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FTS-based face milling of micro structures

J. Köhler[a], A. Seibel[a,*]

[a]Institute of Production Engineering and Machine Tools, Leibniz Universität Hannover, Germany
* Corresponding author. Tel.: +49-511-762-18234 ; fax: +49-511-762-5115 .*E-mail address:* seibel@ifw.uni-hanover.de

Abstract

This article presents a technical concept and machining possibilities for milling of micro structures with a fast tool servo (FTS). The tool is capable of tool tip displacements with a variable frequency up to 4000 Hz and an amplitude up to 30 µm. The control system of the actuator is linked to the angular spindle position, allowing to freely manipulate the excitation signal. Combining this tool system with a single tooth face milling head, micro structures on flat surfaces can be generated on conventional milling centers. Selected micro structures are machined and evaluated in terms of precision and surface quality.

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Keywords: FTS; Fast Tool Servo; Face Milling; Milling; Micro Machining; Micro Structures; Gentelligent;

1. Introduction

The Collaborative Research Centre (CRC) 653, sponsored by the German Research Foundation (DFG), researches 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 [1]. In addition, these advanced properties provide an excellent basis for protection of components against plagiarism. The machining of defined micro patterns into the component's surface during a finishing operation offers a promising possibility to store binary information (Fig. 1). This approach was successfully performed in [2] with a specially designed piezoelectric face milling tool. In addition to that, the tool concept opens up new possibilities in the area of machining micro structures on work pieces of various size and shape.

This article describes the concept and application of the developed face milling tool with piezoelectric-driven fast tool servo, which enables freely adjustable high dynamic tool tip deflections in axial direction.

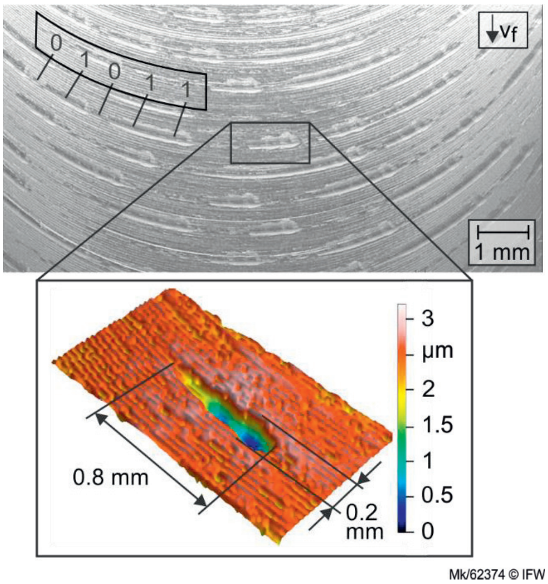

Fig. 1. Machined binary patterns for information storage on a component's surface [2]

The tool is capable of deflections up to 4 kHz with an amplitude up to 30 µm. In terms of plagiarism

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protection, the capabilities can be extended in machining of individual structures or patterns. The machining quality requirements for such micro structures can be diverse. It can reach from just visually appealing structures for the human eye to very precise structure dimensions and edges for optical read out methods. Examples in the last area would be QR-codes or the binary code patterns (Fig. 1). The capability of the tool in the stated areas will be demonstrated in machining of micro structures of different size and forms with different machining parameters.

Considering already existent fast tool servos for machining individual and complex structures, there are numerous developments in the field of turning FTS [3, 4, 5, 6, 7]. All these techniques have in common, that special turning machines have to be used where the structuring movements of the turning tools are performed parallel to the rotary axis of the work piece. That limits the overall flexibility in work piece size, mass or the location of structures. On the opposite, high accuracies and very small structure dimensions up to the nanometer scale can be achieved [7].

The main advantages of the presented tool over these turning tools is the possibility to use it on conventional milling centers and to machine nearly on any work piece size. However, in terms of precision and structure dimensions this technique cannot keep up, but there is room for improvements. FTS-based milling tools like raster milling [8] or vibration-assisted-milling (VAM) [9] follow the approach of tool tip displacements perpendicularly to the rotary axis in one or two dimensions. Although complex structures can be machined, this technique is quite limited in their structuring operations per revolution, resulting in possible slower machining processes.

2. Face Milling of Micro Structures

2.1. Tool Design

Machining of microstructures requires highly dynamic tool movements as well as a high stiffness. Thus, the presented FTS is actuated by a piezoelectric 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 the maximal used voltage of $U_{max} = 500$ V, the actuator has a force of 10 kN and a travel range of $\Delta l_{max} = 30$ µm [2]. The controlled cutting of micro structures 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 Fig. 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.

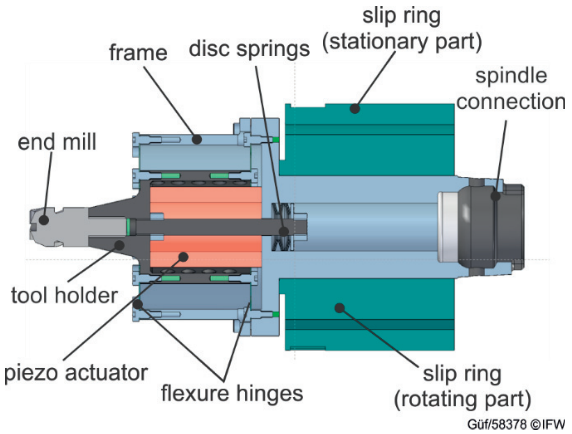

Fig. 2. Sectional view of the piezo-actuated tool for milling operations

2.2. Process Kinematics

The milling of micro structures is performed by a single tooth face milling operation with a high dynamic movement of the end mill along the rotatory axis (Fig. 3). This movement results in a modulation of the depth of cut in the range of the possible piezo deflection. The modulations is performed according to a pre-calculated piezo excitation signal, generated by a control system and is dependent on the angular spindle position.

The micro structure accuracy depends primarily on the macro geometry of the cutting edge, feed and the ratio between the speed in axial movement direction and the cutting speed, as shown in Fig. 4. The maximal axial velocity in up and down direction can differ due to different balance of forces in expansion or shrinking state of the piezo. These stated constraints can result in non-symmetric structuring behavior.

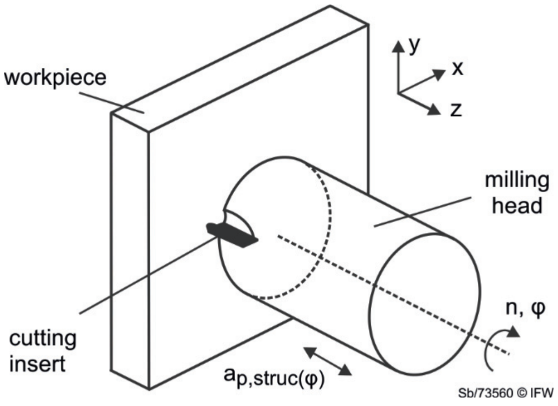

Fig. 3. Tool engagement

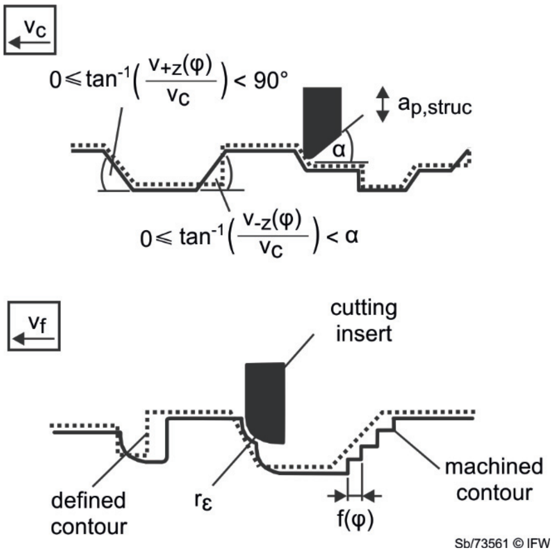

Fig. 4. Contouring limitations in feed and cutting direction

To guarantee that the generated contour along a feed lane is not damaged by the flank face over the following feed steps, a change of the flank face geometry is necessary. A solution for this is to grind the flank face in form of a bar (Fig. 5). The width of the bar limits the minimal distance between two structure edges in feed direction.

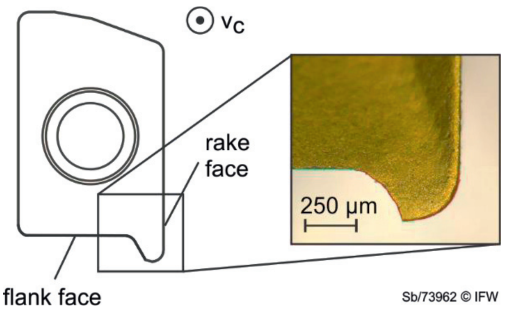

Fig. 5. Special prepared cutting insert geometry XOMX060202

2.3. Control System

In order to machine various structures with a defined quality into the surface, data processing and tool control is of significant importance. Therefore, the image data is transformed into a structuring matrix. This matrix contains the excitations signals for each feed step depending on the angular tool tip position. The matrix size is predefined by the maximal excitation frequency, cutting speed and feed. Following this, a Matlab/Simulink model processes the matrix along with the information of the angular tool position. In order to handle the signals in real time, the Matlab/Simulink model runs on a dSpace real-time computer system. 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 load and smooth tool tip movements. The output signal of the dSpace system is amplified by a high-voltage amplifier. 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. Fig. 6 illustrates the described tool control.

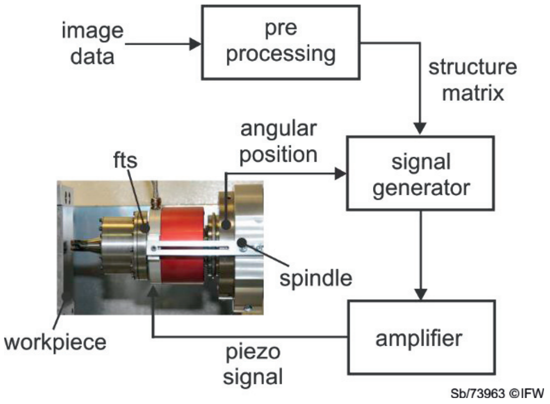

Fig. 6. Control system and data processing sequence

3. Experiments

In order to demonstrate the capabilities of the micro structuring process, three different structures (Fig. 7) were machined under different process parameters on a milling center DMU 125P duoBlock. The workpiece material was Al7075. As cutting insert SECO XOMX060202 were used with a preparation as shown in Fig. 5.

The changed quality relevant process parameters are feed and ratio v_c/v_z. The velocity in z-direction follows directly of the maximal structuring frequency. All structures are machined with two parameter sets, to cover the influence of the structuring matrix size and the tool behavior. The chosen process parameters are shown in Table 1. The structuring range is chosen to be between 45 to 135 degrees to minimize the influence of the changing feed width.

Table 1. Process parameters

parameter set	v_c [m/min]	max. f_{struc} [Hz]	f [mm]	struc. range [°]
1	37.7	2000	0.066	45-135
2	15.1	4000	0.02	45-135

Structure (A) represents continuous sinus like signals in the full excitation range, structure (B) is a combination of static and discontinuous signal in terms of steps and the last structure (C) consists of linear signals interrupted with discontinuous steps. With these structures, possible effects of the transient behavior of the tool system should be detectable in terms of shape deviations.

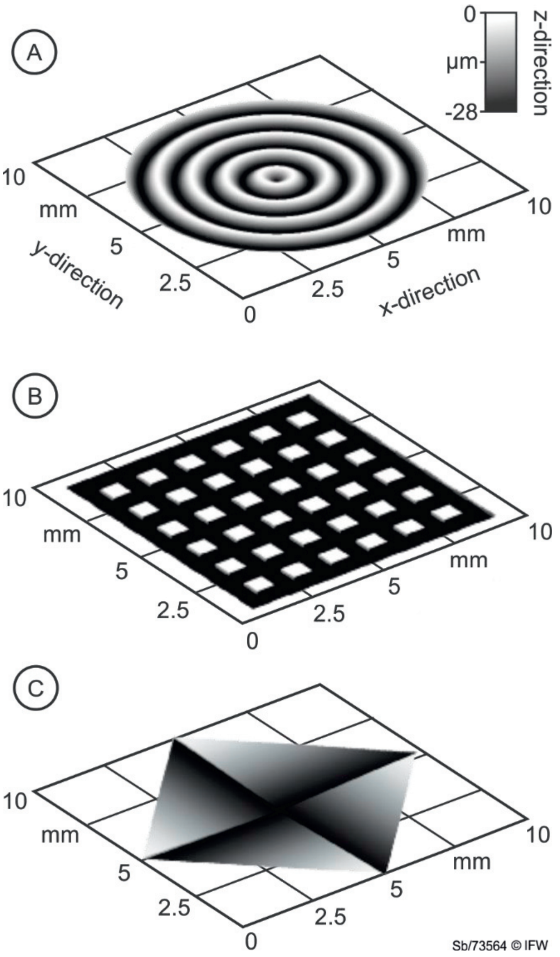

Fig. 7. Simulated structures

4. Results

The machined structures were measured optically with a NanoFocus µSurf System and a 10x lens. The measured data was post processed with a 3x3 median filter to remove measurement noise.

The results for machining with the parameter sets (1) and (2) are shown in Fig. 8. At first sight, all structures were machined satisfyingly in terms of a visual evaluation. In detail, especially the high gradients could not be machined accurately due to overshooting and limitations of the macro geometry of the cutting edge as shown in Fig. 4. This can be seen at structure (B) and (C) on both parameter sets. These effects are shown and described exemplary in a magnification of one of the most outside located knobs form structure (B).

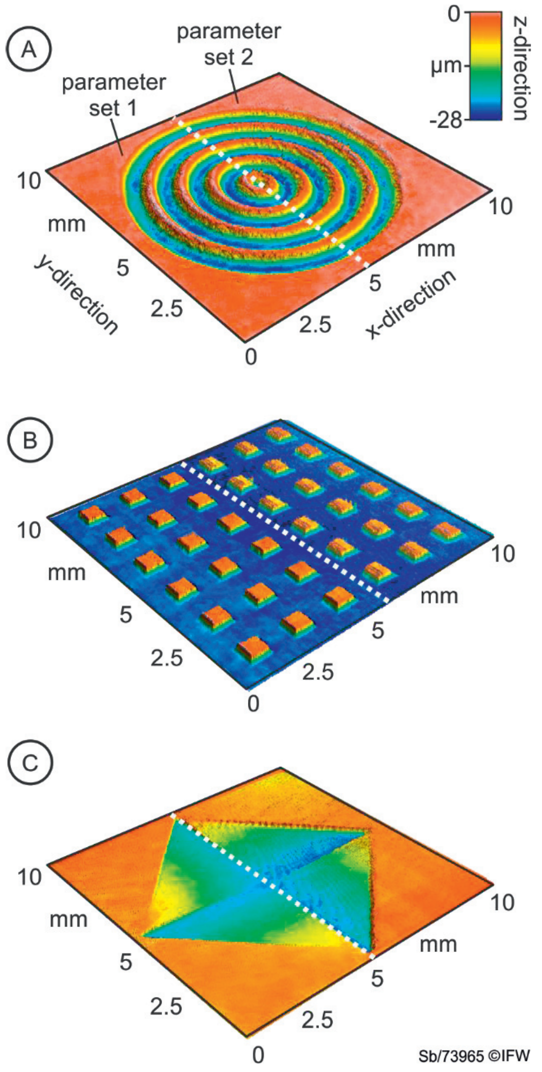

Fig. 8. Measured structures

The detailed view on the edges of one of the most outside knobs shows four different shape deviations (Fig. 9).

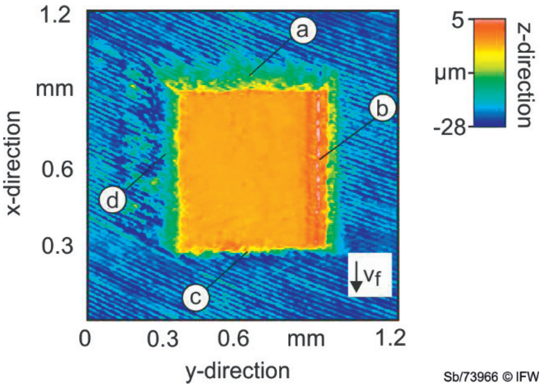

Fig. 9. Top view of one knob

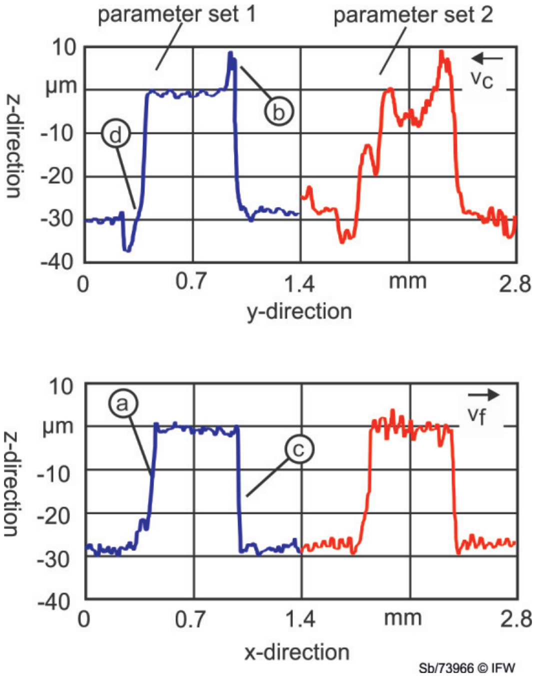

Fig. 10. Profile section in horizontal and vertical direction

Figure 10 displays a sectional view in feed and cutting direction of the described knob.

The ramp on edge (a) is caused partially because of the rake face angle α (Fig. 4) and the relatively big cutting edge radius of $r_\varepsilon = 0.2$ mm in comparison to the knob dimension. The opposite can be seen on the edge (c) where the edge radius is nearly not existent. Overshootings in (b) and (d) are clearly visible. The more right-angled the angel between a feed lane and shape edge is, the higher is the underlying signal gradient. This resulting in overshooting in a non-feedback controlled system, like in this case. In (a) and (b) the mentioned angels are quite flat respectively sharp, that is why the signal gradient is moderate and no overshooting is visible.

In structures machined with parameter set (2), the overshooting are much more distinct and lengthened as shown in the profile section in cutting direction. This is caused primarily by the higher cutting speed.

Regarding the surface roughness, it can be clearly seen that parameter set (2) produces rougher surfaces. The reason is the combination of higher feed steps and in general the missing part of the rake face to smooth out the feed grooves.

5. Summary and Outlook

In this article a method for machining micro structures with an FTS-based face milling tool was presented. The focus was to machine micro structures with different geometrical properties and process parameters. For a possible use as visual plagiarism protection, the machining quality is already sufficient. For information carrying structures to use with an optical read out method, the smooth edge gradients could be a problem especially with lower quality process parameters.

In comparison to FTS-based turning in the area of complex surface designs, this approaches offers more flexibility in terms of usability on different work piece geometries and the possibility to use it on conventional milling centers. So far the accuracy cannot keep up with the FTS-based turning tools, mainly because no feedback control is used and the use of the limiting tool edge macro geometry.

Based on the performed experiments, approaches can be deduced to improve the structuring accuracy. The transient behavior can be improved by a feedback control system or input shaping algorithms. Sharper structure edges can be achieved thru an intelligent tool path and structuring planning. Smaller structure dimensions and better surface finishes can be realized by an improved cutting edge design and even smaller feed steps.

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