Influence of residual stresses in PVD-coatings on cutting performance in turning of AISI 4140

B. Breidenstein¹, B. Denkena¹, B. Richter¹*, J. Vetter²

1. Institute of Production Engineering and Machine Tools (IFW), Leibniz Universität Hannover, Germany
2. Oerlikon Balzers Coating Germany GmbH, Bergisch Gladbach, Germany
* corresponding Author, richter@ifw.uni-hannover.de

ABSTRACT

AlTiN and TiAlSiN coatings are effective wear protection methods for cutting tools due to their mechanical, thermal and chemical properties. Furthermore, residual stresses in coatings significantly affect the wear behavior of tools. The influence of varied residual stress state and its depth distributions in continuous and interrupted cut of AISI 4140 is investigated in this paper. The results show a significant influence of the coating residual stress states near the coating surface and near the interface on cutting performance. Especially in interrupted cutting processes, high compressive residual coating stresses near the interface lead to increased tool life due to prevented crack initiation.


1 INTRODUCTION

Nitride based hard compound coatings prepared by physical vapour deposition methods (PVD) are applied on cutting tools due to increased requirements on tool performance. High hardness, thermal stability and wear resistance in combination with tailored cutting edge microgeometries allow to improve tool life significantly /1, 2/. Based on monolithic binary compounds like TiN and CrN, hard coatings for today’s machining applications have been refined to coatings of a more complex structure with alloyed elements to improve the coatings properties. The addition of aluminium increases the oxidation resistance /3/, the mechanical properties /4, 5/ and thus possible applications in machining due to an increased wear resistance. Further, multilayer coatings with stacks of alternating sublayers and additional different thicknesses, chemical structures and crystallographic textures combine different advantageous properties to increase tool life /6/.

The PVD process induces compressive residual stresses into the coatings. For machining tools these high compressive residual stresses are advantageous as they counteract crack initiation and propagation. High compressive residual stresses increase wear resistance of cutting tools but also can decrease the adhesion between coating and substrate /7, 8/. However, an increase of compressive residual stresses in the substrate increases adhesion /9/. The induced residual stresses in the coatings affect tool life and wear behavior of the coated machining tools and promote or prevent coating failures /10, 11, 12/.

For optimized residual stress conditions in the coatings depth resolved information of the process-related stress depth gradients has to be known. For the non-destructive determination of residual stress depth distributions in thin coatings the methods of the scattering vector /13/, which is used in this study, the grazing incidence (GID) /14/ or energy dispersive techniques /6, 15/ can be used. With information of depth resolved residual stresses of coatings and their states near the coatings surface and near the interface performance can be increased for different cutting conditions like interrupted cut. Therefore, in this study different residual stress states of two coatings were investigated to analyze the influence of the residual stresses on cutting performance due to the known interaction of coatings residual stresses and wear behavior. Thickness, structure and composition of each coating are kept constant to determine only the influence of the residual stresses on the performance. Therefore, hardness and thermal properties of the coatings are comparable.
2 EXPERIMENTAL

2.1 Applied coatings

Two different PVD hard coatings, Al<sub>55</sub>Ti<sub>45</sub>N and TiAlSiN, deposited by cathodic vacuum arc evaporation were investigated. The applied coatings exhibit different coating architectures. The Al<sub>55</sub>Ti<sub>45</sub>N-coatings are monolayer coatings, whereas the TiAlSiN-coatings are bilayer with thicknesses of 3.5 µm of the TiAlN-layer and 0.5 µm of the toplayer TiSiN. In the following the standard coatings are named “AlTiN” and “TiAlSiN”. The coatings “AlTiN var” and “TiAlSiN var” exhibit changed residual stresses by varying process pressure and BIAS voltage in the coating process. Table 1 summarizes the coatings thickness and hardness. Coating thickness was measured by calotte grinding after DIN EN 1071-2. The determined hardness of the used coatings is the average of five measurements with 2,000 µN using a Berkovich indenter with 80 nm tip radius, 5 s force increase and decrease time and a dwell time of 3 s.

**Table 1: Classification of the coatings**

<table>
<thead>
<tr>
<th></th>
<th>AlTiN</th>
<th>AlTiN var</th>
<th>TiAlSiN</th>
<th>TiAlSiN var</th>
</tr>
</thead>
<tbody>
<tr>
<td>thickness</td>
<td>3.7 µm</td>
<td>3.8 µm</td>
<td>4.0 µm</td>
<td>3.7 µm</td>
</tr>
<tr>
<td>hardness</td>
<td>2,400 HV</td>
<td>2,500 HV</td>
<td>3,900 HV</td>
<td>4,100 HV</td>
</tr>
</tbody>
</table>

Depth resolved residual stress measurements of the coatings on the flank face have been performed on a GE X-ray diffractometer type Seiffert XRD 3003 eta equipped with Co Kα radiation (30 kV, 40 mA) and a 2 mm diameter collimator utilizing the scattering vector method. Theoretical basics and mathematical coherences of the scattering vector method are explained in /13/. Due to the absorption coefficients of the TiAlSiN-coatings the penetration depth is smaller than the coatings thickness. Figure 1 presents the Laplace residual stress depth distributions of the coatings. The results are the average of two measurements. Deviations of the measured points are less than the plotted marks, thus not shown in figure 1. The selected peaks for stress determination of the coatings are hkl = 200. Changed process pressure and BIAS voltage lead to a lattice distortion, thus to increasing compressive residual stresses inside the AlTiN and TiAlSiN coating. The residual stresses near the coatings surface and near the interface are almost on the same level. The changed coating process parameters increase the compressive residual stresses of the TiAlSiN-coating distinctly up to -7,000 MPa. Higher residual stresses of the TiAlSiN var coating occur near coatings surface and substrate compared to TiAlSiN. However, the progression of the residual stresses inside the coating do not change significantly.
2.2 Cutting experiments

In this study, external continuous and interrupted turning experiments without cooling were performed on a Gildemeister CTX 520 lathe. The interrupted cut was realized by prepared specimens by milling four slots over the length of the workpiece. As workpiece material AISI 4140 (42CrMo4) was used. The mechanical properties of the material are summarized in table 2.

Table 2: Mechanical properties of the used material

<table>
<thead>
<tr>
<th>material</th>
<th>tensile strength $R_m$</th>
<th>yield strength $R_{\sigma,2}$</th>
<th>elongation A</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 4140</td>
<td>1,033 MPa</td>
<td>926 MPa</td>
<td>16 %</td>
</tr>
</tbody>
</table>

The experiments were conducted with carbide tools CNMG 120412 MS and substrate K313. Rake and clearance angle were set to 5°. The cutting parameters were adjusted according to table 3. Wear measurements were carried out using a digital microscope Keyence VHX600. The criteria of tool life are flank wear land of $VB = 200 \, \mu m$, tool failure due to crater wear or a tool life of $t_c = 10 \, \text{min}$.

Table 3: Cutting parameters

<table>
<thead>
<tr>
<th>material</th>
<th>cutting speed $v_c$</th>
<th>feed $f$</th>
<th>depth of cut $a_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>AISI 4140</td>
<td>200 m/min</td>
<td>0.2 mm</td>
<td>1.0 mm</td>
</tr>
</tbody>
</table>

3 RESULTS AND DISCUSSION

3.1 Continuous cut

In order to investigate the influence of constant mechanical and thermal load, turning experiments with continuous cut have been conducted. Tool life of the used coatings in continuous cut of AISI 4140 is
presented in figure 2. All tools achieved the tool life criterion of $t_c = 10$ min. The changed residual stresses of the AITiN-coatings lead to no significant difference of the width of flank wear land VB with cutting time $t_c$. This leads to the conclusion that the residual stress state near the surface and near the substrate, which are nearly the same for both coatings AITiN and AITiN var (figure 1), influences the wear behavior more than the residual stresses between surface and substrate. Higher compressive residual stresses in the coating between the surface and the substrate of AITiN var cause minor differences regarding cutting performance in comparison to the AITiN coating.

Figure 2: Wear behavior of the used coatings in continuous cut

Whereas, the width of flank wear land VB of the TiAlSiN coatings increases with varying residual coating stresses distribution. High compressive residual stresses of TiAlSiN var lead to an increase of the initial flank wear, thus to an increase of the flank wear of about 20 percent at a cutting time of $t_c = 10$ min in comparison to the TiAlSiN coating. The increasing initial flank wear at high compressive residual stresses can be explained with the tool life limiting critical value of compressive residual stresses, shown by Klocke et al. /12/. Here it is stated that wear increases with compressive residual stresses over a critical value due to increasing brittleness of the coating. This value can be reached in continuous cut of AISI 4140 with the high compressive residual stresses of the TiAlSiN var coating. The width of flank wear VB of the TiAlSiN coating is similar to the AITiN-coatings. Concerning the residual stress state less flank wear in continuous cut of AISI 4140 can be achieved by coatings with compressive residual stresses up to -4 GPa. Near substrate and near surface compressive residual stresses about -1 GPa to -2 GPa are suitable.

3.2 Interrupted cut

Tool life in interrupted cut is limited by tool breakage due to dynamical thermo-mechanical load /16/. Rapidly growing crater wear causes crater lips and thus weakens the tool edge. Tool lifetime and wear behavior of the used coatings are shown in figure 3. Only the residual stress modified coating TiAlSiN var achieved a cutting time of $t_c = 10$ min. AITiN, AITiN var and TiAlSiN coated tools failed due to tool breakage caused by crater wear. The high compressive residual stresses of the TiAlSiN var coating increase the stability of the crater lip and the resistance against tool breakage. Furthermore, the interrupted cut leads to tensile stresses in the tool due to a variation of the thermo-mechanical loads /16/. With high compressive residual stresses the TiAlSiN coating can withstand these superimposed tensile stresses. The experiments point out a significant improvement of the cutting performance in interrupted cut for coatings with high compressive residual stresses. In comparison to TiAlSiN a variation of the residual stresses increased tool
life up to 65 percent. It can be stated that high compressive residual stresses for interrupted cut are suitable, especially near the substrate. However, this leads to a high gradient of the residual stresses in the interface to the substrate due to low residual stresses in the substrate near the interface /17/. Therefore, the effect of high compressive residual stresses in the coating near the substrate on coating adhesion in other applications has to be investigated. Wea

![Graph showing cutting time and flank wear for different coatings](image)

**Figure 3:** Wear behavior of the used coatings in interrupted cut

### 4 CONCLUSIONS

In this study the influence of residual stresses of coatings on cutting performance and wear behavior in continuous and interrupted cut of AISI 4140 was investigated. Therefore, different residual coating stresses were induced in AlTiN and TiAlSiN by varying process pressure and BIAS voltage during the coating process. Depth resolved residual stress states of the coatings were measured by the scattering vector method. It was shown that in continuous cut the residual stresses near the coatings surface and near the substrate influence wear behavior significantly in comparison to the residual stress state between surface and substrate. Compressive residual stresses over -4 GPa lead to increasing flank wear. This can be related to an increasing brittleness of the coating caused by a higher lattice dislocation and hardness due to the high compressive residual stresses. Thus, abrasive flank wear increases. However, in interrupted cut high compressive residual stresses increase tool life significantly. These residual stresses lead to a stabilized crater lip, thus increase the resistance against tool breakage, and withstand superimposed tensile stresses, which occur in the wedge in interrupted cut.

### 5 ACKNOWLEDGMENT

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