Advances in Ultra Precision Manufacturing

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Abstract: In the past many qualified technologies have been established for the manufacture of optical, precision and micro parts as well as precision structured surfaces. In this field mechanical machining processes, like diamond machining, play a dominant role. Novel mechanical manufacturing processes, further development of ultra precision machine tools and the precision machining of challenging materials yield a great potential as enabling technologies. The growing markets of ultra precision technologies will fuel many industrial sectors.

Ultra precision manufacturing, machines, tools, processes

1. Introduction

Mechanical ultra precision machining processes are almost universal and have a long technical tradition. This is due to the fact that a huge class of engineering materials like metals, semiconductors, ceramics, optical glasses, plastics can be processed and a large variety of surfaces with optical, mechanical or other properties can be generated. Therefore, ultra precision manufacturing has become a powerful tool for controlling surface properties and sub-surface integrity of parts with often optical but also other functionalities.

Over the last decades ultra precision machining has provided deterministic methods for the generation of freeform surfaces and complex micro-structured surfaces with unique accuracy and cost effectiveness. The amazing diversity of shapes that can be created today in optical or near-optical quality by multi-axis machining has stimulated the design of complex optics. Application of ultra precision manufacturing ranges from automotive to medical, illumination, astronomy, optics and metrology.

According to Taniguchi [TANI1983] "precision" is a relative idea changing its meaning with the enduring pursuit for higher accuracy. Today, ultra precision machining is associated with relative positional errors $<10^{-6}$. There is, however, an equally important effort towards higher complexity in machine tool building providing more degrees of freedom for controlling the position and orientation of the tool with respect to the work piece, which is a prerequisite for non-rotationally symmetric complex shapes. Diamond machined optical components are needed for projection systems, displays, laser scanners, sensors, scientific instruments, medical and defence equipment, laser beam guiding, illumination systems and many more. These products exhibit a multitude of different surfaces ranging from rotational symmetric aspheres to free form and structured surfaces with arrays, Fresnel or prismatic elements.

A classification of processes towards micro machining has been proposed by Masuzawa [MASA2] and the approach is valid for most existing machining methods. Two guidelines direct towards micro machining reducing the unit removal and improving equipment precision. Masuzawa proposes different types of micro machining processes distinguished by the removal process. These processes are removal by mechanical force, melting and vaporization, ablation, chemical or electrochemical dissolution, plastic deformation, solidification, lamination, and re-composition.

Among the conventional machining processes based on material removal from a work piece, the most popular ones are those in which the useless part of the work piece is removed by mechanical force through plastic or brittle breakage. Referring to Masuzawa, in micro metal cutting, the first requirement for micro machining, small unit removal, is satisfied when a high stress that causes shearing of material is applied to a very small area or volume of the work piece. This means that a highly concentrated force must be applied to an appropriate position of the work piece. Therefore, assuming that the desired unit removal is around 100 nm, a tool that has its edge sharpened to a radius smaller than 1 µm is necessary.

2. Ultra precision machining

A major prerequisite for ultra precision machining is a remarkable precision of the tools, machines and controls down the nanometer range. This technology has originated as diamond machining from the 1950s to 1970s and was originally designed for machining of metal optics at macroscopic dimensions with so far unreached tolerances. During the following decades the machine tools, the mono crystalline diamond cutting tools, the work piece materials and the machining processes advanced to even higher precision and flexibility.

Today, several kinds of fast tool machining and multi axis machining operations can be applied for diamond machining of ultra precision components as well as micro optical elements. These parts can either be machined directly as single or individual component or as mold insert for mass production by injection molding of plastics or hot pressing of glass.

Machining of such surfaces requires at least three numerically controlled machine axes. The respective machining processes can be classified into line contact processes, e.g. non-circular turning and asymmetric contour grinding, turning with fast tool servos, fly-cutting and contour boring, and point contact processes, like raster fly-cutting and raster grinding, asymmetric contour milling and ball-end milling. The technology of figure evaluation of free forms and micro-structured surfaces as well as non-destructive measurement of the micro topography of structured surfaces still need further development.

Multi-axis machining is characterized by the absolute positional errors normal to the surface which have to be extremely small, usually in the order of a few nanometers. This is imperative to all point contact methods where the tool travels a long distance in space before returning to the same coordinate. This imposes a high degree of sophisticated machine design, error motions of the individual axes should be separated instead of being superimposed, backlash is prohibitive, reference scales must be invariant to changing ambient conditions. Thus, the arrangement of slides and rotary axes must carefully be considered.

Furthermore, machining times in ultra precision machining can be extremely long, e.g. up to several days translating into a requirement for outstanding thermal stability of both environment and machine components like motors and spindles. These conditions also have an impact on the machine's numerical control and feedback loops. There are two key elements which enable the evolution of mechanical machining towards higher precision:

- accuracy of the machine tools
- accuracy of the tools

The development of ultra precision machining over the last decades has been summarized by Evans [EVAN1989], Chapman [CHAP2004] and Marsilius [MARS2009] and some important landmarks regarding machine design, feedback systems, control and accessories are given in the following. The developments make today's ultra-precision machining systems more productive, more precise, and lower in price:

- Thermal and mechanical stability as well as good damping properties through machine bases made from epoxy granite or natural granite.
- Linear axes equipped with hydrostatic oil bearings for improved damping and wear free smooth motions at highest geometrical accuracy.
- High-resolution linear scales with resolution of 1 nm and below replacing laser interferometers for nanometric axis position and improved geometrical accuracy.
- High feed rates and excellent dynamic stiffness obtained by linear motors.
- Environmental control by air-conditioning of machine housings and customized systems for enhanced vibration isolation.
- High load capacity and stiff aerostatic spindles guaranteeing high-speed applications.
- Grinding and polishing of diamond tools with well defined geometry and sub-micron cutting edge waviness.
- High speed PC based computer numerical controls allowing data exchange and large part programs.
- Advanced drive and feedback devices to improve work piece accuracy.
- On machine work piece measurement and error compensation systems to access residual work piece errors.
- Multi-axis machines, fast tool servo and slow slide servo turning for freeform machining.
- Dedicated software for free form machining and in-situ metrology.

A common limitation of single point diamond turning and grinding machines, is their inherent ability to generate only rotationally symmetrical surfaces. Although these geometries cover the majority of requirements, there is an increasing demand for optics to incorporate more random, freeform geometries. These surfaces might require raster fly-cutting, or raster grinding, depending on the material.

Today it has become possible to generate free form shapes and structured surfaces by ultra precision machining techniques, even in combination. Increasing complexity is associated with a loss of symmetry of the surface and hence with an increase of the number of degrees of freedom needed for moving a tool past a surface, i.e. an increase of the number of controllable machine axes. This development of machining systems for ultra precision machining towards higher accuracy and increase in complexity is illustrated in figure 1.

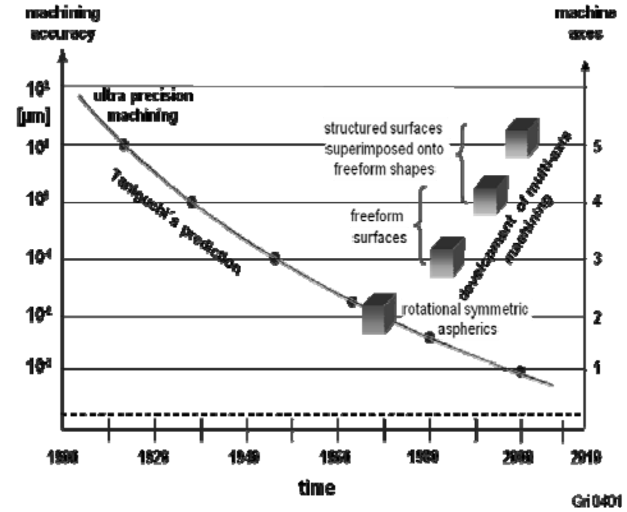


Figure 1: Development of ultraprecision machining systems towards higher accuracy and complexity.

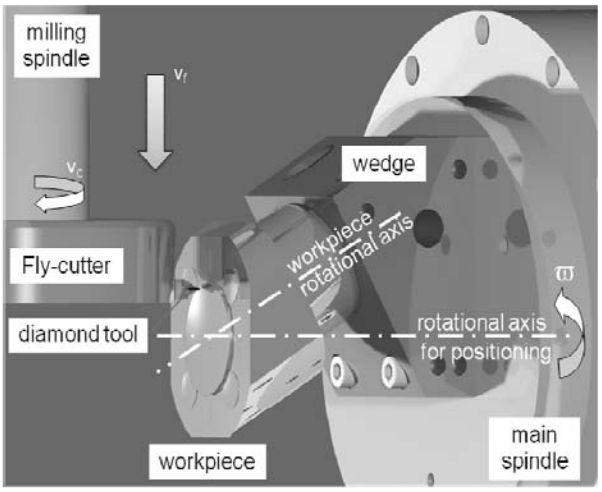
Raster machining processes require the part to be mounted in a static condition, while its relationship with the cutting tool or wheel might move simultaneously in up to five axes. Many advanced design features are built in to such a machine, an example of this is the integral axis configuration, to improve system stiffness, reduce thermal effects, and reduce geometrical errors. Automatic systems have been developed for establishing tool/wheel radius, height, and position on the machine relative to spindle center-line. These devices usually employ kinematic mounting techniques to ensure fast and precise location on the machine and tactile or optical probe technology combined with automatic setting software.

3. Application of ultra precision machining processes

In line contact machining processes continuous cutting is maintained along a certain line in space. The most obvious way of achieving a well-defined departure from a rotationally symmetric asphere is to modify a turning process by moving the tool parallel to the work piece spindle axis C as a function of angular position. This movement can be performed either with the machine's Z-axis slide (so called Slow Slide Servo - SSS) or with a superimposed Z'-axis, a so-called fast tool servo (FTS).

Diamond milling or fly-cutting is a well-known method for generating toroidal surfaces on a 2-axis lathe. If the midpoint of the fly-cutter can be moved freely in space, arrays of toroidal surfaces can be generated.

Point contact is established, if the interaction between the cutting edge and the work piece is restricted to a small surface element and is periodically interrupted, usually at a high frequency, due to the rotation of the tool. Point contact methods are characterized by long machining times but bear the potential of machining almost arbitrary shapes. Line contact fly-cutting changes into point contact fly-cutting when the radius of the fly-cutter is smaller than the local radius of curvature in the fly-cut plane. Figure 2 shows a typical set-up for raster milling of a free form mirror.



source: ESA, Oerlikon Space Zürich AG

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Figure 2: Raster millingof a free form mirror.

Contour boring with a half-arc diamond tool is a line contact process that can be used on a multi-axis machine for generating arrays of concave spheres. If a lateral feed is superimposed to the motion of a half-arc diamond tool spinning about its axis, a transition to ball-end milling takes place. Ball-end milling allows the machining of surfaces with much smaller radii of curvature than is attainable by raster fly-cutting. In order to avoid burnishing of material at the centre of the rotating tool, pseudo ball-end milling diamond tools have been proposed by Takeuchi which exhibit a small gap between the axis of rotation and the beginning of the cutting edge [TAKE1993].

Structured and functional optical surfaces are key components in many optical systems. And ultra precision machining opens up many opportunities for these applications. A new machining process, diamond micro chiseling (DMC), has been developed which is capable of generating micro retro reflectors and other micro optic structure geometries not machinable so far [FLUC2008]. The potential of DMC for allowing more degrees of freedom in optical design for micro structures becomes obvious as shown in figure 3, a large scale corner cube array manufactured by DMC.

Future goals for DMC are to improve process stability, machining time and to increase the complexity of machinable structures by development of dedicated CAM strategies, improved diamond tools and in-situ quality control. Structure arrays will be machined onto flat, spherical and also aspherical work pieces, followed by molding experiments to assess if the DMC machined molding tools fulfill the requirements in terms of accuracy and tool life, which are necessary for their application in mass production of micro structured optical parts.

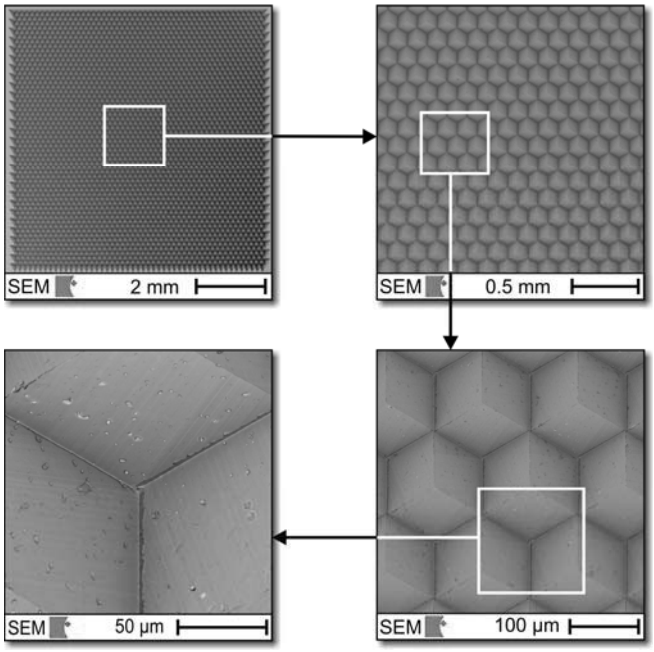

Figure 3: Large scale corner cube array manufactured by Diamond Micro Chiseling (DMC).

The final aim is to apply DMC for the manufacture of advanced molding tools for replication of cube corner retro reflectors or hybrid optics, which contain microstructures for integration of additional optical functions.

Furthermore, refractive components are more and more substituted by diffractive optical elements (DOE) due to their more complex functionality. Despite the extensive amount of research on FTS no existing system offered a suitable combination of stroke, operating frequency and positioning accuracy for fabricating high resolution diffractive optics. Thus, Brinksmeier et al. [BRIN2010b] have recently presented a 350 nm stroke FTS operating at frequencies up to 10 kHz which can be used for the generation of such holograms in metal surfaces for security applications. This so called nFTS system allows for machining DOEs with submicron precision of the structural dimensions. Such DOEs can be used as optical keys for security applications, having the advantage of fast fabrication within a single process step and each DOE having an individual structure.

The nFTS process has successfully been applied to machine diffraction gratings for wavelengths in the range of 600 nm (see figure 4). Despite of the optical design and machining accuracy the work piece material is of essential importance. The material has to be suitable for diamond machining to achieve a sufficient surface roughness. Furthermore, structure accuracy, burr formation and tool wear have to be taken into account.

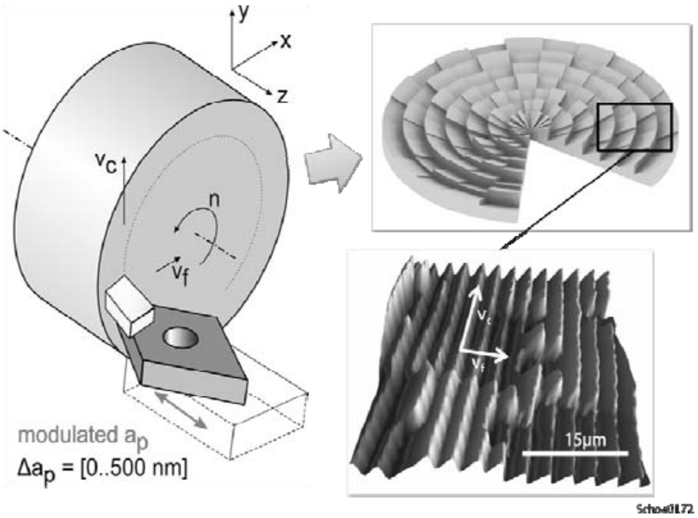

Figure 4: Nanometerstroke fast tool servo (nFTS) turning for the manufacture of diffractive structures.

Figure 5 summarizes the application of all ultra precision machining processes discussed above with respect to the basic geometrical dimension and the attainable geometrical complexity.

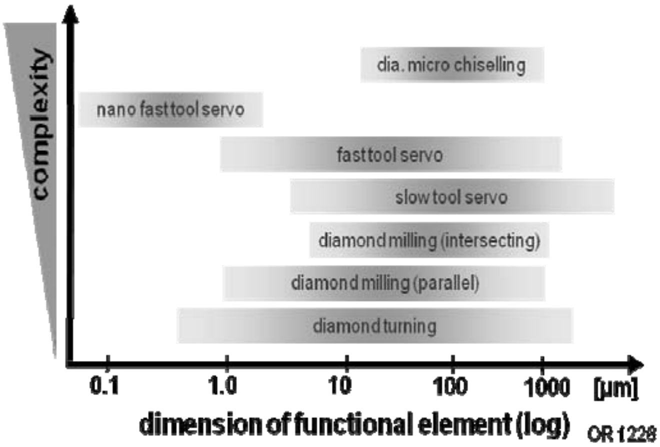

Figure 5: Complexity of ultra precision machining processes.

4. Metrology of ultra precision machined surfaces

Figure evaluation of freeform surfaces and assessment of micro topography are decisive for all types of ultra precision machining processes. The difficulties of figure evaluation of rotationally symmetric aspherics are even exceeded by those imposed by free forms. Most measuring devices, mechanical and optical, do not accept surface slopes beyond a certain limit. Moreover, there are restrictions in size or in departure from certain standard geometries.

Any assessment of surface geometry consists of predefinition of the part coordinate frame with respect to the coordinate frame of the measuring device, retrieval of surface data with sufficient accuracy and resolution, and finally data interpretation. The most universal technique for evaluating the geometry of free form surfaces - although comparatively slow - is collecting surface data with an ultra precise 3D coordinate measuring machine. The urgent need for more convenient, faster and inexpensive methods for testing of aspheres and free forms has been recognized for a long time. Computer generated holograms which are costly and inflexibile are nowadays complemented by interferometric stitching techniques.

For the qualitative imaging of the micro topography of precision machined structured surfaces scanning electron microscopy is commonly employed, although probe size sometimes poses a problem. However, non-destructive quantitative measurements are possible today only within narrow limits. The biggest problems are associated with large slopes and aspect ratios. White-light interferometry, like other optical methods, cannot cope with surface slopes larger than approx. 25°. Stylus instruments accept a somewhat larger slope, but deliver an image convoluted with stylus geometry which is disadvantageous for the assessment of sharp corners. The non-destructive assessment of the topography along steep slopes and vertical walls remains essentially unsolved.

5. Conclusion

Ultra precision machining is generally regarded as a key technology of the 21st Century. Everyday products such as televisions, video players and cameras, contact lenses, binoculars, security systems, compact disc players, personal computers, and many more, rely on advanced manufacturing techniques to produce high performance optics and precision components in a cost effective way.

For many products this has resulted in a need to produce parts with improved size and geometric tolerances, often with the aid of in-process measurement and error compensation techniques. To achieve high precision motion, in the presence of non-linear disturbances, advanced CNC systems require the use of feed forward techniques to achieve zero tracking errors and robust synchronization of motion. The continued increases in processor speed and measuring resolution have advanced the technology to a stage where current machines tools, tools, control algorithms and architectures are capable of very high performance in terms of ultra precision machining. The need to produce precision parts in a mass scale introduces new production requirements for the machine and equipment manufacturers in terms of availability, cost-effectiveness and reliability.

Particularly ultra precision machining processes like turning, milling and drilling using mono crystalline diamond tools and deterministic grinding processes show greatest potential aiming at higher complexity in part geometries combined with higher productivity driven by market requirements. Advances in associated computer assisted technologies like CAD/CAM for complex optics, in-situ metrology and data feedback lead to deterministic ultra precision machining.

Promising and still challenging is the increasing demand for precision components with structured or micro structured surface for optical or mechanical applications. New processes are under development for machining even features with sub-micron size, i.e. diffractive optical elements. At the same time, measuring structures is yet not solved satisfactory for all required characteristics.

Furthermore, the demand for ultra precision machined novel materials, e.g. molds for replication processes, leads to the need to apply precision grinding with all associated challenges. Optical components require surfaces without sub-surface damage, which can be achieved in grinding explained by the phenomenon of ductile-to-brittle transition. Nevertheless, in ultra-precision grinding the situation is different to geometrically defined precision cutting processes. While raster fly-cutting is a well-established process, ductile regime raster grinding is still under development. Since the critical uncut chip thickness of most brittle materials is in the submicron range, it is evident that ductile mode grinding can only be achieved with ultra-precision machines and grinding wheels exhibiting an excellent roundness. Additionally, dressing of the grinding wheels is of highest importance. Here electrolytic in-process dressing (ELID) is a well-established technique to enable ductile mode material removal [OHMO1995]. Additionally, new grinding tool concepts with coarse grains and binderless fine grained diamond tools are under preparation [BRIN2010a]. Finally, precision grinding has significant influence on machine design to ensure that the stiffness of the machine is suitable to handle the increased grinding forces, and that the guarding and coolant containment measures are up to the increased demands [CHAP2004].

Also promising and extensively and long-time investigated is the search for solutions for the precision machining of steel. The catastrophic wear of diamond tools when machining ferrous metals cannot be explained alone by the differences in the mechanical properties of the materials like hardness and fracture toughness. The presence of a chemical component in diamond tool wear as has been pointed out by Paul and Evans [PAUL1996]. The reduction of diamond tool wear was achieved by ultrasonic vibration cutting of steels, in which the contact between the cutting edge and the work piece material is interrupted periodically at a high frequency [MORI1995].

Todays ultra precision machining systems are built on fundamental precision engineering principles coupled to leading edge technologies in controls, drives, and feedback devices. Important technological advances in a number of disciplines – first of all process technologies, but also including measuring and testing, quality assurance as well as the production environment - are necessary for further advances including the development of ultra precision processes, machines, and control systems which can achieve nanometer tolerances and sub nanometer surface finishes as well as new analytical techniques that can observe, measure and provide 3-dimensional images of features at the nanometer level. Finally, it can be concluded that novel mechanical manufacturing processes, further development of ultra precision machine tools and the precision machining of novel materials offer a great potential as enabling technologies in ultra precision manufacturing; ultra precision cutting processes will proceed in a bright future.

The growing markets of precision, optics and micro technologies and systems yield a high potential for engineering tasks in ultra precision manufacturing. In the future, machine developments will continue to be driven by market requirements and progress in the ultra precision machining area will fuel many industrial sectors.

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