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A Time Domain Simulation Approach for Micro Milling Processes

Eckart Uhlmann, Frederik Mahr*

Institute for Machine Tools and Factory Management, Technische Universität Berlin, Pascalstraße 8-9, D-10587 Berlin, Germany

* Corresponding author. Tel.: +49(0)30-39006-411; *.E-mail address*: mahr@iwf.tu-berlin.de

Abstract

Prediction of Process Machine Interactions (PMI) can be achieved using models for conventional milling processes in the time and frequency domain. However, instabilities such as regenerative chatter can also be observed in micro milling processes using filigree cemented carbide end mills. The dominant chatter frequencies are basically related to the end mills eigenfrequencies. Nevertheless, the dynamic characteristics of the machine tool structure and the work piece must not be neglected. In this paper a comprehensive time domain process model is presented. The machine tool dynamics are considered as non-coupled oscillators based on measured frequency response functions at the tool holder. The end mill is modeled as rotating Euler-Bernoulli beam with variable boundary conditions at the tool clamping. At first, the parameter identification for a geometric cutting force model is described. It contains the cutting edge radius as a time-depended parameter. Thereafter, the modeling and parameter identification of the structural parts are presented. A stability criterion is defined with special regard to the tool deflection at the TCP. Finally, simulation results at different stable and unstable operating points for full immersion cutting are discussed in detail and compared to experimental tests.

Keywords: micro milling; stability prediction; process optimization

1. Introduction

In order to simulate the dynamics of cutting processes it is necessary to describe the involved elements such as the structure components that are interacting with the occurring process forces. Various researchers have contributed to this field of manufacturing technology. Therefore, manifold simulation approaches for the calculation of cutting forces with and without the interacting machine tool structure exist also for micro milling processes [1, 2, 3].

Given that, those approaches enable to cover diverse requirements, the later purpose of the prediction model should be determined beforehand. By means of fast computing algorithms models in the frequency domain are especially appropriate for stability prediction, e. g., the generation of Stability Lobes Diagrams (SLD). In contrast to that, time domain simulations require considerably longer computing time. However, they are more adequate when non-linear constraints e. g., varying specific cutting forces, tool wear, etc. have to be taken into account. Due to a wide range of simulation options the presented research work shows some advantages of stability predictions in the time domain. In addition to stability predictions the actual cutting trajectories can be analyzed. The focus of this paper is laid on the illustration of some significant numerical and experimental results with only brief information about the implemented calculation and simulation procedures that are described in [7, 10, 12] in detail.

All experimental tests are carried out on a 3-axis micro milling machine tool Wissner Gamma 303, Göttingen, Germany with a Precise SC3062 spindle with a maximum spindle speed of $n = 60{,}000\ min^{-1}$. For the parameter identification experimental modal analyses are applied on the machine tool structure and two fluted end mills with different nominal diameters. All measured signals are logged with a National Instruments data acquisition system NI9162–USB and signal treated with MATLAB.

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2. Partial Model Approaches

2.1. Cutting Force Model

A complex cutting force model based on the application of specific cutting forces in tangential Kt and radial direction Kr is applied. Figure 1 shows a schematic view of the cutting force model. The trajectories of the cutting edges are stored in order to consider regenerative effects and to illustrate the shape of the machined workpiece.

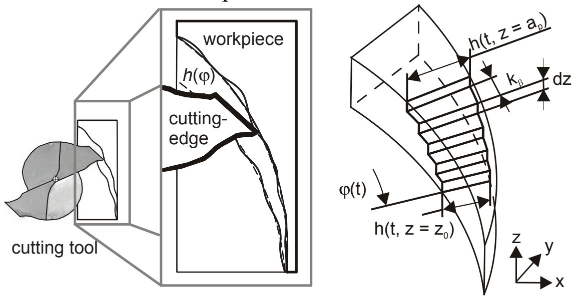

Fig. 1. Schematic view of the cutting engagement conditions

For each simulation step the chip thickness h(φ) is calculated depending on the actual engagement conditions. The staircase-shaped cutting edges enable the consideration of the end mill's helix angle. The level of detail can be set through the resolution of the axial discretization dz. For the consideration of ploughing effects that occur when the chip thickness decreases below the critical chip thickness a geometrical approach is implemented. A comparable approach is described by Malekian et al. [4]. Figure 2 shows the geometrical correlations at the cutting edge.

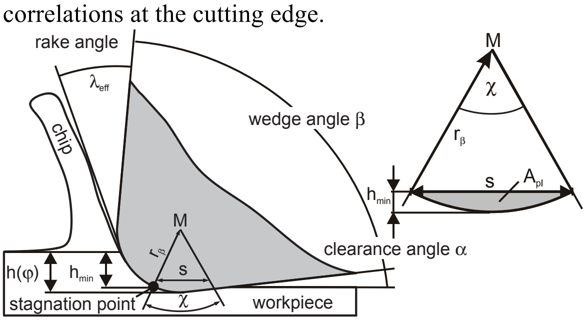

Fig. 2. Consideration of ploughing forces

As a function of the cutting edge radius $r_β$, the locus of the stagnation point, depending on the rake angle $λ_{eff}$ and the clearance angle α, an area, here referred to as ploughing area A_{pl} can be derived. In conjunction with the engagement conditions the additional force ratio can be calculated. Still, the specific coefficients have to be determined experimentally. However, a variation of the helix angle λ and the cutting edge radius $r_β$ provide different force characteristics that can be adapted to measured forces in order to consider e. g. the tool wear. Figure 3 shows simulated radial and tangential forces at the Tool Center Point (TCP) under variation of the above mentioned parameters for one spindle revolution.

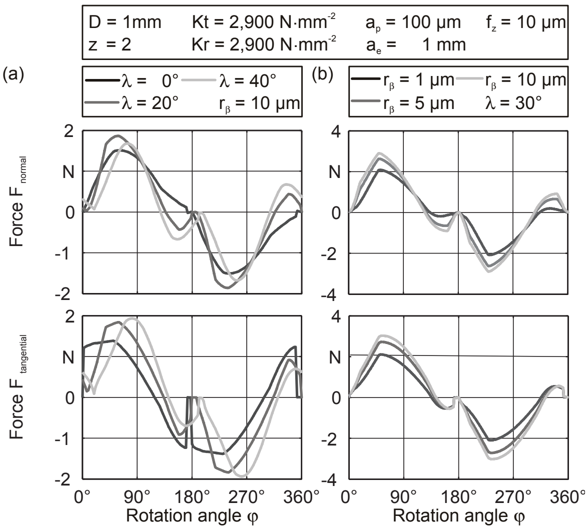

Fig. 3. Simulated Cutting Forces: (a) variation of the helix angle λ, (b) variation of the cutting edge radius $r_β$

The cutting force model is now applied to different kinds of material. In order to directly compare measured cutting forces with simulated ones. The simulation results are transformed into the Cartesian coordinate system by help of a rotary matrix. Some force measurements show different maxima and minima between the cutting edges.

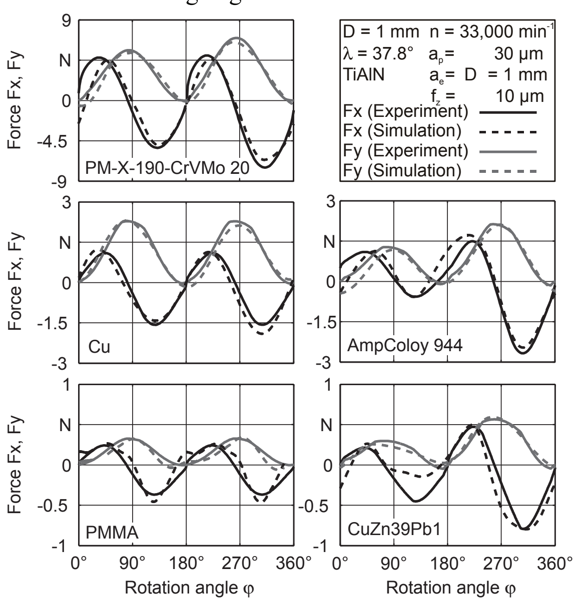

Fig. 4. Comparison between measured and simulated cutting forces using various workpiece materials

This can be due to run out effects that depend largely upon the assembly of the spindle-tool-holder-clamping system and the accuracy of the cutting part itself. By defining an offset between the cutting edges and/or adjusting a static run-out on the spindle those effects can be taken into account.

2.2. Structure Model

The machine tool structure is taken into account through uncoupled harmonic oscillators. The parameters for mass, stiffness and damping ratios are determined applying the method of least squares [6]. Fitted measurements of the Frequency Response Function (FRF) at the tool clamping point represent the upper machine tool structure. A detailed description of the measurement proceeding using an electrodynamic shaker is given in Shi et al. [6].

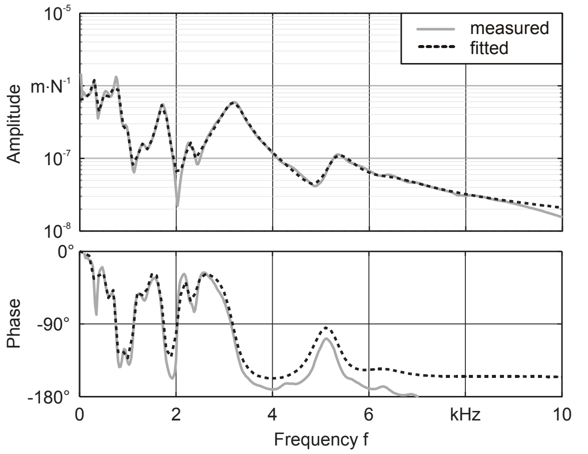

Fig. 5. Frequency Response Function (H_{xx}), of the upper machine tool structure, measured at the clamping position of the tool-holder

The lower machine tool structure is represented by an oscillator fitted FRF of the used dynamometer with the mounted workpiece. Here, an impulse hammer was used as excitation source. Each fittet FRF consists of twenty single harmonic oscillators. According to the manufacturer the first relevant dynamometer's eigenfrequency in x-direction is specified around 4 kHz which is considerably higher in the current setup. Additionaly, a resonant peak around 800 Hz can be seen, which is supposed to be due to the dynamometer's attachment on the machine tool base. With decreasing weight of the mounted workpiece the eigenfrequency is supposed to be lower which can also be confirmed. However, in the current case (worpiece material: CuZn39Pb1, workpiece weight: 420g) two relevant eigenfrequencies can be noticed. The peak around 800 Hz is still unvaried which approves the prior assumption that it can be traced back to the dynamometer's attachment.

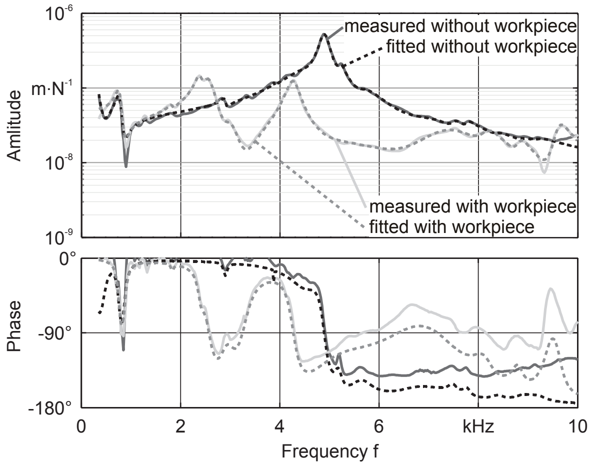

Fig. 6. Frequency Response Function (H_{xx}), of the used dynamometer (Kistler MiniDyn 9256C2) with and without a mounted workpiece

The dynamic behavior of the cutting tools strongly depends on the clamping conditions at the tool shank and the cantilever length of the tools. Filiz et al. carried out measurements using a miniature piezoceramic actuator on a suspended micro milling tool [8]. They could identify the first three bending mode shapes as well as the first torsional and axial mode shape. The first bending mode occurred at around 15 kHz. Malekian et al. identified the first eigenfrequency using the receptance coupling method on a micro milling tool clamped into the tool holder at around 4 kHz [4]. Further verifications showed that the actual eigenfrequencies strongly depend on the boundary conditions given by the machine tool structure [9]. Also, only the first bending mode could be identified whilst machining. Therefore, the cutting tool is modeled as rotating Euler Bernoulli beam with time dependend changeable boundary conditions according to the FRF at the tool holder. Different increments are used in order to take into account the tool geometry of the shank, the transition to the cutting part and the cutting part itself [10].

Table 1. Geometrical properties of the analyzed cutting tools

nominal diameter D [mm]	shank diameter D_s [mm]	shank length l_s [mm]	transition length l_t [mm]	length of cut l_c [mm]	overall length l [mm]
0.1	3	35	4.8	0.2	40
0.2	3	35	4.6	0.4	40
0.5	3	35	4	1	40
1	3	28	6	4	40
2	6	26	7	7	38
3	6	30	7	8	45

To consider the clamping conditions a stiffness factor c_T is implemented which has to be obtained experimentally [9]. The mass distribution of the fluted cutting part is considered as cylinder with 70 % of the nominal diameter as described in [6]. Figure 7 shows measured static eigenfrequencies that show reasonable accordance to simulated results.

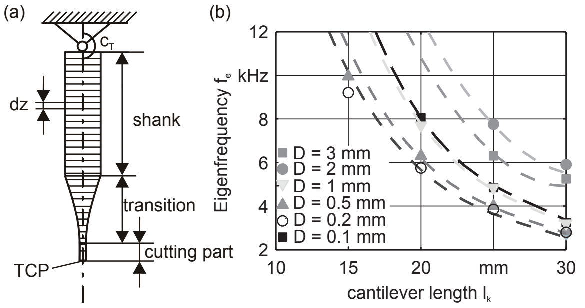

Fig. 7. (a) Schematic view of the cutting tool, (b) measured (symbols) and simulated (dashed lines) eigenfrequencies of non-rotating cutting tools with different nominal diameters

The measurements are carried out using an electrodynamic shaker where the entire STT system (Precise ATC-2-10-6) is mounted on top. The structure response is measured with a one point laser vibrometer OFV-353, Polytec, Waldbronn, Germany. In addition to the static bending mode and displacement behavior also the rotation of the cutting tool has to be taken into account. Figure 8 shows simulated chatter frequencies. They split around the static eigenfrequency and possess frequency shifts at each harmonic of a resonance frequency of the entire system.

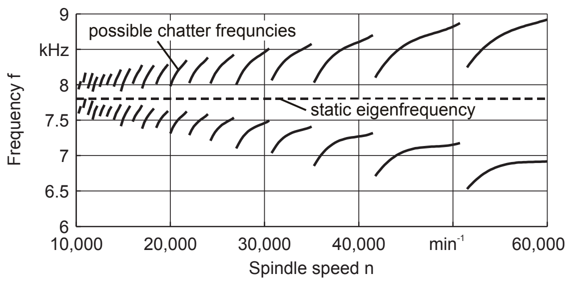

Fig. 8. Possible chatter frequencies as a function of the spindle rotation

3. Experimental Verifications of the Model

3.1. Chatter Prognosis

In order to create stability charts, a criterion for unstable processes has to be defined. Therefore, the trajectory of the TCP is analyzed. Each parameter set is simulated for at least 2 mm of cutting length. Figure 9 (a) shows the simulated movement of the TCP in the x-y plain for different depths of cut at full immersion cutting. Additionally, in Figure 9 (b) a poincaré map is shown. One can see the circular formation of the poincaré points at the highest chip thickness (h(φ = 90°) = f_z) which is typical for a Hopf-Bifurcation. Using the diameter of the imaginary circle that is surrounding the poincaré points $D_{poincaré}$, a reliable stability criterion for the time domain data could be found. Also other parameters than the spindle speed, the depth of cut can now be analyzed with regard to the process stability.

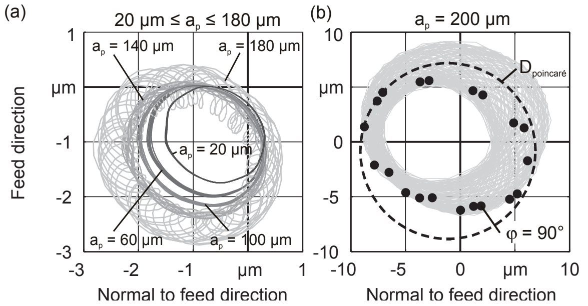

Fig. 9. (a) Simulated trajectories of the TCP at different depths of cut, (b) poincaré map for an unstable operating point

As mentioned above the cantilever length l_k of the cutting tool is of essential influence on the tool's eigenfrequency. This can also be confirmed regarding the three dimensional calculated stability chart in Figure 10.

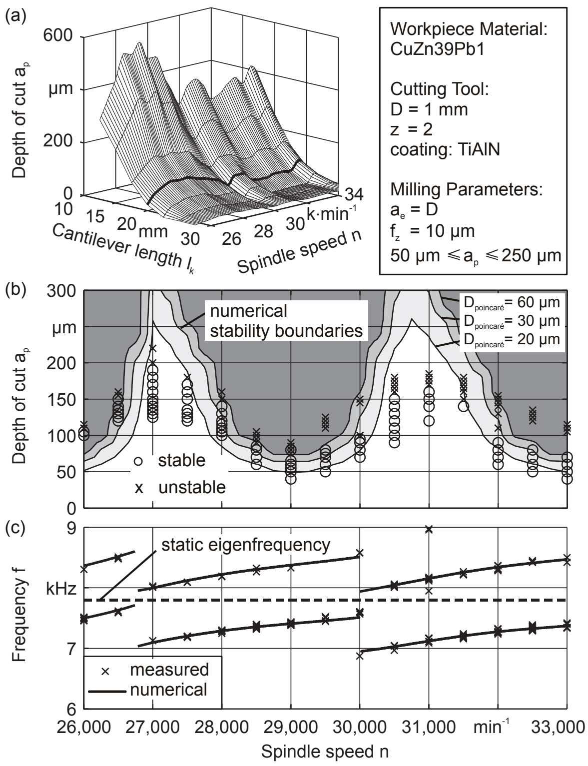

Fig. 10. (a) analytical SLD for different cantilever lengths l_k of the endmill; (b) experimental SLD at a cantilever length of $l_k = 20$ mm; (c) numerically determined and measured chatter frequencies

The numerically determined stability boundaries show reasonable accordance with the experimental tests, where the occurrence of chatter was detected by means of a laser vibrometer. Also, the expected frequency shifts at the stability maxima can be observed. Shi et al. analyzed the same set of results with a different simulation approach using four coupled harmonic oscillators as machine tool model and a Timoshenko model for the cutting tool including gyroscopic effects [11]. However, for small diameters the gyroscopic effects are negelectable. Also the first bending mode modeled with Euler Bernoulli approach shows significant accordance to the Timoshenko model. Therefore, the simplifications for the presented comprehensive simulation approach can be justified.

3.2. Time Domain Simulation Results

Figure 11 (a) shows different microscopic images of a milled groove with a step of 20 μm in the depth of cut. The images of the surface and the milled flanks are taken at different angles of view, using an Infinite Focus system, Alicona, Austria. Because of its high resolution also surface profiles could be measured which can be seen in Figure 11 (b). The transition between stable and unstable cutting conditions is clearly visible. However, the chatter marks seem to begin at the down milling flank. They appear as a fluted surface with periodic patterns that are especially visible at the profile height of the down milling flank.

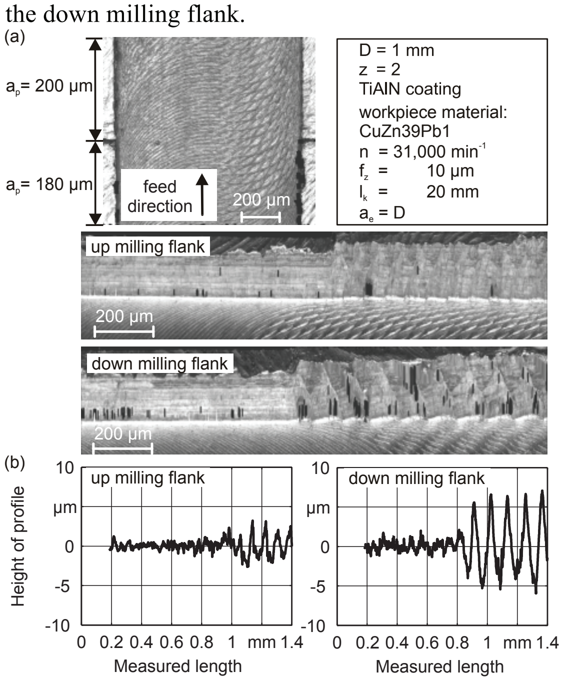

Fig. 11. (a) Microscopic view of the transition between stable and unstable cutting conditions, (b) measured surface roughness of the up- and down milling flank

The distance between the surface peaks amounts to around 130 μm. This circumstance cannot be traced back neither to any resonance frequency of the structure nor to the engagement parameters such as the feed per tooth f_z. A superposition of different resonant frequencies in concert with the phase shift of the periodic excitation of the cutting edges is presumably responsible for the occurring phenomenon.

Simulation results of the same parameter set show almost the same behavior. In Figure 12 the topographies of both milled flanks are displayed for fully developed chatter.

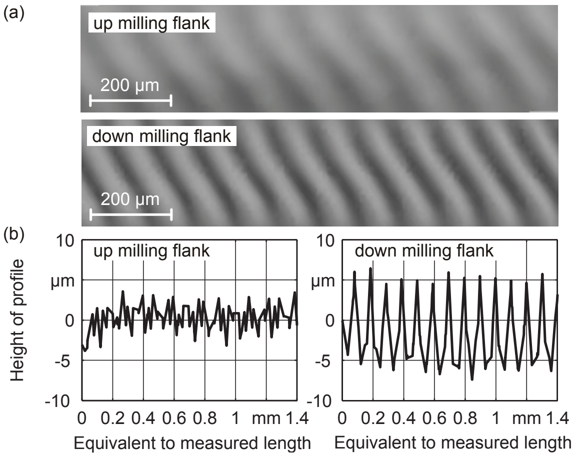

Fig. 12. (a) Simulated topographies of the up- and down milling flank for an unstable operating point (see Figure 11), (b) simulated surface roughness of both flanks

Another simulated operating point shows the identical behavior. Also, the down milling flank is developed more intensively.

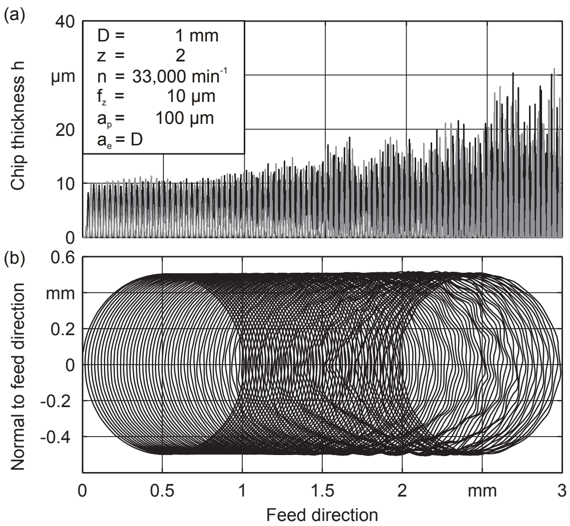

Fig. 13. (a) Simulated chip thickness and (b) cutting edge trajectory at the transition between stable and unstable cutting conditions

The cutting edge trajectories create certain types of patterns for different spindle speeds which resemble to moiré patterns. Depending on the cutting parameters the shape of the surface seems to open whether to the down milling or up milling side. Figure 14 shows two characteristic surface shapes that were obtained. However, the relationship between the location of the operating point on the increasing or decreasing part of the stability boundary and the shape direction cannot be explained satisfactory yet.

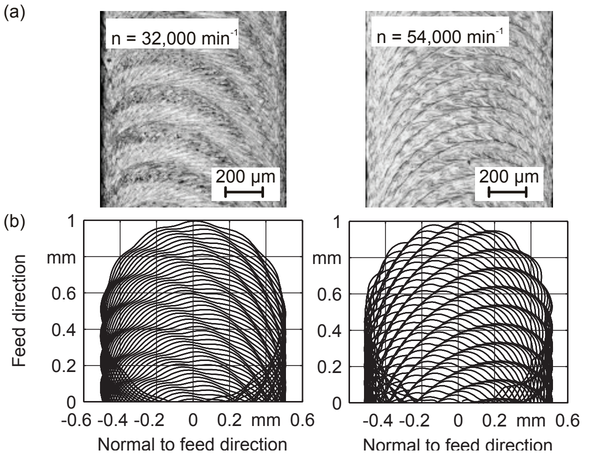

Fig. 14. (a) Microscopic view of milled grooves with unstable process conditions at different spindle speeds, (b) simulated cutting edge trajectories

4. Conclusion and Future Prospects

In this paper results from a comprehensive time domain simulation model for micro milling processes are presented. The partial models that take the dynamics of the relevant components of the machine tool structure into account are discussed. Also the ability of analyzing the resulting cutting edge trajectories for different kinds of process parameters is shown. A numerically calculated SLD for full immersion cutting is then discussed. It shows reasonable accordance to experimentally determined results as well as to analytical results that are obtained using a different simulation approach. Microscopic images at different operating points are interpreted and compared to simulated cutting edge trajectories and the corresponding surface topographies. Current and future research activities focus on the expansion of the presented findings.

The ability of predicting the surface formation is essential for the design and the configuration of surface structuring processes. Therefore, a prototypical setup is being developed at the IWF of the Technische Universität Berlin [12]. By using piezoelectric actuators that are synchronized to the actual position of the cutting edge, vibration assisted milling processes can be carried out and profoundly be analyzed. Also concepts for the compensation of the dynamic TCP deflection, even at stable cutting conditions will be analyzed.

Another focus is the minimal excitation of the cutting tool in order to enable a non-destructive identification of the basic chatter frequencies [9]. In this case, the aim is to achieve a certain reliability that improves the portability between different machine tool systems.

Acknowledgements

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