner Glas KGaA Herbert Kubatz GmbH & Co. (Germany)

In display or semiconductor manufacturing it is a constant drive towards the use of scale effects to reduce costs per unit. For equipment suppliers this leads to ever bigger optical components. To answer this need new cost-efficient polishing technologies are required.

In this work a simulation for long scanning optics starting from Preston equation has been derived. By separating the optical surface into several zones, velocity variable polishing paths has been computed. Including pressure differences at the edges so called removal maps has been plotted.

At the end, it has been verified; that the model approach is able to influence polishing results of meter size optics by velocity controlled polishing.

8884-58, Session 12

Slumping technique for the manufacturing of a representative x-ray grazing incidence mirror module for future space missions

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The Astronomical Observatory of Brera (INAF-OAB, Italy), with the financing support of ESA, is in the final phase of a study regarding a glass shaping technology for the production of grazing incidence segmented x-ray optics. This technique uses the hot slumping technology in which pressure is actively applied onto the thin glass foils (200x200x0.4 mm) to be formed. In particular, a new experimental set-up is described that permits a better contact between mould and glass. The final goal of this study was the manufacturing of an optical module containing a number of slumped pair plates having a representative scale size to be tested initially in UV light and also in X-rays at the Panter facility (Germany). The module is assembled using an integration machine developed specifically for the task, able to permit the precise alignment between a parabola and hyperbola plate and then with any other pair plate to be integrated. In this article is described the slumping technique, the procedure of integration of the slumped segments into a module and the results obtained from the optic measurements on the manufactured module.

8884-59, Session 12

Thin monolithic glass shells for future high angular resolution and large collecting area x-ray telescope

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One of the most difficult requests to be accomplished from the technological point of view for next generation x-ray telescopes is to combine high angular resolution and effective area.

A significant increase of effective area can be reached with high precision but at the same time thin (2-3 mm thickness for mirror diameters of 30-110 cm) glass mirror shells.

In the last few years the Brera Observatory has lead a development program for realizing this kind of monolithic thin glass shell.

The fused silica has been chosen as shell substrate due to its thermal and mechanical properties.

To bring the mirror shells to the needed accuracy, we have adopted a deterministic direct polishing method (already used for past missions as Einstein, Rosat, Chandra) to ten time thinner shells.

The technological challenge has been solved using a temporary stiffening structure that allows the handling and the machining of so thin glass shells.

The results obtained with a prototypal shell at an intermediate stage of its development (17" HEW measured in full illumination mode with x-ray) indicate that the working concept is feasible and can be further exploited using the very large Ion Beam Facility available in our labs for the final high accuracy figuring of the thin shells.

In this paper we present the required tolerances for the shell realization, the shells production chain flow and the ion beam facility up grading. Forecast on figuring time and expected performances of the figuring will also be given on the basis on the metrological data collected during past shell development.

8884-60, Session 12

Effect of polishing plane vibration on large-size optical workpieces in continuous polishing

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Effect of the polishing plane vibration on large-size optical workpieces in continuous polishing is studied. The vibration equation was deduced based on the existence of inclination between the polishing plane and z-axis direction. Influences of different parameters, such as the inclination, rotation speeds of the polishing plane and workpiece, the eccentricity and workpiece radius. on the polishing plane vibration were simulated. The simulations results show that rotation speeds of the polishing plane and workpiece is the most significant factor. The chaotic vibration of the polishing plane increases with increasing rotation speeds differences between the polishing plane and workpiece. When differences are small, periodic ups and downs of the polishing plane occur with the increase of polishing time. Experiments verified the influence of rotation speeds differences on the polishing plane vibration. The vibration affects PV of large-size optical workpieces in continuous polishing.

8884-61, Session 13

Nanoscale optical features via hot-stamping of As₂Se₃ glass

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Chalcogenide glasses (ChGs) contain either sulfur, selenium and/or tellurium, these elements being combined in a continuous fashion with glass-formers such as As, Sb, Ge or Ga. They have found numerous successful technological applications in the fields of optic, photonic, infrared sensing or data storage. Here, taking full profit of their tailorable thermo-elastic properties, we show our ability to fabricate 2D gratings on ChGs with peak-to-valley amplitude of ~200 nm. The fabrication method relies on the nano-imprinting of the glass substrate in direct contact with a patterned stamp, while being held for a certain time-temperature regime under an applied load, so that the glass flow conforms to the shape of the mold cavity. Stamping experiments are carried out using a bench-top precision glass-molding machine, both on As₂Se₃ optically-polished bulk samples and on thermally-evaporated thin films. The stamps consist of silicon wafers engraved with sub-micron etched features. Post-stamping, non-contact light-interferometric and electronic microscopy techniques allow the precise peak-to-valley mapping of the surface of the glass. We demonstrate that the fabrication method described here, enables us to precisely control the viscosity of the glass, and mitigates risks associated with internal structural damages, dewetting, or parasitic crystallization. The stamping fidelity as a function of the Time-Force-Temperature regime is discussed, and further developments and potential applications are presented.

8884-62, Session 13

Chalcogenide-mold interactions during precision glass molding (PGM) of GeAsSe glasses

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Five chalcogenide glasses in the GeAsSe ternary glass system were melted, fabricated into polished flats, and molded between planar, uncoated, binderless WC molds using a laboratory-scale precision glass molding (PGM) machine. Using binary arsenic triselenide (As₄₀Se₆₀), a commonly available industrial glass, as a starting point, this effort examined the effect of adding 5 mol% of either Ge or Se to the composition. Localized defects such as scratch and/or dig marks or deposits, were investigated on the glass surfaces prior-to and after the PGM process. Analysis of the glass surface shows an overall reduction in the RMS roughness (from 40nm to 20nm) after molding, while the RMS roughness of the molds increased (2nm to 9nm, after approximately 15 molding cycles). After molding, the quantity of observable defects increased for both the glass and mold surfaces. Defects found on the WC molds were analyzed using Electron Dispersive X-ray Spectroscopy (EDS) and showed no evidence of any of the glass constituents.

8884-64, Session 13

Novel testing facility for investigating wear on PGM sample tools

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For the fabrication of highly precise glass optics, Precision Glass Molding (PGM) is the state-of-the-art replicative manufacturing process. However, the process efficiency is mainly determined by the service lifetime of the molding tools and, in particular, the performance of the protective coatings. Testing the lifetime in real molding machines is extremely cost and effort intensive.

In a new testing facility the protective coating performance can be evaluated by systematically inducing tool wear under realistic process conditions. A high numbers of pressing cycles can be executed under minimal time and material effort, reducing the cost consumption for such coating validation tests significantly. In this paper, a fast method for evaluating the performance of coatings is provided. The machine concept and evaluation method are presented in comparison to the production conditions. Investigations are targeted on the similarities between tool wear in production and those induced in the testing facility. After inducing wear patterns on test specimens in the new facility, surface alterations are investigated with light microscopy, scanning electron microscopy (SEM), micro probe (EPMA) and XPS. The results show similar degradation patterns as known from production, such as haziness, glass sticking and tribo-chemical wear on the coated tools. It is concluded, that the wear mechanisms can now be analyzed in detail and time-resolved. The results presented show that the facility provides unique information for optimizing coatings, but also glass compositions, for use in Precision Glass Molding.

8884-65, Session 13

Melt spun aluminium alloys for moulding optics

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Melt spinning is a rapid quenching process that makes it possible to create materials with a very fine microstructure. Due to this very fine microstructure the melt spinning process is an enabler for diamond turning optics and moulds without the need of post-polishing. Using diamond turning of melt spun aluminium one can achieve $\leq 2,5$ nm Rq surface roughness. Application areas are imaging and projection optics, mirrors, moulds for contact lenses and spectacles.

One of the alloys RSP produces is RSA-905. This alloy has a solid track record as a better and cheaper concept in the application of moulds for optical components such as contact lenses. The RSA-905 is a dispersion hardened amorphous-like alloy that keeps its properties when exposed to elevated temperatures (up to 400°C). This gives the material unique features for optics moulding applications. RSA-905 moulds are cheaper and better than traditional mould concepts such as copper or brass with or without NiP plating. In addition logistics can be simplified significantly: from typical weeks-months into days-week. Lifetime is typically in the range of 100.000 – 200.000 shots.

For high volume production typically ranging from several 100.000 – several 1.000.000 shots, NiP plated steel moulds are typically used. By using an appropriate optical coating concept RSA-905 can be upgraded to a competitive alternative to steel in terms of price, performance and logistics. This paper presents some recent developments for improved mould performance of such concept. Hardness, wear resistance and adhesion are topics of interest and they can be applied by special coatings such as diamond like carbon and chromium nitride. These coatings make the aluminium alloy suitable for moulding mass production of small as well as larger optics, such as spectacle lenses.

8884-66, Session 13

Shaping of thin glass foils for the fabrication of mirrors with pronounced asphericity

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We present a method developed by INAF (Italian National Institute for Astrophysics) for the manufacturing of mirrors by using commercial off-the-shelf materials. It is based on the shaping of thin glass foils by means of forced bending; then a sandwich structure is assembled for retaining the imposed shape. These mirrors are intended for optical systems with few arcmin in angular resolution working in extreme environments; being their principal mechanical features the very low weight and high rigidity. The cost and production time also turns to be very competitive.

In this paper we report the main achievements of the r&d performed. We recall the investigation of the theoretical limits with finite element analyses and the process implementation. Finally, the case of the mirrors for IACT (Imaging Atmospheric Cherenkov Telescope) is presented with respect to the ASTRI project (Astrofisica con Specchi a Tecnologia Replicante Italiana).

8884-90, Session 13

Interaction of N-FK5 and L-BAL35 optical glass with various carbide and other precision glass mold tooling

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Precision glass molding (PGM) is an optical manufacturing process used to hot press optical glass into a specified lens shape. This is done by taking the glass to a temperature above T_g and exerting force on it using an upper and lower mold. These molds will, together, give the pressed lens its shape.

This study focuses on the high temperature interactions between the mold tooling material and two optical oxide glasses, Ohara's L-BAL35 and Schott's N-FK5. Flat molds were used to press flat glass work pieces at high temperature and force; key post process parameters such as sample and mold roughness using interferometry, surface contamination using EDS and visible degradation via SEM were catalogued and analyzed. The molds used were bare tungsten carbide (WC), silicon carbide (SiC) with an amorphous SiC chemical vapor deposition (CVD) coating, and glassy carbon (GC) inserts.

The results showed that raw WC molds suffered the most degradation including physical damage as well as chemical adherence and reaction. The Ti binder used in the WC as well as some of the tungsten itself transferred to both glasses and caused a white reflective layer to appear on the molded glass surface. Severe damage was evident after only 2 pressing cycles with potassium from N-FK5 being the most prominent chemical contaminant. N-FK5 proved to be the more corrosive of the two glasses in all occasions. The SiC coated molds fared better in terms of degradation than the WC, however sticking of glass to mold was a problem. GC was the most successful in terms of non-interaction, but is not considered practical in industry.