High Precision Optics Production with Precision Glass Moulding

Publishable summary of the results of the Production4µ Project

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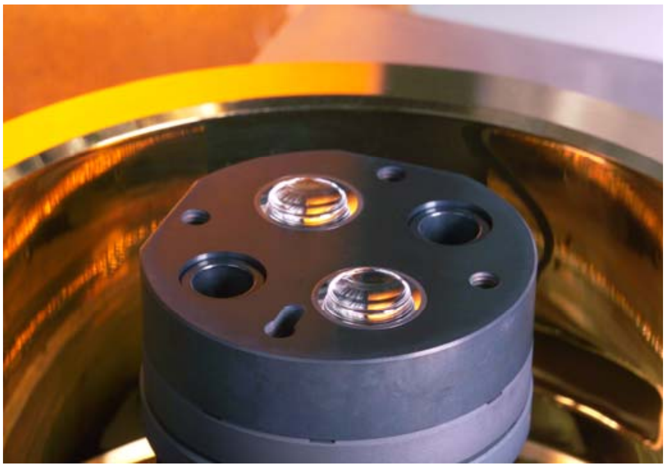
Abstract. A new state of the art technology, Precision Glass Moulding, enables high precision, low cost and sustainability in production of highly demanding optical components. This process technology is versatile enough to enable the production of difficult shapes such as aspheres, arrays or even diffractive optics in glass, rendering costly non-replicative production steps such as grinding and polishing redundant. Industrial interest in precision glass moulding technology and its advantages continues to increase rapidly. To advance the industrial usage of the technology and to provide a supply chain for it, a consortium of more than 20 European companies, institutes and universities was collaborating in a project called "Production4µ". This consortium is managed by the Fraunhofer Institute for Production Technology IPT and funded by the European Commission as part of the 6th framework programme with project number 26765. The project has successfully finished its work in October 2010 with the realization of very demanding glass optics that are demonstrating the capabilities of the precision glass moulding technology. In this summary, the results of the project and the proceeding that was taken to achieve them are described with a focus on the exploitation of the project's achievements.

Keywords: optics manufacturing, precision glass moulding, replicative glass optics production, aspheres, lens arrays, diffractive optics, Production4µ

1 State of the Art Technology Enables High Precision, Low Cost and Sustainability in Optics Production

To meet the requirements of constant miniaturization of products together with an increase in their performance, more and more functions are being integrated in today's everyday technical items. Cell phones that simultaneously act as high resolution digital cameras and modern motor vehicles that use a range of highly integrated microsensors to provide increased driving comfort and safety are nowadays common.

Central to a large part of such applications are extremely demanding optical microsystems. These contain glass components that meet stringent requirements in terms of precision, while at the same time showing very complex geometries in minimal space. The availability of these glass micro components enables a whole range of new functions and is conquering markets in medical and laser technology, the automotive industry and telecommunications. While most micro glass components are still manufactured using time consuming, expensive and resource-intensive conventional process chains (turning, grinding, polishing), the future lies in high precision, resource-effective replicative manufacturing processes, such as precision moulding of optical glass (Picture 1). With this process, high precision optics can be manufactured in a single process step. The main attractions of the technology for industry are the clear cost and resource benefits it offers. However, precision glass moulding is also of interest because it enables the replicative manufacturing of forms that are very difficult to create using conventional processes, such as aspherical elements, arrays or even diffractive optics. The Production4µ project was therefore aiming to advance the development of this technology and to make precision glass moulding for optical products accessible to European business. The goal is to improve the competitive position as well as the sustainability of the European optical industry and its suppliers by developing replicative processes for optical micro components that will enable ecological and economical production of high precision optical components.



Picture 1: Precision glass moulding – the moulding tool with a moulded lens

Technologically, steps have been taken to improve the usability and resource-friendliness of the precision glass moulding technology. Improvements were made both to the moulding process for the optics itself and to the production of the moulding tools. For example, optimized grinding kinematics reduce not only the processing time but, in particular, the number of iterations required to produce the moulding tools. Improved processing strategies ensure higher quality moulding tools, while optimized parameters reduce the processing time. Different local ultra-precision polishing processes have been developed for reproducible polishing of moulding tools made of high strength materials such as nano-crystalline carbide. The highest quality tools are needed to enable a cost-efficient production of high quality optics. In the pressing process, the moulding tools are subject to heavy loads. To increase their life time and thus to significantly improve the efficiency of the pressing process, high precision optimized precious metal coatings have been developed. This enables a quicker and thus cost-saving pressing process and the resource-efficient usage of tools for a large number of cycles.

2 Advancing the complete Precision Glass Moulding process chain "from A to Z"

The Production4µ project is structured into three main research areas which are advancing manufacturing technologies, automation and production planning. With their research work, the research areas are covering the entire process chain of precision glass moulding and its mould making, which can be seen in Picture 2.

Picture 2: The complete precision glass moulding and mould making process chain

While all work packages of the consortium aim at enabling the above process chain, their impact also stretches beyond this into further domains of micro-scale production, such as optical plastic injection moulding. Further information on the work packages and contact information of the responsible partners can be found on the project's webpage www.production4micro.net.

The results of the research work are validated on specific glass optics which were realised after four years of project duration. These demonstrators are on the one hand examples of products that have an enormous market potential and are on the other hand extremely difficult to produce, pushing the newly developed technologies to their limits and beyond. As demonstrator products, a double-sided asphere, a lens array and a diffractive lens were chosen.

Double-sided high precision aspherical lens
New trend studies in laser material processing, especially laser cutting, forecast a global market volume of more than 6 billion €. For efficient laser cutting applications the laser beam needs to have specific characteristics and a tightly toleranced shape. For this focal quality, the optical system is crucial. To achieve maximum focal power the optics must have high power transmission, low absorption and perfect imaging quality. Using standard optical elements like spherical lenses which can be machined in high quality at low prices, multiple elements are needed to correct the aberrations cause by the spherical shape. This leads to a high effort in adjustment and large objective sizes due to the large number of optical elements, while the beam quality and power transmission stays far from optimal. This challenge can be overcome by the usage of aspherical optics (shown in Picture 3), reducing the number of components and resulting in a compact design and a high efficiency.

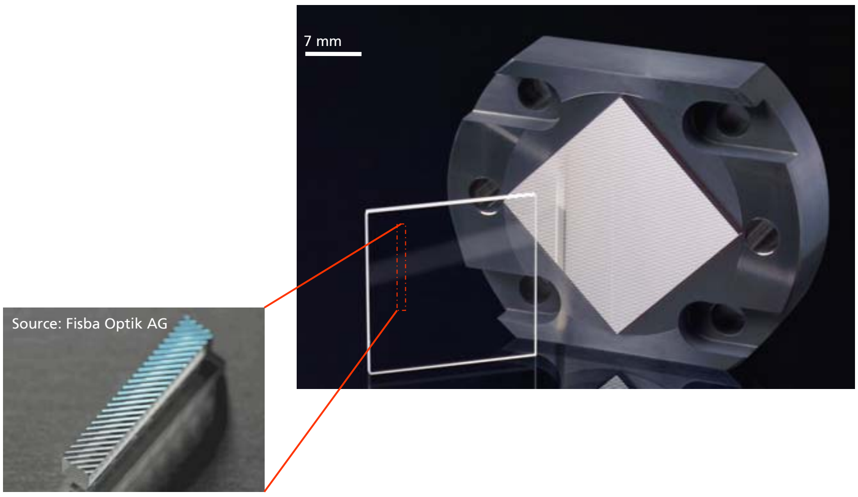
Picture 3: Double-sided aspheres for laser beam shaping, produced by Production4µ-partner Aixtooling

Asphercial lenses can be produced by direct grinding and polishing or by precision moulding. The advantage of precision moulding is its cost efficiency and high reproducibility for large and medium quantities. To meet the market requirements in terms of cost and quantity the moulding process was qualified within Production4µ to achieve high form accuracies and low slope errors. Production4µ-partner INGENERIC, aiming at an application in a high-power, high-precision laser cutting application with a Gaussian beam shape and a wavelength of 900 – 1100 nm, has requested very challenging product specifications from the consortium. To obtain high transmission and low absorption, the number of surface defects has to be very low and a high-end finishing of the surface is required. Finally, the consortium was successful in providing a highest quality product with a finish better than "P3" rating according to ISO 10110, a form deviation of less than 300 nm and less than 5 surface defects per area with a size of 100 µm² over the entire aperture - only to name a few of the µ-precise properties of the final aspheric lens.

Aspherical cylinder lens array

For the operation of such laser systems for material processing, diode lasers are frequently used to pump solid state high-power lasers. In contrast to conventional pumping systems, laser diodes have a much higher degree of efficiency and the wavelength can be adapted very well to the corresponding solid state laser. Typically, a pumping system consists of multiple laser diodes with an unsymmetrical beam profile. To increase efficiency, the generation of a symmetric beam is required. An advantageous solution for this is the usage of cylinder lens arrays. Also, if the beam of a diode laser is to be coupled into a fiber directly for materials processing, efficiency can just as well be increased by generating a symmetric beam. Prior to the Production4µ project, only etched fused-silica solutions were available for this, with a low refractive index leading to large dimensions of the optical devices and less-than-optimal efficiency. Therefore, FISBA OPTIK and the Production4µ consortium have employed precision glass moulding technology to enable an improved solution with higher refractive index glass. Due to the high power level the requirements in terms of transmission and imperfections are similar to those of the aspheric lens described above. However, the moulding is even more challenging due to centering and alignment requirements caused by a non-rotationally symmetric product.

FISBA OPTIK has developed a lens array design for a beam twister made from a high index mouldable glass material, which can be seen in Picture 4. The shape of each single lens has to be aspheric. The requirements in terms of center thickness, flatness and alignment of both sides of the array, that were fulfilled by precision glass moulding, are very high. For example, a pitch accuracy was achieved in the sub-micrometer range and the form accuracy of the final aspherical product was measured to be in the range of 0,1 µm RMS.



Picture 4: Moulding tool, moulded glass plate and single lens array sawed from the plate (source: FISBA OPTIK)

Diffractive Lens

For an imaging application, which is still the largest business area of high-quality optics production, a diffractive lens product was defined by Production4µ-partner VTT from Finland. This lens aims at increasing the optical function density of an imaging system by the use of a diffractive solution for the correction of chromatic aberration. With this, compact solutions for imaging and sensor applications can be realized, reducing the number of required lenses and improving the image quality. Although diffractive features are extremely difficult to mould, the Production4µ-consortium has achieved a high form accuracy in micro scale for high diffraction efficiency, a high form accuracy in macro scale for perfect imaging and a high surface quality. Measured and tested by VTT, the diffractive lens produced by precision glass moulding has proven to reach a diffraction efficiency close to the theoretically calculated value and a much better image quality than a standard plano-convex spherical lens. To achieve this, the consortium has put large efforts especially in qualifying a challenging manufacturing process for producing the micro features on the moulds.

3 Consortium partners turn exciting results into products

At the end of the project, the three different demonstrator products serve as examples of the capabilities that were developed in the project. Anyhow, these demonstrators are only the visible tip of the iceberg of results that were generated in order to enable them. Among these are for example entirely new automation concepts as well as new measurement solutions which will be beneficial for a large scope of micro production applications. These new ideas and concepts have led to many more exciting new products than just the demonstrators described above at the consortium's partner companies, a few of which are for example:

CERATIZIT has developed new carbide tools for precision glass moulding, relying on the newly developed cemented carbide grade CTN01L for moulds in precision form applications. This grade has a very high wear resistance, a microstructure free of metallic binder phase and a very small grain size (<0,2 µm). The material composition and special production process parameters enable a smooth (Ra <3nm) and defect free mould surface after the finishing and grinding process, which is essential for optical applications.

IBS Precision Engineering has developed an new ultra-precision touch probe system, the Triskelion Ultra Precision Tactile System. This probe system is suitable for point measurements as well as scanning. Its excellent measuring uncertainty and full 3D measurement capabilities make it suitable for ultra-precision 3D metrology. Possible applications include 3D ultraprecision (micro-/nano-) CMMs as well as on-machine metrology on machine tools.

LT Ultra has developed a new air bearing spindle, named DK 130. It is characterized by an ultra-precision double sphere air bearing design.

The system has a torque drive and an integrated angle measurement system for automatic positioning during tool changes. The fully integrated, automatic balancing device supports single-plane balancing, with a balancing quality down to 1 µm/sec residual oscillation speed. It allows for automated procedures after the tool change and supersedes manual balancing.

Schott introduces a new glass type named P-SK58A, which is optimized for glass moulding. The transformation temperature of the glass is relatively low and therefore the moulding process can be performed at low temperatures. At the same time the optical quality of the glass is high and enables high quality lenses.

To interconnect the micro-precision production chain, System3R has realized a system called "MacroNano Chuck" which enables an ultraprecision coupling for both workpieces and tools. With a MacroNano system in the production chain, the workpiece can move from machine to machine through the whole production chain without losing the nano precision and reference. This level of precision is made possible through a system approach where all components of the system- the chuck, the pallet and the drawbar- are produced using the best design practices and state of the art manufacturing technology.

Dedicated to the metrology of ultra-precision form tools, Taylor Hobson has developed the Form Talysurf PGI BLU (3D). This system is able to precisely measure the 3D form of shallow and steep aspherical lenses and moulds. Steep aspheric optics provide one of the biggest challenges today to ultra-high precision measurement. The Form Talysurf PGI Blue is able to meet these requirements, offering a λ/12 or 50nm form-measurement ability with fully automatic operation. Providing a rendered 3D map of surface astigmatism, the PGI Blue is the perfect tool for mass production and R&D alike, allowing the full characterization of components without any difficulty.

More information on these and other products can be found on www.production4micro.net.

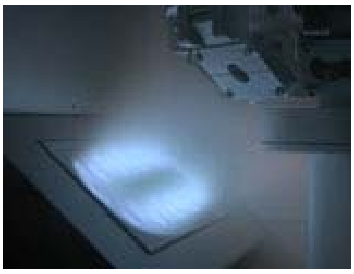
4 Follow-Up projects, dissemination and guidelines

With Production4µ, all project partners aimed at initiating a project with practicable and sustainable results. This objective being met, five follow-up projects were launched that continue and advance the ideas of Production4µ:

"Wafer Level Optics" enables the manufacturing of glass micro optics on wafer level, scaling the currently available process chain for precision glass moulding towards wafer level. To make this possible, new mould manufacturing strategies have to be developed and production processes need to consider wafer stacking and alignment procedures (Picture 5).

Picture 5: Precision glass moulding of wafer-type optics

"*SpeedCoat*" is contributing to the development of an integrated technology platform for the rapid development, qualification and production of individually optimized coating systems for precision glass moulding tools (**Picture 6**). The goal is to maximize the lifetime of the moulding tools in order to guarantee the economic viability of the technology.

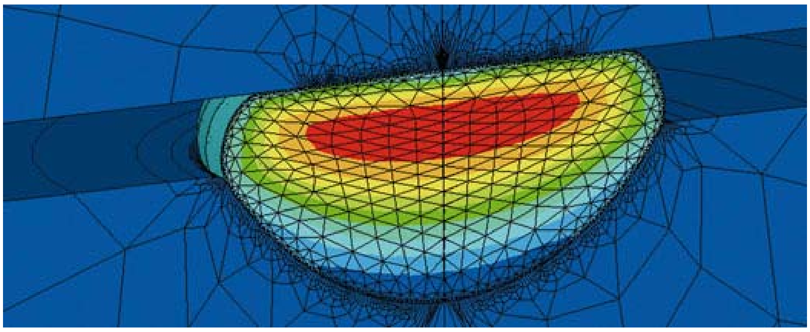


Picture 6: Coating of precision glass moulding tool at the Fraunhofer IPT coating facility

"NGOptics" continues the investigation into the precision glass moulding of sharp, diffractive structures with the use of tungsten carbide and silicon tools.

"KoDaRe" aims at establishing a continuous data representation within the production process of optics with freeform surfaces, ensuring a consistent data exchange between CAD/CAM, design, simulation, metrology, production and assembly.

"SimuGlass" develops a synergistic computational tool for material modelling, process simulation and the optimization of optical glass moulding (Picture 7).


Picture 7: Simulation of the precision glass moulding process

In addition to these projects, many Production4µ partners have intensified their activities in precision glass moulding (e.g. FISBA OPTIK, INGENERIC) and in related topics of the glass moulding supply chain (e.g. System3R, Schott). Production4µ has proven to comprise highly relevant topics both for science and business, which will be continued with varying participation of different Production4µ partners.

Production4µ was additionally very successful in raising the industrial awareness of the precision glass moulding technology. This was achieved by an intensive dissemination of project results towards the open public as well as towards the industrial and scientific expert audience. For example, methods and software tools were developed to help industrial companies to realize the potentials of the new technology of precision glass moulding to their full extent. In order to communicate both the capabilities and the possible uses of the technology, design recommendations have been developed. These present the complex technological interdependencies in a comprehensive yet practical form, allowing optical systems designers to take full advantage of both the potential for cost savings and increased functionality. Optics designers using these recommendations are able to develop manufacturable optical components more smoothly while gaining systematic support. Furthermore, the cost perspective of the full process chain was analysed and communicated to industrial partners.

To further simplify the industrial access to the precision glass moulding technology and to enable standards within the newly-established supply chain, specific guidelines for precision glass moulding and other related parts of the process chain were written by Production4µ-partner VDI:

- Guideline VDI/VDE 5581: Measurement Procedures for Quality Control in Precision Moulding of Asherical, Freeform and Microoptics
- Guideline VDI 5582: Preparation of cleaning of tools and specimens to ensure reliable quality control measurements in the poduction chain of precision glass moulding
- Guideline VDI 5583: Recommendations for Interface Specifications in the Process Chain of Precision Glass Moulding of Optical Elements
- Guideline VDI 5580: Precision Glass Moulding of Optical Elements - Basic Technology
- Guideline VDI 5584: Palletisation for Mechanical Microproduction
- Guideline VDI 5585: Precision Injection Moulding of Optical Components

5 Conclusions and Outlook

The Production4µ project has successfully positioned the precision glass moulding technology in a very attractive market segment of the growing optics market, which is addressing global megatrends such as urbanization, energy or safety. Refraining from a low-cost market which is being served by Asian mass producers, the European precision glass moulding supply chain is enabled for the production of challenging optical components with low to mid volumes and a high degree of complexity. Production4µ has contributed to supplying such customized solutions which require a highly developed design competence. Examples for applications of such optical components are Lasers in Production, Concentrator Photovoltaics, Optical Endoscopy, Infrared Cameras, LED-Lighting, Displays, Optical Sensors or Extreme-UV Lithography. Building up on the foundations laid by Production4µ and profiting from its results and follow-up projects, the European optics industry is able to address these markets.

* All pictures (if no other indication): source Fraunhofer IPT