Innovations in Ultra-Precision Machine Tools: Design and Applications

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Abstract – Ultra-precision machine tools represent a special class of machines that perform at an extreme level of precision. Performance of these machines has steadily evolved with time and this has enabled continuous development of new capabilities. Not only can these machines directly generate surfaces capable of performing a variety of optical functions, the overall shape of these surfaces is not limited to rotational symmetry. Surfaces can be freeform and discontinuous. In addition, very large ultra-precision machine tools have now been developed to generate large scale micro-structured surfaces for high-volume manufacturing. Further development of these ultra-precision machines will continue and enabled by advances in measurement systems and electronics. Future machine systems will address the need for greater size, lower costs, and higher productivity.

Introduction and Historical Review

Ultra-precision machine tools can be defined as those with the ability to generate surfaces suitable for performing optical functions. This definition does not limit the machines from being used to make surfaces and features intended for mechanical functions. However, this definition does serve as a way to differentiate this class of machine from more conventional precision and high-precision machine tools. Conventional precision machine tools are designed specifically for generating features with mechanical functions and are designed and built to operate at an at a lower level of repeatability and accuracy (precision).

Surfaces and features that manipulate light require overall form error on the order of 0.1 µm/100 mm (in optical terms, about λ/4 or better) with surface finish less than 10 nm R_a. In fact, most ultra-precision machine tools are now capable of generating surface finishes on the order of 1 nm R_a in many materials. In the case of a grinding process, the surfaces can be on a very hard material. Fig. 1 shows the measurement of an optical mold made from tungsten carbide.

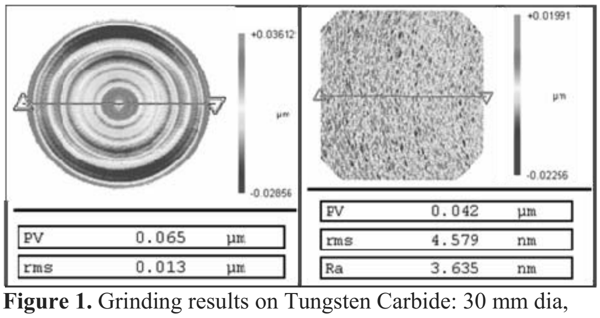

Figure 1. Grinding results on Tungsten Carbide: 30 mm dia, Form PV = 0.065 µm, Surface Finish R_a = 3.635 nm.

Ultra-precision machine tools can achieve this form accuracy and surface finish at the same time on the same workpiece. This is one significant characteristic that differentiates these machines from the more conventional machine tools.

Machine Technology

These ultra-precision machine tools have evolved over the last 50 years and they are now commercially available from several manufacturers [1]. Some common features of these machines over time have been the use of fluid bearings, high resolution measurement systems, non-influencing actuators, and fast, high bandwidth (BW) control systems.

Typical today are machines with aerostatic spindles having error motions < 20 nm. Linear slides use oil hydrostatic bearings constructed with an overall geometry < 1µm/1m (10^{-6} or better). Linear measurement encoders have effective resolution < 0.1 nm over 1 m of travel. Spindles and linear slides use minimum influencing brushless DC motors. Control systems are based on DSP and gate array hardware tightly integrated with the measurement and actuator systems.

Initial Applications

These machines were originally developed to generate optical surfaces with single point diamond cutting tools. This provided a method that is more deterministic than polishing with the added benefit of reduced cycle time. Early applications were hard disk substrates, photocopier drums, VHS read/write heads, and faceted laser scanning mirrors.

One particular shape these machines could generate in a deterministic way was an aspheric optical surface. The ability to do this opened up a large number of applications over the years starting with infrared optics such as those used in night vision systems and laser cutting systems. Many aspheric surfaces are produced this way today. This has been an enabling technology for many consumer, industrial, and military devices.

From this beginning, many new technologies have been employed and the applications addressed by ultra-precision machine tools have grown at an impressive rate. The following are some of the more widely implemented applications along with the technologies that have enabled them.

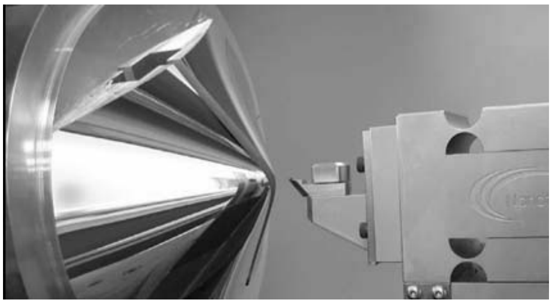

Figure 2. Deterministic Machining of a Highly Aspheric Surface.

Applications and Enabling Technologies

Fast Tool Servo

Initial development of the Fast Tool Servo (FTS) for direct machining of non-rotationally symmetric surfaces took place in the mid to late 1980s [2]. The first commercial application was for contact lenses and this began in the early 1990s. Early applications of this device were limited because control systems at the time could not handle the speeds and complexity needed. Improvements in computational speeds and the use of more flexible open-architecture control systems have enabled this device to address many more applications.

The early FTS devices were based on piezoelectric actuators which enabled high bandwidth operation but were limited in the amount of displacement; typically less than 50 μm. As designs evolved, the displacement was increased through the use of flexures with mechanical advantage [3,4]. This type of tool servo can achieve on the order of 500 μm displacement and these are still used in manufacturing applications today.

Recent innovations in FTS design include long stroke tool servos [5]. Different actuator technology has been developed which enables displacements up to 1 mm at 100 Hz BW and 6 mm at 20 Hz BW. Some even use a counter-mass to minimize influence of the high speed motion on the rest of the machine.

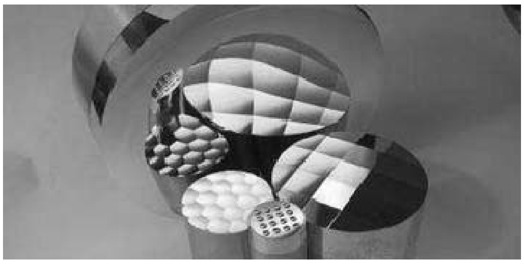

Figure 3. Examples of Complex Surfaces Enabled by Fast Tool Servo Technology.

Slow Slide Servo

For non-rotationally symmetric applications that require displacements beyond a few millimeters, a few of the more recent ultra-precision machine tools have been designed and built so the main linear slides of the machine can be controlled with precision to track a predetermined path as a function of main spindle rotation. One key technology advance that enables this is the use of brushless linear motors. Early ultra-precision machine tools used ball screws for the slide actuators and this severely limited the slide bandwidth and robustness. As with the FTS, improvement in control systems has also been a key enabling technology.

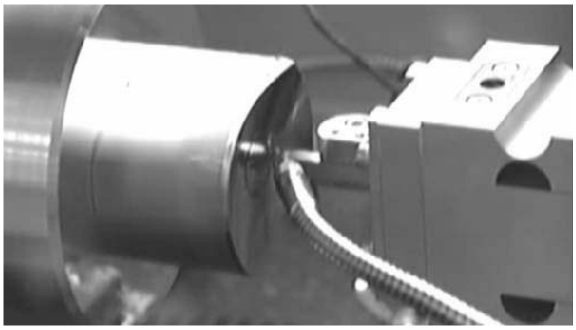

Figure 4. Slow Slide Servo Setup for Surface with Large Departure from Rotational Symmetry.

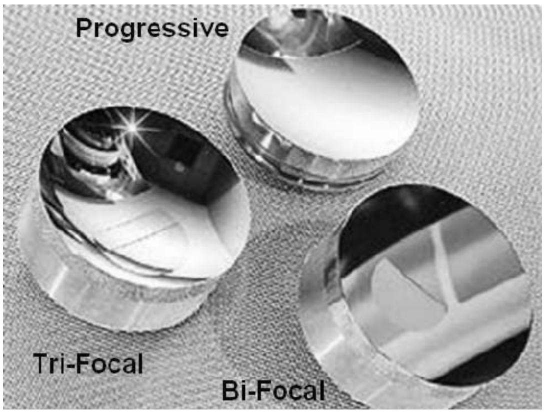

Figure 5. Examples of Optical Molds Made with Slow Slide Servo.

Freeform Shapes

The development of an ultra-precision linear vertical axis has enabled the machining of optical shapes that are not limited to some approximation of rotational symmetry. Surfaces can be of a complex shape, or freeform, and generally limited only by the setup and tooling constraints.

Unlike the turning processes described above, generation of freeform shapes has the workpiece relatively stationary and the cutting tool rotating on the main spindle. Motion of the machine's axes is coordinated so the cutting tool is moved across the workpiece surface along a series of parallel scanning lines with very close spacing. This raster type scanning allows the tool to follow very complex contours. Fig. 6 shows one particular type of freeform optical surface that is machined using this process.

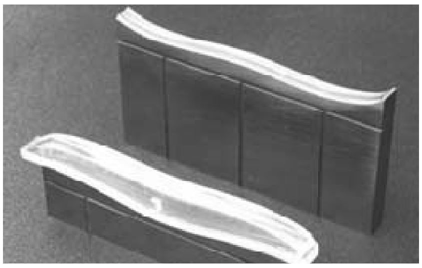

Figure 6. Freeform Surfaces Generated by Raster Flycutting

Micro-Structured Surfaces

The manufacture of products with micro-structured surfaces began in the early 1960s with development of the polymer Fresnel lens used in overhead projectors [6]. From this small beginning, many products have been developed based on micro-structured surfaces. Most notable among them are the Brightness Enhancement Film (BEF) used in LCD displays and the retro-reflective material used in traffic and personal safety products.

Ultra-precision machine tools are the foundation for generating the master tooling for production of these products. Initially, the master tools were small and often pieced together to scale up for manufacturing [7]. This process is still used today for some products. More recently, much larger ultra-precision machine tools have been designed and built specifically for generation of large master tooling. This has enabled companies to increase the volume and lower the cost of manufacturing. Fig. 7 shows a 2 meter ultra-precision drum lathe used for generating master tools for production of optical film for displays.

Figure 7. Large Capacity Ultra-Precision Drum Lathe and Film Manufacturing Line.

The use of hydrostatic bearings for linear slides and spindles was an important enabling technology for the design of these large machine tools. Perhaps more important has been the use of glass linear encoders (instead of interferometers) and the sophisticated open-architecture control systems that are now available. But as these machines have grown in size, the importance of thermal control has grown as well. Technology developed over the last 20 years for control of the thermal environment on a large scale has been critical to development of these large machines.

Many variations of products based on micro-structured surfaces have been manufactured and the use of Fast Tool Servos has been an enabling technology. Fig. 8 shows two examples of BEF pattern modified using an FTS. Advancements continue to be made in the generation of the surfaces for large scale manufacturing.

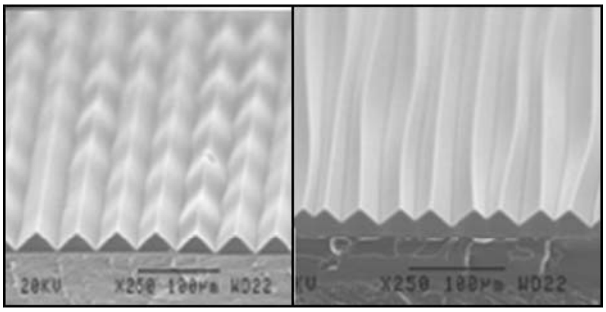

Figure 8. Brightness Enhancement Film Modified with Fast Tool Servo.

Micro-Milling

As with the machining of freeform surfaces, the development of a linear, ultra-precision vertical axis has also enabled the process of micro-milling optical surfaces. One particular type of workpiece that can now be made is a complex array of small lenses. Because each lens is made individually, they are not limited to spherical shapes. In fact, they can not only be aspherical but also non-rotationally symmetric.

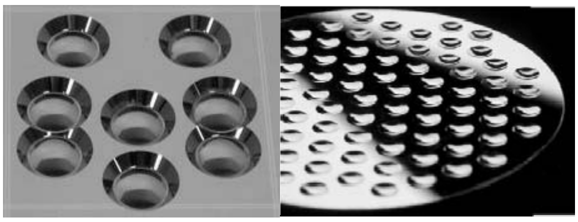

Figure 9. Micro Lens Arrays Generated by Micro-Milling Each Lens Individually.

One application of such a lens array is for the molding of small camera modules for hand-held devices. A lens array mold can be used to mold lenses directly onto a wafer of CCD detectors which can then be diced into individual cameras. This has enabled cost reduction to the point where camera modules can be manufactured for less than one US dollar each. This is an example where the capability of an ultra-precision machine tool has enabled a downstream manufacturing process to move from discrete module assembly to a parallel process and thus reduce cost.

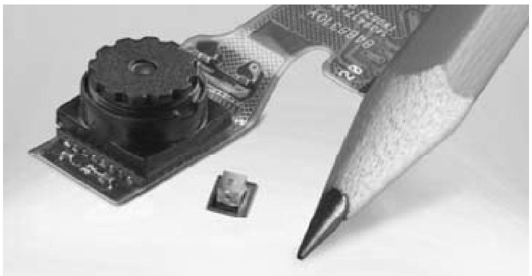

Figure 10. A Conventional Camera Module Compared with a Wafer Camera Module.

Anticipated Future Developments

Automation

Most conventional precision machine tools offer automation features that increase productivity. These features have been well developed on conventional machines, but these ideas have yet to be used to any great degree on ultra-precision machine tools. This is one obvious area for further development. Performance has always been the key motivation behind development of ultra-precision machines and their applications, but productivity is quickly becoming an important factor.

Electronics and Software

The basic principles of ultra-precision mechanical design have been well developed over the last 100 years or more. However, when combined with future high bandwidth control systems and new measurement sensors, ultra-precision machine tools will continue to add capabilities and address many new applications.

Along with this, work must continue in the development of software and firmware to take full advantage of the latest generation of electronic hardware. Opportunities exist to more fully integrate sensors and signals into the control system.

Design Challenges

To help understand future challenges in ultra-precision machine design, it is useful to categorize machines based on a few key attributes. For ultra-precision machines the attributes of size, speed, and price offer a way to consider, or anticipate, future developments.

Figure 11. Normally Exclusive Attributes in Ultra-Precision Machine Design.

Each of these attributes tends to have design objectives that are in conflict with the others so they are somewhat exclusive of each other. Development in two of these areas at the same time, while challenging, will lead to new designs and enable new processes.

For example, the large lathes designed for generating micro-structured master tooling generally require long cycle times to machine a single workpiece. It is a difficult task to design a large, ultra-precision machine tool that can operate at higher speeds to reduce cycle time without losing precision. However, this is a request from those who work to optimize manufacturing.

Application Driven Challenges

There are many types of application challenges presented to developers. One is related to the increased complexity of workpieces. These will require more complex tooling setups and will present a more complex programming task. Software will become a more significant challenge.

Many applications require the use of harder materials. Longevity of the workpiece in subsequent manufacturing processes often dictates this. Working with hard materials will require further development in tooling and a better understanding of the material removal process.

Workpieces with smaller features will continue to be presented. This will require better measurement and setup processes and the sensors and software to support this. It will also put increased emphasis on accuracy and quality of the cutting tools.

Finally, many applications require longer cycle times to complete. This generally increases the amount of cutting done by a single tool and tool life becomes an important issue. For example, on the large cylindrical drums used for making display film, chip lengths can easily exceed 20 km on a single pass of the tool across the workpiece. Longer cycle time also increases the importance of thermal stability of the machine, the tooling and fixtures, and the workpiece.

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