ON THE THERMAL INSULATION EFFECT OF PVD-AlCrN-COATED CUTTING TOOLS IN CONTINUOUS TURNING OF AISI 4140

S. Beblein¹, B. Breidenstein¹, B. Denkena¹

1. Institute of Production Engineering and Machine Tools, Leibniz Universität Hannover, Germany

ABSTRACT
Due to the development of new materials and the increasing demands of productivity in the last decades, cutting tools become increasingly exposed to higher thermal loads. To meet the requirements of modern machining processes, a wide variety of cutting tools is coated, which significantly increases their thermal stability. In recent years, several authors investigated the thermal load of coated cutting tools. Depending on the process, a contrary significance of the thermal insulation effect was reported. Therefore, this study investigated the impact of the coating’s thermal insulation effect in continuous turning of AISI 4140. The temporal dependence of temperature load was analyzed by a newly developed FEM based simulation model. It was shown that the thermal insulation effect decreases significantly with process duration.

KEYWORDS: PVD AlCrN-coatings, Thermal coating load, Thermal insulation effect

1. INTRODUCTION
A key driver of tool development is the use of new high-strength materials and the ongoing desire to increase the productivity of the processes /1/. Machining with increasing feed rates and cutting speeds generally leads to an increasing thermomechanical load on the tools. Particularly in the case of dry machining, a significant temperature load of the tool occurs due to the lack of a cooling effect. This can cause a change in the material properties and significantly reduce the wear resistance of the tools. In the last decades, PVD hard compound coatings are increasingly used to improve the cutting performance of cemented carbide tools. Today approximately 85% of the cemented carbide tools are coated /1/. Such coatings are characterized by optimized frictional properties, higher thermal and chemical stability and by a higher hardness than the substrate material /2/. However, the diversity of the processes in terms of the thermomechanical load require coating systems with application-specific chemical, mechanical and thermal properties. It can be stated, that the knowledge of the temperatures occurring is essential for the design of a coating according to the requirements /3/.

Temperature measurement in metal cutting processes has a long history, which is summarized in /4/. This paper gives an overview of several widely used measurement methods and outlines their uncertainties. The authors point out that in spite of the continuous technological progress in the field of temperature measurement, combined uncertainties of 10% can be expected independently of the measuring method. Müller /5/ developed a fast fiber-optic two-colour pyrometer for temperature measurements of chip and workpiece surfaces. Here, quartz fibers with small diameters enabled measurements at locations with limited optical access. This method was further developed by Bassett /6/ to analyze the temperature distribution near the cutting edge of TiAIN-TiN coated tools with different microgeometries. For this purpose, a glass fiber was mounted in the cutting insert at 12 different positions with varying distance from rake and flank face. The smallest possible distance to the rake face was specified as 350 μm. On the basis of the locally measured values, the temperature distribution in the cutting tool was determined by means of surface interpolation and extrapolation in the direction of the tool surface. Since the expected insulation effect of the coating is not taken into account in this
method, further investigations were carried out with uncoated tools. Here, a maximum relative measurement uncertainty of only 0.3% was calculated. Pantke /3/ developed an in-process monitoring system for the measurement of the temperature load of cutting tools based on the Seebeck effect. This system was realized by applying a temperature-sensitive coating which enabled the measurement of the temperatures on the rake face at distances of 0.8, 1.6 and 2.4 mm to the tool tip. The mentioned experimental methods have in common that, due to the low spatial resolution or the relatively high distance from the surface or working zone, no statements can be made about the temperature distribution within the coating. Since the determination of the temperature is linked to an elaborate experimental effort, simulative methods are increasingly used. The latter enable the analysis of the cutting process with increased spatial and temporal resolution, but also rely on the accuracy of the material data and the implemented friction models.

Kone et al. /7/ investigated the thermomechanical load of differently coated cemented carbide tools during dry machining of AISI 316L using FEM simulations. Here, a significant influence of the coating system on the temperature distribution perpendicular to the surface could be determined after a simulation time of 6 ms. Particularly in the case of Al2O3 based coating systems, which are characterized by a very low thermal conductivity, increased temperature gradients between the substrate and the coating surface were observed. These results correlate well with the findings of Krajinovic et al. /2/. In this study the tool load during milling of AISI4140 with coated cemented carbide tools was investigated using two-dimensional FE simulations. On the basis of the results, it must be deduced that assuming the same friction conditions and a cutting time of 8 ms, the thermal insulation effect decreases with increasing thermal conductivity of the coating. However, similar to the simulations of Kone, the tool had not reached the thermal steady state at the time being examined. The results can therefore only be transferred to longer process duration to a limited extent. This is shown by the results of Yen et al. /8/. In this work a simulation model for orthogonal cutting with coated tools was developed and evaluated with experimental data. The steady-state temperature was calculated by means of an initial chip formation simulation and a subsequent heat transfer simulation based on the previously determined heat flows. It was found that the thermal insulation effect of the coating is significant only in the case of short process times and decreases significantly at the thermal steady state of the tool.

The thermal coating properties differ significantly from those of the substrate materials on which they are deposited /9/. Therefore, it can be assumed that discontinuities regarding the temperature distribution result in the interface between coating and substrate. However, these local changes in the temperature gradient can not be detected by conventional experimental methods. In addition few knowledge exists regarding the resulting temperature gradients in AlCrN-based coatings. Moreover, it is unknown whether coatings influence the cutting process based on tribological effects (lower heat generation in the secondary and tertiary shear zones) or based on thermal insulation of the substrate. The latter depends on the thermal resistances of the tool-chip and the coating-substrate interface as well as the coating itself /10, 11, 12/.

2. APPROACH

In order to analyze the time dependent temperature profile across the coating thickness and the substrate depth a combined method is presented in this work. The approach consists of an experimental measurement of the temperatures within the tool and a subsequent simulation of the temperature distribution based on an iterative optimization algorithm. Within the simulation, the temperature in the contact area is iteratively adjusted until a sufficient agreement between simulation and experiment is obtained. By taking into account the material-specific thermal coating properties and the coating thickness, the calculation errors which can occur with an exclusively mathematical extrapolation of the measured values can be reduced or avoided.
3. EXPERIMENTAL SETUP

Experimental orthogonal face turning tests were carried out on a CNC vertical lathe Gildemeister CTV400 without coolant. Tubes with a diameter of 100 mm and a wall thickness of 3 mm were machined. AISI 4140 (225 HV) was used as workpiece material. Cemented carbide inserts (Ceratizit Grade CTS12D, SNUN120412EN) with a commercially available PVD-AlCrN coating were used. The coating thickness was measured by calotte grinding and the average is calculated for three measurements on the rake face. Here, a coating thickness of 4.3 µm was determined. A cutting speed of \( v_c = 150 \) m/min and an uncut chip thickness of \( h = 0.1 \) mm were used in the investigations. A rake angle of \( \gamma = -6^\circ \) and a clearance angle of \( \alpha = 6^\circ \) were applied. In order to stabilize the cutting edge and to avoid edge chipping an average cutting edge rounding of \( S = 30 \) µm was used /13/. Temperature measurements have been conducted using the two-color ratio pyrometer IMPAC infrared-IGAR 12-LO MB13 with a measuring range of 350 - 1300 °C. The pyrometer evaluates the temperature by using two adjacent wavelengths of the electromagnetic IR-radiation collected by a graded-index-multimode fiber optic mounted in the inserts. The measurements were performed at three predefined points. For this purpose, grooves with a defined distance from the rake face (0.3, 0.4, 1.1 mm) and a depth of 250 µm have been laser machined into the flank face of the cutting insert. The systematic measurement uncertainty determined by Bassett /14/ on the basis of a comprehensive error analysis is approximately 7%. To estimate the statistical measurement uncertainty resulting from repositioning the glass fiber into the grooves, one repetition was carried out for all cutting tests. Based on the results, a statistical measurement uncertainty of 0.7% was determined.

4. FINITE ELEMENT MODELLING

To calculate the temperature distribution in coated cutting tools transient heat transfer simulations were performed using the commercial software SFTC Deform 2D 11.0.2 with an implicit Lagrangian formulation. The temperature distribution in the tool chip interface as well as the thermal material properties along the width of cut \( b \) are assumed to be uniform. According to this hypothesis, the temperature is approximated in a two-dimensional geometrical domain of the tool orthogonal to the main cutting edge, shown in Figure 1.

![Simulation model](image)

**Figure 1:** Simulation model.

The dimensions of tool and coating were defined according to the experimental investigations. The tool was defined as a rigid body and discretized by a finite element mesh consisting of
10,000 isoparametric four-node elements (ISO4) with straight element sides. Mesh density windows are applied to control the element size at the tool tip. Heat transfer within the body is calculated based on heat conduction. Heat exchange with the environment is defined by radiation and convection. The convection coefficient and the environment temperature are specified as constants \((T_{\text{Environ}} = 20 \, ^\circ\text{C}, \ h_{\text{Convection}} = 2 \, \text{W/m}^2\text{K})\). The applied thermal properties of coating and substrate are given in Table 1. The required data for the steel tool holder were taken from the deform library. The properties of the substrate are based on data from the manufacturer. Furthermore, a perfect thermal contact and no thermal resistance is assumed between the coating and the substrate.

<table>
<thead>
<tr>
<th>Temperature T [°C]</th>
<th>20</th>
<th>100</th>
<th>500</th>
<th>900</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity (\lambda) (Substrate) [W/m K]</td>
<td>85</td>
<td>80</td>
<td>68</td>
<td>60</td>
</tr>
<tr>
<td>Thermal Conductivity (\lambda) (Coating) [W/m K]</td>
<td>4.25</td>
<td>5.60</td>
<td>4.50</td>
<td>3.60</td>
</tr>
<tr>
<td>Thermal Conductivity (\lambda) (Tool holder) [W/m K]</td>
<td>41.7</td>
<td>43.4</td>
<td>36.7</td>
<td>34.1</td>
</tr>
<tr>
<td>Volumetric specific heat capacity (c) (Substrate) ([10^6 , \text{J} , \text{m}^{-3} , \text{K}^{-1}])</td>
<td>3.95</td>
<td>3.46</td>
<td>3.97</td>
<td>4.00</td>
</tr>
<tr>
<td>Volumetric specific heat capacity (c) (Coating) [10^6 , \text{J} , \text{m}^{-3} , \text{K}^{-1}]</td>
<td>3.10</td>
<td>3.20</td>
<td>3.70</td>
<td>4.00</td>
</tr>
<tr>
<td>Volumetric specific heat capacity (c) (Tool holder) [10^6 , \text{J} , \text{m}^{-3} , \text{K}^{-1}]</td>
<td>3.62</td>
<td>3.89</td>
<td>5.31</td>
<td>6.11</td>
</tr>
</tbody>
</table>

Table 1: Thermal material properties.

The average temperature on the rake face between tool and chip, which simultaneously is the quantity to be determined, serves as a boundary condition of this simulation model. The determination of the average surface temperature is based on an iterative algorithm, in which an exact solution is successively approximated. The procedure starts with an initial guess for the surface temperature, calculated by the previously mentioned extrapolation method. The temperature value for the subsequent step is determined based on the sum of the quadratic deviations between the measured and simulated temperature-time-curves for each measurement position. Here, the surface temperature is varied until the error between experiment and simulation is sufficiently small. A maximum deviation of the measured values in the range of the statistical and systematic measurement uncertainty of the experimental measurement was used as stopping criterion for this algorithm.

5. RESULTS AND DISCUSSION

Figure 2 shows the simulated temperatures for different distances from the rake face in comparison with the experimental results. Based on the results the experimentally measured temperature profiles can basically be divided into three phases: Heating, quasi-stationary phase and cooling. The beginning of the cutting process is characterized by high heating rates inside the cutting tool. In direction of the tool surface, an increase in the heating rate is observed. This can be attributed to the significant amount of heat, which is generated by energy dissipation during the plastic deformation of the material in the primary shear zone and by friction in the secondary and tertiary shear zones. Furthermore, this process is accelerated by high strains and strain rates, which result in a high heating rate of the chip.
The resulting temperature gradient is one of the main influencing factors for the heat transfer in the tool-chip interface. After 1.3 s, the heating rate decreases significantly for all three measurement positions. It can be assumed that at this point the surface temperature has reached a steady state and does not rise further throughout the cutting process. By applying the iterative algorithm described in Chapter 4, a temperature load of 890 °C was determined. The results exhibit that the experimentally measured temperature profile can be simulated with high accuracy. In the quasi-stationary phase (1.3 s < t < 7.3 s) and the cooling phase (t ≥ 7.3 s), the calculation error for all three measuring points is less than 6%. Thus the calculation error is smaller than the measurement uncertainty. Larger deviations with a maximum error of up to 10% can exclusively be observed at the beginning of the cut (t < 1 s) at a distance of 1.1 mm from the coating surface. This is associated with an underestimation of the heat increase. Possible causes are inaccurate material data regarding the thermal dependence of the heat conductivity and the specific heat capacity of the coating and the substrate. Moreover, this may be attributed to the neglect of the heat flux resulting from the initial wear on the flank face. As described in /14/ further measurement uncertainties are caused by the resulting heat accumulation in front of the groove, which can be attributed to the lower heat transfer to the environment.

A more detailed depth resolved analysis of the temperature profiles is displayed in Figure 3. Here, the experimental data were interpolated by a second-degree polynomial and subsequently extrapolated towards the surface (Red dashed line). Generally, a high agreement between the two methods is observed. However, enlargement of section A reveals significant differences regarding the temperature profile across the coating thickness as well as the maximum surface temperature. In contrast to the extrapolation method, a discontinuous temperature profile and a higher surface temperature are calculated by the developed simulation model (Blue line). The reason for the heat accumulation within the coating is the difference of the thermal conductivities of the coating and the substrate in the simulation, which is not taken into account in the purely mathematical extrapolation method. However, the
The application of the extrapolation method is quite justified to make statements about the general temperature load of the substrate.

![Graph](image)

**Figure 3.** Comparison of depth resolved temperature profiles.

In order to get further insight into the thermal insulation effect two additional simulations with increased process duration (120 s) were carried out. As a reference, one simulation was performed without coating under the same boundary conditions. For both simulations, a uniform rake face temperature of 890 °C was applied. However, it should be noted, that different thermal interface resistances as well as varying tribological effects might alter the heat flux into the tool and thus the surface temperature. This can be the case when comparing coated and uncoated tools. To demonstrate the influence of the thermal resistance of the coating itself those effects were neglected. With respect to the results presented in **Figure 4**, it becomes clear that the thermal insulation effect decreases continuously with increasing process duration. These findings correspond to the results of Yen /8/. Depth resolved temperature profiles for the coated and the uncoated tool are depicted in **Figure 5**. It is shown, that the temperature gradient within the coating decreases by 70 °C in 120 s. It can be concluded that, despite the low thermal conductivity of the applied AlCrN coating, the observed thermal insulation effect during orthogonal turning of AISI 4140 is limited to short process durations.
**Figure 4.** Impact of the process duration on the thermal insulation effect.

**Figure 5.** Depth resolved temperature profiles depending on the process duration.
6. CONCLUSION

In order to analyze the impact of the thermal insulation effect in AlCrN-coated cutting tools temperature measurements were performed during orthogonal cutting of AISI 4140 by means of a two-color pyrometer. In addition, a FEM-based simulation method for the calculation of the temperature distribution has been developed and validated.

Based on the results, the following conclusions can be drawn:

- Measured time-dependent temperature profiles were simulated with high accuracy (mean error: 6.5%) for all measurement positions.
- In contrast to the extrapolation method, the simulation approach enables the calculation of discontinuous depth resolved temperature profiles by taking into account the material properties of the coating and the substrate.
- The simulation approach calculates significantly higher surface temperatures with a difference of up to 70 °C. Within the substrate the differences are negligible.
- The thermal insulation effect is decreasing with increasing process time.
- No significant thermal insulation effect could be observed after reaching the thermal steady state.

However, with respect to an application-specific coating design further research on the influence of the tribological effects in the contact zone between coating and workpiece material and the resulting heat generation is necessary. Furthermore, due to the time dependence of the thermal insulation effect, further investigations should be carried out in interrupted processes. Based on the results it is to be assumed that the thermal insulation effect shields the substrate from temperature fluctuations produced by the interrupted cut. In order to further increase the calculation accuracy, the temperature-dependent thermo-physical coating properties should be taken into consideration for future investigations.

7. ACKNOWLEDGEMENTS

The authors thank the German Research Foundation (DFG) for their financial support within the project “Simulationsoptimierte Schichtentwicklung für die spanende Trockenbearbeitung” and the Ceratizit S.A., Luxembourg for providing the cutting inserts.

8. REFERENCES


