Influence of different asymmetrical cutting edge microgeometries on surface integrity

Eric Segebade\textsuperscript{a,b,}*, Frederik Zanger\textsuperscript{a}, Volker Schulze\textsuperscript{a}

\textsuperscript{a} wbk – Institute of Production Science, Karlsruhe Institute of Technology (KIT)
\textsuperscript{b} Corresponding author. Tel.: +49-721-608-45906 ; fax: +49-751-608-45004. E-mail address: eric.segebade@kit.edu

Abstract

The importance of cutting edge microgeometries in machining operations has been proven time after time again. Not only with regard to wear, but also as an important factor influencing the resulting surface integrity. In this paper the influence of asymmetrical cutting edge microgeometries and different process parameters on the resulting accumulated plastic strain, plastic strain rates and surface layer microstructure of AISI 4140 in cutting experiments and FE-simulations is investigated. To characterize the cutting edge microgeometries a recently published method considering the process parameters such as cutting angles is used.

Keywords: Cutting edge; Surface Integrity; Tool Microgeometry

1. Introduction

Machining processes utilizing geometrically defined cutting edges, such as turning or milling, induce profound changes in the surface layers of the workplace. These changes can be beneficial e.g. for wear resistance and product lifetime. One affected surface layer characteristic is residual stress distribution, which is deepened and driven to higher compressive stresses by utilizing larger tool radii or relative roundness. Another is microstructural manipulation such as grain refinement of the surface layer, which follows a similar trend. Surface layer hardness can also be influenced by varying process parameters of cutting operations [1-4].

In this context, simulations and experiments utilizing the steel AISI 4140 have already been conducted. The resulting nanocrystalline surface layer thickness was analyzed contingent on the process parameters concurrent with the microgeometry of the cutting edge [5]. Asymmetrical cutting edge microgeometries, however, did not factor into this analysis to date. Therefore it is currently not fully understood how asymmetric cutting edge microgeometries influence the formation of nanocrystalline surface layers, and which geometrical or process related parameters are best suited to quantify this influence.

This work focuses on the microstructural changes in the surface layer. Orthogonal cutting experiments on a broaching machine and 2D simulations with asymmetrical cutting edge microgeometries are conducted to analyze the influence of said microgeometries. The cutting edges are characterized by a method introduced in [6].

2. Cutting edges

2.1. Influence of cutting edge geometries on surface integrity

It is well known, that the surface integrity after machining is influenced by the macroscopic- and microscopic cutting edge geometry, which changes important factors like temperature distribution or material flow during machining [7]. Chamfer angles and radii for instance were analyzed in hard turning regarding tool performance and resulting surface roughness concluding, intelligent tool preparation can raise tool life and lower surface roughness [8]. Further works include but are not limited to the influence of tool preparation on residual stresses in bearing steels [9], and the resulting microstructural changes in AISI 4140 [5]. Recently Denkena and Biermann summarized preparation techniques and known resulting influences of cutting edge geometries on various objectives, concluding that effects of cutting edge preparation on surface...


3. Experiments

Experiments were carried out on a Karl Klink vertical broaching machine. The setup featured a static tool, while the clamped workpiece moves downward with the set cutting speed \( v_c \). The dimensions of the workpieces were 80x4x20 mm, with the cutting depth being applied to the height of 20 mm. A Walter Tools cutting edge type WKM P8TN 6028833 with a cutting wedge angle of 90° was utilized. The uncoated cutting edge was prepared by brushing with a SiC-filament-brush with a grain size of 180, and on a drag finishing machine DF4815 of the company OTEC GmbH. The cutting tool microgeometry was determined by a confocal light microscope of the NanoFocus AG and subsequently characterized rake angle dependent utilizing the mentioned geometric dependencies demonstrated in [6]. Process parameters of the orthogonal cutting experiments which were conducted with AISI 4140 QT as well as the cutting edge parameters are listed in Table 1. The chosen parameters ensure the full immersion of the microgeometry into the material. The cutting angles in combination with the cutting edge geometry allow for a wide scatter of most, but not all process related cutting edge parameters shown in Fig. 2, barring chamfers. The workpieces’ microstructure was optically quantitatively analyzed using a Focused Ion Beam (FIB) system.

### Table 1. Parameters of orthogonal cutting experiments with AISI 4140 QT.

<table>
<thead>
<tr>
<th>Experiment/Workpiece</th>
<th>Cutting Speed ( v_c ) [m/min]</th>
<th>Cutting Depth ( h ) [( \mu )m]</th>
<th>Rake Angle ( \gamma ) [°]</th>
<th>( S_1 ) [( \mu )m]</th>
<th>( S_2 ) [( \mu )m]</th>
<th>( K ) [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>75</td>
<td>54</td>
<td>-3</td>
<td>54</td>
<td>173</td>
<td>0.3</td>
</tr>
<tr>
<td>2</td>
<td>75</td>
<td>54</td>
<td>-15</td>
<td>54</td>
<td>173</td>
<td>0.3</td>
</tr>
</tbody>
</table>

### Table 2. Simulated cutting edges and cutting parameters

<table>
<thead>
<tr>
<th>Series</th>
<th>Cutting speed ( v_c ) [m/min]</th>
<th>Cutting depth ( h ) [( \mu )m]</th>
<th>Rake angle ( \gamma ) [°]</th>
<th>( S_1 ) [( \mu )m]</th>
<th>( S_2 ) [( \mu )m]</th>
<th>( K ) [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>from 75 to 150</td>
<td>30</td>
<td>-7</td>
<td>30</td>
<td>30</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>from 100 to 150</td>
<td>50</td>
<td>-7</td>
<td>30</td>
<td>30</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>from 150 to 200</td>
<td>50</td>
<td>-7</td>
<td>30</td>
<td>30</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>from 75 to 150</td>
<td>54</td>
<td>-15</td>
<td>54</td>
<td>173</td>
<td>0.3</td>
</tr>
</tbody>
</table>

4. FE-simulations

The FE-simulations were conducted with ABAQUS/Standard utilizing the same basic model as in [11] with a constant friction coefficient obtained from [14]. The measured cutting edge microgeometries were fitted elliptically for \( S_1 \) and \( S_2 \) in order to generate their simulated counterparts. In addition to simulations following the experimental setup, 11 cutting edges with a wedge angle of 90° characterized geometrically as per Fig. 1 and Fig. 2 with a range of geometries and process parameters as shown in Table 2 were used. Grain refinement was modelled strain and strain rate dependent with a Zener-Hollomon approach as described in [11], starting with a homogenous grain size of 10 \( \mu \)m.
5. Results and discussion

The FIB analyses of the two workpieces are shown in Fig. 3. It is clearly visible, that the different rake angles led to profoundly different microstructures in the workpieces. While workpiece 1 only shows a grain refined layer depth of about 3 μm, workpiece 2 features a grain refined surface layer depth of roughly 14 μm. This is most likely explained by the big resulting difference of the cutting edge microgeometry orientation relative to the workpiece.

Since the cutting depth was the same for both experiments, there is a difference between the ratio of the height of the break-off point \( P \) and the cutting depth \( h \) which mathematically amounts to 1.1 in experiment 1 and 1.5 in experiment 2 due to the different rake angle alone. Together with the effect of increased grain refined surface layer depth concurrent with increasing relative roundness \( r/h \), which was analyzed in [11], this could be seen as one factor leading to these results. The effect as shown in [11] however is not as profound as the results at hand, which suggests additionally operative factors which are currently neither known nor understood.

Regarding the results of the simulations a clearer image can be seen. Fig. 4. shows, that different form-factors can lead to different grain refined depths without changing any other process parameter. The microgeometry of the cutting edge alone therefore changes grain refinement critical process characteristics like temperature, strain rate and total strain sufficiently to incite profound differences in the agency of the grain refinement process. The exemplary depiction of the accumulated plastic strain distribution for different form-factors in Fig. 5 underlines this by clearly showing a deeper layer of material being deformed plastically during the process correlating to a deeper grain refined surface layer.

Additionally the grain size distribution of these deeper layers is very homogeneous for the first few micrometers hinting at another factor influencing the process, namely the strain rate. As can be seen for series 1 in Fig. 6, high maximum strain rates can be found for form-factors of one and above, while form-factors below one exhibit much smaller maximum strain rates.

At the same time the lowest form-factor sees the highest percentage of simultaneously deforming elements (values smoothed to centroids) with a strain rate at or above 2 000 \( \text{1/s} \) still well above the strain rate needed for grain refinement to take place. Therefore a much larger volume of the workpiece deforming leads the simulation to predict deeper grain refined surface layers.

In order to better compare the results, the depth to be considered as grain refined was defined to be the depth measured from the resulting surface, in which the grain size (\( g_s \)) surpasses 1 μm, namely \( z_{gs}=1 \mu m \). When putting this depth in perspective with the form-factor, as has been done in Fig. 7 for all conducted simulations, the influence of the form-factor becomes less apparent, especially for series 1 between a form-factor of 5 and 0.6, which is depicted in red. The form-factors of 0.3 and 0.2 on the other hand show a much deeper surface layer depth of up to 13 μm. The previously mentioned dependence on the relative roundness can be observed for the cutting edges with a form-factor of 1. With the cutting depth always at or above the radii this effect is moderate at best. For
series 2 and 3 one can also observe the effect of the cutting speed, as has been observed in [5], where lower cutting speed leads to a deeper grain refined surface layer. While the result of the simulation for experiment 2 is in agreement with the experiment itself, this is not the case for experiment 1, where a significantly smaller grain refined surface layer depth was measured.

When finally moving to the geometrically calculated parameters of the cutting edges a few striking dependencies become apparent. One of them is between the grain refined surface layer depth \( h_{\text{min}} \), and the height of the ploughing area \( h_{\text{plough}} \) as shown in Fig. 8. Almost independent of many other process parameters, like cutting speed and depth, a tendency for greater grain refined surface layer depth with increasing \( h_{\text{min}} \) can be deduced. It may even be prudent to assume a connection between the ploughing area height, length or area and many surface integrity related workpiece properties like hardness distribution or even surface characteristics. These workpiece properties however will have to be analysed separately. It has to be mentioned, that differences in \( h_{\text{min}} \) between series 4 and the experiments are rake angle dependent and stem from the idealization of the real geometry for the simulations, which were primarily fitted for rake angle independent form-factor conformity.

\[ \text{Fig. 8: Ploughing area height related to grain refined surface layer depth. } v_c: \text{Series 1 and 4: 75 m/min, Series 2: 100 m/min, Series 3: 150 m/min} \]

6. Conclusion

This work demonstrates a correlation of characteristic, rake angle dependent parameters of cutting edge microgeometries and aspects of the resulting surface integrity, namely the depth of the grain refined surface layer. It was found, that the classic characterization of asymmetric cutting edges by form-factor is insufficient, but applicable parameters for adaption to real cutting situations, as those from [6], exist and show clear tendencies in simulations. These dependencies are seemingly not as contingent on process parameters like speed and cutting depth as previously thought. Since in this work a constant friction was assumed, future studies should include a temperature and sliding speed dependent friction model like the one from [14]. The conducted experiments as yet lack in number and scope and are not fully in agreement with the simulations, whose method of grain refinement prediction was verified in [11]. Additional simulations and experiments are needed to make definitive assertions regarding the microgeometry of cutting edges and the resulting surface integrity. These further studies should take into account the demonstrated dependencies and relate them to process characteristics like temperature and forces.

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References