Available online at www.sciencedirect.com

SciVerse ScienceDirect

Procedia CIRP 1 (2012) 144 – 149

www.elsevier.com/locate/procedia

5th CIRP Conference on High Performance Cutting 2012

High-Performance Cutting of Micro Patterns

Berend Denkena, Jens Köhler, Tobias Mörke*, Olaf Gümmer

Institute of Production Engineering and Machine Tools, Leibniz Universität Hannover, Germany

* Corresponding author. Tel.: +49-511-762-4839; fax: +49-511-762-5115. E-mail address: moerke@ifw.uni-hannover.de.

Abstract

This research report presents an innovative piezo-actuated fast tool servo (FTS) for milling operations introducing the high-performance cutting of micro patterns. The outstanding dynamics of the tool enable a highly dynamic depth of cut variation during the cutting process. Unlike commercial technologies, such as ultrasonic tools, the presented device does not oscillate in resonance, but controlled. Its first natural resonance frequency of $\omega_0 > 4.5$ kHz and its capability to provide a maximum amplitude of $\Delta l_{max} > 30$ microns establish the basis to cut micro patterns, while using process parameters applied in real-life industrial processes.

Keywords: micromachining; servosystem; piezo-electric; mechatronic; information

1. Introduction

The Collaborative Research Centre (CRC) 653, sponsored by the German Research Foundation (DFG), researches on innovative component properties and concepts for their manufacturing and implementation in production engineering processes. One of the CRC's visions is the inherent storage of significant component information, such as production date, process parameters, process forces or even production drawings on the component itself. In addition, these advanced properties provide an excellent basis to protect the component against plagiarism [1].

The machining of defined micro patterns into the component surface during a finishing operation offers a promising possibility to store information. In a first step, the data is decoded to a binary sequence. Following this, it can be induced into the surface in the form of cavities and the absence of such representing ones and zeros. Figure 1 illustrates the conversion of the digital information to a varying depth of cut, which in turn leads to the cutting of defined cavities. In order to retrieve the stored information, fast and robust optical readout methods can be applied [2].

Common technologies, for example micro milling or laser material removal, require additional process steps or machine tools. In order to accomplish a commercial application, a machining technology that allows the cutting of defined micro patterns on conventional machine tools by highly productive process parameters is mandatory. For turning operations, the described micro patterns are cut by piezo-electrically actuated turning tools. Previous tool concepts are used for the machining of optical or medical components and for high-precision machining [3-10].

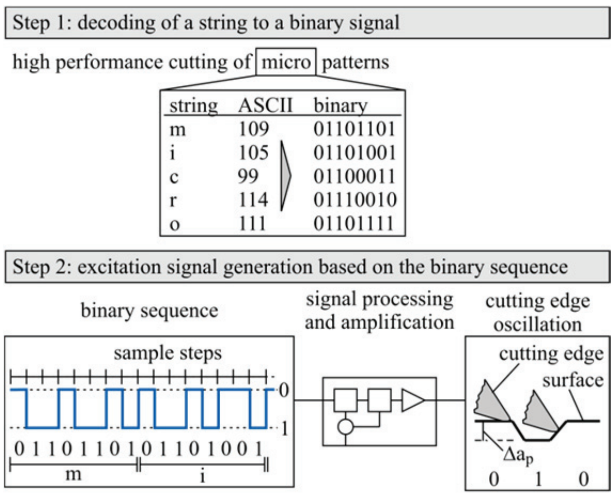

Fig. 1. Binary conversion of information.

2212-8271 © 2012 The Authors. Published by Elsevier B.V. Selection and/or peer-review under responsibility of Professor Konrad Wegener
Open access under CC BY-NC-ND license. http://dx.doi.org/10.1016/j.procir.2012.04.024

In most cases, the systems are designed for diamond turning and do not fulfill the required productivity due to low first natural resonance frequencies or small amplitudes. Thus, a FTS for turning operations with a high first natural resonance frequency ($\omega_0 > 6$ kHz) is developed within the CRC 653. Previous publications demonstrate the functional capability of this technology for turning processes [11, 12]. A highly dynamic, radial tool tip oscillation results in a varying depth of cut.

In order to extend the information storage by means of micro patterns, the technology is transferred to an additional machining process. Existing actuated milling technologies, for example ultrasonic tool units used for commercial purposes, operate in resonance at ultrasonic frequencies and small axial amplitudes. They are not considered due to the requirement of a controlled axial oscillation. Actuated spindle systems [13, 14] have low resonance frequencies due to highly moving masses. An insufficient data density on the surface is therefore achieved or unproductive process parameters must be applied.

The eminent achievement presented in this paper is the development of a FTS for milling and its application during face milling. Due to an intelligent design, the tool is capable of a highly dynamic, controlled axial positioning. This represents the basis to cut defined micro patterns and therefore to store information on a component surface. The application of the developed tool extends to a wider field of machining due to the fact that it can be also used to influence tribological properties of a workpiece surface or to modify its optical appearance as well as its haptics.

Nomenclature

ω_0	first natural resonance frequency
ω_{piezo}	eigenfrequency of the piezo-actuator
φ_{entry}/ φ_{exit}	entry and exit angle of the cutting edge
C	capacity of the piezo-actuator
c_{piezo}	stiffness of the piezo-actuator
d	end mill diameter
$F_{dynamic}$	dynamic force
f	structuring frequency
f_z	feed per tooth
i_a	continuous current
i_{max}	peak current
Δl	travel range of the piezo-actuator
$m_{moving\ mass}$	moving mass of the FTS
m_{piezo}	mass of the piezo-actuator
n	revolutions per second
o_{max}	oscillations per cutting edge engagement
o_{rev}	oscillations per revolution
U	voltage amplitude of excitation
v_c	cutting speed
z	number of teeth

2. Highly dynamic piezo-actuated end mill holder

In order to cut micro patterns during finishing operations in milling, a FTS that actively actuates an end mill in axial direction is developed. This active milling tool must allow high dynamics and a precise movement of the tool at the same time in order to produce fine patterns with a high data density.

2.1. Design description

Especially for a highly dynamic positioning, piezo-electric actuators are suitable because of their high dynamics and stiffness. Similar to existing FTS turning tools, the presented FTS is actuated by a piezo-electric element. Due to the fact that highly dynamic operations cause a significant heat development, a ring-actuator is used for a better heat dissipation. At a maximum voltage of $U_{max} = 1000$ V, the actuator has a force of 20 kN. The maximum travel range is $\Delta l_{max} = 60$ microns. The ring-actuator has a stiffness of $c_{piezo} = 350$ N/µm and an eigenfrequency of $\omega_{piezo} = 15$ kHz.

The controlled cutting of micro patterns requires oscillation frequencies below the eigenfrequency due to occurring phase shifts above this frequency range. The moving mass must therefore be as small as possible. For an active positioning in axial direction, the piezo ring-actuator is placed between a tool holder and a frame. The tool holder is mounted with two flexure hinges designed as steel spring membranes. The flexure hinges themselves are attached to the frame. By means of this type of bearing, only one degree of freedom – namely the translation in axial direction – is possible for the tool holder. For the integration into conventional milling machines, a standard spindle connection (DIN 69893 HSK-A 63) for milling spindles is considered. The realization of the piezo-actuated tool is shown in figure 2.

In order to reduce the moving mass, the tool holder is made of titanium. End mills with screw-in threads, up to a diameter d = 20 mm, can be mounted into the tool holder. Since piezo actuators can only generate a force in one direction, the actuator is preloaded by a central disc spring assembly. The preload can be implemented centrally through the ring-actuator. Beside a good heat dissipation, the ring-actuator offers the advantage of a central preload. This is important with regard to the imbalance of the FTS during rotation. The utilized disc springs for the preload have the advantage of a constant spring force at small spring strokes because of their declining behaviour. Thus, the travel range of the piezo-electric actuator is not reduced due to a not constant counterforce. The piezo actuator is preloaded with a force of about 10 kN. With the combination of a piezo actuator and a central preload a highly dynamic positioning of the end mill in axial direction is realized.

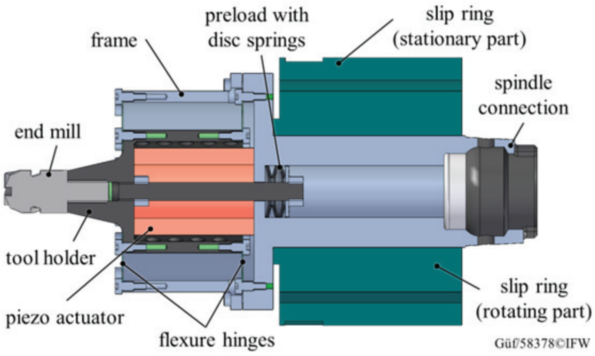

Fig. 2. Sectional view of the piezo-actuated tool for milling operations.

In order to produce defined patterns, the piezo-electric actuator must be supplied with energy. By changing the applied voltage, the structure's depth can be controlled. Since the piezo-actuated tool is rotating during milling, the energy of the piezo actuator must be transferred into the rotating system. For the dynamic control of the piezo actuators, piezo-electric amplifiers are used at high power. They cannot be integrated into the rotating system so that a slip ring is used for the power transmission. To reduce the peripheral speed of the slip contact, the slip ring transmission is directly placed on the lower shaft section in front of the tool holder.

In addition to the voltage of the piezo-electric actuator, the supply voltage and the measurement signal of the strain gauges as well as the signal of a temperature sensor are transmitted through the slip rings. The strain gauges and temperature sensor are directly applied on the piezo-electric actuator. Thus, the temperature can be monitored and the structuring depth can be controlled by the signal of the strain gauges during operation.

2.2. Theory of the dynamic behavior

For the highly dynamic cutting of micro patterns, an amplifier that ensures a high continuous and peak current is required. The used ring actuator has a capacity of C = 900 nF. According to the requirements of the intended optical micro-pattern recognition method (cf. [2]), a structuring depth above $\Delta l = 30$ microns is not required. For this reason, an amplifier with a maximum voltage of U = 500 V is sufficient to provide the piezo actuator's maximum travel range of $\Delta l = 30$ microns. Only a small part of the actuator's full deflection is used to decrease its internal friction with the result that the thermal losses of the piezo-electric elements decrease. A continuous operation without the risk of overheating can be achieved in this way.

Only analogue amplifiers can be considered with the targeted structuring frequency of up to f = 4 kHz. Conventional digital amplifiers can only amplify signals with a frequency of up to 2 kHz due to their switching frequency. According to the formulas in [15], a constant current of i_a = 1.8 A and a peak current of i_{max} = 5.6 A are needed for a sinusoidal oscillation with 4 kHz.

$$\begin{aligned} i_a &= f \cdot C \cdot U \\ &= 4000\,Hz \cdot 900\,nF \cdot 500\,V = 1.8\ A \end{aligned} \quad (1)$$

$$\begin{aligned} i_{max} &= \pi \cdot f \cdot C \cdot U \\ &= \pi \cdot 4000\,Hz \cdot 900\,nF \cdot 500\,V = 5.6\,A \end{aligned} \quad (2)$$

There is currently no commercial analogue amplifier on the market with a comparable performance. Thus, an analogue amplifier with a constant current of i_a = 0.7 A and a peak current of i_{max} = 2 A is used. The lower output involves that the full stroke of the piezo cannot be used for the high frequency range.

The controllable structuring dynamics significantly depend on the natural frequency of the positioning system. A controlled positioning of the end mill is possible below the natural frequency. Again, the natural frequency depends on the moving mass. The moving mass is approximately $m_{moving\ mass}$ = 365 g corresponding to the design in figure 2, showing an end mill with a diameter of d = 20 mm. According to the formula in [16], the resonance frequency amounts to ω_0 = 4.5 kHz.

$$\begin{aligned} \omega_0 &= \frac{1}{2\pi} \cdot \sqrt{\frac{c_{piezo}}{m_{moving\ mass} + \frac{1}{3} \cdot m_{piezo}}} \\ &= \frac{1}{2\pi} \cdot \sqrt{\frac{350 \frac{N}{\mu m}}{365\,g + 76\,g}} = 4.5\,kHz \end{aligned} \quad (3)$$

The calculation shows that the natural frequency is above the desired structuring frequency of 4 kHz. According to [15], the dynamic forces that are required for a sinusoidal positioning of a moving mass with a frequency of 4 kHz can be estimated as follows:

$$\begin{aligned} F_{dynamic} &= \pm 4 \cdot \pi^2 \cdot \left(m_{moving\ mass} + \frac{1}{3} \cdot m_{piezo} \right) \cdot \frac{\Delta l}{2} \cdot f^2 \\ &= \pm 4 \cdot \pi^2 \cdot 441\,g \cdot \frac{30\,\mu m}{2} \cdot (4000\,Hz)^2 \\ &= 4180\,N \end{aligned} \quad (4)$$

The calculation of the dynamic force shows that it can be applied by the selected piezo actuator with a maximum force of $F_{piezo,max}$ = 10 kN at U = 500 V. Even the preload of about F_{pre} = 10 kN is sufficient to generate appropriate counterforces. The following experimental studies show the validity of these considerations.

2.3. Dynamic analyses

The dynamic behavior of the tool is analyzed by means of a sinus sweep signal with different amplitudes. The sweep signal generates excitation frequencies from f = 1 Hz to 10 kHz. The amplitude is increased for each sweep sequence from U = 50 V to 250 V. The response is measured with a state-of-the-art laser Doppler vibrometer, measuring the speed and amplitude of the tool surface. Since the axial oscillation is of great importance, the tool response is measured in this direction. The measured frequencies of the tool and phase response are illustrated in figure 3. The first natural resonance frequency can be clearly identified at $\omega_0 = 4.5$ kHz. Since the dynamic analysis is done including the end mill and cutting inserts, the moved mass will not increase during milling.

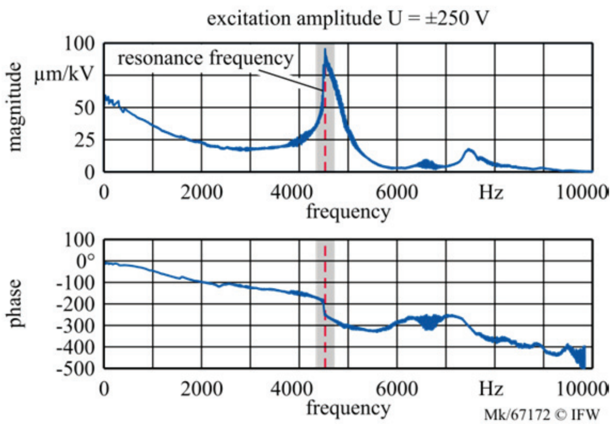

Fig. 3. Measured frequency response at an excitation amplitude of U = ±250 V.

The experimental studies show that the natural frequency coincides with the calculations in chapter 2.2. Due to the limited power of the amplifier, figure 3 shows the expected decrease of the maximum structuring depth with an increasing frequency. At a frequency of 4 kHz, a structuring depth of about 12.5 microns is realized.

2.4. Piezo-actuated tool control

In order to be able to store information by means of micro patterns, the tool control is of significant importance. At first, the data is converted to a binary sequence. Following this, a MATLAB/SIMULINK model processes this sequence along with the information from the machine tool, regarding the rotation angle of the spindle. In addition, the temperature control and strain gauge signals from the tool are input signals of this model. In order to process the signals in real time, the MATLAB/SIMULINK model runs on a dSpace real-time computer system. The binary signal, respectively the excitation signal of the piezo actuator, can be provided depending on the angularity of the spindle and cutting edge. The binary sequence is converted into a square wave signal which is filtered with a FIR maximally flat and low-pass filter to protect the piezo element against damage. The dSpace system's sampling frequency of $f_s = 40$ kHz is set to the decuple of the maximum structuring frequency of f = 4 kHz to gain satisfying results regarding the processing and filtering of the signal. The output signal of the dSpace system is amplified by the high-voltage amplifier mentioned in section 2.2. The amplifier is directly connected to the piezo-actuated end mill holder. The amplified signal leads to a defined oscillation of the piezo actuator and therefore of the cutting edge. Thus, the depth of cut is varied and the micro patterns are cut into the surface. Fig. 4 illustrates the described tool control.

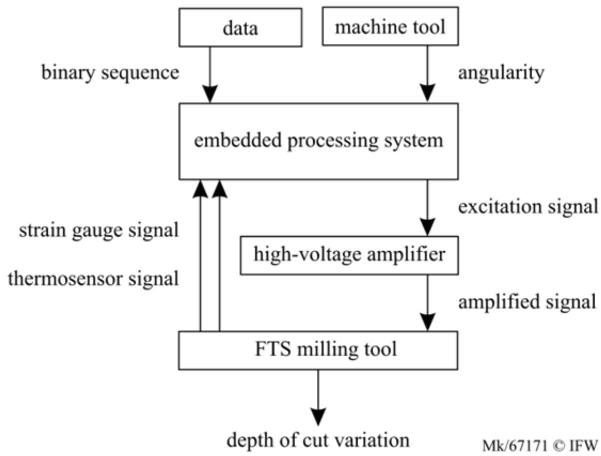

Fig. 4. Control of the piezo-actuated tool for milling operations.

As a compact control unit, this setup can be transferred to standard machine tools in order to manufacture individual micro patterns. The experimental results of the implemented cutting test are presented in the following section.

3. Experimental results

A face milling operation of AISI 1045 steel is chosen to demonstrate the capability of the presented technology. Conventional cutting tools and parameters are applied as summarized in table 1 and table 2. It is used an exchangeable milling head of the type Combimaster Super Turbo made by Seco.

Table 1. Cutting tool parameters

cutting insert geometry XOEX 120402R-M07 F40M			
tool diameter	d = 20 mm	number of teeth	z = 1
clearance angle	α = 14°	rake angle	γ = 20°
corner radius	r_ε = 0.2 mm		

Table 2. Process parameters

process parameter							
cutting speed	v_c	= 300 m/min	feed per tooth	f_z	=	0.05	mm
depth of cut	a_p	= 0.5 mm	width of cut	a_e	=	20	mm
excitation amplitude	U	= 100 V	structuring frequency	f	=	4	kHz

In order to design micro patterns, the basic kinematics of a milling process must be kept in mind. The cutting speed v_c and tool diameter d determine the number of revolutions per second n. Along with the applied structuring frequency f, the maximum number of oscillations per revolution and therefore the maximum number of cut marks for a single revolution can be described. It must be considered that micro patterns can be only cut between the entry φ_{entry} and exit angle φ_{exit} of the cutting edge. Therefore, a maximum number of micro patterns per cutting edge engagement o_{max} can be described by the following equation:

$$o_{max} = \frac{f \cdot d}{v_c} \cdot \frac{\varphi_{exit} - \varphi_{entry}}{2} \qquad (5)$$

The process parameters described in table 1 and table 2 result in a maximum number of marks for a single cutting edge engagement of $o_{max} = 25$.

Figure 5 illustrates the prototype of the piezo-actuated tool mounted in a four-axle mill center of the type Heller MCi16. The slip ring is attached to the spindle housing to avoid uncontrolled rotation.

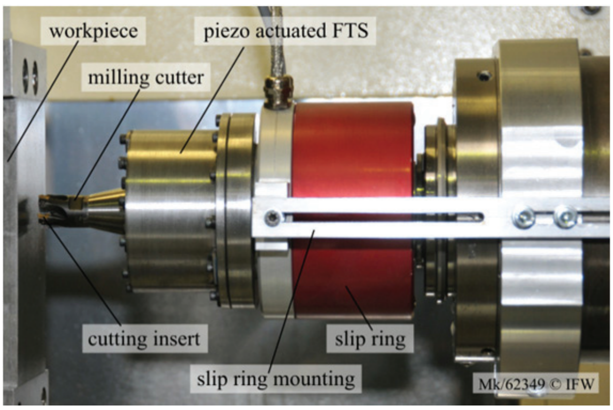

Fig. 5. Fully operative prototype mounted in four-axle mill center.

As an example, figure 6 shows a microscopic picture of a micro-patterned surface and a three-dimensional surface scan that gives detailed information on the dimensions of a single cavity. The width of a single cavity depends on the amplitude of the excitation signal U, the axial clearance angle α and the corner radius r_ε. Due to the tool geometry, an excitation of the tool and an increasing depth of cut lead to an increasing engagement of the rake face. The width of the cavity is therefore greater than the feed per tooth. While designing micro patterns for data storage, revolutions without excitation must be considered to keep single cavities from overlapping.

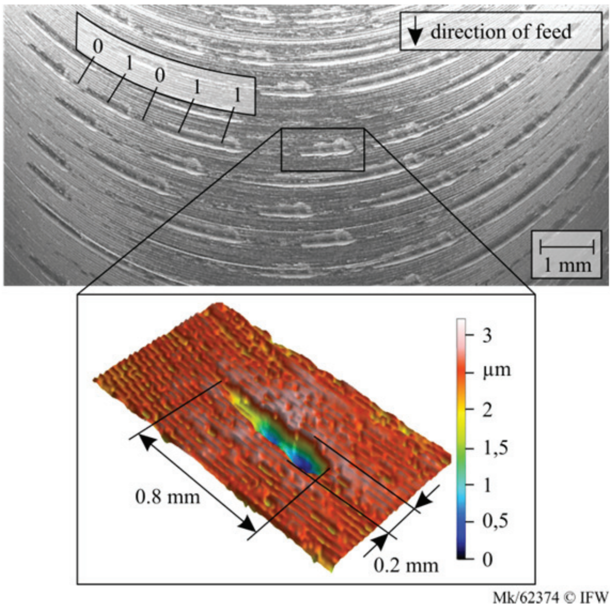

Fig. 6. Micro-patterned surface by means of face milling.

The grooves on the surface due to the feed can be determined. Single bits can be identified by the cavities following the cutting edge path. For this process parameter combination (table 2), the achievable data density is approximately 6 bit/mm².

The optical readout method presented in [2] is adapted to the curved shape of the micro patterns providing a fast and robust data assessment technology. The focus of current research activities is the reduction of the mark width and depth without an increasing bit error rate. In this way, the data density and surface quality can be increased significantly.

4. Summary and outlook

A new FTS concept for milling operations is introduced and presented in detail. It provides a high first natural resonance frequency and large axial oscillation amplitudes. These are key properties to realize a high-performance micro patterning process. It could be demonstrated that defined micro patterns can be cut by applying process parameters and commercial cutting inserts used in the industry.

The idea of storing information by means of micro patterns bears great potential. The presented actuated tool for milling operations extends its field of application by transferring the technology from turned to face-milled components. The experimental results prove the high dynamics of the tool and its capability to provide a controlled axial oscillation. Defined patterns can be cut in combination with a real-time computer system that processes the cutting edge position. Several cavities can be cut within a single cutting edge engagement depending on the cutting edge position while realizing highly productive process parameters.

By designing cutting edge geometries tailored to an actuated face milling process, the pattern dimensions can be reduced and the data density can be increased. Current research focuses on the cutting edge design and the application of micro patterns against plagiarism. The information stored on the component surface allow a fast proof of the components' authenticity without the need of an external database. The combination of distinctive workpiece information and inherent micro patterns on the surface raise the potential of this technology.

Acknowledgements

The results presented were obtained within the Collaborative Research Centre (CRC) 653 - Gentelligent Components in their Lifecycle. The authors thank the German Research Foundation (DFG) for the financial support.

References

Denkena B, Henning H, Lorenzen L-E. Genetics and intelligence: new approaches in production engineering, Prod. Eng. Res. Devl. 2010;4/1:65-73.

Dragon R, Becker C, Rosenhahn B, Ostermann J. Reading from a scratch – a vision-system for reading data on micro-structured surfaces. 31st DAGM symposium, Jena, Germany, Lecture Notes in Computer, Science Springer 2009;5748:402-411.

Weck M, Özmeral H. A fast-tool-servo system based on electrodynamic and piezoelectric actuators. Prod. Eng. Res. Devl. 1996;3/2:57-60.

Klocke F, Rehse M. Intelligent tools through integrated micro systems. Prod. Eng. Res. Devl. 1997;4/2:65-68.

Zhu W-H, Jun M B, Altintas Y. A fast tool servo design for precision turning of shafts on conventional CNC lathes. International Journal of Machine Tools and Manufacture 2001;41/7:953-965.

Woronko A, Huang J, Altintas Y. Piezoelectric tool actuator for precision machining on convertional CNC turning centers. Precision Engineering 2002;27/4:335-345.

Altintas Y, Woronko A. A piezo tool actuator for precision turning of hardened shafts. CIRP Annals - Manufacturing Technology 2002;51/1:303-306.

Lu X, Trumper D-L. Ultra fast tool servos for diamond turning. CIRP Annals – Manufacturing Technology 2005;54/1:383-388.

Bruzzone A A, Costa H L, Lonardo P M, Lucca D A. Advances in engineered surfaces forfunctional performance. CIRP Annals – Manufacturing Technology 2008;57/2:750-769.

Kim H-S, Lee K-I, Lee K-M, Bang Y-B. Fabrication of free-form surfaces using a long-stroke fast tool servo and corrective figuring with on-machine measurement. International Journal of Machine Tools and Manufacture 2009;49/12-13:991–997.

Denkena B, Ostermann J, Becker C, Spille C. Mechanical information storage by use of an excited turning tool. Prod. Eng. Res. Devl. 2007;1/1:25-30.

Denkena B, Böhnke D, Spille C, Dragon R. In-process information storage on surfaces by turning operations. CIRP Annals – Manufacturing Technology 2008;57/1:85-88.

Will C. Adaptronische Spindeleinheit zur Abdrängungs- und Schwingungskompensation. PhD Thesis, Leibniz Universität Hannover 2008.

Neugebauer R, Drossel, W-G, Bucht A, Kranz B, Pagel K. Control design and experimental validation of an adaptive spindle support for enhanced cutting processes. CIRP Annals – Manufactoring Technology 2010;59:373-376.

Physik Instrumente (PI) GmbH & Co.KG. Die ganze Welt der Nano- und Mikropositionierung. Gesamtkatalog KAT 2010:117

Piezomechanik GmbH. Einstieg in die Piezoaktorik. Katalog der Piezomechanik GmbH 2010.