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Compact hydrodynamic spindle module for micromachining applications

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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 fulfil 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).

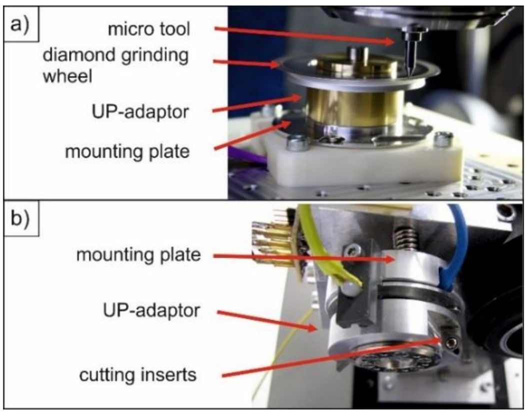

Figure 1. a) Compact spindle module with diamond grinding wheel b) compact spindle module used for ultra-precision milling

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 Seeeduino v3 with an Atmega Atmel chip[1]. 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 Seeeduino 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).

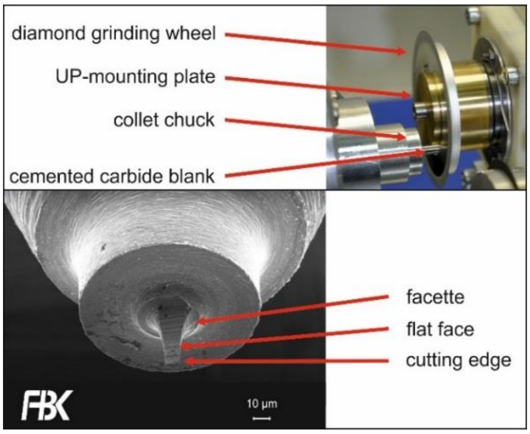

Figure 2. Setup and 10 µm diameter ultra-small micro end mill ground with CSM

Therefore, cemented carbide blanks (tungsten carbide grain size 0.3 µm, 9 % cobalt, 4 800 N/mm² bending strength) were clamped in an ABL MM125[1] 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 v_c = 30 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-H10[1] 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 µm, the feed per tooth f_z = 2.5 µm and the cutting speed v_c = 1 000 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_a = 0.038 µm, 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 %.

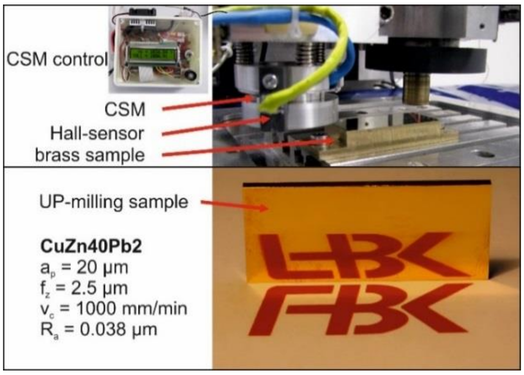

Figure 4. Setup for UP-milling of brass and result

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_a = 0.038 µm). 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.

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[1]Naming 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.