

Ultra-precision Machining Systems; an Enabling Technology for Perfect Surfaces

Gavin Chapman

Moore Nanotechnology Systems LLC, PO Box 605, 426a Winchester Street, Keene, NH 03431, USA

A Historical Overview

The technology of ultra-precision machining, spanning almost three decades, has only in recent years experienced major advances in machine design and, subsequently, performance and productivity. In the 1970's, ultra-precision machining techniques were successfully adopted for the manufacture of computer memory discs used in hard drives, and also photoreceptor components used in many photocopier machine and printer applications. Such applications required extremely high geometrical accuracies to be achieved, in combination with super smooth surfaces. These surfaces were found to be most effectively manufactured by single point diamond turning, as opposed to multiple processes such as machining, lapping, and polishing.

The machinery developed for such applications typically required only one linear axis of motion, to generate a cylindrical or plano form. The machines often utilized an air bearing work holding spindle, and linear slide, mounted to a granite base. Machinery soon evolved into multi-axis systems, with major advances seen in CNC control, and position feedback technology. An example of one of the early multi-axis machines is shown below.



An early multi-axis single point diamond turning machine

During this era, the use of ultra-precision machining continued to revolve around the core technology of single point diamond turning. As such, the process was limited to those materials that could be machined by a diamond tool. These materials include most all Face Centered Cubic elements, fundamentally non-ferrous alloys such as

Aluminum, Copper, Nickel, Gold, Brass, & Bronze. In addition, it was found that diamond machining was well suited to cutting crystal materials such as Germanium, Silicon, Zinc Sulfide & Selenide, as well as polymers such as polymethylmethacrylate, polystyrene, and polycarbonate.

It is not surprising that applications soon developed for defense optics, in addition to commercial products. The emerging technologies of infrared night vision systems required a range of reflective components such as toroids, polygons, frame mirrors, and cold shields. These were typically machined in aluminum alloys such as 6061. In addition, lenses in Germanium were required for windows and lenses. Designers were now making use of aspheric geometries to reduce spherical aberration, minimize the number of elements thus reducing weight, and ultimately reducing the amount of costly Germanium required.

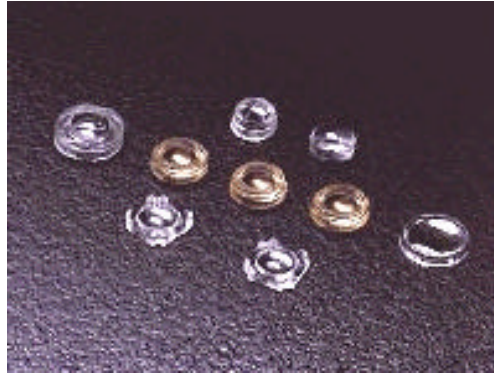
Infrared systems operating at different wavelengths utilized Silicon lens and window elements. Silicon had, and has to this day, distinct cost saving benefits, and is considerably lighter than Germanium. Silicon is however extremely difficult to diamond machine, primarily due to its hardness, and therefore did not proliferate to widespread use with aspheric geometries. With today's machine technology, incorporating stiffer axes, smoother drives, and more precise spindles, silicon aspherics can be single point diamond turned more effectively than ever. At the same time, deterministic micro-grinding developments at establishments such as the Center for Optics Manufacturing at the University of Rochester allow Silicon aspherics to be deterministically ground to a precision that often requires no further polishing.

Widespread Application

Commercial applications for single point diamond turning developed throughout the United States, Europe, and interestingly, later in the Far East. The boom in consumer electronics, and a certain dependence on optics technologies has fueled a massive growth in the use of aspherics, and other rather non-conventional geometries. Optical design software has allowed designers to optimize system performance in all respects by building in complex, yet manufactureable surface forms. In parallel to machinery being developed for general sale on a commercial basis, certain leading companies, such as Philips of The Netherlands, developed highly innovative machining technologies "in house", in order to exploit opportunities in, for example, the Compact Disc player market. Many of these applications however required optics in vast numbers and so individual diamond machining was not cost effective. Grinding processes were therefore developed that utilized basic ultra-precision machining practices, while adopting a fixed abrasive wheel in place of the single point diamond tool. This, in combination with injection molding, and hot pressing, was adopted to produce the optics required in the many consumer electronic products that we now take for granted.

The grinding process allowed mold inserts to be generated with primarily aspheric forms, but did not allow more complex diffractive geometries due to the restrictive

diameter of the grinding wheel. Mold inserts manufactured from harder, and more brittle materials are still commonly used today. Materials such as tool steels, Tungsten Carbide, and Silicon Carbide can be consistently ground to surface textures better than 10nm RMS, and figure accuracies as low as $\lambda/10$.



CD & DVD Pick-up Lenses

More Recent Developments

It is in the past 10 years however that some major advances in controls, feedback systems, servo drives, and general machine design and construction have evolved to the point where today's ultra-precision machining systems are more productive, more precise, and lower in price. This has resulted in a proliferation of their use throughout the world for a wide range of applications.

Today's single point diamond turning machines have evolved to utilize a host of new technologies. When combined in a regimented manner, these allow surfaces to be single point diamond turned in all the aforementioned materials, to a surface texture often as low as 2nm RMS, and with figure accuracies, low in absolute error, and exhibiting very low slope characteristics.

Many of these enabling machine features are listed below.

- Epoxy granite or natural granite machine bases, for thermal and mechanical stability, damping characteristics, lower center of mass, and design flexibility.
- Optimally located air isolation, for optimized servo performance, and enhanced vibration isolation.
- Hydrostatic oil bearing box-way linear axes, for enhanced damping, smoothness of motion, geometrical accuracy, and wear free operation.
- DC linear motors provide rapid feed rates, smooth, wear-free, and non-influencing motion, and superb longitudinal dynamic stiffness.
- High-speed air bearing spindles allow faster feed rates, therefore reduced cycle times, as well as smooth rotational motion, high load capacity, and stiffness.

- High speed CNC controls, utilizing PC technology, to allow networking, huge part program storage, and utilization of 3rd party programs. Also to facilitate the use of advanced drive and feedback devices to improve workpiece accuracy.
- High-resolution linear scales, providing precise axis position feedback for nanometric incremental moves, improved dimensional stability, and ultimately, consistent and precise geometrical accuracy.
- On machine workpiece measurement and error compensation systems allow residual workpiece errors to be assessed, and practically eliminated, providing they are of a repeatable nature.

A current state-of-the-art single point diamond turning machine is shown below. This has the spindle mounted on the X-axis, and would typically have the diamond turning tool mounted on the Z-axis. The Axes are mounted in a classic “T” configuration, and as such allows any rotationally symmetrical part to be machined.



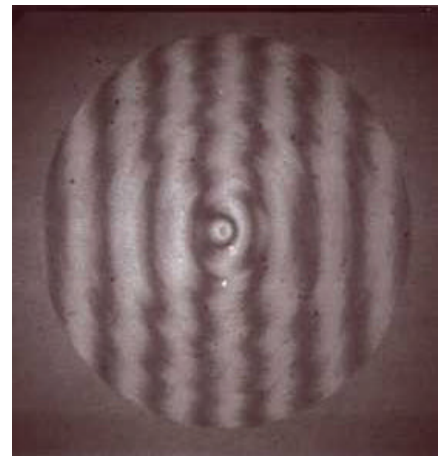
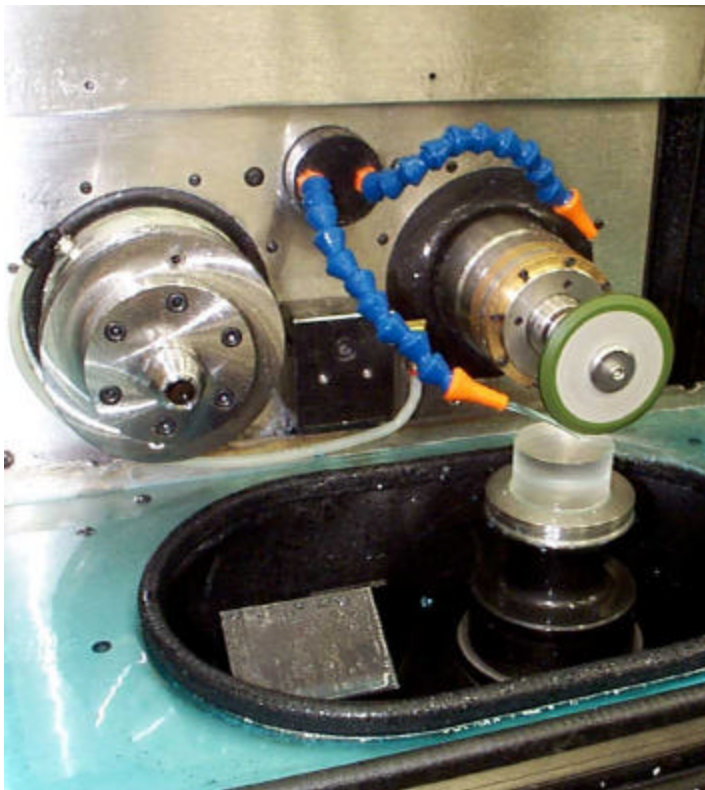
Current state-of-the-art single point diamond turning machine (base & slides)

The Need to Grind

Single point diamond turning machines are often provided with add-on grinding attachments, to extend their usage to those materials that are not diamond machineable, as described earlier. This approach provides for an extremely flexible machining system, but extreme care must be taken at the earliest design stage to ensure that the stiffness of the machine is apt to handling the increased grinding forces, and that the guarding and coolant containment measures are up to the increased demands. Due to the limited space available, the grinding attachment may also be limited to a single spindle. This might then require wheels to be changed more often than desired, for rough grinding and finish grinding operations.

If applications revolve purely around the grinding of mold inserts, or for the direct grinding of glass aspherics, then a dedicated grinding machine may be more appropriate. This type of system will be designed to handle the increased forces and coolant volumes, and will likely incorporate both a rough and finish grinding spindle for improved productivity. The workpiece might also be mounted in a vertical axis orientation that is familiar to many glass processing operatives. The ability to directly grind precision aspheric glass lenses economically has opened a floodgate of applications in both commercial and defense fields.

For example, current technology is able to take a 50mm diameter rough glass molding or pre-generated blank, and finish grind to a $\lambda/2$ figure and 3nm RMS finish, within 15-30 minutes. The specific accuracies and cycle times are of course very dependent on specific glass types, such is the process-related nature of grinding.

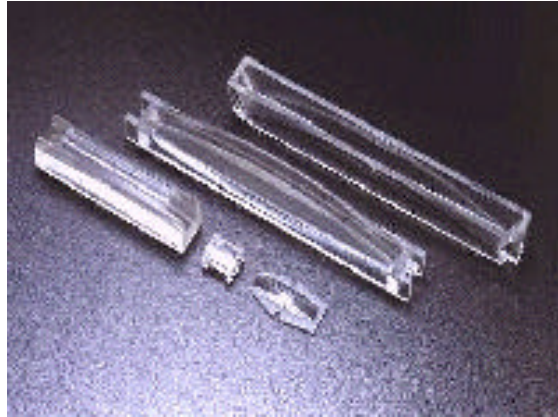


View of a typical aspheric grinding process, and resulting figure accuracy

Freeform Geometry

A common limitation of the previously mentioned 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 flycutting, or grinding, depending on the material.

The raster machining process requires the part to be fixtured in a static condition, while it's relationship with the cutting tool or wheel might move simultaneously in 3, 4 or even 5 axes. This type of machining is now possible, either directly by raster flycutting on non-ferrous metals, polymers, and crystals, or by raster grinding glass or mold inserts. Examples of these "freeform" geometries might be advanced laser printer optics, as shown, or "conformal" windows that blend into the leading edge of an aircraft's wing.



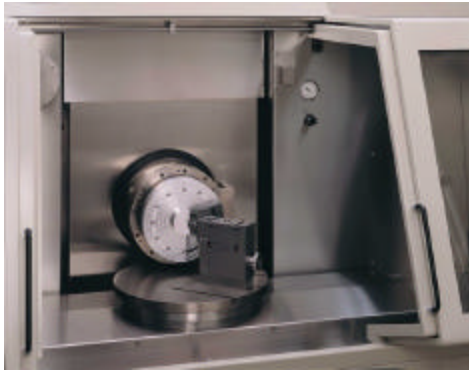
Advanced freeform optics

A new breed of multi axis machines has been developed that are able to generate shapes that are no longer limited to rotational symmetry, but extend to these freeform geometries. This type of machine features three extremely stiff hydrostatic oil bearing linear axes, X, Z & Y, in addition there are air bearing B & C rotary axes, and an oil bearing grinding spindle. The machine base comprises a massive natural granite slab, mounted on optimally located air isolation mounts. An advanced CNC controller, with PC front end is utilized, while 10nm linear scales provide position feedback.



Ultra-precision 5 Axis Freeform Generator

Although it is advantageous for a machining system to be able to single point diamond turn, and also grind, and this is often accomplished by expanding a lathe platform to one of a grinding platform. This type of machine is however often compromised by inadequate guarding, coolant containment, or stiffness. It is therefore critical that the grinding requirements are considered at the point of conceptual design, to allow for all the provisions of this demanding process. The illustrations below depict a machine being used in both a single point diamond turning and grinding mode.



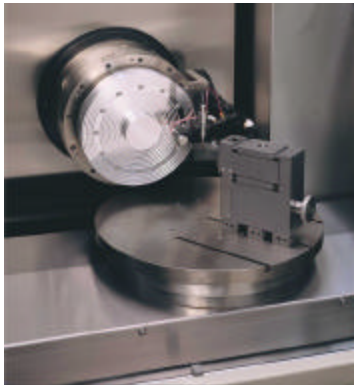
Advanced Features

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. The view below demonstrates this technique. Note how the vertical Y-axis is buried within the Z-axis, rather than stacked one above the other. Also shown is a non-influencing, air bearing counter balance, to allow the vertical axis to be tuned to optimum performance, bi-directionally.



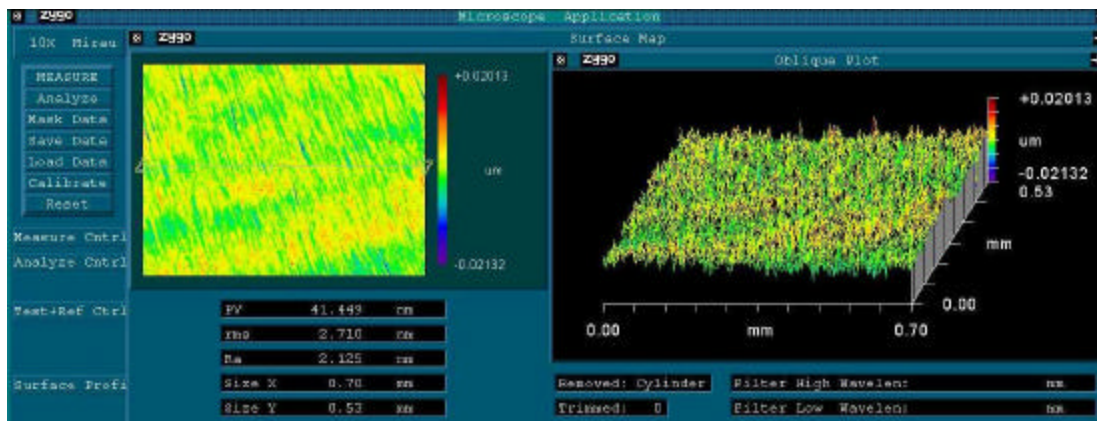
Non-influencing air bearing counter-balance

Understanding the relative position of the cutting tool or the grinding wheel on the machine is also critical to the final workpiece accuracy, and automatic systems have been developed for establishing tool/wheel radius, height, and position on the machine relative to spindle center-line. Many of these devices employ kinematic mounting techniques to ensure fast and precise location on the machine, and LVDT or optical probe technology combined with automatic setting software.



Kinematically Mounted LVDT Tool/wheel Setting System & Linear Motor Driven Hydrostatic Slide

Advanced PC based CNC motion controllers are now used in conjunction with Athermalized linear scale feedback devices and previously illustrated state-of-the-art linear motors, allowing surfaces as smooth as 2nm to be generated directly from the machine.



BK7 Glass Sphere Directly Ground – Surface Texture: 2.1nm Ra

In Conclusion

It can be seen that the technology contained within the ultra-precision machining system of today is certainly related to its earliest origins, in basic form. Time tested fundamental precision engineering principles continue to be adopted, yet at the same time these are now coupled to leading edge technologies in controls, drives, and feedback devices.

Advances in Computer Aided Design, and in particular, Finite Element Analysis, have allowed the mechanical design of machining systems to benefit from specifically selected materials and new structural configurations. This, combined with certain basic rules for oil bearing slide design, and finely tuned assembly techniques, results in machining systems that are more precise, thermally stable, flexible, more reliable, faster, and less expensive than the machines of yesteryear.

The use of ultra-precision machining techniques, originally developed for commercial applications, then fuelled by demand in defense related products, is once again being predominantly exploited by commercial industry. 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 cost effectively. In the future, machine developments will continue to be driven by market requirements. Advances in computing technology, and photonics, will likely yield further advances in control and feedback technology that will allow ultra-precision machining technologies to continue to advance in line with market requirements.