From micromachining to ultra-precision

Micromachining and ultra-precision machining are now firmly established in the range of machine tool applications. They are however significantly different from conventional machines, and they also cater to a **WIDE RANGE OF APPLICATIONS** – from optics to microfluidics through to medical technology.

Figure 1. Aspherical mirror in aluminium

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The terms ultra-precision (UP) and micromachining have been established for a long time. Around three decades ago, Germany had already developed a small branch of industry to pursue the trend, that originally emerged in the USA and Japan, here in the domestic market. UP machines are still fundamentally different from conventional machines. Attempts to achieve a higher level of accuracy based on conventional machines have led to the development of precision or high-precision machines, but these still have limits. UP systems remain essential for the highest positioning accuracies and the best optical surface properties.

Process forces and surface quality

Ultra-precision technology and micromachining are both primarily characterised by low process forces. Micromachining involves a functional element in the micrometre range, where this can also be the total dimensions of a structure. However, the optical surface quality is often subordinate. UP technology takes over at the point where both very high accuracy and optical surface quality are needed. The dimensions covered by UP machining span the µm-range all the way up to several metres. Regardless of the production method, monocrystalline diamond tools are almost exclusively used in UP processes, achieving roughness values of up to Sa ≈ 1 nm, while for micromachining coated and uncoated solid carbide tools are also used.

UP machining or micromachining are used wherever other production processes reach the limits of their capabilities. The primary applications are in optics of all kinds. Particularly with reflective metal optics, there are crucial advantages in UP machining with a geometrically defined cutting edge, which are discussed in more detail below.

Aspherical laser optics

Aspherical mirrors enjoy widespread use, particularly in laser technology. In contrast to conventional focusing optics, the spherical form of the mirror is modified with higher order mathematical coefficients in order to further correct the beam in addition to merely focusing or defocusing it. The aspherical equation clearly describes the geometry of the mirror, but where the variations from a simple sphere are sometimes just a few nanometres or micrometres. Aspherical mirrors are often used in an off-axis configuration and – in terms of the optical properties – have rotational symmetry **(Figure 1)**.

Freeform surfaces with no restrictions

If the degree of beam shaping is not sufficient, there are further options. In addition to rotationally symmetrical optics, freeform optics are also within the scope

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Figures: LT Ultra

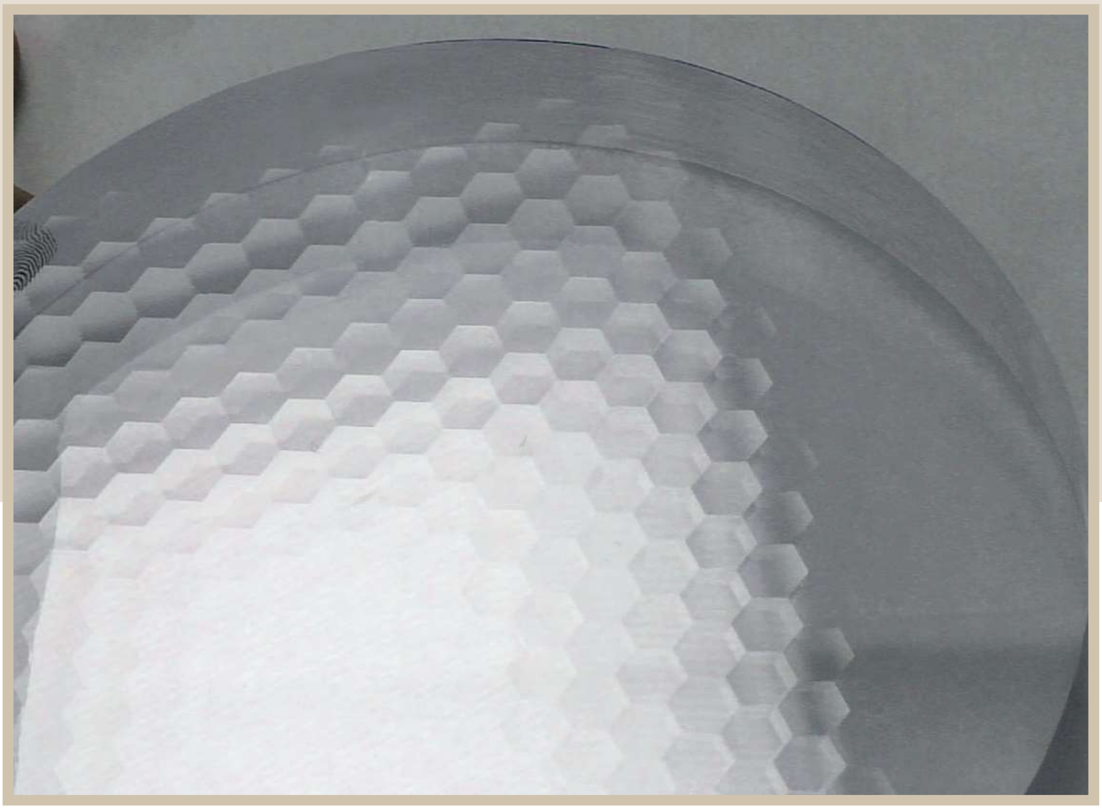

Figure 2. Honeycomb structure turned using Fast Tool

of UP machining. In this case, and depending on the application, UP milling, planing or turning enable geometries of almost any shape to be produced. In particular there are numerous applications for UP turning with support from the dynamic axis mode (also known as slow tool or out of round turning) and the use of fast tool axes (FTAs) in optical production. Typical applications include UP turned lens arrays or honeycomb structures **(Figure 2)**.

Laser-based space communication

Alongside communication technology using glass fibres, free beam communication technologies are

Figure 3. Metal optics for laser-based space communication

Figure 4. Example of a milled microstructure

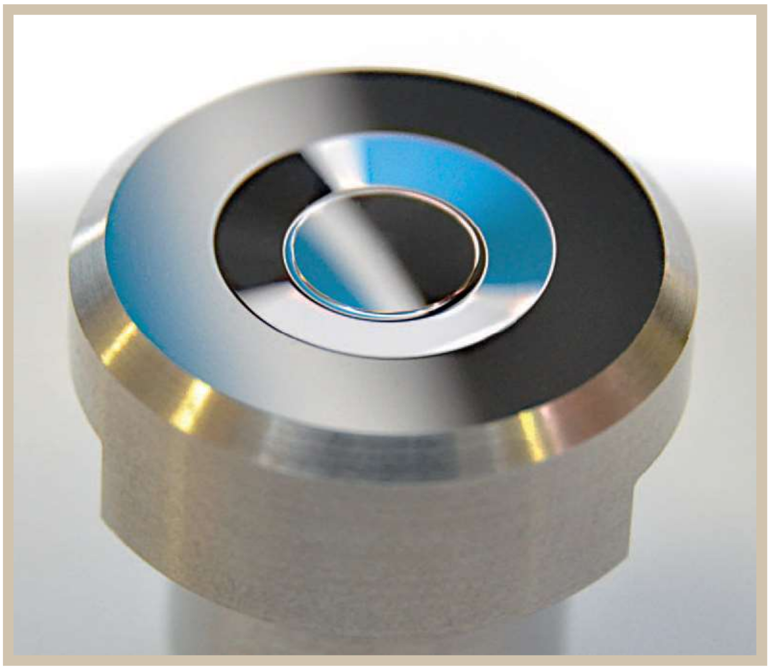

Figure 5. Mould insert made of steel for contact lens manufacture

increasingly being used. Worldwide, several companies are currently engaged in planning or implementing satellite networks that will span the globe. They are using almost exclusively nano-satellites, of which up to 100 can be transported into orbit on each carrier rocket. The nano-satellites weigh just a few kilograms and thus allow a lower orbit than conventional communication satellites. Communication between the satellites themselves and with earth is via laser. The UP turned laser optics direct the laser beam onto the correct path and thus allow transmission ranges of tens of thousands of kilometres **(Figure 3)**.

Micromachining, watch parts and lab-on-a-chip

The main applications for micromachining are in the watch-making industry and for fluidic or lab-on-a-chip systems **(Figure 4)**. For example, hundreds of the filigree elements in mechanical watches are galvanised on a wafer, although this particular process only provides for 2.5D structures. Micromilling enables additional details to be carved out on the components, for example, chamfers, functional steps, counter bores or decoration in the form of engravings.

Lab-on-a-chip systems describe the miniaturisation of complex structures. The required structures are milled directly in plastic for prototyping, or a replication master or mould insert is produced, for example, in electroless nickel phosphorous plating. Flow cytometry is one typical application. Implemented as a replicated disposable chip, the required sample quantities are extremely minute and handling is much easier. These chips contain components that focus the sample flow and ensure that the cells/blood cells to be analysed are located in the centre of the flow. The optical and electrical analysis methods are also attached to the chip and allow identification and analysis of the cells. Additional actuators enable the cells to be sorted. This involves targeted incorporation of pressure impulses located directly before a Y-branch, which force the cells onto the correct path. As with UP milling, production of the optical components uses diamond tools, while by contrast the fluidic channels are often created with solid carbide milling tools. One of the advantages of milled fluidic structures compared to lithographically created structures is the option of actually producing defined circular duct cross-sections using ball cutters.

From retro-reflectors to artificial eye lenses

Large mass markets often only emerge with a low-cost replication process. A typical application is found with lenses that are replicated in different plastics, such as contact lenses or camera optics for mobile

Figures: LT Ultra

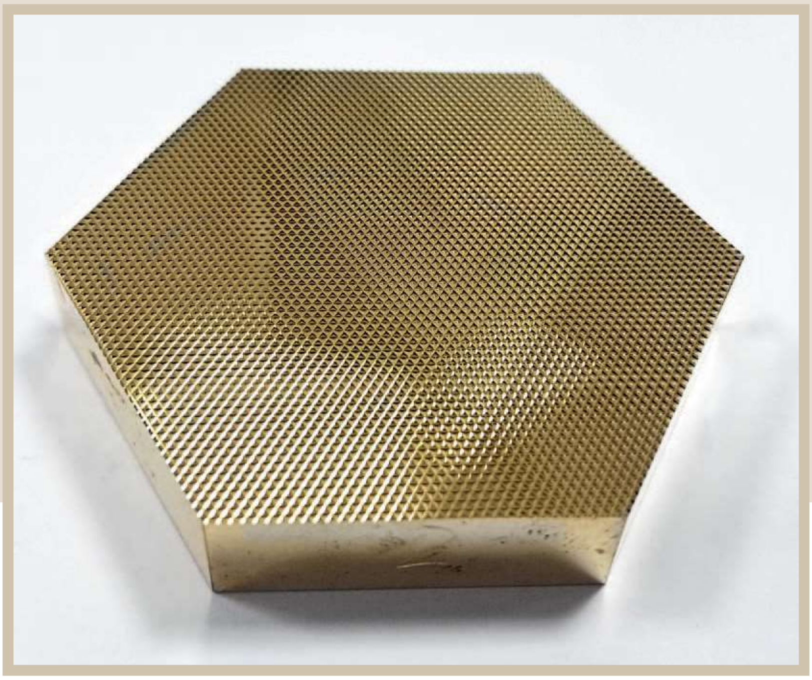

Figure 6. UP milled (fly cutting) replication master for retro-reflectors

phones. The replication masters and mould inserts are often turned directly in steel using monocrystalline diamond tools **(Figure 5)**. Here, ultrasonic-assisted machining is utilised to drastically reduce tool wear and to make UP cutting economically efficient. The same roughness values are achieved as in non-ferrous metals (Sa ≈ 1 nm). The advantage over polishing is that the shape accuracy is retained and microstructures, Fresnel lenses and freeform surfaces can be incorporated directly in steel using UP turning without the need for any subsequent rework.

UP technology is also used for production of ▶

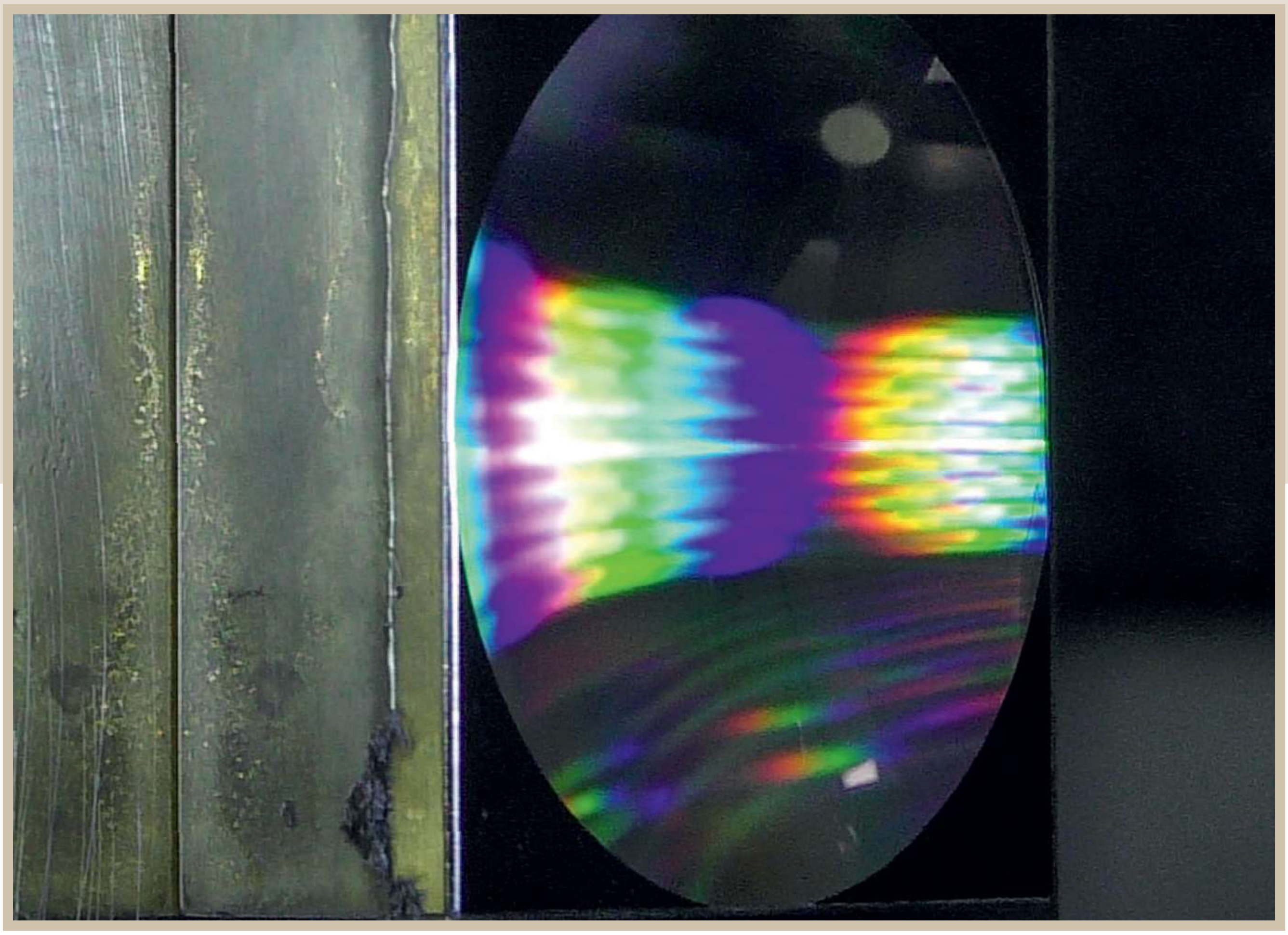

Figure 7. A hybrid optic combining DOE and spherical optics. Spectral decomposition of a white light LED array

artificial lens replacements (intra-ocular lenses, IOLs) to treat cataracts. However, it is normal in this case to produce the lens directly from the material to be implanted, with freeform surfaces commonly implemented to additionally correct the patient's various visual impairments. The lens elements for fixing the implant in the human eye are also created using UP turning or micromilling depending on the structure.

The highest replication volumes are achieved in the field of reflectors. A UP produced master is used for casting or injection moulding a very large number of retro reflectors **(Figure 6)**. These days, the replication is performed fully automatically. The basic shapes are often planar bodies and different production methods from the UP field are possible to create the retro-reflector structures from the master. However, the basis shapes can also be freeform surfaces, into which the retro-reflector structure is then either UP milled or UP planed. Typical applications here include the reflectors in vehicle brake lights.

Diffractive optical elements (DOEs)

A perfect example of UP technology where optimum surface quality and positioning accuracy have to be combined are for diffractive optical elements (DOEs, blazed gratings). The diffractive nano and microstructures can also be produced directly on a spherical basic body. These hybrid optics combine two key properties: On the one hand, the shape of the basic body focuses the beam path, and on the other hand the diffractive structure ensures spectral decomposition **(Figure 7)**. This simplifies the adjustment work and reduces the required space, as the number of optical elements required in the system is reduced. Furthermore, no static charge occurs as it does with glass optics. These advantages are often critical, especially in space applications. In addition to individual production, replication masters are also used with hybrid optics, whether in laboratory equipment or lab-on-a-chip systems.

These are just a few examples of where UP machining and micromachining are being used today. For production of the applications presented here, the company LT Ultra-Precision Technology is a single source producing the necessary machines, peripherals and software tools. Their services also include contract production on one of over 30 UP machines, from individual units to series production. ■

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Figure: LT Ultra