Merging Technologies for Optics

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Abstract

The market for optical and optoelectronical components is a rapidly growing global market. The development of new manufacturing technologies for the fabrication of optics enables the fabrication of optical components with nanometer roughness and submicron form accuracy for mass markets like digital cameras, video projectors and automotive applications, even for low cost applications with short product life cycles. Therefore, the process chain for fabricating optical high quality mass products has to be deterministic flexible as well as in order to suppress cost intensive and time consuming iterations within the manufacturing chain. This paper introduces several approaches to take up this challenge.

1 Introduction

Optics and optoelectronics are an ever growing global market. The global market for optoelectronics grew from 1997 to 2004 from 139 billion USD up to 236 billion USD turnover [1]. Mass products like DVD, camera phones, are the drivers for such growing turnover.

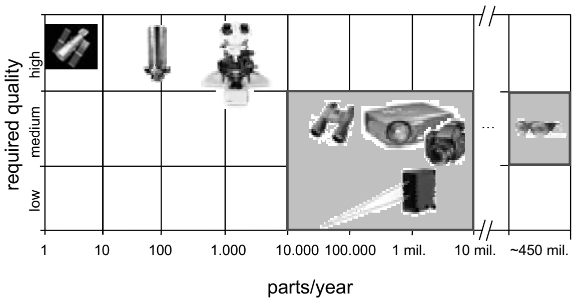


Fig. 1. Applications like video projectors or digital cameras require low to medium quality complex optical components. They have to be fabricated by replication to meet the demands of mass market products. [after Zeiss, VKE, Spectaris]

Optics and optronics are key technologies for high volume consumer products, that are getting faster, smaller, a higher functionality and even more easy to handle and cheaper (cf. Fig 1.). The driver for innovation is the need for increasing precision of optical parts and the integration of several functions within one component.

For meeting these market needs, optical components for mass products have to be fabricated in replication processes. The process for making optical components of plastics or glasses by replication requires: a broad knowledge in optical design, mold making, coatings, the replication processes itself and advanced measuring techniques as well as the ability to merge all these disciplines to a powerful, effective, fast and economic process chain for mass production.

The Frost & Sullivan report "Machine Vision Systems" gives a broad view on the technologies of the next decade. It is reported that the drivers for important innovations of the coming decade are the manufacturing technologies (discussed in [2]). This leads to the idea, that the improvement of manufacturing processes for replicated optics are the keys to innovations in optics. Moreover, those innovations are the drivers to new degrees of freedom in optical design.

Yamamoto divides the innovations in manufacturing processes for optical components into four groups [3]:

- integration of functions
- providing the productivity of the machining process
- improving of the quality of machined components
- improving of the quality of the machining process

The integration of several functions in one component will be a challenge for the optical design. It suffers, however, from the limitations of the mold manufacturing and the replication process. Furthermore, intelligent combinations could lead to new functionalities and, therefore, to new degrees of freedom in optical design. An example is the diffractive structure on an aspherical lens for decreasing aberration of an optical system. After having succeeded in this innovative step as well as secondly having found an appropriate manufacturing technology for machining such parts, the productivity of the machining process has to be improved for reducing the costs per piece. In the third step the machining process has to be developed to higher quality, so the machined products could be used for similar applications in a broader spectrum of usage e.g. at shorter wavelengths. Finally, the manufacturing process has to be improved to a flexible module in a lean production system. This final step is the driver for a mass production of high quality optical products.

However, there are several limitations in a process chain for the replication of plastic and glass components. Replicating plastic parts will be done by injection molding at temperatures less then 200°C, so temperature sensitive mold materials like electroless nickel are appropriate. The advantage of this material in contrast to steel materials and ceramic is its excellent machinability by diamond milling or turning.

If higher hardness or temperature stability is demanded steel could be an alternative mold material. The machining process suffers, however, from tool wear when diamond turning or milling are applied. This is caused by chemical interaction between the steel workpiece and the carbon of the diamond tool [4]. As an advantage, diamond turning and milling operations do not require subsequent polishing processes, however they are applicable only to a small selection of mold materials useful for molding of plastics. The improvement of grinding, polishing and diamond machining processes to higher flexibility, higher precision and a larger spectrum of machinable mold materials is therefore an important goal for current research activities.

The relatively low viscosity of plastic at replication temperature will provide the possibility to integrate mechanical interfaces for mounting and assembly of the lens or haptic components. Nevertheless, the most important advantage of replication of plastic in contrast to glass is the short cycle time and the low wear of the mold, so that hundreds of thousands parts can be manufactured using a single mold. However, the optical quality of plastic lenses is strictly limited by deviations of the geometry and invariance of the plastic density and consequently the variation of refraction. Moreover, the range of plastics optical properties like refraction index or aberrations of the optical system is limited too, which results in limitations in optical design using plastic lenses.

In contrast to plastics, glass optics are showing a much smaller tendency to irregular deformation under invariant thermal, chemical and mechanical environmental conditions like deviations in temperature or moisture. So, the replication of glass is a key technology for fabricating high performance optical products e.g. for projection lenses. However, molding of glass needs precision molds with high temperature stability, even if new innovative glass materials with softening point not much higher than 400°C are applied. Therefore, glass molds should be made of hard and brittle materials like ceramics that require grinding and polishing in contrast to diamond machinable ductile metals like electroless nickel.

During the replication process the mold material will suffer from tribological stress. Hard coatings with tailored mechanical, chemical and thermal properties may help to overcome those limitations for enlarging the parameter window for the replication process and the spectrum of replicated materials. Finally, measuring techniques have to move closer to the replication process to reduce time consumptive handling operations.

Each process step from design over mold making to the replicated part comprises its own limitations and restrictions e.g. form deviations when machining or shrinkage of the replicated part when it cools down. An exact knowledge about the deviations in roughness and geometry of the mold and replicated part is necessary for geometry compensation in an earlier stage of production. This is the first step to a deterministic process chain and presupposes a holistic view to the complete chain. This procedure will take all limitations of each process step into account will merge the process chain to an advanced and powerful instrument for fulfilling the current and coming industrial needs.

2 Applications

There are a large number of products that are drivers for the development of innovative and more precise optical components. Their applications lie in the field of mass markets, so the applied optical components have to be fabricated by replication.

Tab. 1 shows typical applications utilizing replicated optics. The range of the size of the optical components and optic material varies. Each application has its own needs and limits in relation to the process chain. Moreover, there are many technologies needed for fabricating replicated optics - almost different if molding optical glass or plastic components. The technologies in a typical process chain are optical design, fabrication of the mold, possibly using a hard coating for wear reduction and better relief of the replicated part, replication process and finally metrology and quality management. Nevertheless, the required accuracy and complexity of shape will increase in future as discussed above.

Table 1. Markets and applications for replicated optical parts

Markets	**Applications**
Automotive	Headlights Head-Up-Displays
Life science	Optics for endoscopes Head-Mounted-Displays
Display equipment	Video projectors Flat displays
Optical I/O equipment	Fiber optics
Measuring / Sensing	Optical sensors
Storage	CD / DVD / HD-DVD
Cameras / Mobile phone cameras	Digital optics

3 Design and layout of process chains

The process chain for an economic mass production of complex optical elements resulting from this concept is shown in Fig. 2. The process chain comprises all aspects of production ranging from the design phase to mold fabrication, replication and performance tests of the final products. It can only be realized by qualified measuring and testing. Quality chain management is of overall importance, since it guarantees a holistic view of the complete process chain assuring an effective interaction between the individual process steps.

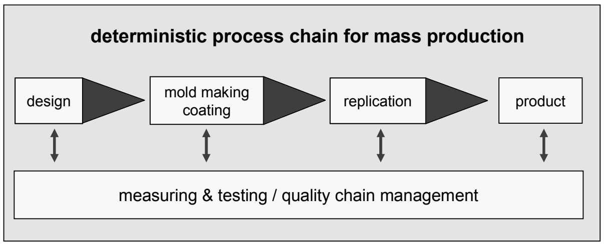


Fig. 2. Deterministic process chain for the replication of high precision optical components

The following chapter will give an overview on current research activities for meeting these challenges. Moreover, it will be shown, that an optimized process chain for fabricating precision optical components has to consider the interaction between mold design, mold making and replication.

Table 2. Requirements, limitations, challanges, and interactions between mold design, mold making and replication process.

mold design process	mold making process	replication process
geometry and dimension - flat - (a)spherical - free-form - superimposed structures	machining process - dynamic stiffness and temperature stability of machine tool - cutting tools - number of axis	replication temperature molded material - rheology / viscosity
roughness	machining process - diam. machining - grinding - polishing mold material - molding temp.	
optical material - glass - plastic		rheology mold material - corrosion resistance - mold life replication process - injection mold. - inj. embossing - hot pressing
accuracy	machining accuracy mold material - creep tendency	

In the mold design process several boundary conditions will be determined for the mold making and replication process. After planning the design of an optical surface, the mechanical interface, the material to be molded and the mold machining process are almost determined too. Moreover, the spacial dimensions do also affect the replication process, because of the temperature dependent shrinkage of plastic when injection molding large, thin parts like mirrors for head-up-displays. Another issue is the required accuracy of the optical component that leads to the choice of the replication process and the mold material selection. The latter is of interest for the long-term dimensional stability of the mold which requires the use of ceramic mold inserts instead of steel for hot pressing of glass. Moreover, for plastic replication processes the step from conventional injection molding to injection embossing (embossing utilizes an additional compression of the replicated part during the cooling process) can be used for increasing the form accuracy.

The replication of glass is carried out at higher temperatures than injection molding of plastic, even if lowTg glasses (softening point at temperatures between approx. 400 and 500°C) are used. Therefore, the spectrum of mold materials differs for molding glass and plastic.

More aspects of interaction between design, mold making and replication process are shown in Tab. 2. It can be seen, that a close interaction - or merging - between the three disciplines is evident for taking the specific advantages and limitations into account.

3.1 Design

Design in a deterministic process chain must not only focus on optical design but has to consider also inherent strategies for predicting and compensating process dependent deformations of the mold insert and the replicated part. For developing such strategies calculating tools for optical design and simulation of injection molding (discussed in chapter 3.6) are needed as well as suitable measuring techniques.

A basic requirement for the comparison of designed and simulated geometries with the produced results like the deformation of glass in a hot pressing procedure or the filling procedure of a plastic forming process is to use a uniform surface data description. State of the art mathematical descriptions are Non-Uniform Rational Basic Splines (NURBS). Due to their ability to describe any type of surface, especially those without analytical function behind, and the small amount of required data, this type of data is ideal for the use in optical applications.

The designed surface data can be further used as reference data for the entire process chain - for comparison of measured interferometric data of the mold as well as of the replicated plastic part.

In Fig. 3 the simulated topography of a designed optical surface described by NURBS is shown. This topography is calculated by an optical calculation program. The data can be directly used for calculating the NC-program for machining the mold insert. The calculation of the tools trajectory has to take the machining process, the tool geometry and its position in the machine tool into account. Calculating the trajectory could be done off-line (before machining), nevertheless, the calculation will take some time, because of the small distance between the nodes to be programmed needed for nanometer precision. This leads to a large amount of data. Moreover, processing of these data is difficult for most numerical machine controls, because of the large data volume and the necessary fast data processing. The consequent step is to use the NURBS surface data for on-line controlling of the machine tool so there is no need to store and provide the data, however, a fast computer system for calculating the data is necessary. Applying this technique to a diamond turning operation a Fast-Tool-System can be used for the control of the tool's motion parallel to the spindle axis [5].

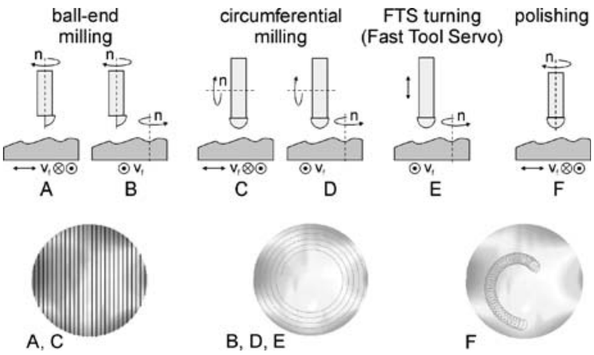


Fig. 3. Simulated, topography of a calculated optical surface (color/gray shade indicates the height in Z direction) and referenced trajectory for the respective machining technology [source: LFM-Bremen]

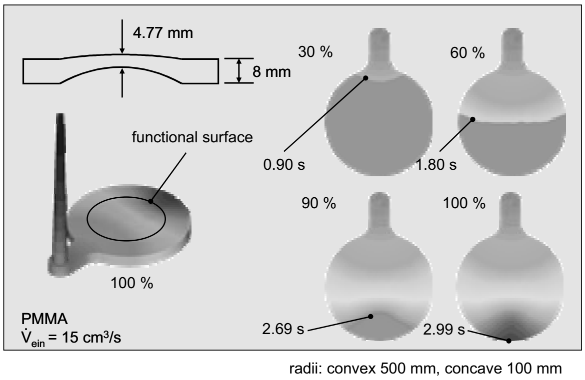


Fig. 4. Simulation of mold filling [source: IKV-Aachen]

Another design aspect is the design of the injection mold. The injection mold has to hold the mold insert in a fixed position, it has to provide the molding temperature and it has to maintain all its functions precisely under the mechanical and thermal load during the injection process. It was found out, that an important aspect for getting plastic parts with low form deviation is the need for a constant and symmetrical pressure distribution during the filling and cooling phase of the molding process. However, during replication any component of the injection mold will affect the geometry of the replicated part more or less. E.g. the clamping torque of the screw for fixing the insert will influence the form deviation considerably [6]. It was proven that molding is a multivariable process, where the form of the replicated part is nearly impossible to predict precisely. However, a simulation program for calculating the filling process can support the design process for the injection mold, mold insert and filling parameters under consideration of the lens geometry, size and thickness as well as the position and size of the sprue (Fig. 4) [7].

However, the simulation has not yet the ability to predict the filling process and the following cooling/shrinking process precisely cause of the noted multivariable situation. Therefore, the geometry of the replicated optical component and its density distribution as a consequence of the locally distributed cooling gradients has to be measured after replication. For achieving high precision plastic parts, the form deviations have to be removed by correcting the mold in a couple of iteration steps. However, simulation techniques and a broad knowledge about the replication process will definitely reduce the number of iteration steps.

3.2 Mold making

There is a large number of machining processes available for making mold inserts made of steel or ceramic material [8]. The processes differ in the spectrum of machinable geometry, material, removal rate, achievable form accuracy and roughness. Diamond machining is a state-of-the-art machining technology with various opportunities for further process improvements that makes this technology more flexible. The spectrum of machinable geometries by grinding or polishing is limited in contrast to diamond machining, but harder materials like ceramics are better machinable by abrasive processes.

Diamond machining

The largest spectrum of geometries is machinable by diamond turning and milling. The processes are adaptable to continuous and structures surfaces as well. The machining of structured surfaces can be done by circumferential or ball end milling. For machining structures like prisms or spherical lens arrays, diamond tools with high form and angular accuracy are necessary. Moreover, the tools have to be in an accurate position within the tool holder and in relative position within the coordinate system of the machine tool.

To prevent geometrical deviations when machining micro structures, the diamond tool has to be positioned in the machine tool with respect to its coordinate system. Besides a geometrical error of the cutting edge ($\Delta\varepsilon$) a profiled diamond tool exhibits three degrees of freedom inside the tool fixture (Fig. 5): tilt error κ (kappa) in the Y-Z-plane of the tool, tilt errors ξ (ksi) in the X-Y-plane of the tool, and tilt error ψ (psi) in the X-Z-plane of the tool. These tilt errors lead to a misalignment of the tool which has to be avoided for the manufacturing of defined microstructures. Whereas the errors a, b and d Fig. 5 will lead to deviations in the including angle of the V-groove, the misalignment Fig. 5c will lead to an angular tilt between the adjacent V-grooves. For tool alignment a tool holder is necessary that offers six degrees of freedom for tool positioning at micrometer scale. The design must be capable to be used at spindle speeds up to several thousands rpm [13]. Customized scratch traces and reversal tests as well as the machining of witness samples have to be performed for exact positioning of the tool is the tool holder. Fig. 6 shows an example of a manual 2-axis tool holder as preliminary work for a 5-axis piezo-electric driven tool holder that can be dynamically (re)positioned during the machining process. The two axes can be used to compensate for the tools radius and angular deviations of ε and ζ by alignment of Ψ.

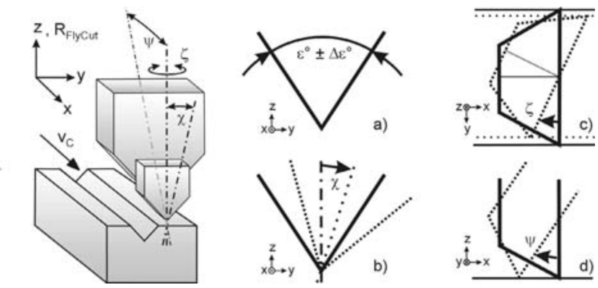


Fig. 5. Degrees of freedom for positioning the diamond tool in a circumferential milling process (left) and in ball end milling (right)

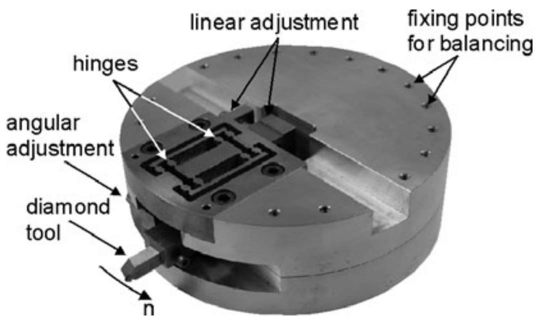
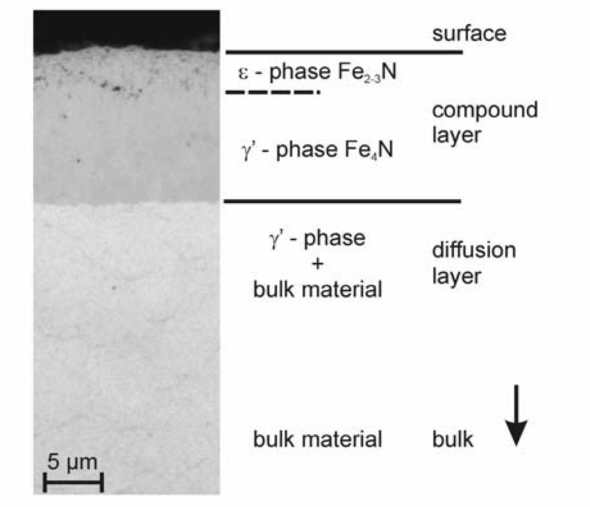
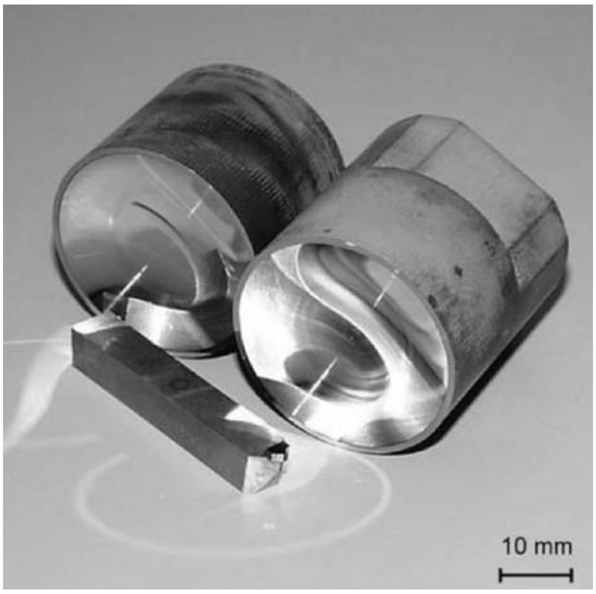


Fig. 6. Study on a manual tool holder for 2-axis positioning of V-shaped monocrystalline diamond tools used in circumferential diamond milling (diameter 150 mm) [source: LFM-Bremen]

In the following new possibilities for the diamond machining of steel molds shall be addressed. Due to the catastrophic tool wear when diamond turning steel, the spectrum of machinable materials is so far limited. Thus, the amorphous electroless nickel coating is the only diamond machinable hard material (approx. 550V). This is state of the art for making mold inserts for injection molding, but this material suffers form its low hardness and low temperature stability above approx. 200°C, e.g. for hot pressing of glass. Mold materials with sufficient properties are - up to now - machinable by grinding and polishing only, therefore, structured surfaces or cavities with small radii are almost not machinable. However, two alternative processes seem to beat this limitation. The ultrasonic assisted diamond turning introduced by Moriwaki [9] and revisited by Brinksmeier [10] and the thermo-chemical modification of the mold material by a new nitriding process [11].



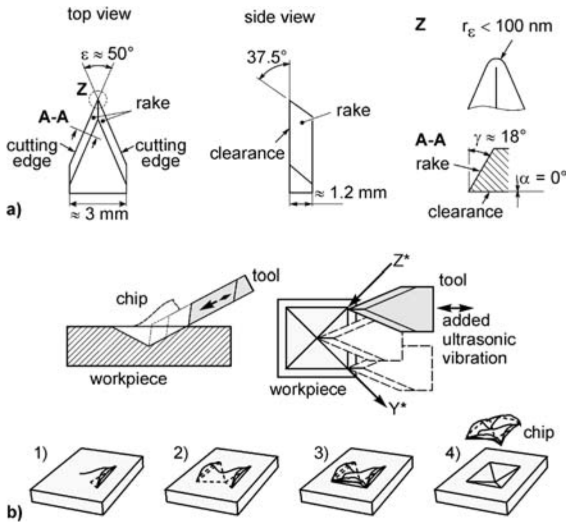
a



b

Fig. 7. Cross section and dominant phases of steel after thermo-chemical treatment; b diamond turned aspheric high alloyed tool steel molds (1200HV)

The basic idea of the new method is to avoid chemical reactions between the carbon of the diamond tool and the iron of the workpiece by establishing a chemical bond between the iron and another chemical element. A propriety thermo-chemical process for altering the chemical composition of the subsurface zone of the workpiece was developed and succeeded in reducing diamond tool wear by more than two orders of magnitude (cf. Fig. 7a). The surface roughness obtained in single point diamond turning of carbon steel was better than 10nm Ra. Similar results were obtained with sintered high alloyed tool steel with a Vickers hardness of approx. 1200HV. Fig. 7b shows two aspherical hard steel molds diamond turned with one diamond tool.



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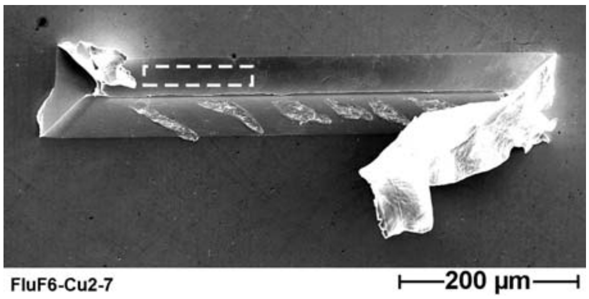

b

Fig. 8. Geometry of the monocrystalline diamond tool and tool motion and cutting process for micro cutting of a four sided pyramidal micro cavity; b SEM image of a four-sided V-groove (80 µm x 500 µm) machined in OFHC-copper by diamond micro chiseling

Another challenge in mold making is the direct diamond machining of micro cavities. The spectrum of machinable structures by diamond turning and milling is inherently limited by the tool geometry and its intrinsic kinematic. Whereas the machining of retro-reflective triple structures is state of the art in diamond cutting the machining of a more efficient retro-reflective cube corner array cannot be machined because of the need to generate a 3-fold pyramidal cavity. A machining technology that offers the ability to machine sharply ended discontinuous structures in a range between 50 to 500 µm will be a key technology for new applications. With this technology available new optical functions can be implemented in complex optical components leading to a new degree of freedom in optical design.

For meeting this challenge a novel cutting process, diamond micro chiselling, is being developed. This process enables the generation of discontinuous structures like V-shaped grooves with defined endings and perpendicular bends. The applied tool is similar to a V-shaped diamond tool and the cutting procedure for a 4-sided pyramidal cavity will take at least 4 individual cuts (cf. Fig 8a). Fig. 8b shows a sharply ended V-shaped groove as first result of this investigation. Roughness of approximately Sa = 4 nm (measured in the indicated area of Fig. 8b) is realizable using this process [14].

Precision Grinding

Precision grinding technologies have to be developed in order to get optical or near optical surface quality when machining steel or ceramic mold materials. A key technology is the electrolytic in-process-dressing (ELID) and shaping technology for the metallic bonded diamond grinding wheels for maintaining its sharpness and form accuracy even for machining of hard materials in (near) optical quality [15][22]. Another strategy for sharpening and shaping diamond grinding wheels is electrical discharge machining (EDM) that also allows integrating small shaped profiles to the grinding wheel in order to machine structured molds in near optical quality in ceramic materials like tungsten carbide WC or silicon nitride Si_3N_4.

Polishing

In some cases the surface quality of precision molds with structured elements super imposed onto envelope surfaces like plane, spherical, aspheric as well as free formed surfaces is not sufficient for optical applications. Therefore, deterministic polishing processes to improve surface roughness of structured surfaces are necessary. However, since polishing of aspheres, free-forms and structures is a point polishing process, the challenge of the polishing process is to maintain the form accuracy during the polishing process. Several approaches for point polishing of optical components are known. For fast polishing of free-form surfaces Klocke et al. introduced an adaptive polishing head [16][17].

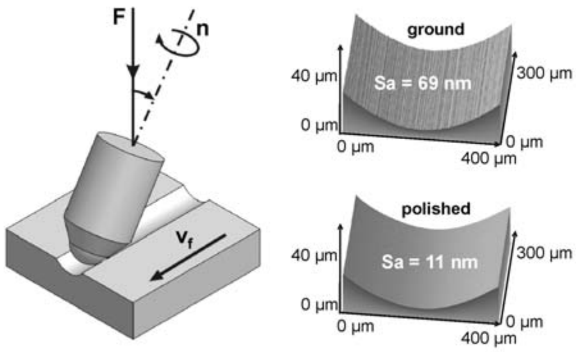

Fig. 9. Structure polishing process for polishing a cylindrical groove using a plastic polishing pad and (right) white light interferometric images of a cylindrical groove in tungsten carbide after grinding and additional structure polishing [source LFM-Bremen]

Besides the continuous optics, structured optics with V-shaped or cylindrical groves with structure size less than 1 mm are increasingly required. These kinds of structures cannot be polished using state of the art polishing technology. A new structure polishing technology to meeting these demands has been introduced in [12]. By using conical pin type tools or conical polishing pads cylindrical and V-shaped groves with structure size less than 1 mm could be polished after grinding (cf. Fig 9). The goal is, to decrease surface roughness without loss of form accuracy.

The process chain for making steel or ceramic molds is to grind and polish them after premachining as described above. A future target is to substitute one of the used processes - grinding or polishing. However, when substituting the polishing process, the grinding process has to produce nanometer roughness. In the other case polishing has to have a much higher removal rate and to produce a deterministic form accuracy. It was found, that the grinding process can indeed substitute polishing when machining steel molds. The fabrication of ceramic molds can be done by optimized grinding process only, because the higher hardness that leads to a reduced roughness [19].

Polishing of steel or ceramics is still a process that bases on the experience of the operator of the polishing machine tool. A kind of 'polishing process feeling' is necessary for finding optimal process parameters. Moreover, the demands on the form accuracy of polished steel and ceramic molds are almost below one micrometer with aspherical or free-form shapes. Therefore, the necessary step to a deterministic polishing process needs a fundamental knowledge about mechanical and chemical interaction between workpiece and tool during the polishing process. Basic research is underway to in describe and model the surface and contour generation when grinding and polishing [18][19].

3.4 Hard coatings

Hard coatings are essential as interfacing layers for the relief of the molded part from the mold and may considerably increase mold life. They will be used in two different ways: (1) a coating that will be placed on the mold after the mold surface has been completely machined and (2) a coating that is machined itself by the final finishing process. An example for the latter type is diamond machinable electroless nickel commonly used for machining of mold inserts for plastic forming.

Innovative coatings which are diamond machinable and also wear resistant in molding processes are deposited by magnetron sputtering with a thickness of at least 20 µm. The coating properties considered to be necessary include high adhesion, low stress, small grain size, moderate hardness, and sufficient oxidation resistance [20]. Sol-gel-layers can be micro-structured by diamond turning or milling prior to hardening were presented in [21]. The coatings consists of metals of organic sol systems for the deposition of machinable Al_2O_3 and ZrO_2-coatings which show plastic like properties in a pre-ceramic state. Deposition techniques like dip-coating and spin-coating or the electrophoretic aided sol-gel deposition are applied to steel molds. Finally, a thermal treatment with temperatures up to 700°C is applied in order to achieve maximum hardness for the sol-gel-coatings. The deposited coatings have to be characterised regarding film thickness, density, porosity, (ultra micro) hardness, adhesion and phase composition.

3.5 Replication

Replication techniques are particularly suited for large volume production and possess a great potential for improving the quality of molded optical elements.
The machining technology for injection molding has to optimize by analyzing process behavior of different optical plastics materials, machine technology, processing and process control. Besides the analysis of the injection molding process, it is important to investigate the influence of the injection compression and injection embossing technology .

For glass molding of (structured) optical components hot pressing of glass is the technology that could be used for replicating high precision parts. The goal is to extend the potential of this technology. A new approach is the implementation of a concept with separates the heating of mold and glass material [24]. The aim is to avoid sticking of glass to the mold and to achieve shorter process times by improving the heating and cooling management.

3.6 Measuring techniques and quality chain management

For describing the geometrical condition of the mold insert as well as the replicated part micro- and macro-geometrical properties have to be determined.

An important issue is the integration of measuring equipment into the machining process, since there is a great demand of in-process and in-situ measuring techniques regarding the optimisation of process chains.

A new approach to characterise the functional properties of lenses, mirrors, replication tools and molds at micro scale combines two laser optical measuring principles to measure local and integral features of continuous and structured surfaces. The method of double scattering by speckle pattern illumination characterises the integral measure surface roughness in the range of Ra < 100 nm. A modified measuring arrangement based on the principle of angle resolved scattering (ARS) analyses local defects (e.g. scratches, cracks, chips) and structure deviations. Scattered light techniques are generally parametric and fast and therefore show in-process capabilities for micro-form and micro-structure measurement [25].

For measuring the form deviation of a mold with optical aspheric or free-form surface in production machines using interferometry the vertical measurement range of the interferometer has to be extended. Another more flexible way is the use of multiple wavelength interferometry [26]. In the end, such a system could be used for the online quality control of production processes of injection molding or pressing forms with continuous surfaces.

As an innovative non destructive near surface zone analysis photo thermal techniques are applied yielding information about hardness(-profiles), layer thickness, adhesion defects, flaws like cracks and pores, and residual stress of tools and replicated objects in near surface zones from a depth of few micrometer down to 1mm below the surface [27].

Especially for determining the properties of the hard coatings presented above an extensive study of the near surface mechanical nature of these coatings has to be performed as high resolution surface and subsurface analysis by using nano indentation and nano scratching technique [28]. Measured information about the mechanical state of the surface layer concerning its processing conditions can be used to create the surfaces and their resulting mechanical state. E.g. elastic modulus E and hardness H, of the molds, coatings and final glass/polymer optical components can be determined for characterizing its mechanical properties.

4 Merging Technologies

The manufacture of optics in high volume requires process chains including optical design, mold making and replication as well as measuring techniques. Any applied technology within a process chain has its advantages and limits. And for making a powerful process chain, it is necessary to take all advantages and limits of each process step into account. Moreover, it is important to transfer the applied processes to deterministic processes, so, the result of a process step should be known in advance. This information can be used as data for a knowledge base for planning process chains with less time consumptive and, therefore, expensive iteration steps. Precise physical or empirical models as well as simulation tools have to be taken into account to reach this goal. Additionally, qualified metrology including surface and subsurface inspection as well as figure evaluation plays a vital role.

Nevertheless, a holistic view of the complete process chain is required. Quality chain management is of overall importance since it guarantees an effective interaction between the individual process steps. Therefore, closed process chains comprising all aspects of production will open the possibility to produce high precision complex optical elements as mass-product articles for many optical applications.

Deterministic process chains have their foundation in merging technologies by separate process steps which means, that anybody in a process chain will act with the knowledge, what anybody else in the chain needs for his step and vice versa. An example is a NURBS based common description of the geometry from the optics design, the simulated shape, the shape to be machined for fabricating the mold insert, the measured shape of the insert to the shape of the replicated part. Converting errors or miscommunication can be avoided using a common data description.

The quality chain management has to organize the connections and the process steps - or in other words - it has to spread the filtered common knowledge to all individual processes. So, any process step of the chain will get sufficient data, in order to eliminate process time for unneeded specifications of the finished part.

The connections are represented by requirements to following or preceding process steps as shown in Fig. 10. The requirements could be the designed form and roughness, maximum size or weigh of a part, predicted (simulated or measured) shrinkage or anything else what is necessary to guarantee an unobstructed and fast procedure of the process chain. Moreover, the information could also show organizing or logistic character like a date of delivery. This schematic view of a process chain is easy to convert to a web-based computer application. So, it can be used for planning, for performing and for evaluating process chains in the large group of the process chain participants, especially, if not all process steps are carried out at the same location [29].

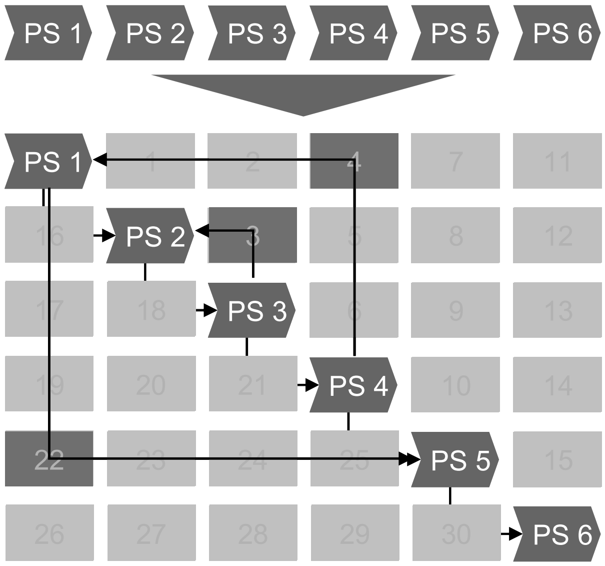

Fig. 10. Each process step (PS) in a process chain (PS1...PS6) has requirements to following or precede process steps [source: IPT-Aachen]

5 Conclusion

The mass production of high precision molds with aspheric, structured or free-form shape is still a great challenge, whereas, the number of optics, its complexity and its quality needed increases year by year. Innovative fast, precise and deterministic machining and measuring technologies are required to meet this challenge and the integration of measuring techniques is required. Moreover, a holistic view over the entire process chain is necessary to transfer a conventional optics fabrication into a powerful and effective process chain.

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