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Generation of tailored subsurface zones in steels containing metastable austenite by adaptive machining and validation by eddy current testing

Erzeugung definierter Randzonen in Stählen mit metastabilem Austenit durch adaptive Zerspanung und Validierung mittels Wirbelstromprüfung

Abstract: In order to withstand high mechanical and tribological loads, it is important that the components not only have a high core ductility but also a hard surface. Typically, a suitable microstructure is created by heat treatment processes before the workpiece is machined. However, these processes are time and energy consuming and can lead to component distortion. It would therefore be of great advantage if no additional heat treatment process would be required to produce a hardened subsurface zone. Since turning is often already integrated as a machining process in production lines, it would be advantageous to create a hardened subsurface within this process. As there is no possibility to measure the hardness directly during the turning process, a soft sensor was developed to determine the properties of the subsurface directly during the machining process. Steels with metastable austenite are of particular interest in this context, as metastable austenite can be converted into martensite by deformation. The amount of martensite produced in the subsurface can be adjusted provided that suitable turning parameters can be found. For this purpose, a process parallel material removal simulation was used to determine the actual conditions governing the process. It was found that there is a correlation between the martensite content and the amplitude of the 3rd harmonic of eddy current testing. Therefore, an eddy current sensor accompanying the process can be used as a basis for controlling the turning process for tailored martensite volume content adjustment.

Keywords: Eddy current testing, adaptive machining, deformation-induced martensite.


Schlagwörter: Wirbelstromprüfung v Adaptive Zerspanung, verformungsinduzierter Martensit.
1 Introduction and state of the art

It would be beneficial if a tailored hardened subsurface layer in steels could be produced directly in the machining process in production lines to shorten the production line and to save time and energy. Mayer et al. already showed that it is possible to produce a hardened subsurface by turning using metastable austenitic steels [1, 2]. In those steels, the soft, metastable austenite can be transformed by deformation into hard martensite [1–3]. Various process parameters influence the transformation of austenite to martensite. For example, Mayer et al. reported that high mechanical loads and low process temperatures are required [1]. Thus, cryogenic turning is a promising approach to produce tailored, hardened martensitic subsurface zones.

Several studies have already monitored the martensite formation upon plastic deformation of stainless steels with magnetic testing methods [4–6]. However, most non-destructive, magnetic testing methods lead to a misjudgment of the martensite fraction due to the inhomogeneous martensite distribution over the thickness [7]. More accurate results can be achieved using eddy current testing since the excitation frequency can be varied and different studies demonstrate a good correlation between the martensite content and measured values in eddy current testing. For example, Silva et al. showed an exponential correlation between martensite volume fraction and phase angle [8] and Khan et al. between coil impedance, impedance phase and martensite content [9]. Therefore, eddy current testing is a promising tool to detect the martensitic transformation within the turning process.

To be able to adjust the turning parameters to generate a specific martensite content, it is crucial to know the actual cutting conditions prevailing while machining. Various geometric modeling techniques exist in literature to describe the engagement between tool and workpiece. The engagement between tool and workpiece leads to varying chip thickness and cutting conditions which can be used to evaluate force, torque, power, vibration and other process states along the tool path [10]. This is done by determining correlations between simulated data of the engagement conditions with the target value. These data can be used to evaluate and optimize e.g. the outcome of relevant quality values, like shape errors by means of a process parallel simulation determining the engagement condition based on the actual axis positions [11] or providing force predictions while cutting [12, 13]. Saadallah et al. developed an approach with a feedforward Artificial Neural Network (ANN), which is trained with results of a cutting simulation [14]. A real-time stability monitoring system for cutting processes was achieved by using the trained model to predict the current process stability. Combining measurement data with a material removal simulation is therefore useful for process planning by depicting the acquired data and simulated engagement conditions [15]. The establishment of systematic feedback mechanisms for returning process data is a factor that improves the whole process planning process. Brecher and Lohse used a feedback loop to support a Computer-Aided Manufacturing (CAM) system with process data [16]. In their approach, dynamic signals of the tool center point are deployed and used to evaluate the quality of toolpaths to identify potentially critical areas. Thus, the quality of numerical controlled CAM planning is assessed by the information of the process. Hence, a process control with feedback loop and steady increase of knowledge using collected data from the process has high potential to produce individually tailored subsurface zones.

Therefore, the combination of a process parallel material removal simulation with an eddy current sensor as a soft sensor is a promising approach to detect the actual martensite content within the subsurface of the workpiece. This can be used as a basis for a process control to produce tailored subsurfaces using the machining process.

2 Approach

The adaptive control implemented to obtain tailored subsurface properties is described in Fig. 1. The selection of different process parameters changes the mechanical and thermal loads during the turning process, which influences the formation of martensite. For example, higher feed rates cause higher mechanical loads, which increase the formation of martensite. In contrast, higher cutting speeds tend to inhibit martensite formation due to higher thermal loads. With the appropriate combination of process parameters, the amount of martensite can therefore be varied. In the process, different disturbance variables such as wear etc. can influence the phase transformation. A control system can compensate such effects by adjusting the process parameters. To be able to generate the desired workpiece properties, these have to be determined directly within the process. This is achieved by using a soft sensor system. An eddy current sensor is placed directly in the machine tool. The martensite content is then determined by analyzing the measured voltage signals. In particular, the analysis of higher harmonics is used, since this shows a great potential to detect the generated martensite [8, 9].
The process parallel simulation, on the other hand, calculates the actual engagement conditions in the process from the recorded axis data to correlate these with the martensite content. The data are stored in a database and merges the information of the simulation and the eddy current sensor. Both information are finally combined in the developed soft sensor. This can be used to model correlations between process parameters and martensite content. Based on the knowledge of the correlations, suitable process parameters to generate the desired subsurface microstructure can be derived. The approach is supposed to enable manufacturing of a tailored, hard martensitic subsurface layer in external cylindrical turning.

### 2.1 Analysis of higher harmonics of eddy current testing

In addition to the conventional application, i.e. flaw inspection, eddy current testing can also characterize a material, its condition and its properties very quickly. Furthermore, its application does not require direct contact between workpiece and sensor [17]. Eddy current testing uses an excitation coil, which generates an alternating primary magnetic field, which induces eddy currents into an electrically conductive material. The formation of eddy currents depends on the magnetic and electrical material properties. Those eddy currents create an opposing secondary magnetic field, which overlaps with the primary magnetic field. The resulting magnetic field induces a voltage into the measuring coil. Especially the transformation of an austenitic microstructure with paramagnetic properties into a microstructure with ferromagnetic properties, such as martensite, is accompanied by a significant change in magnetic permeability and shows therefore a great influence on the eddy current signal [18–20]. Pure austenite does not distort the waveform of the measurement signal with respect to the excitation signal. In contrast, the non-linear magnetic hysteresis in ferromagnetic materials produces higher harmonics in the measured signal [19]. A discrete Fourier transformation of the measured signal allows a representation of the signal as a sequence of higher harmonics. Ferromagnetic materials create higher harmonics, and the 3rd harmonic is particularly suited to provide information about the martensite volume content of the samples [18, 20, 21].

The penetration depth of eddy currents and therefore the measurement depth depends on the excitation frequency of the primary magnetic field, and the higher the frequency, the lower the penetration depth gets. To evaluate which excitation frequency is best suited for the eddy current testing, different frequencies were considered to determine the influence on the penetration and therefore measurement depth on the results. In order to correlate the measured signal to the martensite content, the samples were analyzed after turning by X-ray diffraction (XRD) with Cr-Kα-radiation. The martensite content was obtained by a heuristic method developed by G. Faninger and U. Hartmann [22]. Here the average values of the ratio of the intensities of martensite and austenite of different crystallographic plans are determined. Using this, the martensite content could be derived for each crystallographic plane ratio. Afterwards, the average over all crystallographic planes is calculated. By turning a texture is created within the samples and therefore, high standard deviations were found for the different crystallographic planes. To obtain the desired information throughout the whole sample subsurface, 10–30 micrometers were removed by etching before a new measurement was conducted. The results obtained were then integrated to evaluate the average volume martensite content within the subsurface.

It is known that eddy current testing is sensitive to the distance between probe and sample [23–25]. This effect is called lift-off effect. Hence, a study outside the turning machine was conducted to evaluate the influence of this parameter on the measurements. In these experiments, the distance between the sample and the eddy current sensor was varied between 0–1 mm and the orientation between sensor and workpiece was tilted from 0°–15°.
2.2 Process parallel simulation

In order to obtain a virtual representation of the process, the axis positions are taken directly from the control of the machine tool during machining and transferred to the material removal simulation to determine the actual cutting conditions between tool and workpiece. The material removal simulation IFW CutS [26], which is particularly suited for this purpose was used in the present study. IFW CutS provides an open simulation platform for the technology-oriented simulation of manufacturing processes by representing machine and process kinematics. The basic application provides a calculation of material removal using various dexel models as well as a 3D visualization of the machine tool, workpiece and tool. The actual axis positions are taken as input to avoid possible deviations between the given nominal position data from the numerical control (NC) code and the actual position data, which may differ due to acceleration and deceleration behavior. This also has an effect in the resulting cutting conditions. Therefore, the determined actual cutting conditions on different locations of the workpiece from the simulation can be used to predict the formed martensite as non-static input. In the future, the approach will also allow to estimate the martensite content in more complicated machining processes. Based on the predicted martensite content, the process can be adjusted by changing the process parameters at the respective locations.

The overall system of the process parallel simulation has the following structure: The communication with the machine tool control (Siemens 840D) is realized with a Beckhoff IPC and the TwinCAT development environment. For this purpose, the data from the control system are acquired in a TwinCAT real-time system. Data are exchanged between the TwinCAT environment and the controller via a Profibus connection. The axis positions are transferred together with a time stamp from the TwinCAT environment to IFW CutS, which uses them to carry out a process-parallel removal simulation. The NC provides the axis positions signal each 12 ms to the material removal simulation. The error in the calculation of material removal due to the latency time is negligible. This is because the time required from standstill until the set feed rate at the start of the process is achieved in two seconds on average and is therefore higher than the latency time. With regard to the time resolution, this means that the material removal simulation is fine enough to capture the changes during this transition, which represents the worst case in changing the engagement conditions during the turning process. Cartesian dexels are used here as workpiece model. The resolution of the discretization in \( x \) - and \( y \)-direction is 10.24 dexels/mm and in \( z \)-direction 5.12 dexels/mm.

With this workpiece model, only an offline simulation is possible. A process parallel simulation leads to errors, because the material removal is delayed. For the process-parallel calculation of local engagement conditions by means of the material removal simulation, a balance must be found between simulation accuracy, calculation, and storage effort. To improve the calculation time and increase the simulation accuracy, different dexel models are investigated in [27]. Here, the contour line model is suitable to determine the local engagement conditions between tool and workpiece. It is particularly suitable for external longitudinal turning of rotationally symmetric workpieces and was used in the present study for the online calculation of the engagement conditions.

### 3 Experiments

In order to analyze the correlation between cutting conditions and martensite content as well as the dependence between the soft sensor and the martensite volume within the subsurface, several samples were machined. Experimental tests were carried out on the turning center DMG MORI CTX 800 4A. Here, different contents of martensite were generated by specific adaptation of the process parameters. The process parameters were changed separately, while the remaining parameters were set to defined reference values. For the reference values, the following parameters were used: cutting speed \( v_c = 150 \text{ m/min} \), feed \( f = 0.2 \text{ mm} \), depth of cut \( a_p = 0.2 \text{ mm} \), average cutting edge rounding \( S = 10 \mu \text{m} \) and initial temperature in the core of the workpiece \( T = -115 \text{ °C} \) to ensure that the temperature is low enough to trigger the martensitic transformation upon machining. The process parameter ranges are shown in Tab. 1.

The temperature was set between \(-196 \text{ °C} \) and room temperature and was adjusted using liquid nitrogen. The samples were placed in a container filled with liquid nitrogen until the desired temperature was reached. The temperature was measured using a thermocouple type K in a borehole in the core of the samples directly before placing

### Table 1: Process parameters.

<table>
<thead>
<tr>
<th>Cutting speed in m/min</th>
<th>Feed in mm</th>
<th>Depth of cut in mm</th>
<th>Workpiece temperature in °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>30–150</td>
<td>0.2–1.0</td>
<td>0.2–1.5</td>
<td>(-196–20)</td>
</tr>
</tbody>
</table>
the samples in the lathe. No further cooling or lubricant was applied during cutting. After cutting the temperatures within the core were about 10 °C higher than prior to cutting.

To analyze the influence of the process parameters in this study the metastable austenitic steel AISI304 was used as workpiece material since it is known to be sensitive to the deformation-induced martensitic transformation [28–30]. The material was homogenized by holding it for 45 min at 1050 °C so that the influence of microstructural inhomogeneity within the material was minimized.

4 Results

4.1 Eddy current testing

In Fig. 2 the 3rd harmonic is depicted as a function of the martensite content within the subsurface zone, which was determined by XRD until a depth of 100 µm. The average martensite content within the first 100 µm is displayed, it was assumed that the whole subsurface, where deformation induced martensite was found, plays an important role regarding the surface properties. As seen in Fig. 2, the martensite content has a high standard deviation due to the coarse grains of the steel. Below 100 µm, no martensite was found. Eight samples, where the temperature and the feed were varied to induce different martensite contents, are displayed. The amplitudes of the 3rd harmonic are normalized with respect to the reference sample that contained no martensite.

In Fig. 2, it can be seen that the 3rd harmonic increases with the martensite content, and the correlation between the martensite content and the 3rd harmonic can be used provided that a suitable excitation frequency is employed. Hence, to produce tailored subsurface zones the 3rd harmonic of the eddy current testing can be used to monitor the martensite content within the workpiece while turning. The measured amplitude while turning can then be compared to a measurement amplitude of the desired martensite content within the subsurface to adapt the cutting conditions needed using the adapted manufacturing system.

From Fig. 2, the distinction between the different martensite contents within the subsurface becomes clearer when using the higher frequency of 6400 Hz. The higher the frequency, the lower the measurement depth and hence, the influence of the subsurface on the measurement results is more pronounced. Looking at Fig. 2b), a martensite content as low as approx. 7 % can be detected at 6400 Hz. However, a martensitic content of 2 % cannot be distinguished from a sample containing no martensite. Clearly, an even higher frequency would be needed to detect very low martensite contents of 2 % and below.

Nevertheless, it can be seen that not only the martensite content seems to influence the amplitude of the 3rd harmonic. Between 14 % and 15 % martensite a considerable increase in the 3rd harmonic becomes apparent. The samples from 2 % to 14 % were produced by lowering the workpiece temperature. However, from 15 % on the temperature was kept constant at −115 °C and since Mayer et al. reported that an increase of feed will lead to higher martensite contents [1], the feed was increased. Therefore, the applied force during turning was increased. The applied force does not only transform austenite to martensite, it also causes an increase in dislocation density and residual stress. The change of the residual stresses can be seen in Fig. 3. With increasing cutting feed the tensile residual stress in axial direction increases and the residual compressive stress maximum decreases. These factors also seem to influence the amplitude of the 3rd harmonic [31],...
Figure 3: Residual stress in axial direction with increasing cutting feed.

In Fig. 3, the influence of the tilt and the distance between sensor and workpiece is shown. The amplitudes are normalized with respect to the amplitude measured without distance and tilt, cf. Fig. 4d) for spatial arrangement of the workpiece and sensor. From Fig. 4a) and c) it is obvious that the greater the distance and the greater the tilt between the sensor and the workpiece, the smaller the amplitude measured is. Moreover, the influence of the distance and tilt is more pronounced for the $3^{rd}$ harmonic than for the $1^{st}$ harmonic. Therefore, great attention should be paid on keeping the distance and orientation between the sensor and workpiece constant.

However, looking at the results of the influence of the distance on the phase of eddy current testing in Fig. 4b), it can be seen that the phase of the $1^{st}$ harmonic increases with the distance. Hence, the $1^{st}$ harmonic can be used to determine the distance between the sensor and workpiece if no other significant influence of the materials properties on the phase of the $1^{st}$ harmonics is present.

4.2 Correlation between simulated data and martensite content

The determined parameters from the simulation, that describe the engagement conditions between tool and work-
Table 2: Linear regression model between simulated data and martensite content.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Standard Error</th>
<th>t-Value</th>
<th>p-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1.9418</td>
<td>2.1596</td>
<td>0.8991</td>
</tr>
<tr>
<td>$Q_w$</td>
<td>-0.0893</td>
<td>0.0417</td>
<td>-2.1422</td>
</tr>
<tr>
<td>$A$</td>
<td>254.1741</td>
<td>107.2841</td>
<td>2.3692</td>
</tr>
<tr>
<td>$T$</td>
<td>-0.1182</td>
<td>0.0220</td>
<td>-5.3620</td>
</tr>
</tbody>
</table>

With the help of other modelling methods, $R^2$ might still be improved. The use of other machine learning methods for the subsequent work is planned to model non-linear correlations. The trained model will then be used to predict the target value in process planning. Based on this knowledge, an inverse problem can be solved that allows to choose appropriate process parameters to achieve a specific target value. In combination with the measurement data of the eddy current testing, the process parameters can be adjusted autonomously to achieve the desired subsurface of the workpiece.

5 Conclusions and outlook

An adapted manufacturing system with an integrated soft sensor system is required to be able to machine a tailor-made subsurface zone, since direct hardness measurement during the turning process is not practicable and many parameters influence the deformation-induced martensitic transformation. In the present study, a process parallel simulation was used to determine the actual engagement conditions that show a correlation with the martensite content. Utilizing an in-process eddy current testing sensor, it was possible to determine the martensite content using the amplitude of the 3rd harmonic. However, when integrating an eddy current sensor into a machine it is important to ensure information about the sensor position relative to the workpiece. It is crucial to keep the distance and angle between the eddy current sensor and the workpiece as constant as possible. As the phase of the 1st harmonic is influenced by the spatial arrangement of sensor and workpiece this can be used as an indicator if the sensor and workpiece arrangement. Moreover, the excitation frequency needs to be adapted to the depth of transformation in order to be able to detect the martensite content reliably. To detect high and low martensite contents within the subsurface a multi-frequency approach could be useful so that the measurement is simultaneously conducted at different measurement depth.

The developed soft sensor is a suitable basis to regulate the machining process. In the next step, the use of machine learning methods to model the correlation between process parameters and martensite content based on the data of the soft sensor is planned.

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References


22. G. Faninger, U. Hartmann, Physikalische Grundlagen der quantitativen röntgenographischen Phasenanalyse, HTM 27 (1972) 233–244.


28. A. Weiß, H. Gutte, J. Mola, Contributions of $\alpha$ and $\delta'$ TRIP Effects to the Strength and Ductility of AISI 304 (X5CrNi18-10) Austenitic Stainless Steel, Metall and Mat Trans A 47 (2016) 112–122.


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