Automation for accuracies in the sub-micron range

In order for manufacturing processes of ultra-precise components and surfaces to be performed with utmost precision – in one setup and without manual intervention – ultra-precision milling machines require special features such as **AUTOMATIC** tool changing and **INTEGRATED** measurement capabilities.

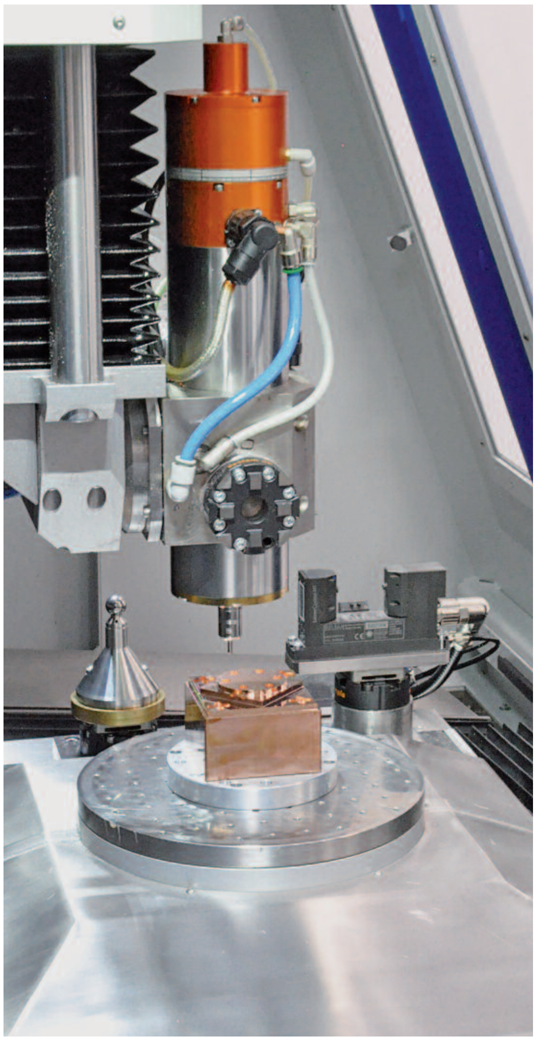

Figure 1. ›MMC 900H‹ ultra precision milling machine with a 10x tool changer and side view of the working chamber of a machine with additional rotary table

Figures: LT Ultra-Precision Technology

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The manufacture of ultra-precise components and surfaces has continued to gain in importance in recent years. In particular due to the growing demand for optical components, there is increasing interest in the corresponding manufacturing processes.

Ultra-precision machining using a defined cutting edge plays a crucial role here. Via various turning, milling or planing processes, from the large-scale processing of telescope mirrors to the manufacture of micro-structured freeform surfaces, it offers a wide variety of manufacturing options for optical surfaces. Geometrical accuracies of less than 100 nm and roughness values of R_a < 1 nm can be achieved. At the same time, these processes and machines are increasingly applied in adjacent disciplines such as micro-machining. Due to the high accuracies that can be achieved, ultra-precision (UP) machining and

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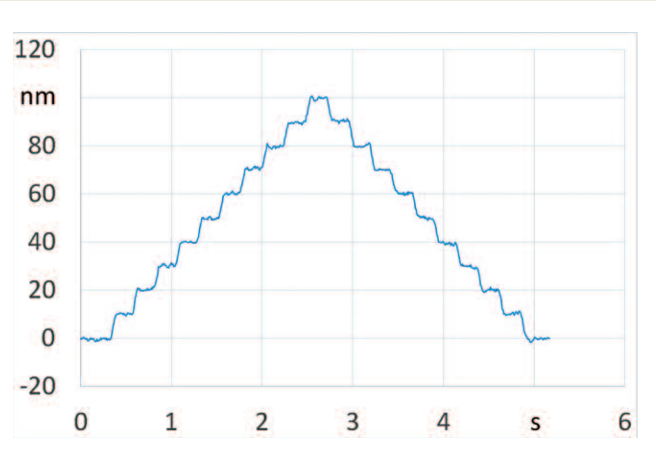


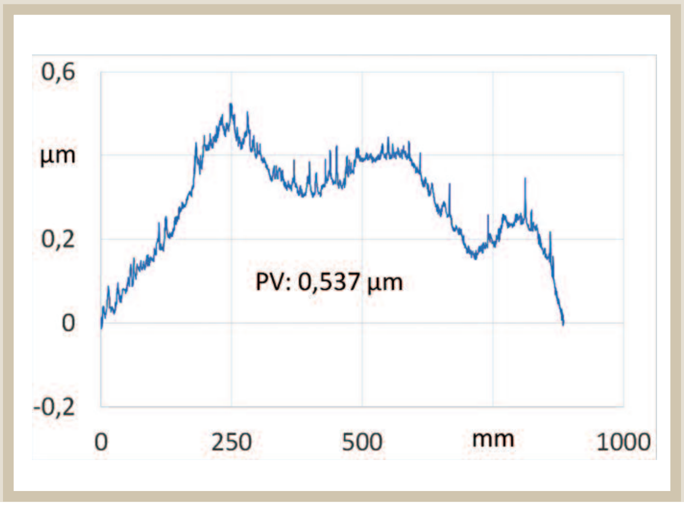


Figure 2. Stepping test and straightness measurement of the X-Axis (in Y-direction) of a MMC 900H ultra precision milling machine

UP milling are taking a special place in these disciplines and must therefore meet new requirements.

Automatic tool changing

Due to the complex and delicate nature of the manufacturing process, UP processing is still labour intensive. Manual intervention is often unavoidable, from setting up the tool to final cleaning and inspection of the workpiece. Increased automation is usually only worthwhile for processes offering the prospect of achieving high volumes, e.g. in contact lens manufacturing. However, the growing volumes of UP-manufactured parts and new fields of application for ultra-precision machines has lead to boundary conditions and requirements.

Automatic tool changing is among the most important of requirements, and yet it has been widely neglected for a long time. Changing stationary tools on UP lathes, for example, is relatively easy to implement and with high levels of accuracy, namely by arranging multiple tools along a linear axis on the tool slide or by using high-precision rotary tables that serve as a tool turret. This means that tool change accuracies in the sub-micron range can be achieved without problems if the machine temperature is controlled properly.

However, with driven tools (e.g. during milling processes), the situation is different. In order to achieve high surface qualities, the run-out of the tool or the error motion of the spindle used should be less than 1 µm or less than 100 nm, respectively. This means that only air-bearing spindles are suitable. At the same time, an interface for automatic tool changes must be provided, which results in special requirements for the spindle used.

Calibration and measurement inside the machine

Each tool change also creates disturbances that affect the accuracy of the machine and the position or run-out of the tool. Most notably, these include temperature fluctuations arising from the start/stop behaviour of the spindle. In addition, different rotation speeds, the forces occurring during tool changes as well as the angular position of the new tool can affect the position of the rotational axis and the rotating tool as well as the balance of the system.

To achieve sub-micron accuracies, a tool setting system must therefore be integrated. The measurement can take place directly, for example by means of a laser sensor or camera systems, or indirectly, by manufacturing and measuring a sample part. The alignment and measurement of components in the

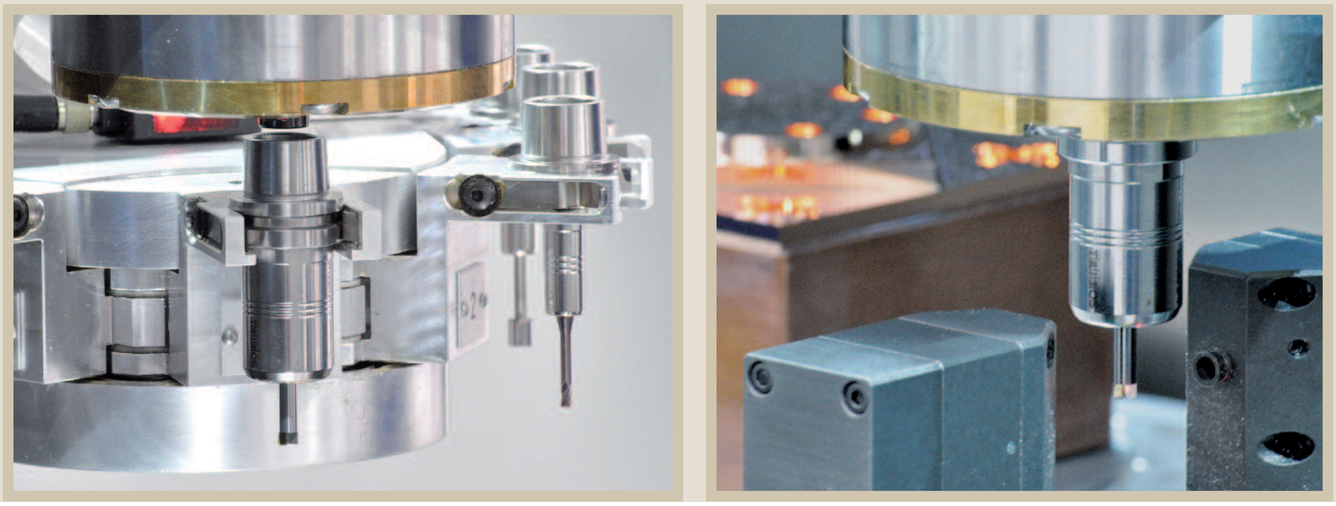


Figure 3. Tool change and measurement of a monocrystalline diamond milling tool

Figure 4. Measurement of workpiece with a 3D-tactile probe

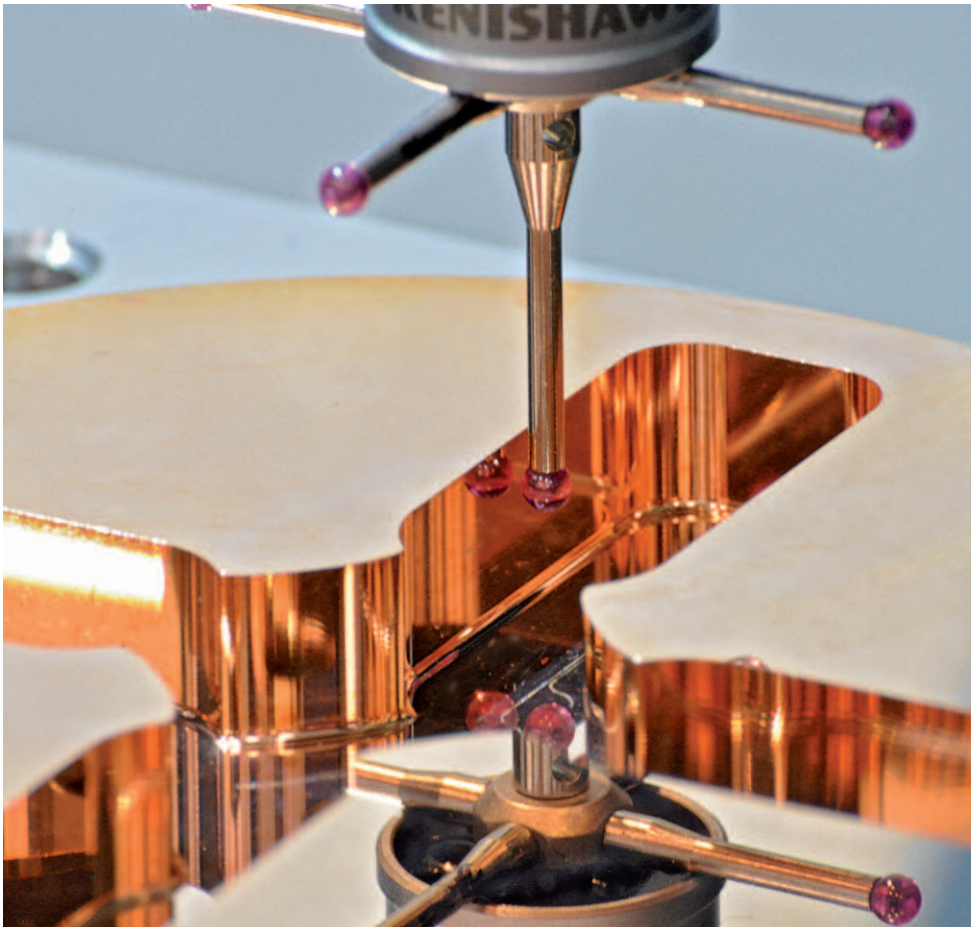
machine is therefore another step towards automation, but it also represents an important means in order to achieve high accuracies after a tool change.

Multi-axis and ultra-precision milling

The ultra-precision milling machine ›MMC 900H‹ from LT Ultra-Precision Technology, based in Baden-Württemberg (Germany), relies on a concept which, on the one hand, stands for highest accuracy, while on the other hand permits automatic tool changes and measurements, in-situ measurement of the workpiece geometry as well as 5-axis machining **(Figure 1)**.

In addition to end milling, the machine is also suitable for planing and fly cutting. The latter is useful for planar milling, while raster fly cutting can be used for the manufacture of aspherical or structured optics. Thus planar substrates can be pre-processed directly on the machine prior to their subsequent microstructuring.

With this processing technique, using monocrystalline diamond tools, accuracies of approximately 100 nm per 100 mm of workpiece diameter and maximum roughness values of $R_a \leq 2$ nm can be achieved. These values are reached in various non-ferrous metals or plastics. The processing of steels is however limited, as diamond tools can not be used.



To promote temperature and long-term stability, large parts of the machine are made of natural granite. The linear guides use oil-hydrostatic bearings that, in conjunction with the dimensionally stable bed, enable a linear motion accuracy of less than 190 nm per 100 mm of travel **(Figure 2)**. Furthermore, the oil-hydrostatic bearings ensure high stiffness, good damping characteristics and a stick-slip-free movement of the axes. All linear axes are equipped with linear motors, that together with the oil-hydrostatic bearings and the high-resolution linear scales yield an excellent positioning performance **(Figure 2)**. The travel amounts to 900 mm, 350 mm and 250 mm (X, Y, Z, respectively). The axis configuration can be extended by a second Z-axis, a hydrostatic

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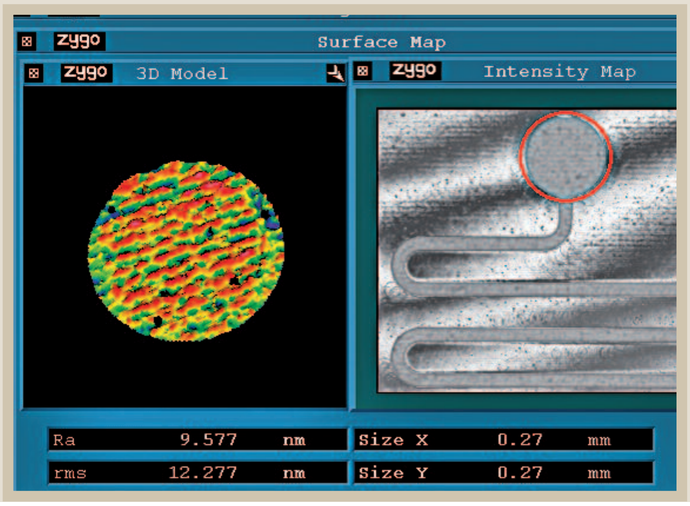
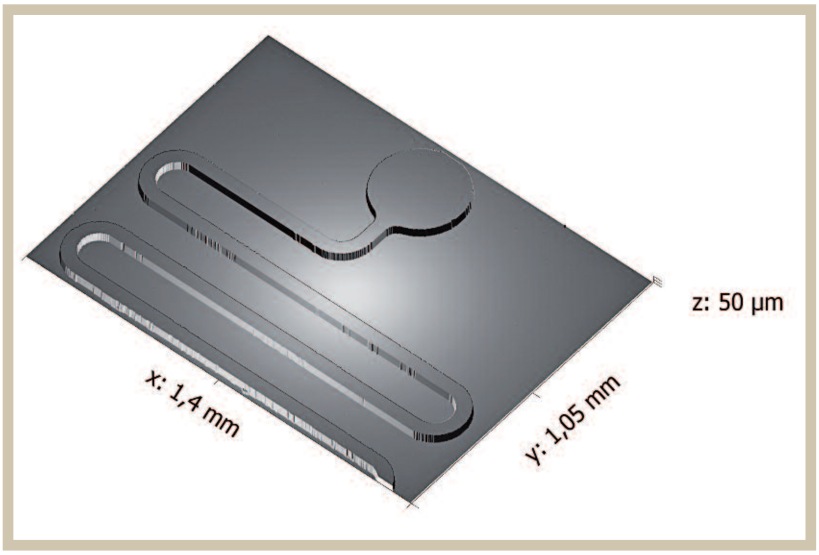


Figure 5. Measurement of a milled fluidic structure using a solid carbide tool (D = 60 µm, 60 000 rpm, in brass), R_a = 10 nm



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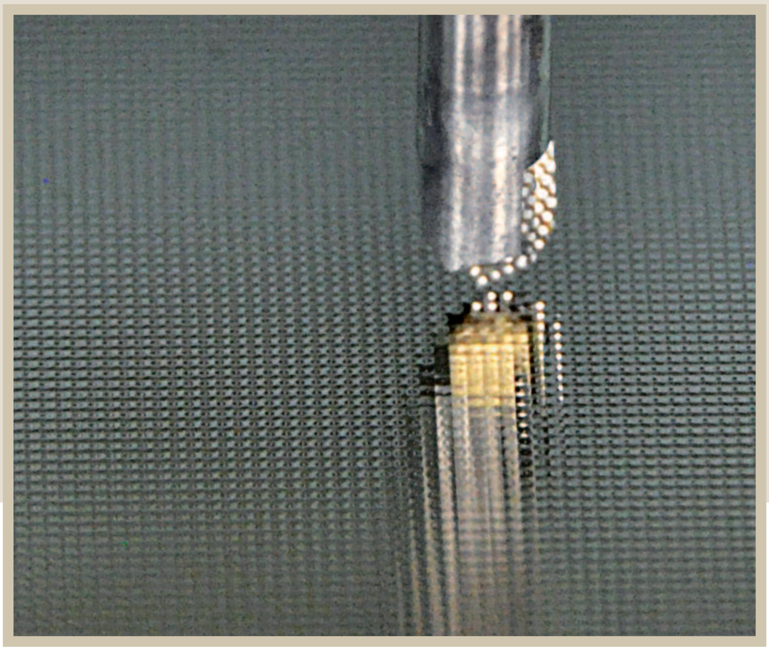
rotary table and/or a rotary/swivel unit. Customized features such as special vacuum chucks, robot loading systems or the integration of laser machining capabilities are also possible.

Tool measurement using a laser sensor

An air-bearing high-frequency spindle serves as a milling spindle **(Figure 3)**. It is available in different versions with a collet or HSK-25 interface and a maximum speed of 60 000, 80 000 or 90 000 rpm. In conjunction with the tool changer, it enables an automatic, highly accurate tool change. The machine can be equipped with different tool changers providing space for ten or 35 HSK-25 tool holders, respectively **(Figure 3)**. The tools are measured by means of a laser sensor.

Machine control for UP- and micro-milling

The travel amount in the X-direction is 900 mm. Thus it is not only possible to machine large workpieces, but also implant additional processes inside the machine. For this, a second Z-axis can be integrated into the machine, which can be equipped with tooling or with special measurement systems. 3D tactile probes or chromatic point sensors can also be integrated **(Figure 4)**. Both the workpiece as well as the microstructuring can thus be measured in situ on the machine. This plays an important role in determining the current milling diameter or the drift of micro-tooling. As the milling diameter can easily change depending on the spindle speed and clamping position, this is vital in order to achieve accuracies of a few hundred nanometres.



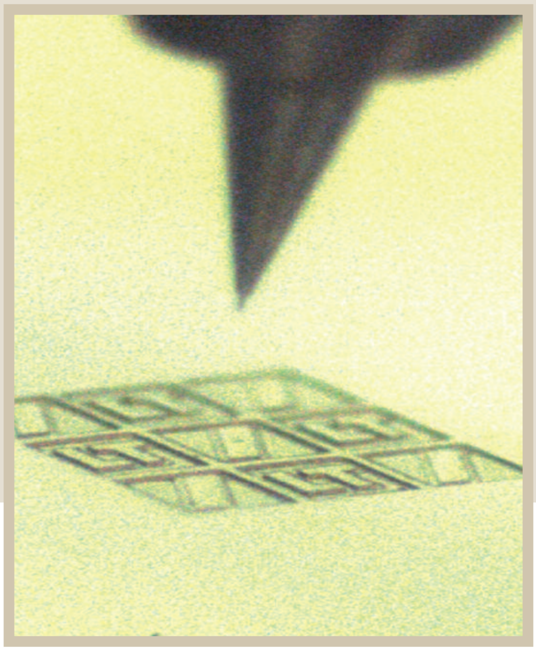


Figure 6. UP-milling of a lens array with a monocrystalline diamond tool and micro milling with a cylindrical solid carbide tool, D = 60 µm

To achieve a high level of dimensional accuracy during long machining processes, long-term stability of the machine is of great importance. The temperature stability required for this purpose is achieved by managing the temperature of the individual machine components. This is accomplished by conducting heat loads generated inside the machine away from the machine before a measurable impact occurs. Ground vibration is excluded by utilising passive or active damping systems or by vibration isolation systems. This is particular important when manufacturing optical surfaces.

The machine control system is specially adapted to the needs of UP and micro-manufacturing. In contrast to other control systems, processes can be reliably programmed with a resolution of well below one nanometre. Short servo times and fast block processing ensure lag-free manufacturing of highly complex structures or moulds with high resolution and at processing speeds of a few thousand lines of G-code per second.

Micro-fluidics, micro-lenses, complex surfacesn

An example of micro-milling is the manufacture of micro-fluidic systems. For this purpose, moulds made of different materials, such as brass, electroless nickel or steel, are manufactured that are then used for the efficient replication of the components by means of injection moulding or hot embossing. **Figure 5** shows a fluidic mould made of brass using micro-carbide mills. It was manufactured using a solid carbide end mill with a diameter of 60 µm at a speed of 60 000 rpm. The measured arithmetic surface roughness of the shown structure ranges between 9.5 and 13 nm R_a (S_a), depending on the measurement location. After correcting the tool geometry, the web widths and heights can be maintained to an accuracy in the sub-micron range.

In order to process the micro-lens array as fast as possible, a large number of very small structures must be diamond-milled with optical surface requirements within the shortest possible amount of time **(Figure 6)**.

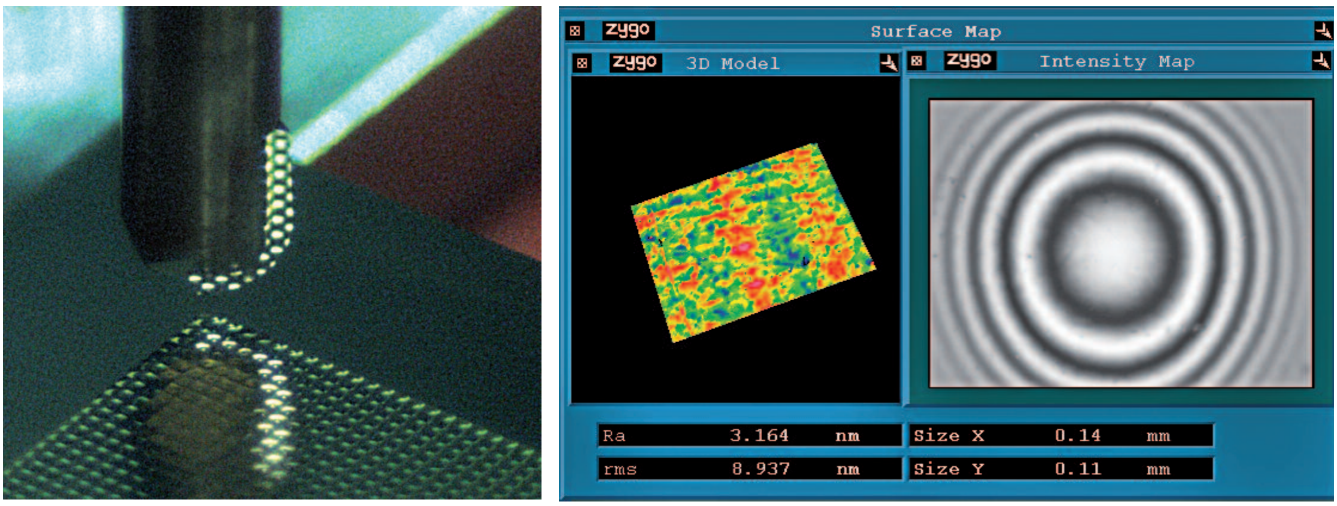


Figure 7. UP-milling of a micro-lens array and measurement of a lens (depth 16 µm, r = 350 µm)

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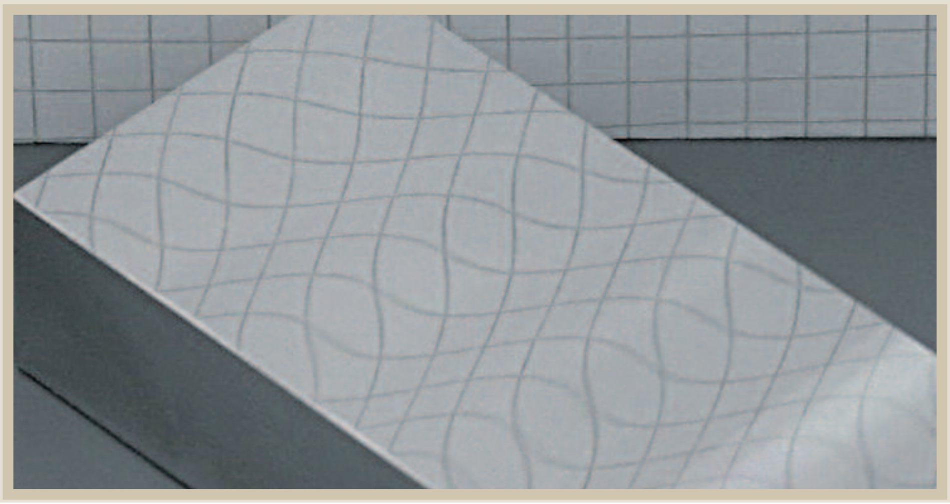

Figure 8. Planed optic with a sinusoidal shape, arithmetic surface roughness of R_a (S_a) < 3 nm

Depending on the size of the array and the surface to be structured, processing can take hours or even days. Despite the high manufacturing speed in the depicted application example (more than 16 microlenses/second), the arithmetic surface roughness Ra (Sa) amounts to approx. 3 nm **(Figure 7)**.

Similar to fast-tool machining on UP-turning machines, planing allows for the manufacture of freeform surfaces in optical quality. In the example shown on **Figure 8**, the feed-in axis follows a sinusoid curve while another axis is responsible for the longitudinal planing movement. Depending on the complexity of the surface, several linear and rotary axes may be involved in the movement. The sinusoidal surface shown in **Figure 8** was created by means of a total of three axes and has a surface roughness R_a (S_a) of < 3 nm. ■

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