Mould cavity production in UP quality

Efficient manufacture of moulding tools for replication of ultra-precise and micro-structured components is only possible if the entire **PROCESS CHAIN** is effectively managed – from data processing to high-precision in-situ metrology.

Figure 1. Ultra-precision moulding tools

Figures: LT Ultra

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Modern plastics and appropriate process control enable ultra-precise replicative moulds to be produced. They are required in the automotive sector, in the optical industry and in medical and metrology sectors. Different requirements are emphasised, depending on the application – high-dimensional accuracy and surface quality for camera lenses, large-scale application of micro-structures for displays, ultra-fine and highly pre-cise structures for micro-fluidics, nanometric lattice structures for analysis systems and, in many cases, combinations of these **(Figure 1)**.

The moulding tools required are complex and have to satisfy very stringent requirements. One of the most important methods for manufacturing ultra-precise moulds is ultra-precision processing with a geometrically defined cutting edge that is usually made of monocrystalline natural or artificial diamond. This

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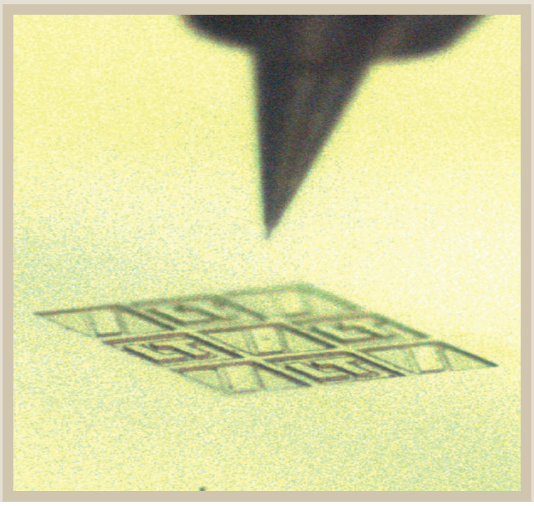


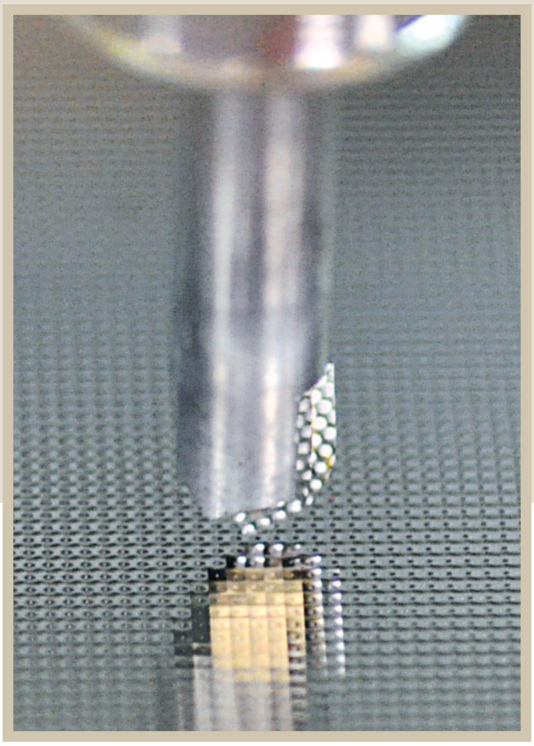


Figure 2. Left: micro-fluidic structure; right: lens array

enables optical surfaces or micro-structures with low burr formation to be created. An adequate surface quality is possible without subsequent polishing. Compared to conventional methods, a process step can be eliminated and the dimensional accuracy is not impaired due to the polishing step. In addition, plastics can be processed directly, which shortens the process chain for manufacturing samples and prototypes.

UP milling with diamond tools

The cutting material is diamond. No materials with carbon affinity are used as they would cause very rapid wearing of the tools. Nickel-phosphorous (also called electroless nickel) is a popular material. When ultra-precision machines are used, cutting materials such as CBN or ultra-fine grain cemented carbide allow an optical surface quality to be achieved in steel without subsequent polishing. This reduces the associated accuracy variations to a minimum. This method is often used for injection moulding for replication of (opto-fluidic) analysis chips – optical and fluidic components can be combined in a very tiny space **(Figure 2)**.

Possibilities of UP turning

Due to the ultrasonic-assisted oscillation of the diamond tool, there are no restrictions on the ma-terials that can be processed when turning with ultra-precision machines. Comparable rough-ness values can be achieved in so-called plastic mould steels to those obtained in non-ferrous metals or nickel-phosphorous.

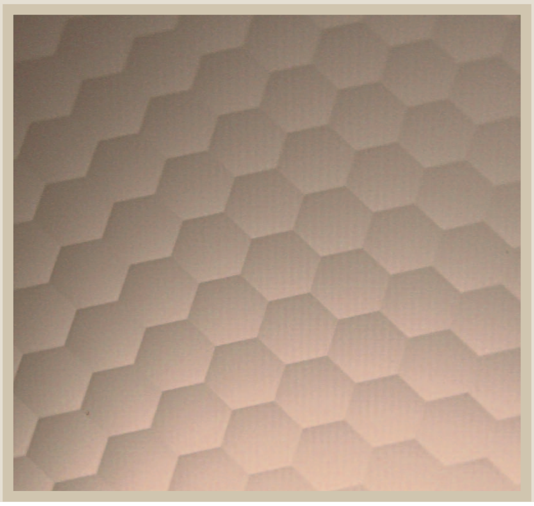
Contrary to popular opinion, in addition to optics or structures with purely rotational symmetry, dynamic axis mode also enables free-form surfaces or lens arrays to be produced. For structures with high spa-tial frequency, an FTA (fast tool axis) is the ideal solu-tion to reduce production times. The piezo-driven axis on the ›FTA 100‹ can achieve maximum travel of up to 100 µm **(Figure 3)**. Depending on the stroke, production with a piezo actuator frequency of up to 1 kHz is possible. Depending on the structure to be created and the material, the roughness values R_a are in the range of 3 to 5 nm and the geometrical error is in the sub-µm range.

Ultra-precision production on special machines

To create long-lasting moulds or masters, roller turning machines are also suitable. For example, they can apply optical micro-structures to cylinders with a length of several metres. The rollers are used for ›roll-to-foil‹ replication, for example to quickly and cost-effectively produce large-scale foils for display applications **(Figure 4)**.

In addition to these very large-scale workpieces, hybrid optics represent the other extreme case. These ultra-precise masters, that include both refractive (conventional geometrical optics) and diffractive elements, often measure just a few millimetres or centimetres in diameter. A spherical basic shape is typical here, and is then overlaid with a diffractive micro or nanostructure **(Figure 5)**.

The fusion of these two functions in a single component increases efficiency on the one hand and reduces the number of optical components on the other. It also makes it easier to adjust the entire optical system. Manufacturing is carried out by combining different production methods such as milling or turning with planing or grooving on a single machine. Typical applications include high-resolution metrology systems, such as the case for spectrometers that, due to these aspects, are then suitable for use in space applications.



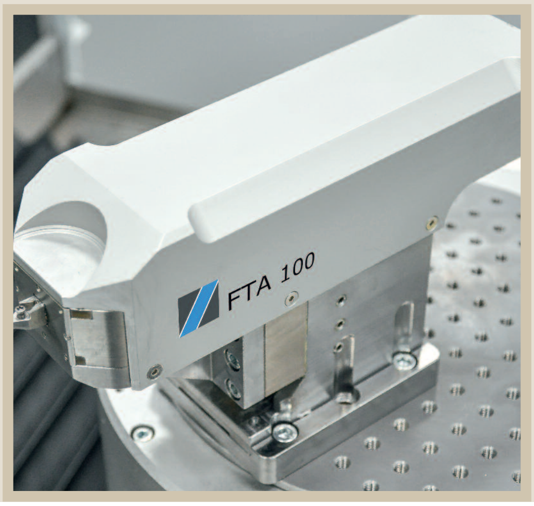
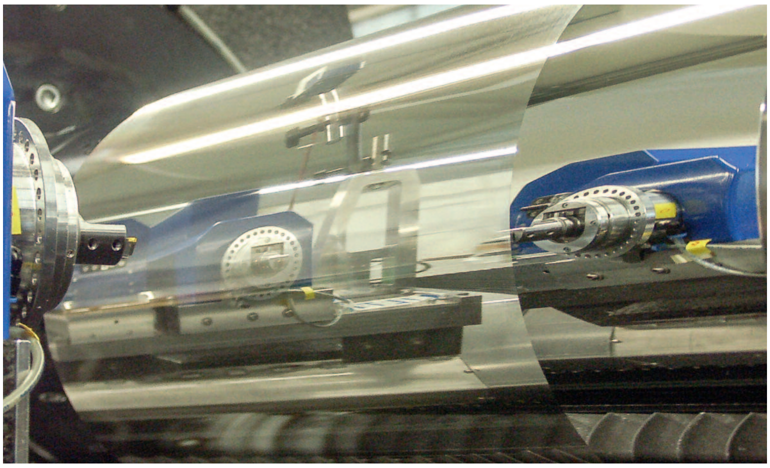


Figure 3. Left: turned freeform surface (honeycomb structure); right: ›FTA 100‹ (fast tool axis) for ultrasonically-induced machining with diamond

From data processing to metrology

The NC program is adapted for processing of a complete production chain for mould cavity production in UP quality. However, CAD/CAM solutions that are already established in 5-axis programming of milling machines or machining systems are not suitable for ultra-precision processing of complex geometries. The resulting chord errors are too large and lead to form errors. These chord errors occur during path calculation in the CAM software. They denote the error that is tolerable for the end product, and the point at which further refinement of the calculation is truncated. Standard CAD/CAM solutions rarely go below a chord error of 5 or 10 µm. However, in ultra-precision technology a chord error in the nanometre range is often required.

A further weakness is the dot pitch, which has to be much lower for ultra-precision machining than conventional machining. The greatly increased data volume extends calculation times proportionally or, under some circumstances, makes them completely impossible. Therefore, there is a need for path planning algorithms that create a significantly higher point density with an identical calculation time.



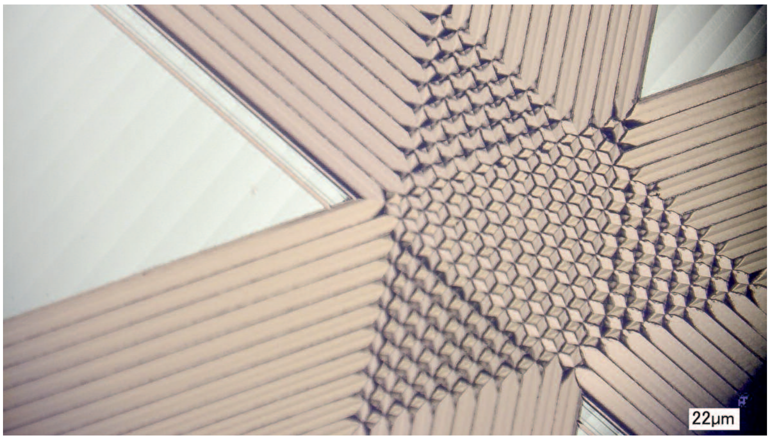


Figure 4. Top: a roller turning machine; bottom: micro-structure on a roller

Figures: LT Ultra

In order to be able to manufacture an end product in UP quality, the CAD model requires a corresponding resolution, which must be better than the intended component accuracy. In the STP/IGES exchange formats, it is important to set the resolution sufficiently high. The best results are achieved if the mould can be reproduced analytically and the CAM system supports direct entry of surfaces as equations.

Calibration of the tools used is also important, as any errors occurring here are reflected directly in the end result. As a result, the length, the diameter and – if necessary – the radius can be precisely calibrated to achieve a low geometrical error.

For example, the ›MMC 600H‹ ultra-precision milling machine from LT Ultra calibrates milling tools using a laser

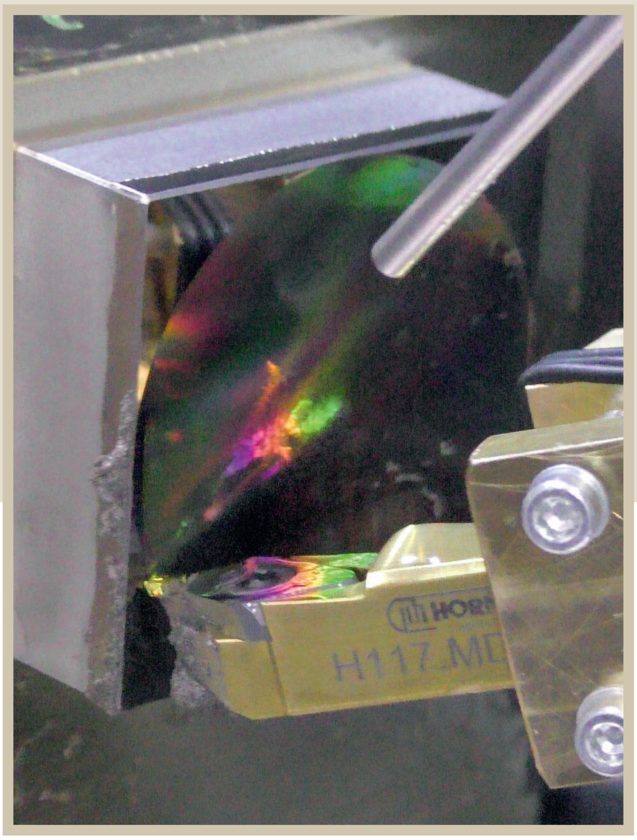


Figure 5. Production of hybrid optics in nickel-phosphorous

measurement bridge **(Figure 6)**. The measurement routines have been adapted and allow calibration with a repetition accuracy in the nanometre range. The ultra-precision turning machines have a high-resolution microscope camera to measure the exact cutting edge position and the exact radius without contact.

Recording and compensating for errors

Despite careful preparation, program creation and tool calibration, the result can sometimes have a geometrical error, for example, due to irregularities in the tool. On the one hand, this is the case if the individual structures have a very filigree design or a low stiffness or, on the other hand, if the process conditions fluctuate too much due to external influences. It is useful to calibrate the workpieces directly in the machine and to adapt the CAM program using these values, for example by using a modified allowance or an overlaid target contour. In practice, calibration of the workpieces has proved effective when using different tactile or optical metrology tools whose measurement accuracy is comparable to that of measuring machines. Typical measuring instruments include tactile switching 3D probes, measurement probes or non-contact optical measurement systems.

When it comes to production of ultra-precision moulding tools, LT Ultra-Precision Technology can supply the necessary machines, peripherals and software components from a single source. Job order production on ultra-precision machines is also offered as a service – from single workpieces through to series production parts. ■ MI110515

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Figure 6. An ›MMC 600H‹ 5-axis simultaneous ultra-precision milling machine from LT Ultra