Modification of the Tool-Workpiece Contact Conditions to Influence the Tool Wear and Workpiece Loading during Hard Turning

B. Denkena¹, L. de León¹ and R. Meyer¹
¹Institute of Production Engineering and Machine Tools (IFW), Leibniz Universität Hannover, Germany
denkena@ifw.uni-hannover.de, leon@ifw.uni-hannover.de, meyer@ifw.uni-hannover.de

Abstract:
Tool wear during hard machining leads to unfavourable changes of the workpiece surface and subsurface layers. Due to increasing flank wear, thermal and mechanical loads affect the microstructure and the residual stress state of the workpiece subsurface. These effects cause a reduction of the lifetime of the machined components during operation. This article presents an approach of modified corner radii of cutting tools for hard turning processes to change the tool wear progression and the influence on the machined subsurface layers. Hereby the size and direction of the contact length of the cutting edge is adjusted as well as the specific load during machining. The results show the potential of controlling the tool wear and the workpiece subsurface properties by the contact conditions of the tool-workpiece interface during hard turning.

Keywords: Hard turning, tool microgeometry, workpiece subsurface

1. Introduction
Finishing of hardened steel components is a widely-used technique in the production industry and it is an object of high interest for researchers. Besides abrasive processes, cutting processes are established to machine hardened steel components [1, 2]. Due to high removal rates, short machining times, flexible process design and the possibility to work without cooling lubricant, hard turning is very interesting for industrial manufacturers [3]. On the one hand the productivity of hard turning processes is important [14]. Under operational conditions, hardened components are often loaded near their physical limits. Therefore the surface quality, dimensional and form tolerances as well as the surface integrity are important characteristics to evaluate hard machining processes.

From numerous investigations an advanced understanding of basic mechanisms during hard turning is achieved up to now. Several authors [4–9] report of the influences of hard turning processes on the surface integrity of machined components. Field and Kahles [7] describe surface integrity as the relationship between the surface geometric values and the physical properties such as residual stress, hardness and microstructure of the surface layers. The surface integrity has a large impact on the lifetime of the machined component. This influence is caused by the high stresses and temperatures during the cutting process as well as the high stress and temperature gradients that subject the outer subsurface zone to immense plastic deformation and thermal stress [4, 6]. The workpiece surface and subsurface are affected by the tool conditions such as the microgeometry and the wear state of the cutting edge. When the tool flank wear increases the thermal and mechanical loading of the workpiece subsurface zone increases also. If a certain width of flank wear is exceeded, an annealed zone is formed. This zone is called “white layer”. Within this layer, the residual stress state is influenced significantly.

The passive force $F_p$ strongly depends on the tool flank wear and is an indicator for the loading of the workpiece surface layer [8]. Vomacka and Walburger describe the formation of residual stress as normal force applied on the workpiece by the tool, causing plastic deformation and as a consequence raising of the compressive stress on the surface layer. Friction between the tool and the workpiece results in heat development leading to residual tensile stress gradients on the surface layer [9]. Figure 1 shows exemplary micrographs of AISI 5115 workpiece surface layers, that were machined with an unworn sharp tool and a tool edge with a flank wear width of $V_{Bc} = 250 \, \mu m$. Due to the high degrees of friction, plastic deformation and heat generation at the clearance face of the worn tool, a white surface layer is formed. Within this layer, tensile residual stress gradients are present.

Figure 1: Formation of white layers during hard turning.
Proceedings of 4th CIRP International Conference on High Performance Cutting, 2010

Previous investigations on hard machining processes show that the formation of residual stress proceeds by an overlapping of thermal and mechanical mechanisms in the workpiece subsurface.

The interaction and outcome of these mechanisms depends on the workpiece material as well as the applied tool and process conditions. De León shows, for example, during milling of aluminum, that unlike to the mechanical load impact at the cutting tool edge, the process temperature has no significant influence regarding the residual stress formation and workpiece distortion [10]. Brinksmeier et al. prove that surface hardening processes can be arranged by deep rolling of premachined workpieces. This leads to a strain induced martensitic transformation of the surface zone of X210Cr12 steel material. This mechanical treatment is suitable for increasing the wear resistance and fatigue strength of such machined workpieces [11].

Recent findings document that modifying the tool-workpiece conditions by the tool geometry offers possibilities for tool life improvement and reduction of wear induced negative influencing of the surface during hard turning. Denkena et al. apply an undercut at the tool clearance face to restrict the growth of the width of flank wear during the hard turning process [12, 13]. In dependency of the size of the undercut, a significant enhancement of the tool life time, up to 200 %, is achievable. A nearly constant wear level of the tool flank face is available during a distinctive period of cutting time whereas the passive force and the hertzian stress in the tool-workpiece contact area are nearly constant. This causes a constant mechanical and thermal loading as well as a constant residual stress state of the workpiece surface zone. Thereby, the characteristic of the residual stress level and penetrating depth can be controlled by controlling the geometric contact conditions.

The approach is to modify additionally the contact conditions between the tool corner radius of the major and minor cutting edge and the workpiece. As displayed in Figure 2 the corner radius influences the size of the effective contact length between the tool and the workpiece as well as the cross section of the uncut chip thickness.

Modification of the contact length can thereby be beneficial to control the amount and the direction of the thermal and mechanical tool and workpiece load as well as the tool wear rate.

Although new knowledge about the influence of the tool edge corner on the process factors are present, the basic understanding of the hard turning process is not complete yet. The aim of this article is to investigate the influence of the contact conditions between the tool and the workpiece on the tool wear and the resulting workpiece properties during hard turning. This is part of the approach of the functional design of cutting edges regarding the specific load conditions during hard turning.

2. Experimental Procedure

The influence of the tool edge corner geometry on the hard turning process is examined by external cylindrical turning of case-hardened 16MnCr5 (AISI 5115) steel. The hardening depth is about \( E_{\text{th}} = 1 \text{--} 1.5 \text{ mm} \). The micro hardness averages about 770 HV 0.05 decreasing to 630 HV in a depth of \( z = 1 \text{ mm} \). The cutting tests are carried out using a CNC lathe Gildemeister CTX 520 linear. This lathe has a drive power of \( P_{\text{max}} = 149 \text{ kW} \) and a maximum rotational speed of \( n_{\text{max}} = 10,000 \text{ min}^{-1} \).

For the cutting tests the cutting tool material WBN560 with a CBN content of 56% is applied. The tool corner modification is done by using sharp inserts of the type CNGA 120412. The tools are prepared by grinding the corner to adjust the major cutting edge in the range of \( r_{\varepsilon 1} = 100 \text{--} 1200 \mu \text{m} \). The minor cutting edge remains constant at \( r_{\varepsilon 2} = 1200 \mu \text{m} \) and will be examined in a separate investigation. By these tool geometries the size of the effective contact length \( l_k \) as well as the average uncut chip thickness \( h_m \) and the shape of the cross section of the uncut chip thickness vary (Figure 3).

![Cross-section of uncut chip thickness at conventional tool geometry](image1)

![Cross-section of uncut chip thickness at modified tool geometry](image2)

Figure 2: Modification of the contact length.

![Shape of cross-section of uncut chip thickness](image3)

Figure 3: Shape of cross-section of uncut chip thickness.
Due to the increase of the corner radius, the shape of the cross section of the uncut chip thickness changes from a compact form to a slim comma-shaped form. The orientation of the cross section turns hereby more parallel to the workpiece axis, whereas the effective tool cutting edge angle $\kappa_{\text{eff.}}$ decreases. In Table 1 a summary of the specific process adjustments of the modified tool corners are given. The geometric process characteristics of the small radius $r_{\varepsilon 1} = 100 \, \mu m$ differs significantly from the radii $r_{\varepsilon 1} \geq 400 \, \mu m$.

Table 1: Geometric process characteristics.

<table>
<thead>
<tr>
<th>corner radius $r_{\varepsilon 1}$</th>
<th>cross section of uncut chip thickness $\Lambda$</th>
<th>av. uncut chip thickness $h_\text{av}$</th>
<th>cutting edge angle $\kappa_{\text{eff.}}$</th>
<th>contact length $l_k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 $\mu m$</td>
<td>10,000 $\mu m$</td>
<td>63.3 $\mu m$</td>
<td>45.0 $^\circ$</td>
<td>159 $\mu m$</td>
</tr>
<tr>
<td>400 $\mu m$</td>
<td>10,000 $\mu m$</td>
<td>34.6 $\mu m$</td>
<td>20.7 $^\circ$</td>
<td>289 $\mu m$</td>
</tr>
<tr>
<td>800 $\mu m$</td>
<td>10,000 $\mu m$</td>
<td>24.8 $\mu m$</td>
<td>14.5 $^\circ$</td>
<td>404 $\mu m$</td>
</tr>
<tr>
<td>1200 $\mu m$</td>
<td>10,000 $\mu m$</td>
<td>20.3 $\mu m$</td>
<td>11.8 $^\circ$</td>
<td>494 $\mu m$</td>
</tr>
</tbody>
</table>

During the cutting tests the effective rake angle is about $\gamma_{\text{eff.}} = -30^\circ$ and the chamfer angle is about $\gamma_f = -24^\circ$. The geometrical accuracy of the ground corner radii is $\pm 20 \, \mu m$. Figure 4 shows an overview of the applied tools. The process parameters are constant at cutting speed $v_c = 150 \, \text{m/min}$, cutting depth $a_p = 0.1 \, \text{mm}$ and feed $f = 0.1 \, \text{mm}$. The nominal cutting edge angle of the insert holder is $\kappa_0 = 95^\circ$.

3. Results of the Experimental Cutting Tests

3.1 Tool wear and process forces

The tool wear tests are performed by measuring the width of flank wear $V_B$. The results show a distinctive wear progress over the cutting time (Figure 5). Each tool geometry is applied two times in external cutting. From these results one curve is shown in this diagram. The maximum divergence for each run is below $V_B = 15 \, \mu m$, whereas a good repeatability of the tool wear behavior is achieved.

Low corner radii $r_{\varepsilon 1} = 100 \, \mu m$ cause faster tool wear than big radii. With increasing corner radius, the tool wear speed decreases. The difference in the wear behavior of the tools $r_{\varepsilon 1} = 800 \, \mu m$ and $r_{\varepsilon 1} = 1200 \, \mu m$ is small and the tool lifetime reaches comparable values at $t_c > 80 \, \text{min}$.

Figure 5: Influence of the corner radius on the tool wear.
During cutting, a distinctive tool wear in terms of flank and crater wear appears on the flank and rake face. Due to the geometric operation conditions of the applied tool radii, the shape and the width of the wear appearance is significantly different (Figure 6).

At small edge radii, the crater wear forms a circle-like shape on the rake face. The contact area between the tool and the workpiece is concentrated at the corner. For big corner radii, the shape of crater wear changes in a comma-shaped form, whereas the flank wear is much smaller and more uniform at the tool edge. The reason for this effect is the bigger contact length \( l_k \) (Table 1). With increasing cutting time, the contact length expands in the direction of the minor cutting edge and local notch wear of the wear mark increases. This influences the workpiece surface roughness with increasing cutting time.

The types of operating tool geometry and engagement conditions lead to distinctive wear action, that is caused by the resulting mechanical and thermal load distribution at the cutting edge. The load is significantly influenced by the size of the main cutting edge corner \( r_{c1} \). The measured process forces show that the increase of the corner radius up to \( r_{c1} = 1,200 \, \mu m \) in the unworn state leads to a rise of the passive force (Figure 7). This can be expected due to the direction of the cross section of uncut chip thickness. The cutting force increases marginally. Reason therefore is the generally rise of the specific cutting force by decreasing uncut chip thickness \( h \).

The size of the force in feed direction is influenced by increasing tool wear and the tool corner radius size. The direction of the force load during hard turning is changed more into the workpiece surface by increasing corner radii. This is caused by the characteristic shape of the cross-section of uncut chip thickness, which is increasingly oriented towards the workpiece. Due to the wear progression up to \( VB_c = 170 \, \mu m \), the process force increase, in particular the passive force is significantly influenced.

By changing the tool corner and the shape of the cross section of uncut chip thickness \( A \), the average uncut chip thickness \( h_m \) as well as the specific cutting force \( k_c \) are influenced (Figure 8). It can be seen, that the decrease of the average uncut chip thickness \( h_m \) in the range of \( h_m = 63.3 \, \mu m \) to \( h_m = 20.3 \, \mu m \) (Table 1) towards big corner radii effects a rise of the specific cutting force up to \( k_c = 5,600 \, N/mm^2 \). This results from the rise of the cutting force, while the size of the cross-section of uncut chip thickness remains approximately constant. Due to the tool wear, the specific cutting force increases. This is influenced by a rising crater wear depth and a higher energy consumption due to increasing chip deformation, which can also be seen on chip micrographs, and friction at the crater ground on the rake face.

The calculation of the specific passive force \( k_p \) shows, that a high amount of energy is exposed to the tool clearance face and workpiece surface. With rising corner radius \( r_c \) and lower cutting edge angle \( \kappa_{eff} \) values up to \( k_p = 7,400 \, N/mm^2 \) are reached. Hereby more process energy for the surface impact than for the workpiece material separation is needed. Due to rising tool wear the
Although the specific tool load rises, big corner radii show a better wear behavior. Hence, an additional specific value regarding thermal processes will be used to analyze the tool load. Schmidt and Tönshoff et al. show, that the friction power per contact length $P'_\alpha$ is a value to characterize the friction process at the cutting edge, regarding the tool wear and the contact conditions [4]. $P'_\alpha$ is determined by:

$$
P'_\alpha = \frac{\mu \cdot F_d \cdot l_k}{k_c}
$$

The friction power per contact length considers the resulting thrust force $F_d$ that is applied to the contact length $l_k$ at the tool edge. According to Schmidt, friction after the coloumb’s friction law is applied by $\mu = 0.26$.

Small corner radii lead to high degrees of friction power during hard turning. The small contact length of the tool at $r_{1e} = 100 \mu m$ overcompensates the small amount of the passive force. Due to the rise of the feed force values of $P'_\alpha > 500$ W/mm are reached. For increasing radii, the high values of the passive force is distributed over a bigger contact area of the engaged corner radius, whereas the specific tool load $k_c$ has less impact on the tool wear progress. With increasing tool wear, the friction power rises significantly. In Figure 9 the theoretical contact length from Table 1 is applied.

By measuring the real contact length at the tool corner at the maximum tool life time, the value of the friction power is lower in general. The real contact length is expanded into the minor cutting edge due to progressive wear.

### 3.2 Workpiece Surface and Subsurface properties

Due to the cutting process a distinctive profile of thermal and mechanical loads is applied to the workpiece surface layer. The corner radius as well as the geometrical cutting conditions at the tool tip cause a heating and cooling of the workpiece material in a short time. The heat dissipation from friction and the hertzian stress lead to the formation of microstructual changes and residual stress gradients in the workpiece surface layer. The measurements of residual stress of the machined parts show the clear influence of the tool corner radius and the tool wear state on the residual stress profile of the surface zone (Figure 10).

The unworn tool causes compressive residual stresses at the workpiece surface and surface layer in all cases. Low corner radii lead to high degrees of compressive stress up to $\sigma = -1,200$ MPa as minimum. The increase of the tool corner radius leads to a shift of the stress state in the direction of tensile stress. The maximum depth of the influenced surface layer is bigger for increasing tool radii.

Regarding the worn tools ($VB_c = 170 \mu m$), tensile residual stresses are formed at the surface in all cases whereas the level of minimum stress beneath the surface keeps approximately constant compared to the unworn tool state. The surface tensile stress value of machining with big radii is higher than by using the small radius $r_{1e} = 100 \mu m$.

![Figure 10: Depth profiles of residual stress.](image)

By applying small corner radii, the thermal and mechanical load impact on the workpiece and tool corner has a punctual characteristic. This leads to faster tool wear on the one hand. On the other hand, the absolute amount of heat that is applied to the workpiece is small in comparison to big radii whereas a lower penetration depth of the temperature into the workpiece takes place. Thereby, the mechanical impact by local pressure and plastic deformation of the workpiece leads to major compression stress values of the surface layer. For big corner radii, the thermal loads are applied to a bigger contact area. Also the specific cutting force, passive force and heat amount are higher than for small radii. This results altogether in a brighter and deeper temperature penetration and higher values of temperature in the surface area than compared to small radii. The residual stress profile is overall shifted towards tensile stress.

The micrographs of the machined surface layers show the influence of the described process conditions on the workpiece microstructure (Figure 11). By using unworn tools the surface has no significant microstructual changes, except the small corner radius $r_{1e} = 100 \mu m$. Here, the workpiece exhibits a structural changing, that is related to the characteristic of white layers. The application of worn tools leads to the formation of white layers in all cases of tool corner radius size. The reason for this
effect is the generally higher level of force and friction impact at the workpiece surface.

![Micrographs of the workpiece microstructure](image)

**Figure 11:** Micrographs of the workpiece microstructure.

### 4. Conclusion

In this paper, the influence of the tool corner geometry during hard turning has been investigated. The results show that the corner radius, the size and direction of the cross section of uncut chip thickness influence the tool wear behavior and the force impact. Small corner radii cause low process forces but lead to a punctually loading of the tool edge. Cutting with increasing tool corner radii leads to an increase of the process forces and to a significant change of the load that is applied to the workpiece surface layer. Due to the broader contact area of the tool, the load is more distributed along the cutting edge. On the one hand, the tool the wear proceeds slower over the cutting time and has a more uniform progression at the tool edge. On the other hand, the residual stress state is shifted more into the direction of tensile stress. However, a critical level of the residual stress state of the surface layer by using a big radius does not occur.

It can be outlined, that an increasing contact length of the tool in the tool reference plane $P_r$ is beneficial for the hard turning process although the absolute process forces rise. Contrary to this, the size of contact in the tool orthogonal plane $P_0$ should be minimized to avoid negative influencing of the workpiece in terms of tensile residual stress and workpiece microstructure. For the prediction of the resulting residual stress state during hard turning not the geometrical process conditions but the mechanical load at the new generated surface, perpendicular to the workpiece, is suitable.

### Acknowledgement

The authors like to thank the German Research Foundation (DFG) for funding this work within the project “Methode zur Reduzierung der Bauteilbeeinflussung bei der Hartzerspanung” (DE-447/23-2).

### References


