Innovative Components for Microfactories

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Highly automated micro machines are the main parts of microfactories. In these machines, small scaled measurement systems are needed to detect the position of micro components and tools or to evaluate the workpiece quality. Another part of the machines is the guidance of the axes. Friction free aerostatic and magnetic micro guidances can be used in micro machines. They enable a high precision and a low power consumption of the machine tool. For these axes small scaled capacitive sensors are a possibility to detect the distance between stator and rotor as an input value for the control systems. The design of the guidance is complex and the demands on the surface quality are high. To enable a highly productive production of the guidance, grinding technology with micro profiled grinding wheels is used. With this technology multiple grooves can be machined in one step. However, technologies for a highly productive micro structuring of large surfaces can also be utilized to produce for example micro dimples for tribological loaded surfaces, riblet structures on turbine blades or for the storage of information directly in the surface of components.

1. Introduction

Microfactories are intended to produce small dimension products. The Institute of Production Engineering and Machine Tools (IFW) supports the view that the only miniaturization of conventional machine tools is not sufficient to compose a microfactory. Often, the demands of the workpiece tolerances increase by decreasing the products dimensions. The IFW has made contributions to high precision engineering in different fields. In the first part solutions are presented to build frictionless axes for micro-machines that assure high positioning accuracy by the use of active microguides. By avoiding contact between moving parts, slip-stick effects that would decrease the positioning performance are avoided completely.

When manufacturing small machine parts with microstructures (e.g. aerostatic microguides), micromachining is used. Other applications of micromachining at the IFW are the improvement of the tribological performance of surfaces, reducing flow losses on compressor blades or storing information on workpiece surfaces.

In order to check the dimensional accuracy of microstructures, an optical measurement system is presented that allows a three-dimensional object capturing according to the principle of stripe projection.

2. Components for Microfactories

2.1 Frictionless Guides for Micro Machine Tools

Friction in guides restricts the positioning accuracy of machine axes significantly. As positioning accuracies below one micrometer were required for microsystems, the IFW has investigated active frictionless guides for small systems within the framework of the Collaborative Research Centre 516 (CRC 516, funded by the DFG). Two concepts (aerostatic and electromagnetic) are presented here.

2.1.1 Active Aerostatic Microguides

![Fig. 1 Principle of a miniaturized active aerostatic guide](image)
The application of aerostatic bearings and slide ways in precision engineering machines is well-proven (e.g. ultraprecise milling machines of Kugler GmbH). In addition to general requirements for slide ways like high carrying force, stiffness, damping (stability) and low air consumption, specific requirements result by miniaturization. Due to the smaller driving forces in micro-machines, pneumatic connections to the slide, as it is known from conventional air guides, result in undesirable disturbances. Furthermore, missing installation space on the small slide makes it difficult to integrate air bearings. The guide concept as shown in Fig. 1 meets these requirements by installing the air bearings and supply hoses in the stationary guide parts. By keeping the slide longer than the guides, moving is possible without wasting air due to uncovered areas. To compensate for unequal air gaps resulting from unbalanced loads on the slide, that can occur due to process forces and shifting centre of mass as well, a closed-loop gap control is applied. By observing the gaps at the segmented guide areas, a control of all degrees of freedom except for the sliding direction is possible.

The main design optimization criterion that is derived from the above mentioned requirements is to minimize dead volume and have an extensive pressure distribution on the bearings surface at the same time. The IFW has investigated different approaches of building air guides especially designed for use in microsystems and micro-machines. In addition to bearings made of air-permeable porous ceramics [1] and bearings with multiple discrete micronozzles [2], ceramic bearings with single nozzles ending in micro-channels were designed supported by Computational Fluid Dynamics, manufactured by micro-grinding and characterized.

The outer dimensions of the smaller guide (Fig. 2.a) are 2 x 4 x 15.9 mm³, while the carrying capacitance is 1.85 N at an air gap of 5 μm and a supply pressure of 2 bar. The nozzle of each bearing is ending in a rectangular pocket providing an appropriate bearing force. The nozzles of the bigger guide (Fig. 2.b) are ending in branched micro-channels that provide 42% more bearing force than rectangular pockets at the same dead volume. The golden electrodes of the capacitive displacement sensor are deposited directly on the bearings surface by Physical Vapour Deposition and coated with Silicon Nitride as isolation layer.

Fig. 2 a) Aerostatic microguide with rectangular pockets and decoupling channel, b) aerostatic microguide with air gap measurement system

Fig. 3 Bearing forces of the bigger guide at varying air gaps and varying supply pressures

The results of the force measurements of one bearing section can be seen in Fig. 3. The force increases by increasing the supply pressure. The decreasing of the force with increasing air gap is very important for the function of the guide, as static stiffness is the derivation of the force with respect to the gap.

2.1.2 Electromagnetic Microguides

An alternative possibility to avoid contact between moving machine parts is the use of magnetic guides [3]. In contrast to aerostatic guides, magnetic guides need a powerful closed-loop control to become stable. The main properties like the carrying force, stiffness and damping are defined by the controller parameters and are mainly restricted by saturation and sensor noise.
Within the CRC 516 a miniaturization of magnetic guides for application in microsystems was investigated. Therefore, a prototypical setup was realized in order to study the control behaviour together with hardware. A mechanically rigid rack allows an adjustment of the operating gap by moving the magnet carrier or the sensor carrier (Fig. 4). Four electromagnets are arranged over the slide that is equipped with iron parts concluding the flux. Four capacitive displacement sensors observe the air gap of about 70 µm between sensors and slide. As the slide drops down due to gravitation, the control increases the solenoid currents to lift the slide up and vice versa. Since the input variables (magnetic forces) and the output variables (air gaps) are coupled, a decoupled control design is applied that consists of three linear single-input-single-output controllers for each guided degree of freedom (DOF). The decoupling is done by transforming the four gaps into three DOFs (altitude, rolling and tilting) and reversely transforming the three determined generalized forces into four regulating currents [4].

In both guides a miniaturized gap measurement system is mandatory. Due to the geometry of the microsystem developed in the CRC 516, the installation space for sensing electrodes was restricted to 1 x 1 mm². Commercial capacitive distance sensors cannot provide these dimensions. According to the demands of the microguides concerning the available space, the travel range, the gap measurement range, the resolution and the dynamics, a capacitive displacement sensor has been developed.

To avoid any electric leads on the slide, an arrangement according to Fig. 6 has been chosen. The slide forms the middle electrode in a series connection of two capacitances that are evaluated by an evaluation circuit. The sensing electrodes are surrounded by shielding electrodes that are homogenizing the electrostatic fields at the fringes. According to Electrostatic-Finite-Elements calculations this measure increases the sensitivity by 2% at an air gap of 10 µm.

Fig. 6 Principle of the displacement sensor

Fig. 5 shows a step response of the magnetic guide. The controller is able to levitate the slide autonomously from the ground to the operating height of 70 µm within 20 ms. The standard deviation at the operating point is about 200 nm. This value is a combination of the measurement noise of 150 nm and remaining oscillations of the slide due to missing lateral guiding.

Fig. 5 Step response to a given step of 70 µm
The fabricated electrodes are shown in Fig. 7. Further details about the design, fabrication, alignment, calibration and the evaluation circuit can be found in [5]. A calibration trajectory can be seen in Fig. 8. Starting from 10 µm, the gap should be decreased step-wise with a step size of 1 µm until contact and then turn back to the start position. There is a nonlinear relation between the sensor output and the distance due to the inverse proportionality of both factors. Due to the slackness of the threaded spindle of the translation stage used in the calibration setup, a hysteresis at the reverse points is found. Because of the high repeat accuracy, the slackness can be quantified as a constant value of approximately 1 µm. A deviation of 23 nm at a reference air gap of 5 µm and a sample frequency of 5 kHz could be achieved without any mechanical vibration damping efforts.

2.2. Drives for Micro-Machine Tool Axes

Within the framework of the CRC 516, multiple rotational and translational electromagnetic actuators for use in microsystems have been developed and characterized. In [6] the design, fabrication and characterization of a variable reluctance (VR) micro actuator is described. This actuator can be used as a miniaturized linear motor. The components (stator and slide) are fabricated by thin-film technology using NiFe45/55 for the magnetic components, Cu for the electrical parts and SU-8™ as an insulation material.

A micro solenoid is placed around each core on the stator with six windings distributed on two layers (Fig. 9). The gap between slide and stator is defined to 7±1 µm. Due to the shape anisotropy, the permeabilities of the tooth structures in vertical direction are smaller than expected, which has a negative effect on the thrust force. Applying 300 mA at an air gap of 7 µm resulted in 9 mN in vertical direction. The thrust force reached 0.54 mN. When comparing these values, the importance of friction reduced guides becomes very clear.

A further important issue that has to be considered while designing miniaturized electromagnetic actuators is the heat generation that can lead to damages especially in the small dimensioned windings. Temperatures up to 180 °C have been measured on the actuator at a current of 350 mA [6]. A step motion has been achieved with a current of 250 mA using ball guides.

2.3. Components for assembly of microsystems

Assembling and handling of components for micro-machines becomes more complex with decreasing dimensions. In order to handle and manipulate very small objects multiple types of micro grippers were investigated within the framework of the CRC 516.

In [7] a silicon micro gripper is presented that can handle objects smaller than 25 µm (Fig. 10). It is using flexure gearings driven by thermal expansion actuators. A total opening of 26.1 µm has been achieved at an actuator temperature of 232 °C. The power dissipation at the maximum opening point was 1.3 Watts.

Surface charges on bodies in the process environment can cause unwanted forces and handling with small parts can become very complex. In [8] an active neutralization is presented that raise the gripping process stability from 65% (without neutralization) to 94% successful handling operations.

3. Surface Texturing and Micro-Grinding

Microstructures fulfil various functions in various applications. They can be found in products for mechatronics, fluidics, medical technology, optics, energy technology, biotechnology, (micro-)forming and tool construction [9]. In the following sections, works of the IFW on microstructures are presented.
Investigations concerning friction reduction with microdimples (Fig. 11.a), flow loss reduction with riblets (Fig. 11.b), information storing with microstructures (Fig. 11.c) and microgrinding of structures for micro machine components (Fig. 11.d) are presented.

3.1. Microdimples for reduced friction

In order to reduce mechanical friction between lubricated sliding parts (slide bearings, cylinder liners, e.g.), microdimples are machined on the surface of one partner. Each of the microdimple acts like a micro hydrodynamic bearing. The convergent dimple geometry ensures that pressure builds up due to compression of the lubricant that is fed by shear stress forces resulting from relative motion of the sliding parts. Fig. 10.a) shows the final topography of a machined surface for tribological applications. The average dimensions of the dimples are 1–2 mm in length, 50–100 µm in width and 5–30 µm in depth. While the development of fly-cutting kinematics for flat and rotation-symmetric surfaces is finished [10], the development, machining and tribological investigation of the fly-cutting kinematics for inner diameter machining is part of current work.

3.2. Riblets for reduced flow losses

In a similar application, microstructures are used to reduce the skin friction and wall shear stresses in turbulent flows leading to a reduction of flow losses by up to 10% compared with smooth surfaces [10]. The so-called riblets increase the efficiency of gas engines significantly, when they are machined on the compressor blades. In order to generate riblets on large scale areas, microprofile dressing and grinding processes have been developed. Multiple V-shaped profiles have been dressed on vitrified bonded grinding wheels by profile shift kinematics. In order to obtain adequate riblet densities with uniform distances, profile overlapping has been applied in the grinding process.

After each pass, the next grinding step is done with an axial profile offset (Fig. 12.a). Profiles with a width of 60 µm, and a height of 20 µm could be achieved at an infeed of 30 µm (Fig. 12.b). After the grinding process burr formation can be observed, which decreases the flow loss reducing effect that is strongly dependent on the riblet tip radius. The impact of grinding strategies and parameters on the burr formation can be found in [11].

In Fig. 12.c) the riblets profile after a spark out grinding process can be seen, while the whole profile grinding process is repeated without any additional infeed. A riblet tip radius of 1 µm has been achieved.

3.3 Storing information on surfaces with microstructures

In addition to works on friction and flow loss reduction, the IFW uses microstructures to store data directly on surfaces of workpieces. The application scope of this technology is wide open:
- Stored information about the production conditions can be very helpful at malfunction and can be used for better understanding and production improvements.
- At the end of a life cycle, stored information about the materials can be used for disassembly and recycling.
- Micro products can be identified by means of the data stored on their surfaces.
The information containing microstructures are currently produced by a turning process using a highly dynamic piezo-driven tool holder (Fig. 13). By controlling the elongation of the piezo actuators, the depth of cut as well as the distance between two structures in cutting direction can be varied according to the data that has to be stored. The coded structures can be described as a mixture of pits used on CDs and grooves with variable gap width used on gramophone records. The frequency dependent cutting depth can vary between 3 µm and 30 µm. Currently, the data density is about 4 kBit/cm².

The information is read by an optical system that consists of a light source for directly illuminating the surface, a camera for capturing the reflected light and evaluation software for image processing and information extraction [12].

3.4 Grinding of microstructures with multiple profiled grinding wheels

In manufacturing of complex microstructures on small components that are needed for micro-machines, brittle-hard materials are very suitable due to their geometrical accuracy.

An economic manufacturing of these challenging materials can only be managed by microgrinding with metal bonded diamond grinding tools providing favourable wear behaviour. In order to dress multiple microporfiles on these tools, the IFW has developed a dressing process basing on electro contact discharge dressing (ECCD).

The heat of electrical discharges profiles the grinding wheel by removing the metal bond. The dressing process is controlled by the voltage, the current limitation and feed of the electrode. In order to reduce the minimum profile size, the application of thin copper wire electrodes with a feed direction perpendicular to the peripheral wheel surface has been investigated. The influences of the process parameters on the specific material removal rate can be found in [13]. The minimum achieved width of the ground micro channels (Fig. 11.d) is about 300 µm, slightly more than the width of the copper wire electrodes of 224 µm. The aerostatic microguides presented in Sect. 2.1.1 were successfully manufactured using this technology.

4. Optical three-dimensional quality control of micro-workpieces

In order to analyze microstructures, a micro-measurement system has been developed with the aid of a binocular microscope. These special microscopes are characterized by two separate optical paths, which allow stereovision of small object.

The applied principle is that of stripe projection. The projector that is replacing one ocular (Fig. 14) uses one beam pass to project stripes on the object that is observed by the camera through the second beam pass. Assuming central projection and calibrated cameras (the projector is also considered as a camera), the depth of the objects surface can be calculated due to the stripe deformations.

Therefore, the evaluation software has to know the order of the stripes. Counting the stripes fails if they get disrupted on the object. This problem can be solved with a coded sequence of projected stripes that generates a unique identifier for each stripe. Due to its robustness, the Gray-code is used for coding.

5. Conclusions

This paper presents key technologies for microfactories. Drives and guides are main components of machine tools. More attention must be paid when designing a micro machine that has to meet high requirements concerning the positioning accuracy. Two concepts for guides are presented in this paper: Aerostatic and electromagnetic guides are able to assure contactless sliding. Both guides need an accurate measurement system. A capacitive sensor has been developed for this application.
One possibility to drive micro machines is the use of miniaturized electromagnetic drives. But special attention must be paid on the reluctance forces that can get one order higher than the thrust forces. An appropriate heat management is a precondition when using electromagnetic drives. Heat can lead to unwanted machine component deformations and in the worst case it can lead to damages in the small dimensioned windings.

In a microfactory, electrostatic forces are not negligible. They can reduce the process stability (e.g. in handling) significantly when the process is not well prepared.

Microstructures can be found in various components fulfilling various functions. Recent works are focused on reduction of friction and flow-loss, information storing and manufacturing of components for micro machines.

Fabrication of micro devices and surfaces demands appropriate measurement and quality assurance systems.

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