Compact hydrodynamic spindle module for micromachining applications

Martin Bohley¹, Ingo G. Reichenbach¹, Christopher Müller¹, Benjamin Kirsch¹, Jan C. Aurich¹

¹University of Kaiserslautern; Institute for Manufacturing Technology and Production Systems

Martin.bohley@mv.uni-kl.de

Abstract
To meet the increasing demand for miniaturization of components and functionalization of surfaces by micro machining, optimized machine tools have to be developed. Commercially available machine tools for micro machining require a high installation space and extensive strategies to minimize thermal expansion. The workspace of commercially available machines used in micro manufacturing exceeds dimensions of the produced microstructure and workpieces by several orders of magnitude. Most of the workpieces are relatively small, with sizes under 100 x 100 mm² and the micro tool's (e.g. micro end mills or micro pencil grinding tools) diameter range is between 3 µm and 3 mm. To minimize the installation space and first of all to improve the axes dynamic properties, workpiece size and micro tool size adapted machine tools are required. To achieve this minimization and improvement of the performance of machine tools, new small and lightweight parts have to be developed. At the Institute for Manufacturing Technology and Production Systems, a compact spindle module based on a hydrodynamic spindle motor with a run-out error of less than 1 µm and a size of 58 x 58 x 25 mm³, as well as a speed controller for its implementation in machine tools has been developed. The research described in this paper shows the effectiveness of the compact spindle module for micro machining. This new spindle module can be used for ultra-precision milling or to produce tools by grinding for micro milling or micro grinding applications. To demonstrate the capabilities of this compact spindle module, surfaces have been face milled and micro tools with diameters below 10 µm were produced via grinding.

Keywords: Micromachining, micro milling, micro grinding, spindle

1. Introduction
The miniaturization of components and the functionalization of component surfaces are of increasing importance. This demands for a high manufacturing accuracy and economic processes [1]. An efficient way to produce these parts and surfaces is micro machining. The commercially available machine tools used for e.g. micro milling in most cases exceed the produced microstructures and workpieces by several orders of magnitude [2]. Commonly, the workpieces are relatively small, with sizes under 100 x 100 mm² and the micro tool’s (e.g. micro end mills or micro pencil grinding tools) diameter range is between 3 µm and 3 mm on desktop machine tools. To minimize the installation space and first of all to improve the axes dynamic properties, much smaller, workpiece size and micro tool size adapted machine tools are required [3]. To achieve this minimization and improvement of the performance of machine tools, new small and lightweight parts have to be developed. Typical tasks in micro machining are grinding of micro tools or face milling of surfaces. The development of a new compact spindle module based on a hydrodynamic spindle motor to improve this is presented here.

2. Compact spindle module
The spindle has to be able to be used as a grinding spindle for the production of micro tools (e.g. ultra-small micro end mills [4] or micro pencil grinding tools [5]) as well as a spindle for ultra-precision milling operations. To fulfill the demands for micro machining, the spindle has to be usable in horizontal as well as vertical orientation, provide low run-out errors and has to exhibit small dimensions. Such a compact spindle module (CSM) was developed at the Institute for Manufacturing Technology and Production Systems Kaiserslautern (Figure 1).

![Figure 1. a) Compact spindle module with diamond grinding wheel b) compact spindle module used for ultra-precision milling](image-url)

The CSM is based on a commercially available hydrodynamic axial and radial bearing and driven by a brushless DC motor (BLDC). This motor type allows small dimensions (no commutator needed) and has a high efficiency (low heating). On this bearing, an ultra-precision turned adapter is mounted. Diamond grinding wheels to produce micro tools (Fig.1 a)) or inserts for ultra-precision milling (Figure 1 b)) can be clamped on this adapter. The overall size of the CSM in this configuration is 58 mm in diameter and 25 mm in height. The control of the CSM enables a continuous speed adjusting between 0 and 12 500 rpm.

The CSM’s hydrodynamic axial and radial bearing allows for an adequate stiffness and a low run-out error. The total indicated
run-out error measured with capacitive sensors at 12 500 rpm in
horizontal orientation of the CSM is 0.98 µm and in vertical
orientation 0.7 µm. The control of the CSM is based on a Seeed
Seeduino v3 with an Atmega Atmel chip1. For speed
determination, Latch-Hall-Effect sensors are used. The
rotational speed is detected every revolution. With a cascade
control the average actual value of 15 revolutions is determined,
compared to the nominal values and adjusted if needed. The
Seeduino drives a brushless electronic speed controller which
powers the CSM with 12 V enabling a motor power of
approximately 6.4 W.

3. Proof of concept

To show the capabilities and the fulfilment of the
requirements, ultra-small micro end mills were ground and brass
samples were milled to mirror quality with the CSM.

Ultra-small micro end mills were ground on a precision three
axes milling machine according to [5] in horizontal CSM
orientation (Fig.2).

![Figure 2. Setup and 10 µm diameter ultra-small micro end mill ground with CSM](image)

Therefore, cemented carbide blanks (tungsten carbide grain
size 0.3 µm, 9 % cobalt, 4 800 N/mm² bending strength) were
clamped in an ABL MM1252 air bearing spindle with a run-out
error < 2 µm at 40 000 rpm. To manufacture the micro end mills,
two grinding wheels, each with a diameter of 58 mm were used.
A resin bond diamond grinding wheel with a grit size of #800 was
applied for roughing and a diamond grinding wheel with a grit
size of #4800 for finishing. The cutting speed used was
\[ \nu_c = 30 \text{ m/s.} \] The results show the capability of the CSM. The low
run-out error and low vibrations enable the production of micro
end mills with a diameter below 10 µm.

For ultra-precision milling, the CSM was equipped with a
Sandvik DCGX 07 02 02 AL-H101 cutting insert. The CSM was then
mounted on a three axes precision milling machine in vertical
orientation. The sample to be cut had a size of 26 mm by 76 mm
according to DIN ISO 8037-1 (Fig. 4). The material was
CuZn40Pb2. The depth of cut was \( a_p = 20 \mu m \), the feed per tooth
\( f_t = 2.5 \mu m \) and the cutting speed \( \nu_c = 1.000 \text{ mm/min}. \)
The spindle power of the CSM proved to be high enough to keep the
feed per tooth constant. The resulting surface had a roughness of
\( R_z = 0.038 \mu m \), the total cutting time was 327.5 s. The surface
roughness is suitable for milling microstructures and in addition,
the sample preparation time is very short. Conventionally, air
bearing spindles with collet chucks are used in micro machining.
This limits the diameter range of the tools for face milling (same
diameter as the tool shank). In comparison to a face milling
process with a two flute end mill of 3 mm in diameter, milling
with the CSM reduces the sample preparation time by 90 %.

![Figure 4. Setup for UP-milling of brass and result](image)

4. Conclusion

To minimize parts and enhance the efficiency of micro
machining applications, a small spindle module was developed.
The spindle has a diameter of 58 mm and a height of 25 mm. The
run-out error is below 1 µm and the power is about 6.4 W.
Grinding test show the suitability of these spindle modules for
producing ultra-small micro end mills with diameters below
50 µm at high quality. By ultra-precision milling of brass, the
capabilities of the spindle was demonstrated for face milling
larger samples with high quality (\( R_z = 0.038 \mu m \)). The surface
roughness is suitable for milling microstructures and the process
time was very short compared to common face milling.

In future research, the mounting of the module is going to be
optimized to improve the straightness of the UP-milled surfaces.

Acknowledgement

This research was supported by the German Research
Foundation (DFG) within the CRC 926 “Microscale Morphology
of Component Surfaces”.

References

[1] Dornfeld D, Min S, Takeuchi Y 2006 Recent Advances in
Mechanical Micromachining: CIRP Annals -
Manufacturing Technology 55 (2) pp 745–768.
Werkzeugmaschinen für kleine Werkstücke:
Zielstellungen und Vorgehensweise des DFG-
Schwerpunktprogramms 1476: wt Werkstattstechnik
dynamic high precision compact milling machine:
Proceedings of Euspen International Conference vol 1
pp 443-447.
Micro grinding tool for manufacture of complex
structures in brittle materials: CIRP Annals -
Manufacturing Technology 58 (1) pp 311–314.
Manufacture and application of ultra-small micro end
mills: CIRP Annals - Manufacturing Technology (61) (1)
pp 83–86.

1Naming of specific manufacturers is done solely for the sake of
completeness and does not necessarily imply an endorsement
of the named companies nor that the products are necessarily
the best for the purpose.