euspen's 18th International Conference & Exhibition, Venice, IT, June 2018
www.euspen.eu

Vibration-assisted air bearing spindle for micro machining – development of a magnetic field controlled ultrasonic actuator

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Abstract

The trend of miniaturization of components and the functionalization of surfaces require the continuous improvement of micro machining processes. This includes maintaining tight tolerances and to expand the range of machinable materials, also including difficult-to-cut materials. One possibility to enhance the efficiency of machining is the implementation of vibration-assisted cutting in machine tools. This results in altered cutting conditions that can lower forces, tool wear and hence expand the machinable material range. However, present commercially available vibration-assisted spindles are not able to achieve sufficient cutting speeds at adequate accuracy to be used in the field of micro machining.
The research in this paper describes the development of an ultrasonic actuator, which will be part of a vibration-assisted air bearing spindle. The tool spindle will be designed to achieve rotational speeds > 100,000 rpm at a low run out error. The actuator is directly integrated into the spindle's rotor, avoiding additional radial run-out. The proposed actuator reaches an vibrational amplitude of up to 3.8 µm, qualifying the rotor-actuator-system for vibration-assisted cutting in the field of micro machining. The stepless and contact-free adjustment of the amplitude and frequency of the actuator's vibration is realized via a magnetic field. The actuator's concept, which is based on the magnetostricitve effect, is decribed. The setup of the rotor with its integrated ultrasonic actuator is explained and the actuator's design processs, supported by a magnetic field simulation, is shown. The paper is concluded by measurements of the actuator's amplitude, which are compared to the values provided by the simulation.

Keywords: micro machining, vibration-assisted cutting, air bearing spindle

1. Introduction

Miniaturization of components and the related application of micro machining processes are continuously increasing [1]. To achieve the required tight tolerances and to expand the tool life, the processes have to be further improved. In addition, the range of machinable materials needs to be enlarged, including machining of difficult-to-cut materials in the field of micro machining. Micro machining with ultrasonic vibration assisted cutting promises to fulfill all those demands [2]. In the case of ultrasonic assisted spindles, the vibration is induced to the cutting zone by an oscillation of the tool in axial direction [3]. Existing ultrasonic assisted spindles reach low radial run-outs of about 0.7 µm at 1,000 rpm with frequencies of the tool vibration of 25 kHz [4]. These rotational speeds are not sufficient to reach the required cutting speeds of micro tools with diameters < 50 µm, as they are current state of the art [5, 6].

An air bearing spindle with an integrated ultrasonic actuator is developed. It combines the high rotational speeds and low radial run-out of air bearings with a vibrational tool movement in axial direction. The concept of the spindles rotor with its integrated ultrasonic actuator is explained. The output of a simulation, used for the prediction of the actuators amplitude is compared to experimental results.

2. Spindle Concept

The concept of the ultrasonic vibration assisted spindle is shown in figure 1. The spindle is airdriven, providing easy speed and torque control by regulating the air-mass flow hitting the turbine. The rotor will be guided in aerostatic bearings, enabling low radial run-out and high rotational speed due to low friction. In the front of the rotor an electric coil and a Terfenol-D rod is located, that functions as ultrasonic actuator using the magnetostricitve effect.

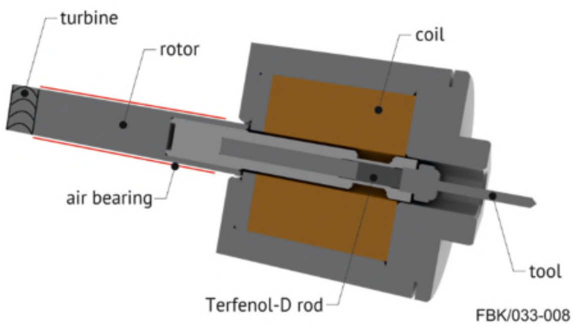

Figure 1. Concept of the integrated magnetostricitve actuator

The magnetostricitve effect describes an elongation of magnetic materials as a function of the surrounding magnetic field. The length extension of the highly magnetostricitve Terfenol-D rod and the vibrational frequency can be controlled by the frequency and amplitude of the electric current flowing through the coil. In the proposed concept, a magnetic field, surrounding the Terfenol-D rod, is generated. Hence, a contactfree vibration control for the ultrasonic actuator is generated. As the magnetic field has to permeate the rotor to cause the elongation of the Terfenol-D rod, the rotor consists of non-magnetic aluminium to keep the influence on the surrounding magnetic field as low as possible.

3. Numerical Simulation of the Magnetic Field

As the magnetic field strength H is responsible for the length extension of the Terfenol-D rod and thus the actuators vibrational amplitude, a magnetic field simulation was done.

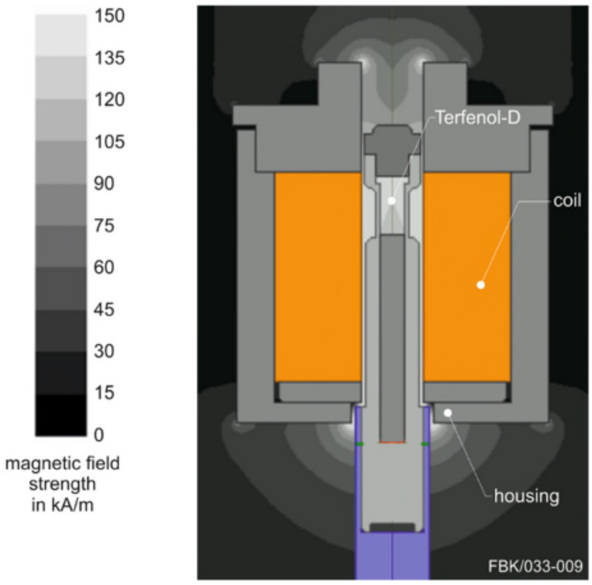

Figure 2. Magnetic field simulation (Ansys Maxwell)

The coil with its 575 windings and an electric current of 15 A led to a simulated magnetic field strength of up to 150 kA/m in the surrounding of the Terfenol-D rod. According to the material specifications, this magnetic field strength can lead to length extensions of the 14.9 mm long Terfenol-D rod from 2.7 to 20.9 µm depending on the mechanical prestress within the Terfenol-D.

4. Experimental Results

To validate the concept and the calculated amplitude of the actuator, a non-rotating prototype was built. The elongation of the Terfenol-D was measured via a confocal chromatic measurement sensor, which remains unaffected by the magnetic field. As the amplitude was measured in static mode, a sampling rate of 1 kHz was chosen. The current flowing through the coil was set to 10 A and 15 A, in order to correspond to the simulated magnetic field strength as well as proving the dependency of the amplitude on the electric current.

Figure 3 shows two examples of measured amplitudes of the actuator by variation of the electric current. The depicted values represent the average of 5 measurements. Amplitudes of 2.3 µm (σ = 4.5 %) were reached by using an electric current of 10 A. Increasing the electric current to 15 A raised the measured length extension to 3.8 µm (σ = 3.7 %). It can be seen, that the length extension of the Terfenol-D rod is depending on the selected electric current. The amplitude of the ultrasonic actuator may therefore be controlled by the electric current.

Frequency measurements showed a duplication of the actuators vibrational frequency (400 Hz) compared to the coils current frequency (200 Hz). This duplication is caused by the expansion characteristics of Terfenol-D when passing its elongation hysteresis. This behaviour will be taken into account when designing the stepless frequency control in future works.

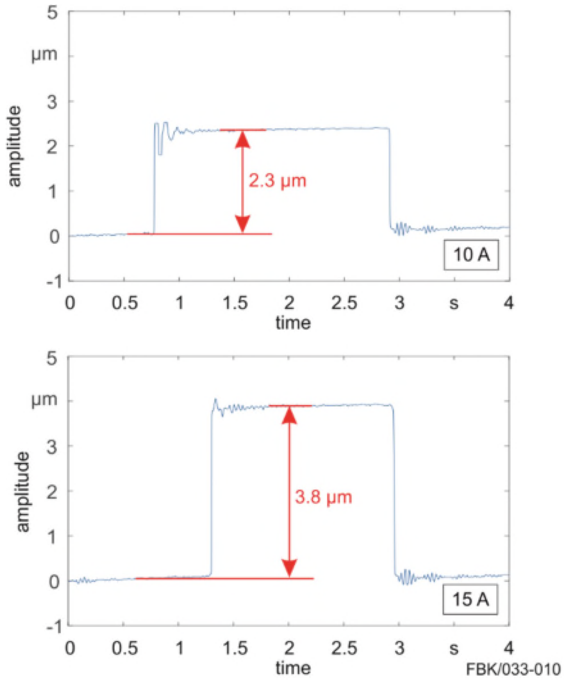

Figure 3. Measured actuator amplitude using 10 and 15 Ampere DC

5. Conclusion

This paper introduced the concept of an ultrasonic vibration assisted air bearing spindle with a contact-free and stepless control of the tools vibrational amplitude and frequency using the magnetostricitve effect. A magnetic field simulation was conducted to predict the magnetic field causing the length extension of the Terfenol-D rod. The simulated amplitude is in the same range as measured amplitudes. The measured amplitudes of 2.3 µm with a current of 10 A and 3.8 µm with 15 A are sufficient for vibration assisted cutting in the field of micro machining. In further research the acutators frequency will be increased to qualify for ultrasonic vibration.

Acknowledgement

The authors would like to thank the German Research Foundation (DFG) for the financial support within the project AU 185/57-1 “Ultrasonic air bearing spindle for micro machining”.

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