1. Introduction

The combination of machining processes and (ultrasonic) vibrations is still subject of different researches. In case of ultrasonic vibration assistance typically resonant systems with a frequency of about 20 kHz are applied. Using this type of system higher working outputs are achieved with a reduced energy input. Resonance occurs when the chosen excitation frequency is matched with an eigenfrequency of the system. Most of the existing ultrasonic systems use piezoelectric actuators to excite the system. The actuator’s eigenfrequency is influenced by the system’s mass, the stiffness and the damping behaviour. In the case of resonance, the amplitude is depending on the damping behaviour.

There are some industrial applications for vibration assisted machining. Usually, the goal is to reduce the cutting force or increase the tool life, respectively. In addition, a decrease of the surface roughness value is often intended as Brehl and Dow already summarize in the case of resonance, the amplitude is depending on the damping behaviour.

However, with regard to the ratio of the machining parameters as well as the vibration parameters and the tool geometry, respectively, there are some possibilities for a reproducible surface micro structuring processes. For example, such surfaces may contribute to ensuring a high degree of conformity with the machined surfaces could already be achieved. Thus, a possibility for economic micro structuring of components made of steel was developed.

Very few researcher address a micro structuring of the workpiece surfaces by a superimposed oscillating motion. Guo and Ehmann used elliptical ultrasonic vibration assisted turning for the generation of micro structures in aluminium and copper through a variation of the feed and the cutting direction (Guo and Ehmann, 2013). Using a superimposed oscillation motion in the sub-ultrasonic range (with a frequency of approx. 3 kHz), Zhu et al. (2016) connected a slow-tool-servo (STS) with a y-cutting tool and generated micro as well as nano structures in brass with diamond tools.

At Chemnitz University of Technology, ultrasonic vibration assisted
turning has been investigated for different applications to generate various surface micro structures. While Nestler and Schubert investigated the effect of different directions of the ultrasonic vibration motion on the surface parameters at external turning experiments (Nestler and Schubert, 2014), Zhang et al. (2014) used the same ultrasonic vibration assistance system for the micro structuring of the specimen’s flat surface with face turning by the variation of the process parameters.

Denkena investigated the use of vibration-assisted machining for the production of micro structures for in-process information storage. On the one hand, turning experiments with a highly dynamic piezo-driven tool holder with a natural frequency of 6 kHz were carried out. In connection to the sinusoidal tool motion perpendicular to the workpiece the depth of cut changed periodically in cutting speed direction and therefore left different micro grooves with a data density of 4 kBit/cm² on the machined surface (Denkena et al., 2010). On the other hand, a conventional milling tool equipped with a piezo-driven fast tool servo system to superimpose the face milling operation with a high dynamic movement along the rotary axis. This enabled the in-process generation of Data-Matrix-Codes (DMC) without any additional machining steps (Denkena et al., 2016). Commercially available systems that enable ultrasonic vibration assisted machining are offered by SAUER GmbH of the DMG-MORI Group as well as by SCHOTT-Diamantwerkzeuge. The main application is grinding of brittle-hard materials such as glass or ceramics, which is often described as ultrasonic assisted milling. Gong et al. (2010) found that the tool wear is much lower when using rotary ultrasonic milling (RUM) of hard and brittle materials (aluminium ceramics and optical glass) compared to a conventional micro milling process. Moreover, in the micro milling of glass Jin and Xie (2015) obtained an improvement of the surface quality (decreased surface roughness) with the vibration superimposition in the feed and the cutting direction. They found that the oscillation in normal direction as well as high frequencies (up to 11 kHz) are mostly responsible for decreasing the surface roughness.

The superposition of vibrations in the direction of the tool axis during milling has an influence on surface structure formation and is described for example from Maurotto and Wickramarachchi (Maurotto and Wickramarachchi, 2016). The results of the investigations show that a change in the surface roughness can be achieved by the variation of the machining parameters as well as the vibration parameters. Furthermore, they concluded that due to the symptomatic tool wear it is necessary to develop tools as well as coatings for the application of ultrasonic vibration assisted milling processes. Kuruc et al. (2014) demonstrated the dependance of the surface roughness on the ratio between a constant ultrasonic frequency and the spindle speed. The best results were achieved with the highest amplitudes (3 μm) and frequencies (3 kHz) compared to a conventional micro milling process. However, due to its
complex kinematics, the application of previous process simulation is required.

2. Surface prediction tool

2.1. State of the art of surface simulation models

In order to investigate the influence of the machining process on the resulting surface, a description using analytical or geometric models is necessary. While analytical models represent mainly physical process properties by means of mathematical relationships, the geometrical models are used for the prediction of the geometric process properties, like shown from Zabel (2010). For this purpose, the modelling of the tool, the workpiece and their relative movement is necessary. The main approach for the simulation of a machined surface contains the stepwise intersection of the tool with the workpiece to subtract the overlapping volume from the workpiece model. Depending on the application, different modelling approaches exist for the representation of the intersection of the tool with the workpiece. Brecher et al., (2015) distinguished between the volume oriented CSG (Constructive Solid Geometry) or boundary representations and the spatially discretized dexel or voxel representations, respectively. The CSG methods are frequently used for simulative purposes, as described from Weinert et al. (2008). The description of the machining process is achieved by Boolean intersection of CSG models, such as geometrical primitives in the form of cuboids, cylinders, and spheres. To reduce the computational effort, Klimant et al. (2014) show that the geometric material removal can also be represented by a sweep volume, in which the tool cross-section is extruded along the tool path (trajectory) and then intersected with the tool (Klimant et al., 2014). Both the workpiece and the tool can be presented in various ways. In general, however, the tools are simply represented as an envelope. Thus, an exact modelling of the resulting micro structure is only possible to a limited extent. This simplified surface representation is sufficient for many applications using the geometric information for the determination of cutting forces, temperatures or collision calculation. However, for a precise modelling of the surface micro structure as a function of the tool geometry, a spatially partitioned prediction model, such as a dexel model, is more appropriate. In this model a surface is represented by discrete points (“dexels”) aligned over a regular grid in the X-Y-plane and with a high resolution Z-value. Nevertheless, the term dexel is used differently in literature. Odendahl described a dexel as a virtual stick element with more than one height value that can be disjoint in intervals (Odendahl, 2016). In contrast Zabel (2010) used the term equally for sticks that carry only one height information, while Altintas et al. (2014) called such a set of unidirectional elements that share the same start value the z-buffer model.

Denkena and Boß introduced a NC (Numerical Control) simulation system for research called CutS. It consisted of a number of independent modules to simulate the machine kinematics, material removal, the deformation of the workpiece, etc. and therefore it could offer information about the workpiece shape, contact zone, cutting forces, dynamic vibrations and tool wear. The centrepiece of the software, the material removal module, used a CAD model for the tool and a three dimensional dexel model (three perpendicular to each other arranged dexel models) for the workpiece that allowed the simulation of multi axis cutting operations like milling and grinding with high accuracy (Denkena and Boß, 2009). Later Denkena et al. used the simulation software for the simulation of the kinematic surface micro structure by ball end mills (Denkena et al., 2011). Three-axis ball end milling is a popular field of investigation for surface simulation since the ball end contour is mathematically easier depictable compared to an end milling tool. Arizmendi et al. (2008) and Piotrowska Kurczewska and Vehmeyer et al. (2011) presented two different analytical descriptions in the context of the modelling of the cutting edge geometry of ball end mills. For a more realistic display of the surface both took the tool runout into account by defining a tool parallel axis offset. Piotrowska-Kurczewska, Vehmeyer and Twardy later improved the model for micro milling by adding a tool sweeping algorithm to sweep the cutting edge instead of the whole rotational volume (Vehmeyer et al., 2013). Denkena et al. (2011) stated that the consideration of the cutting edge movement describes a more accurate method compared to a simple Boolean subtraction. Furthermore, he extended the common approach of simulating the kinematic surface micro structure by taking the stochastic topography into account. It characterizes the surface effects generated by tool deflection, current tool geometry and stochastic influences. Therefore a workpiece was experimentally machined with the same process parameters like the kinematic simulation. Afterwards the stochastic topography was generated by removing the computed topography from the measured workpiece surface with an empirical approach. The subsequent combination of both simulations created the real surface topography that showed that high values of the feed per tooth and width of cut favour the dominance of the kinematic topography in relation to the stochastic topography.

Another way to apply deterministic surface structures is high feed milling. This process is characterized by high feeds in combination with a low axial and radial depth. The special cutting geometry of the milling tool allows higher feed that leave unmachined material sections on the finished surface. Consequently, this process results in a higher roughness. Freiburg, Kersting and Biermann simulated high feed milling to predict process forces, process dynamics and surface structures (Freiburg et al., 2015). In their investigations they compared a CSG modelled tool generated by scanning data from 3D light microscopy with a tool generated by an enveloping mesh. Although the first approach was more time consuming it delivered better simulation results in connection to the experimental measured data: the simulation with the enveloping meshed tool model showed a difference in peak height but was still sufficient to qualitatively predict high feed surface structures much faster. Zabel et al. (2010) presented a more complex, multi-scale simulation system for milling processes which was able to model the five-axis milling process by combining different simulation technics. While the tool was represented as a rotationally symmetric CSG solid they used two different representation forms for the workpiece. On one hand, a global model represented the workpiece at every time step with a multi dexel model. The simulated intersection of the CSG tool with the dexel workpiece removed dexel parts that were used as chip volume for the calculation of the average cutting force during one tooth engagement. On the other hand, the second workpiece model was based on the CSG technique. It only described the current local workpiece section by subtracting the CSG tool model from the CSG workpiece model at the nearby area of the actual tool position. Hence, this approach was used to calculate the forces during the course of one tooth engagement with a high temporal resolution to predict the resulting dynamic behavior of the tool and the machine. For the generation of the surface structure the calculated tool vibration amplitude was superimposed with the NC path. The cutting edges were modelled by parametric curves which were used for the generation of a triangulated sweep volume. This so called B-Rep (boundary representation) model was projected onto a dexel height map to generate a dexel based representation of a workpiece section. The combination of both techniques allowed the separation of an efficient visualization of the workpiece with the dexel approach and a detailed calculation of machining forces with the CSG approach. Consequently, that enabled the reduction of runtime without any loss of information and precision.

Detailed investigations on the surface finish with ultrasonic vibration assisted milling (UVAM) have been carried out mainly experimentally. Approaches to the modelling of the tool trajectory and the simulation of the resulting workpiece surface with superimposed vibrations in the feed direction and the cutting direction were described and developed by Ding et al. (2010a) and Ibrahim (Ibrahim, 2010). Their approach included a dynamic cutting force model and a dynamic
response model for the machining process to compute the real tool path. Subsequently, those information were used in the surface model to predict the surface micro structure in a dexel-like calculation algorithm. The tool profile was mapped along the tool path so that multiple tool engagements can be taken into account.

For the machining with an ultrasonic vibration assistance in the direction of the tool axis, such analytical investigations do not exist yet. However, surface prediction models are already available for other vibration assisted machining methods such as the elliptical vibration machining by Guo and Ehmann (2013) and vibration assisted turning by Zhang et al. (2014). They both used a dexel model with an analytical description of the tool. Consequently, these models are able to vary certain geometric tool parameters. However, a change of the tool geometry is more complicated to integrate. In difference to the other geometric models, Wang et al. (2010) described a pure analytical model to analyse the influence of the tool tip vibration on the surface micro structure.

In reference to the state of the art referring to surface prediction, the dexel model is an appropriate model for the simulation of the generated surfaces. The exact geometrical representation of the cutting edge geometry enables an accurate evaluation of the tool influence on the generated surface of the machined workpiece. Aiming for an efficient modelling approach, each grid point on the reference surface is assigned only one height value. Although this unidirectional model cannot represent undercuts, it takes up less storage and computation effort than multi dexel models. In comparison to other models, like the CSG or the B-Rep model, the storage usage does not increase during the simulation. Actually, CSG offers an easy and more accurate description of the surface as dexel representations suffer from discretization errors. Especially for the simulation of surface structures resulting from dynamic effects a high accuracy is needed. But such effects are not considered in the following simulation model since it is only the objective to simulate and investigate the kinematic micro structure. Therefore the accuracy of a unidirectional dexel model is sufficient to meet these requirements.

2.2. Development of a kinematic surface prediction tool

A surface simulation model as well as the design of a system for the ultrasonic vibration superimposition of the workpiece were developed simultaneously. Accordingly, simulated and machined surfaces can be compared with each other. If a sufficient prediction reliability is achieved, the simulation model is used to reduce the number of machining experiments for micro structuring. Subsequently, the surface micro structure is evaluated, for example by analysing the adhesion strength of an applied CVD diamond layer on steel substrates. For the adhesion strength of a coating, the amount of the isotropy of a surface is of high relevance. Since micro structures with dominant directions are rather likely to produce areas with strong compressive stresses within the CVD diamond coating, an isotropic arrangement of the surface micro structures is to be aimed at.

In ultrasonic vibration assisted face milling the relative motion of the tool and the workpiece is a combination of the tool feed motion, the tool rotation and the ultrasonic vibration. In the experimental setup the direction of the ultrasonic vibration coincides with the rotational axis of the tool and it is perpendicular to the workpiece surface and the feed direction, respectively (Fig. 1).

A simulation model has been developed in MATLAB for the calculation of the surface micro structure. The approach is called “kinematic simulation”, because no physical effects such as burr formation, chipping as well as cutting forces or temperatures are considered. The tool together with its enveloping surface is moved through the workpiece volume. Any intersecting volume between the tool and the workpiece is subtracted from the workpiece volume leaving a track of the cutting edge in the workpiece. Different to most CAM algorithms not only the solid of revolution generated by the rotating tool but the trajectory of all geometry elements of the tool is incorporated in the calculation. This increased level of complexity becomes necessary because the ultrasonic vibration frequency is by orders of magnitude higher compared to the tool rotation.

The simulation is implemented by modelling both workpiece and tool in a dexel-based data model. In relation to the ambiguous explanation of the term dexel in literature the term designates in this paper a set of discrete points aligned over a regular grid in the X-Y-plane.

The cutting tool is created by means of a CAD software or measured directly and then transformed into a dexel model (Fig. 2). This allows the integration of any tool geometry with an unrestricted geometric level of detail. The exact cutting edge geometry leads to a high detailed simulated surface topography which is a more precise approach in comparison to the Boolean subtraction of a joint volume of primitives.

Due to the simple dexel format the tool geometry can be created from every CAD or measurement data format. In contrast to a CSG model the effect of tool angles and wear on to the surface micro structure can be investigated.

The trajectory of the tool is divided into discrete points in contemporary intervals represented by a list of path vectors. Each path vector \( p = (X_p, Y_p, Z_p, \phi_p) \) consists of the tool coordinates \( X_p, Y_p, Z_p \) in the coordinate system of the workpiece and the current tool rotation angle \( \phi_p \). The simulation algorithm transforms the tool dexels by the path vectors into the workpiece coordinate system and compares each tool dexel with the closest workpiece dexel. If the tool dexel has a smaller \( Z \)-value than the workpiece dexel, the workpiece dexel is dropped to the \( Z \)-value of the tool dexel. This intersection algorithm is shown as a pseudo code in Fig. 3.

The transformation of a tool dexel \( g = (X_g, Y_g, Z_g) \) in the tool coordinate system into a tool dexel \( h = (X_h, Y_h, Z_h) \) in the workpiece coordinate system consists of a rotation around the \( Z \)-axis and a translation by the path vector \( p \):

\[
\begin{align*}
X_h & = X_g \cos(\phi_p) - Y_g \sin(\phi_p) \\
Y_h & = X_g \sin(\phi_p) + Y_g \cos(\phi_p) \\
Z_h & = Z_g + 1
\end{align*}
\]

For the calculation of the path vectors \( p \) a sampling rate \( f_{\text{sim}} \) defining the time resolution

\[
t_{\text{sim}} = 1/f_{\text{sim}}
\]

between two path vectors has to be picked. With a number of \( N = 50 \) path vectors for one complete ultrasonic oscillation and an ultrasonic frequency of approximately \( f_{\text{US}} = 20 \) kHz the sampling rate, which is

![Fig. 1. Kinematics of ultrasonic vibration assisted face milling.](image-url)
calculated by
\[ f_{\text{sim}} = N \cdot f_{\text{US}} \]  
results in a time resolution of \( t_{\text{sim}} = 1 \mu s \). The components of the path vectors can be calculated from the kinematic parameters:
\[ p = \frac{\begin{bmatrix} X_p \\ Y_p \\ Z_p \\ \phi_p \end{bmatrix}}{\begin{bmatrix} n \cdot f \cdot t_i \\ 2\pi \cdot n \cdot t_i \\ \nu \phi_i \cdot t_i \\ L \end{bmatrix}} \]

The calculation applies to one milling process along a straight line in the X-direction. For the simulation of a parallel path the value for \( Y_p \) needs to be altered with a multiple of the value of the width of cut \( (a_e) \).

In order to limit the computational effort as much as possible, only the simulation of a single rotation is performed along the path vectors. This is subsequently patterned in the distance and the direction of the feed. In addition, the computing processes are performed on several CPU cores in parallel. The data output of the simulated surface results in a point cloud, which can be further studied in the surface analysis software MountainsMap®.

3. Experiment

3.1. Experimental set-up

The experimental investigations were carried out at a high precision machining centre (KERN Pyramid Nano). A common transducer of the type Hielscher UIP 2000 hdt was used to generate the ultrasonic vibration. According to Fig. 5 the set-up was clamped on the machine table. It consists of inert masses, a bolt for preload, piezoelectric discs and electrodes (Fig. 4). The discs transform the applied electric field into a linear motion using the inverse piezoelectric effect. The electrodes transfer the voltage to the piezoelectric discs. The natural eigenfrequency of the discs is above 1 MHz. However, using the masses it becomes possible to adjust the system to the desired frequency. In case of an insufficient preload by the bolt, clamping the components of the transducer together, the components start to chatter and the eigenfrequency of the system changes significantly, until the controller stops due to high energy loss. The specimen were made of tool steel 1.2379 (X135CrMoV12), which is used for forming tools for example, in the hardened state (60 HRC), respectively. To reduce the mass and ensure the resonant vibration case the specimens were designed only with a very small height \( (3 \text{ mm}) \). Using a hexagonal profile with width across flats (WAF) of \( 32 \text{ mm} \) a torque of up to \( 150 \text{ N m} \) for the soft annealed specimens and \( 50 \text{ N m} \) for the hardened specimens can be applied.

The direction of the vibration should coincide with the rotational tool axis to generate the desired micro structure on the specimen’s surface. An element was required to connect the specimen to the converter. On the one hand, the direction of the oscillation was changed by \( 90^\circ \). This is based on the eigenfrequency of the converter, where an elongation in the horizontal direction will result in a contraction in the vertical direction (Fig. 4). On the other hand, the converter carries the specimen by a screw connection (thread: M14 × 1, Fig. 5).

The amplitude of the relative motion between the tool and the specimen had to be determined for the generation of the surfaces with a predefined micro structure. Therefore, the relation between generator output power and the amplitude achieved at the specimen’s surface was examined before the experiments. The set point value for the amplitude at the generator was increased in increments of 10% and the amplitudes were determined on the specimen surface by a measurement with a laser vibrometer in order to check the performance of the system in an idle state, Table 1. Slight deviations of the measured values are attributed to the transmission characteristics of the oscillation system. The vibration amplitude was transformed in the orthogonal direction \( (f_{\text{ats}}, \text{Fig. 5}) \) with negligible vibration in the parallel direction (in feed direction, but only in the sub \( \mu \text{m} \) range). During the process, one additional piezoelectric disc (see Fig. 4) is used as a sensor element. The measured signal is used within the control circuit to ensure operation in resonance mode. The resonant frequency \( f_{\text{ats}} \) was within the range between 19.15 kHz and 19.18 kHz.

3.2. Realisation of the experiments

For the micro structuring of the specimen, cemented carbide end milling cutters (single- and double-edged, \( D_{\text{tool}} = 5 \text{ mm} \)) from vohtosoe Werkzeuge GmbH with a TiAlN / TiSiN coating system were used (NVV 02256050, “Hardlox” coating). To protect the sharp cutting corner they had a very small chamfer \( (20 \mu \text{m} \times 45^\circ, \text{Fig. 6}) \). In order to exclude a possible height offset between the two cutting edges due to

```plaintext
loop all path vectors p
  loop all tool dexels
    transformation tool dixel \rightarrow workpiece coordinate system
    find closest workpiece dixel
    if z(tool dixel) < z(workpiece dixel)
      then z(workpiece dixel) = z(tool dixel)
```

Fig. 3. Pseudo code of the intersection algorithm.
the manufacturing process of the tools, the active parts of one cutting edge were mechanically removed, except for investigations with double edged tools to compare the results.

To determine the machining parameters referring to an Amplitude of $A_p = 1.8 \mu m (\approx 20\%)$, it was necessary to set limit values for the feed and the cutting speed, which prevent a collision between the tool and the generated surface micro structure. According to this, the minimum feed ($f_z, \text{min} = 100 \mu m$) and cutting speed ($v_c, \text{min} = 85 \text{m/min}$) were calculated by (5) and (6) with regard to the tool’s geometry and the maximum ultrasonic speed $v_{US}$. The angular relationship for the calculation of the minimum cutting speed is shown in Fig. 7.

$$f_z, \text{min} = \frac{A_{US}}{\tan \angle^2} \quad (5)$$

$$v_c, \text{min} = \frac{v_{US}}{\tan \alpha} = \frac{(2 \cdot \pi \cdot f_{US} \cdot A_{US})}{\tan \alpha} \quad (6)$$

The “wavelength” $\lambda$ of the micro structure in the circumferential direction (Figs. 1 and 7) is defined by the ratio of the rotational speed and the oscillation frequency. In order to adjust the same distances of the micro structure in the feed direction and the cutting direction, the value for the cutting speed was increased to $v_c = 120 \text{m/min}$, which corresponds approximately to a wavelength of $\lambda = 100 \mu m$. Moreover, two comparative tests were carried out with “unfavourable” engagement conditions of the relevant cutting parts: on the one hand, the distances of the micro structure were halved ($f_z = 50 \mu m, v_c = 60 \text{m/min}$) and on the other hand the amplitude was increased up to $3.3 \mu m (\approx 30\%)$, schematically illustrated in Fig. 7. Those conditions led to a contact between the minor flank face as well as the minor cutting edge and the micro structure and resulted in high mechanical stresses at the minor cutting edge and the tool tip. This can be a probable cause of wear because it also leads to a hammering motion or impact movement on the surface in addition to the cutting process, which results in a high dynamic stress of the cutting edge.

With a maximum possible width of cut of $a_e = 4.8 \text{mm}$ (to ensure the overlap of the milling paths), the specimen surface was milled translationally in parallel paths with a depth of cut of $a_p = 20 \mu m$. Compressed air was supplied to remove the chips from the cutting zone. The experimental parameters used for both the soft annealed and the hardened steel are shown in Table 2.

The characterization of both the milled and the simulated surface micro structure was carried out using the surface analysis software MountainsMap® as well as the software VK Analyzer from Keyence. For this purpose, sections of the surfaces of the experimentally machined specimens were measured with a laser scanning microscope (Keyence VK-9700). The selected measuring field according to ISO 25178-3, which was located centric along the milling path, amounts to $0.5 \text{mm} \times 0.5 \text{mm}$. This ensures that at least five surface features in both the X-direction and the Y-direction are included in the calculation of the surface parameters. In order to remove inclination deviations, the measured surfaces of the specimens were aligned by means of a subtraction method and a form filter (2nd degree polynomial) was used to eliminate possible shape deviations. In order to document and analyse the tool wear, SEM micrographs of the cutting edges were prepared before and after machining.

![Fig. 5. Experimental set-up for UVAM.](image)

<table>
<thead>
<tr>
<th>Set point value</th>
<th>Amplitude $A_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20%</td>
<td>1.8 $\mu m$</td>
</tr>
<tr>
<td>30%</td>
<td>3.3 $\mu m$</td>
</tr>
<tr>
<td>40%</td>
<td>4.5 $\mu m$</td>
</tr>
<tr>
<td>50%</td>
<td>5.7 $\mu m$</td>
</tr>
<tr>
<td>60%</td>
<td>6.6 $\mu m$</td>
</tr>
</tbody>
</table>

![Fig. 6. Schematic tool tip.](image)

![Fig. 7. Angular relationship for the calculation of the minimum cutting speed (left) and schematically illustration of an “unfavourable” engagement of the minor cutting edge by increasing the amplitude (right).](image)
Table 2
Experimental plan and machining parameters.

<table>
<thead>
<tr>
<th>#</th>
<th>z</th>
<th>(A_p)</th>
<th>(f_l (= \lambda))</th>
<th>(v_c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1</td>
<td>1</td>
<td>1.8 (\mu m)</td>
<td>100 (\mu m)</td>
<td>120 m/min</td>
</tr>
<tr>
<td>V2</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V3</td>
<td>1</td>
<td>50 (\mu m)</td>
<td>60 m/min</td>
<td></td>
</tr>
<tr>
<td>V4</td>
<td>3.3 (\mu m)</td>
<td>100 (\mu m)</td>
<td>120 m/min</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 8. Simulated surfaces as a variation of reference test V1 (\(f_z = 100 \mu m, v_c = 120 m/min, A_p = 1.8 \mu m\)).

Fig. 9. Simulated surfaces V4_b (\(f_z = 100 \mu m, v_c = 120 m/min, A_p = 3.3 \mu m\), with displacement) and profile section in the direction of the cutting speed.

4. Results and discussion

4.1. Evaluation of the surface micro structure

4.1.1. Surface simulation

Based on both the machining parameters and the oscillation parameters as well as the tool geometry (especially the relevant part of the tool tip, Fig. 6), four different simulation models were created. By lining up individual cycloids in the feed direction, it is possible to set a defined offset of the sinusoidal structure after each rotation. Since there are both fluctuations within the spindle speed as well as the resonant frequency in the real machining process, a clear ratio of these variables cannot be predicted. In the most cases it is not an integer, which results in a slight misalignment. In the simulation, therefore, the two “extreme cases” are compared: no offset (\(\Delta \phi = 0\): “valley follows valley”, a) + c) and maximum offset half a wavelength (\(\Delta \phi = \lambda/2\): “valley follows hill”, b) + d)), below named without and with displacement. Furthermore, both variants were simulated with (c) + d) and without the “recutting effect” (a) + b) of the rotating cutting corner. For the surfaces without recut, only a path with the length of the tool diameter was simulated. The resulting surfaces from the simulation are shown in Fig. 8 exemplary for the experimental parameters of test V1 (reference).

Also for the “unfavourable” conditions of engagement of the active cutting parts, the four cases were simulated and analysed. The simulated surface of V4_b (with displacement) is shown in Fig. 9. For high amplitudes, both minor cutting edge and the minor flank face get in contact with the previously generated micro structure. This results in an interruption of the sinusoidal curve on the peaks as well as a flattening of the curve in the direction of the cutting speed, which is clearly visible in the section A-A.

For the quantitative analysis of the simulation, the surface parameters are shown Table 3. Because the simulation represents an ideal process, the values of V1 and V2 are identical. The order from a) to d) results from the functional volume parameter of the material volume Vm, which was calculated for a material ratio of \(p = 100\%\) and decreases due to the value of theoretically removed material. In simulation d), the case of the most intensive recutting effect occurs, since the structural displacement is maximal (\(\Delta \phi = \lambda/2\)) and the values of Vm are the smallest. In particular, the high values of the texture aspect ratio of the surfaces showing a micro structure with displacement (b) and (d)) are conspicuous compared to those without displacement (a) and c)). The evaluation of the texture aspect ratio of all simulated cases show the same trends.

In addition, it can be seen that for reference test V1 as well as V4 the surface parameters Sz and Sa tend to decrease from a) to d), while the surface magnification, expressed by the developed interfacial ratio Sdr, increases. For the simulated case V3 it can be determined, that the values for b), c) and d) are constant and only slightly smaller than for case a). The values for Sa, Sdr and Vm, respectively, are shown in the chart in Fig. 10. It is clear that the surface magnification for the simulated surfaces V3 and V4 are nearly the same, although the material volume has different values.

4.1.2. Experimental investigations

The visual comparison of the surfaces from the experiments with the soft annealed specimens shows that only in the case of V2 (S) recutting effects as well as a displacement of the micro structures in the feed direction occur (Fig. 11). As a result, the surfaces can be clearly separated in terms of their isotropy: while the arrangement of the micro structure at V2 (S) is almost isotropic, the surfaces of V1 (S), V3 (S) and V4 (S) show only small values for Str (8% - approx. 13%, Table 4).

Table 3
Results of the surface analysis of the simulated surfaces.

<table>
<thead>
<tr>
<th>Simulation of V1 / V2</th>
<th>Simulation of V3</th>
<th>Simulation of V4</th>
</tr>
</thead>
<tbody>
<tr>
<td>V1_a</td>
<td>V1_b</td>
<td>V1_c</td>
</tr>
<tr>
<td>V3_a</td>
<td>V3_b</td>
<td>V3_c</td>
</tr>
<tr>
<td>V4_a</td>
<td>V4_b</td>
<td>V4_c</td>
</tr>
<tr>
<td>Sz ((\mu m))</td>
<td>7.27</td>
<td>6.98</td>
</tr>
<tr>
<td>Sa ((\mu m))</td>
<td>1.3</td>
<td>1.28</td>
</tr>
<tr>
<td>Vm ((\mu m^2/\mu m^2))</td>
<td>3.44</td>
<td>3.42</td>
</tr>
<tr>
<td>Str in %</td>
<td>10.3</td>
<td>89.1</td>
</tr>
</tbody>
</table>
Fig. 10. Comparison of the surface parameters $S_a$, $S_{dr}$ and $V_m$ for all simulated cases.

Fig. 11. Milled surfaces of the specimens in the soft annealed state with profile sections in V1 (S) (A-A and B-B → Fig. 12).

Table 4
Results of surface analysis of the milled surfaces.

<table>
<thead>
<tr>
<th></th>
<th>Soft annealed</th>
<th></th>
<th>Hardened</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V1 (S)</td>
<td>V2 (S)</td>
<td>V3 (S)</td>
<td>V4 (S)</td>
</tr>
<tr>
<td>$S_z$ ($\mu m$)</td>
<td>7.15</td>
<td>8.59</td>
<td>7.47</td>
<td>12.2</td>
</tr>
<tr>
<td>$S_a$ ($\mu m$)</td>
<td>1.28</td>
<td>0.98</td>
<td>0.74</td>
<td>1.73</td>
</tr>
<tr>
<td>$S_{dr}$ in %</td>
<td>1.6</td>
<td>2.5</td>
<td>3.2</td>
<td>2.9</td>
</tr>
<tr>
<td>$S_{tr}$ in %</td>
<td>10.3</td>
<td>76.7</td>
<td>12.8</td>
<td>8.2</td>
</tr>
<tr>
<td>$S_{k}$ ($\mu m$)</td>
<td>4.06</td>
<td>3.27</td>
<td>2.52</td>
<td>5.59</td>
</tr>
<tr>
<td>$S_{vk}$ ($\mu m$)</td>
<td>0.41</td>
<td>0.71</td>
<td>0.7</td>
<td>0.53</td>
</tr>
</tbody>
</table>

V1 (S)

Fig. 12. Profile sections in the direction of the cutting speed (top) and the feed direction (bottom) of test V1(S) (see Fig. 11).

Fig. 13. Comparison of the graphical representations in false colours as well as the depth histograms and the areal material ratio of the simulated (a) and milled (V1 (S)) surfaces with high visual correspondence.

Fig. 14. Comparison of the graphical representations in false colours as well as the depth histograms and the areal material ratio of the simulated (c) and milled (V1 (H)) surfaces with high visual correspondence.
Particularly in the case of the experiment with a larger amplitude (V4 (S)), dominant ridges can be perceived in the feed direction, whereby a dominant direction is created. In addition, it becomes clear that the feed per tooth and the cutting speed are too small to generate a micro structure without a large area contact between the micro structure and the minor flank face as well as the minor cutting edge.

Furthermore, the surface of V1 (S) has the smallest developed interfacial area ratio (Sdr = 1.6%), although V2 (S) was generated with the same process parameters. This results from minimal different values of the cutting length of the tool from V2 (S) (in the axial direction to the tool shank) as well as recutting effects which lead to a slight increase of Sdr. This assumption also correlates with the tendency of the simulations. As expected, the increase in the amplitude at V4 (S) has a still greater influence. The highest value of the developed interfacial area ratio is achieved at V3 (S) (Sdr = 3.2%) for the specimen in the soft annealed state. This can be explained by an approximately doubled aspect ratio ($A_{US}/\lambda$) of the micro structure: while the height of the structure is only slightly lower, the structure distances were halved, thus increasing the (real) surface area. It should be noted that the surface of V4 (S) is scaled differently from the others.

The analysis of the surface parameters of the soft annealed and the hardened state in Table 4 shows that, although the surface magnifications are nearly in the same range, the material volume as well as the arithmetic mean height of the hardened specimens is much lower compared to the soft annealed specimens. This becomes clear by considering the functional parameters Sk, Spk and Svk. While the reduced valley depth Svk is nearly in the same range over all tests, the reduced peak height Spk and especially the core roughness depth Sk of the soft annealed specimens are much higher. Moreover, it could be determined, that there is no correlation between the surface magnification Sdr and the arithmetic mean height Sa.

The difference of the surface micro structure in the cutting and the feed direction can be seen by means of profile sections of the soft annealed state of V1 (S) (in Fig. 11). While a nearly sinusoidal curve is detectable in the direction of the cutting speed (Fig. 12, top), the profile in the feed direction has the shape of the kinematic roughness (approx. 2 μm high). In addition, the adjusted amplitude ($A_p \approx 2 \mu m$) can be seen in the profile section in the cutting direction. The slight deviation from the theoretically designed to the measured wavelength (100 μm compared to 95 μm) is due to rounded values ($v_c = 120$ m/min). Moreover,
there are slight fluctuations within the ultrasonic frequency (as described in 3.1) as well as the spindle speed during the machining process.

4.1.3. Comparison of selected surfaces

For a comparison of the reference experiment V1 (soft annealed and hardened, respectively) with the results of the simulation, the simulated surfaces with the highest visual correspondence were selected. Consequently, the surface of V1 (S) is compared to simulation a), while the surface of V1 (H) shows high correspondence to simulation c). This qualitative assessment becomes clear by the consideration of the surface parameters: in particular, the characteristics Sz, Sa, Sdr and Str show a high degree of conformity for the surface of the soft annealed state. However, the parameters of the areal material ratio show slight deviations, which is also visualized in Fig. 13. This is explained by a small tool wear, in particular on the cutting corner and the engaged part of the minor cutting edge. The increase of the edge rounding occurring in this case leads to an uneven cutting edge offset, which becomes larger towards the cutting corner. This results in a change in the geometry of the micro structure, which induces differences between the simulated and the milled micro structure in the submicron range.

In a qualitative surface analysis of the hardened specimens it becomes clear that in comparison to the micro structuring of the soft annealed samples both recutting and tool wear are of much greater importance with respect to the surface micro structure (Fig. 14). Only the surface of V3 (H) is similar to that of the soft annealed state, although a significantly lower height of the profile is measured. The surface analysis of V2 (H) and V3 (H) shows that the influence of the tool wear has significantly increased. A fast cutting edge wear leads to a large increase in the chipping of the cutting edge and results in a greater deviation from the simulated surfaces than in the soft annealed state. However, in V1 (H) the recutting effect dominates the surface micro structure. This can be attributed to a higher passive force during the cutting which results from the hardness of the specimen. Since the Young’s modulus assumed to be constant, greater elastic deformation of the steel specimen occurs by the cutting in the hardened state compared to the soft annealed state. The spring back of the material after the (elastic) compression is correspondingly stronger and a recut becomes more probable. It is conceivable that in the case of the soft annealed state due to the elastic spring back of the material the undeformed chip thickness is still below the minimum undeformed chip thickness and thus only the ploughing effect and no recut occur.

4.2. Tool wear analysis

The representation of the cutting edge in Fig. 15 (upper left) is representative for all new tools. It can be seen that the tools of the tests carried out with “favourable” engagement conditions (V1 (S) and V2 (S)) have nearly unworn cutting edges and cutting corners. Only a very small rounding could be determined, which can be attributed to a successive wear of the coating. However, the wear of the tools of V3 (S) and V4 (S) is clearly conspicuous. Larger edge sections at the minor cutting edge as well as the rake face (up to 300 μm, Fig. 15, bottom right) are broken off, and the coating in this area is spalled. This is attributable to the unfavourable engagement conditions during the machining process, where the hammering contact between the minor flank face and the micro structure resulted in high mechanical stresses at the cutting edge and the tool tip. Those vibrations ultimately led to the local failure of the coating as well as of the cutting material and consequently to a rapid increase of the tool wear.

The wear analysis of the tools used for the micro structuring of the hardened specimens confirmed the results of the surface analysis: in particular the minor cutting edge as well as the cutting corner showed considerable chippings. Thus, the chipping of the cutting edge increased and led to a higher deviation from the simulated micro structure in comparison with the machining of the soft annealed state. The main wear type is abrasion. In addition, large areas of delamination of the coating on the rake face could be determined. It can be concluded that the coating or its adhesive strength is not suitable for the hard machining with regard to the mechanical loading. The slightest wear occurred at the tool used for V3 (H), where the feed per tooth and also the cutting speed were lower (Fig. 16).

5. Summary and conclusions

The aim of the investigations was the generation of defined micro structures on specimens (1.2379) by means of UVAM as well as the simulation of the resulting (kinematic) micro structure. According to this, a system for ultrasonic vibration assistance was implemented in a machining centre to realise the vibration excitation of the workpiece. In addition, a simulation tool was developed with MATLAB, which provides a virtual surface by using the machining parameters and a Boolean interpolation. It could be shown that both the machining of the micro structure is technologically possible as well as a high degree of conformity is achieved with the different simulation models. However, there are still significant differences in the surface micro structure depending on the hardness of the machined material. The surface simulation model allows the prediction and modelling of surfaces with defined micro structure, which could significantly reduce the experimental effort. In addition, it became clear that the engagement conditions as well as the properties of the tool, e.g. the coating or the type of cemented carbide, have a strong influence on the wear development and also on the reproducibility of the micro structure, respectively. It is therefore of great importance to match the cutting geometry and the process parameters. Currently available ultrasonic actuators are limited in their flexibility especially regarding the generation of different kinds of micro structures. The restricting factor is the limitation to one single system immanent eigenfrequency that is excited in resonant mode.

Acknowledgements

We gratefully acknowledge the support of this project provided by the German Research Foundation (Deutsche Forschungsgemeinschaft DFG) within the scope of the priority programme SPP 1676 “Dry Deep Drawing of Aluminium for Automotive Production”.

References


