HPPMS tool coatings: Chip formation and friction

Planing at various cutting speeds

K. Bobzin, T. Brögelmann, N.C. Kruppe, M. Carlet, D.C. Hoffmann, B. Breidenstein, A. Krödel, S. Beblein

Introduction

During the machining of steel, mechanical and thermal loads occur. Adhesive and abrasive wear as well as oxidation appear as damage mechanisms of the tools and lead to a reduction of tool performance and lifetime. The energy required to overcome the friction between tool surface and chip as well as the workpiece during machining is almost completely converted into heat and increases the temperature of the tool surface, as described in the fundamental principles of machining [1]. Thus, as the coefficient of friction increases, the surface temperature of the cutting tool increases. The higher temperature facilitates diffusion and oxidation processes and reduces hardness and resistance against abrasive wear. These cause changes in elastic-plastic properties and microstructure and damage the tool surface during the machining process. A reduced friction is therefore advantageous for machining processes. The thermal and mechanical loads on the cutting edge depend on the coefficient of friction and the contact length between rake face and chip.

Thin hard coatings deposited by physical vapor deposition (PVD) for wear protection of cutting tools are state of the art. The low-pressure plasma during PVD allows the synthesis of metastable nitrides like TiAlN, CrAlN, and TiCrAlN. Aluminum and chromium increase the thermal resistance of the hard coatings. This is caused by the formation of a dense, firmly adhering passivating oxide layer of chromium oxide and aluminum oxide on the surface, which inhibits the diffusion of oxygen into the coating [2,3]. In the coating system CrAlN+Mo:S, molybdenum and sulfur are incorporated into a CrAlN coating. Out of these, the self-lubricating transition metal dichalcogenide molybdenum disulfide (MoS2) is formed under tribological load. The layers in the crystallographic structure of the transition metal dichalcogenide are bonded by relatively weak van der Waals forces. This leads to a low shear strength and to a self-lubricating effect [4]. As a result, the adhesion properties against steel in technical applications such as dry cold bulk metal forming can be improved. Moreover, the coatings show a high abrasion resistance [5]. Previous work has shown that the friction against steel can be reduced for CrAlON compared to CrAlN coating in tribologically tests [6]. Moreover, the resistance of coated carbide tools to damage caused by adhesive and abrasive wear during machining can be improved by increasing the oxygen content in the CrAlON coating system CrAlN+Mo:S, CrAlON, and TiAlCrSiN were investigated. A special planing test setup enabling the simultaneous measurement of the contact length between chip and rake face, the chip thickness and the coefficient of friction during planing was used. Process forces and chip formation can be analysed on basis of high-speed recordings. The influence of the coating on the contact length, the chip thickness and the coefficient of friction during planing as well as the influence of the cutting speed were investigated. The CrAlON coated tool showed a lower adhesion tendency against the steel workpiece compared to the CrAlN+Mo:S and TiAlCrSiN coated tools at all cutting speeds investigated. This prevented adhesive wear and reduced friction which decreased the chip thickness during planing. Moreover, the CrAlON coated tool showed a reduced contact length. A reduced friction and a reduced contact length are generally accompanied by decreased thermal tool load and therefore enhance the cutting performance.

SUMMARY

In the current study, the three different HPPMS deposited wear protection coating systems CrAlN+Mo:S, CrAlON, and TiAlCrSiN were investigated. A special planing test setup enabling the simultaneous measurement of the contact length between chip and rake face, the chip thickness and the coefficient of friction during planing was used. Process forces and chip formation can be analysed on basis of high-speed recordings. The influence of the coating on the contact length, the chip thickness and the coefficient of friction during planing as well as the
coatings [7]. A reduction of friction and adhesive wear might be attributed to the changed chemical bond character. The addition of silicon to the quaternary system of TiAlCrN leads to the formation of an amorphous silicon nitride matrix. This matrix interrupts grain growth during the deposition of the coating and leads to a nanocrystalline microstructure with enhanced properties, such as an improved indentation hardness of TiAlCrSiN compared to TiAlCrN [8,9]. Moreover, the coefficient of friction can be reduced and tool life during cutting can be improved [10].

Hard coatings can be deposited by magnetron sputtering. High power pulsed magnetron sputtering (HPPMS) has technical advantages compared to direct current magnetron sputtering (dcMS), such as a more homogeneous coating thickness distribution on flank and rake face [11]. DcMS, in contrast, shows higher deposition rates and therefore has a higher economic efficiency. Both processes can be combined in a hybrid process, taking benefit of the advantages of both processes.

The mean coefficient of friction in the contact area between tool and workpiece during machining with geometrically defined cutting edges in continuous cutting can be calculated from cutting and feed force. The measurement of the forces is usually performed by piezoelectric force transducers [1]. The forces are composed of the normal force on the rake face $F_{N\alpha}$ and the tangential force on the rake face $F_{T\alpha}$. Due to tool wear as well as elastic and plastic deformation of the tool the normal force on the rake face $F_{N\alpha}$ and the tangential force on the rake face $F_{T\alpha}$ additionally occur [12]. Thus, the coefficient of friction includes therefore both, the friction, which occurs on the rake face and the friction, which occurs on the flank face. In order to determine the mechanical stress distribution on the cutting edge, it is necessary to measure the contact area between tool surface and chip. The width of the contact area corresponds to the chip width. The contact length in the direction of chip flow, on the other hand, is primarily determined by the material properties, the tool geometry, the process parameters and the friction between tool and work-
The contact length on rake face and flank face affects the distribution of the normal and tangential stress distribution on the cutting edge [13]. The normal and tangential stress distribution on the cutting edge influences the effective stress distribution inside the cutting edge and are therefore of great interest for the design of cutting tools. The contact length is also one of the essential boundary conditions when calculating the stress distribution using FEM, based on the load stresses and temperatures in the contact zone.

In order to measure the contact length, the chip thickness and the coefficient of friction simultaneously during continuous cutting within a single experiment, a special experimental setup was developed. For this purpose, a planing test rig was used, which is equipped with a simultaneous measuring system for the analysis of process forces and chip formation on the basis of high-speed recordings. In preliminary studies in [14], the influence of the coating on the contact length, the chip thickness and the coefficient of friction during planing was already investigated at a specific cutting speed. The current study aims to additionally investigate the influence of the cutting speed.

Materials and experimental details

The coatings were deposited by a hybrid process consisting of dcMS (direct current magnetron sputtering) and HPPMS (high power pulsed magnetron sputtering) using the industrial coating unit CC800/9 HPPMS, CemeCon AG, Würselen, Germany. The coating unit is equipped with four dcMS cathodes and two HPPMS cathodes. Fig. 1a shows the target configuration for the deposition of the coating system CrAlN+Mo:S, which is schematically depicted in Fig. 1b) in nitride CrAlN bond coat were deposited using the cathodes HPPMS1, HPPMS2, dcMS-2, dcMS-3 and dcMS-4. These targets were equipped with chromium targets plugged with 20 aluminium plugs. The CrAlN+Mo:S toplayer was deposited additionally using the cathode dcMS1, which was equipped with a molybdenum disulfide target. Since this toplayer is in direct contact with the workpiece during cutting, the entire coating system is designated shortly by the material system of the toplayer CrAlN+Mo:S. Fig. 1c) shows the target configuration for the deposition of the coating system CrAlON, which is schematically depicted in Fig. 1d). It consists of a thin metallic Cr and a thin nitride CrN bond coat. Those were deposited using the cathodes HPPMS2 and dcMS-3, which were equipped with chromium targets. A CrN/AlN nanolayer was subsequently deposited using the cathodes dcMS1 and dcMS4, which were equipped with aluminium targets. Finally, the CrAlON toplayer was deposited only using the cathodes HPPMS1 and dcMS2, which were equipped with chromium targets plugged with 20 aluminium plugs. Since the oxynitride toplayer is in direct contact with the workpiece during cutting, the coating system it is designated shortly as CrAlON.

| Process parameter | CrAlN+Mo:S | CrAlON | TiAlCrSiN |
|-------------------|------------|--------|-----------|
| Total pressure p [mPa] | 710 | 445 | 550 |
| Argon flow j[Ar] [sccm] | 200 | 200 | 150 |
| Krypton flow j[Kr] [sccm] | 0 | 0 | 60 |
| Nitrogen flow j[N2] [sccm] | 182 | 20 | 97 |
| Oxygen flow j[O2] [sccm] | 0 | 40 | 0 |
| Heating power P [kW] | 4.0 | 4.5 | 8.0 |
| Bias voltage U [V] | -100 | -100 | -160 |
| Average power of HPPMS-1 cathode P [kW] | 5.0 | 5.0 | 5.0 |
| Power of dcMS1 cathode P [kW] | 3.0 | 3.0 | 5.0 |
| Power of dcMS2 cathode P [kW] | 3.0 | 0.0 | 5.0 |
| Power of dcMS3 cathode P [kW] | 2.0 | 0.0 | 5.0 |
| Power of dcMS4 cathode P [kW] | 2.0 | 0.0 | 5.0 |

TABLE 1: Process parameters for the deposition of the toplayer of the three hybrid coatings.

The targets had a size of A = 500 mm x 88 mm. Titanium has a purity of x(Ti) = 99.0 wt.%, chromium of x(Cr) = 99.9 wt.%, aluminium of x(Al) = 99.5 wt.%, silicon of x(Si) = 99.0 wt.%, and molybdenum disulfide of x(MoS2) = 99.5 wt.%.

In order to control the oxygen content and the microstructure of CrAlON, the total pressure, the reactive gas flows and the bias voltage were varied for the different layers, see Table 1. For TiAlCrSiN, two different pressures and nitrogen flows were selected in order to achieve a suitable working point for the deposition of both, the interlayer and the toplayer.

The roughness values Rz of the coatings were measured using the confocal laser scanning microscopy VXK 210, Keyence Corporation, Osaka, Japan. The morphology of the coatings was investigated using scanning electron microscope cross-section (SEM) images. A SEM ZEISS DSM 982 Gemini, Jena, Germany, was used for this purpose. The chemical composition of the coatings was measured by electron probe micro-analysis (EPMA) using a JEOL JXA8530, Jeol, Tokyo, Japan. The SEM and EPMA investigations were carried out by the Central Facility of Electron Microscopy of the RWTH Aachen University. Nanoindentation measurements without any further post-treatment were performed after deposition. The indentation hardness Hm and the indentation...
modulus $E_p$ were determined according to DIN EN ISO 14577 using the Tribolindent T1 950, Bruker Corporation, Billerica, Massachusetts, USA. An indentation force of $F = 8$ mN was applied. Moreover, the indentation depth was limited to approximately 10% of the coating thickness in order to eliminate the substrate effect. Poisson's ratio was assumed as $v = 0.25$, as usual for ceramics and the results were evaluated according to Oliver and Pharr [15]. The indentation hardness $H_p$ and the indentation modulus $E_p$ were determined by averaging the results of 20 indents on each coating.

The influence of the coatings and of the cutting speed on the contact length between chip and rake face, on the chip thickness and on the coefficient of friction were investigated during a planing process. Coated indexable inserts made of cemented carbide were used as tools. They had a sharp cutting edge radius of $r_c < 5$ µm. 42CrMo4+QT was used as workpiece material. The planing tests were carried out using an uncut chip thickness of $h = 0.1$ mm, a width of cut of $b = 3$ mm, a rake angle of $\gamma = 6^\circ$, a clearance angle of $\alpha = 6^\circ$ and the three different cutting speeds of $v_c = 50$ m/min, $v_c = 100$ m/min as well as $v_c = 150$ m/min. The cutting speed of $v_c = 150$ m/min is a common cutting speed for high-speed machining of 42CrMo4 in industrial applications. The cold light projector Simodrive 1FN1, Siemens, Berlin, Germany, generates the continuous cutting operation. The linear direct drive Linear direct drive was fixed on a dynamometer during the planing tests and to ensure enough brightness. To ensure a sufficient temporal resolution, the frame rate was chosen depending on the cutting speed, see Table 2.

The high-speed images were taken at a resolution of $A = 512 \times 512$ pixels with $V = 6x$ magnification. This results in a geometric resolution of $R = 3.3$ µm per pixel. To ensure plain strain conditions during machining, the tool and the workpiece were mounted against sapphire glass. Immersion oil was applied in the contact zone between tool and glass to reduce the friction between glass and tool as well as to achieve the best optical conditions.

After performing the planing tests, the coated tools were investigated using SEM. Furthermore, the chemical composition after the cutting tests was measured using energy dispersive X-ray spectroscopy (EDS). A Phenom XL, Thermo Fisher Scientific Inc., Waltham, Massachusetts, USA, was used for both the SEM and EDS analysis.

### Results

#### Coating characterization

Three different coating systems were investigated in the scope of this article. Figure shows the SEM crosssections of the CrAlN+Mo:S (a), CrAlON (b) and TiAlCrSiN (c) coatings. Table 3 shows the coating properties.

Since the toplayer of the coating systems is in direct contact with the work piece during cutting, Table 3 only shows the chemical composition of the toplayer. The cutting speed was varied from 50 to 150 m/min. The frame rate was chosen depending on the cutting speed, see Table 2.

| Cutting speed [m/min] | 50  | 100 | 150 |
|----------------------|-----|-----|-----|
| Frame rate [fps]     | 10,000 | 20,000 | 30,000 |

**TABLE 2:** Frame rate depending on the cutting speed.
the toplayer. The coating system CrAlN+Mo:S consisted of a pure metallic CrAl and a CrAIN nitride bond coat as well as a CrAIN+MoS toplayer, see Fig. 3 a). The coating thickness was \( s = 1.7 \, \mu m \) in total. It showed an average roughness of \( Ra = 0.04 \, \mu m \) and a dense and fine columnar morphology. The indentation hardness was \( H_{\text{IT}} = 20.1 \pm 3.5 \, \text{GPa} \) and the indentation modulus is \( E_{\text{IT}} = 332.4 \pm 53.0 \, \text{GPa} \). CrAlON consisted of a pure metallic Cr and a CrN bond coat, a CrN/AIN nitride nanolayer and a CrAlON oxynitride toplayer, see Fig. 3 b). The coating thickness was \( s = 2.9 \, \mu m \) in total. The coating showed a smooth surface with an average roughness of \( Ra = 0.05 \, \mu m \). It showed a similar indentation hardness compared to the CrAlN+Mo:S coating of \( H_{\text{IT}} = 20.5 \pm 3.3 \, \text{GPa} \) and a similar indentation modulus of \( E_{\text{IT}} = 351.5 \pm 65.3 \, \text{GPa} \). Moreover, it exhibited a dense and fine crystalline morphology. The CrN/AIN interlayer showed a fine columnar morphology. The toplayer showed no columns due to its even more fine crystallinity or high amorphous share caused by the high amount of oxygen. TIAICrSiN consisted of a TiAIN bond coat and a TIAICrSiN toplayer, see Fig. 3 c). The coating thickness was \( s = 2.0 \, \mu m \) in total. The coating showed an average line roughness of \( Ra = 0.09 \, \mu m \) and a dense morphology. There were no columns visible. The fine crystalline morphology was caused by the nanocomposite coating architecture as proven in earlier publications [17,18]. The coating showed a slightly increased indentation hardness of \( H_{\text{IT}} = 23.2 \pm 2.2 \, \text{GPa} \) and a slightly decreased indentation modulus of \( E_{\text{IT}} = 291.5 \pm 31.3 \, \text{GPa} \) compared to the CrAlN+Mo:S and CrAlON coatings.

**Analysis of chip formation and friction**

In order to investigate process forces and chip formation during cutting simultaneously, a special experimental setup was developed, as described in section 2. Fig. 4 shows images recorded by the high-speed camera of the CrAlN+Mo:S coated tool during planing with \( v_c = 100 \, \text{m/min} \) at a cutting length of \( l = 10 \, \text{mm} \), \( l = 30 \, \text{mm} \) and \( l = 80 \, \text{mm} \). At the beginning of the planing operation, at a cutting length of \( l = 0 \, \text{mm} \), the chip forms out and the contact length as well as the chip thickness increase from \( l = 0 \, \text{mm} \) and \( h' = 0 \, \text{mm} \) on.

The high-speed camera enables the measurement of the contact length and the chip thickness depending on the cutting length, see Fig. 5 a). After reaching a critical cutting length of approx. \( l = 100 \, \text{mm} \), the chip hits the edge of the workpiece. The results after reaching this critical cutting length are therefore not considered for further analysis. The cutting force \( F_c \) and the feed force \( F_f \) were measured simultaneously depending on the cutting length using a dynamometer. The coefficient of friction \( \mu \) was calculated from those forces according to the force diagram proposed by Merchant [16]. Fig. 5 b) shows the cutting force \( F_c \), feed force \( F_f \) and coefficient of friction \( \mu \) depending on the cutting length \( l \).
The planing tests were conducted using differently coated tools at different cutting speeds. Fig. 6 shows images from the high-speed camera of the CrAlN+Mo:S (a), CrAlON (b) and TiAlCrSiN (c) coated tools during planing with $v = 100$ m/min at a cutting length of $l = 80$ mm.

The CrAlN+Mo:S coated tool showed the highest contact length of $l_c = 1.01$ mm and the highest chip thickness of $h' = 0.29$ mm. For the CrAlON coated tool contact length of $l_c = 0.71$ mm and chip thickness of $h' = 0.21$ mm were the lowest.

Fig. 6 additionally shows images from the high-speed camera of the CrAlN+Mo:S coated tool during planing with $v = 50$ m/min (a), $v = 100$ m/min (b) and $v = 150$ m/min (c) at a cutting length of $l = 80$ mm. During planing with $v = 100$ m/min the contact length of $l_c = 1.01$ mm was the lowest and the chip thickness of $h' = 0.29$ mm was the highest compared to $v = 50$ m/min and $v = 150$ m/min.

Fig. 7 shows the contact length $l_c$ and coefficient of friction $\mu$ of the coated tools during planing at different cutting speeds $v$ depending on the cutting length $l$. The results reveal that the contact length and the coefficient of friction increase during the planing operation over the cutting length. This was most pronounced for the CrAlN+Mo:S coated tool and least pronounced for the CrAlON coated tool. The contact length $l_c$ correlated with the coefficient of friction. The chip thickness did not depend on the cutting length, which is why it is only exemplary shown in Fig. 5 a) for the CrAlN+Mo:S coated tool at $v = 100$ m/min.

Fig. 8 shows the contact length $l_c$ (a), chip thickness $h'$ (b) and coefficient of friction $\mu$ (c) averaged over the cutting length for two planing operations depending on coating and cutting speed. It was not possible to measure the contact length of the second planing operation at $v = 100$ m/min and at $v = 150$ m/min. This was due to incorrect measurements, which are e.g. caused by the chip rolling up or twisting off during the planing process.

For the CrAlON and TiAlCrSiN coated tools the contact length decreased, when the cutting speed increased. For the CrAlN+Mo:S coated tool, the contact length at $v = 100$ m/min was the lowest. Furthermore, the contact length of the CrAlN+Mo:S coated tool was higher compared to the CrAlON and TiAlCrSiN coated tools at $v = 50$ m/min, $v = 100$ m/min and $v = 150$ m/min. The CrAlON coated tool showed similar contact lengths compared to the TiAlCrSiN coated tool at $v = 50$ m/min. However, at $v = 100$ m/min and $v = 150$ m/min, the contact length of the CrAlON coated tool was significantly reduced.

An increased contact length is generally accompanied by an increase in thermal tool load due to the increased friction distance, since the friction power is largely converted into heat. In addition, as calculated in [13], the tool is subject to greater mechanical stress at higher contact lengths, especially in feed direction. A reduced contact length during cutting is therefore advantageous.

The chip thickness $h'$ of the coated tools was similar at $v = 50$ m/min, see Fig. 8 b). At $v = 100$ m/min and $v = 150$ m/min, the chip thickness of the CrAlON coated tool showed similar contact lengths compared to the TiAlCrSiN coated tool at $v = 50$ m/min. However, at $v = 100$ m/min and $v = 150$ m/min, the contact length of the CrAlON coated tool was significantly reduced.

The cutting speeds $v$ used during the tests were $v = 50$ m/min, $v = 100$ m/min and $v = 150$ m/min. The contact length at $v = 100$ m/min was the lowest. Furthermore, the contact length of the CrAlN+Mo:S coated tool was higher compared to the CrAlON and TiAlCrSiN coated tools at $v = 50$ m/min, $v = 100$ m/min and $v = 150$ m/min. The CrAlON coated tool showed similar contact lengths compared to the TiAlCrSiN coated tool at $v = 50$ m/min. However, at $v = 100$ m/min and $v = 150$ m/min, the contact length of the CrAlON coated tool was significantly reduced.

An increased contact length is generally accompanied by an increase in thermal tool load due to the increased friction distance, since the friction power is largely converted into heat. In addition, as calculated in [13], the tool is subject to greater mechanical stress at higher contact lengths, especially in feed direction. A reduced contact length during cutting is therefore advantageous.

The chip thickness $h'$ of the coated tools was similar at $v = 50$ m/min, see Fig. 8 b). At $v = 100$ m/min and $v = 150$ m/min, the chip thickness of the CrAlON coated tool showed similar contact lengths compared to the TiAlCrSiN coated tool at $v = 50$ m/min. However, at $v = 100$ m/min and $v = 150$ m/min, the contact length of the CrAlON coated tool was significantly reduced.

An increased contact length is generally accompanied by an increase in thermal tool load due to the increased friction distance, since the friction power is largely converted into heat. In addition, as calculated in [13], the tool is subject to greater mechanical stress at higher contact lengths, especially in feed direction. A reduced contact length during cutting is therefore advantageous.

The chip thickness $h'$ of the coated tools was similar at $v = 50$ m/min, see Fig. 8 b). At $v = 100$ m/min and $v = 150$ m/min, the chip thickness of the CrAlON coated tool showed similar contact lengths compared to the TiAlCrSiN coated tool at $v = 50$ m/min. However, at $v = 100$ m/min and $v = 150$ m/min, the contact length of the CrAlON coated tool was significantly reduced.

An increased contact length is generally accompanied by an increase in thermal tool load due to the increased friction distance, since the friction power is largely converted into heat. In addition, as calculated in [13], the tool is subject to greater mechanical stress at higher contact lengths, especially in feed direction. A reduced contact length during cutting is therefore advantageous.

The chip thickness $h'$ of the coated tools was similar at $v = 50$ m/min, see Fig. 8 b). At $v = 100$ m/min and $v = 150$ m/min, the chip thickness of the CrAlON coated tool showed similar contact lengths compared to the TiAlCrSiN coated tool at $v = 50$ m/min. However, at $v = 100$ m/min and $v = 150$ m/min, the contact length of the CrAlON coated tool was significantly reduced.

An increased contact length is generally accompanied by an increase in thermal tool load due to the increased friction distance, since the friction power is largely converted into heat. In addition, as calculated in [13], the tool is subject to greater mechanical stress at higher contact lengths, especially in feed direction. A reduced contact length during cutting is therefore advantageous.
coated tool was lower compared to the CrAlN+Mo:S and TiAlCrSiN coated tools. The difference between the two measurements of the CrAlN+Mo:S coated tools was relatively high at \( v = 100 \text{ m/min} \) and \( v = 150 \text{ m/min} \). Therefore, no distinct statement can be made regarding the ratio of the chip thickness between the CrAlN+Mo:S and TiAlCrSiN coated tools.

The coatings had a significant influence on the coefficient of friction, see Fig. 8c). The difference between the two measurements of the coefficient of friction were relatively low, especially compared to the measurements of the chip thickness. The coefficient of friction was higher for the CrAlN+Mo:S and TiAlCrSiN coated tool at \( v_c = 50 \text{ m/min} \) compared to \( v_c = 100 \text{ m/min} \). For the CrAlON coated tool it was similar at both cutting speeds. At \( v_c = 150 \text{ m/min} \), the coated tools showed a reduced coefficient of friction compared to \( v_c = 100 \text{ m/min} \). Overall, the CrAlON coated tool showed the lowest coefficient of friction followed by the TiAlCrSiN coated tool. The CrAlN+Mo:S coated tool showed the highest coefficient of friction. An increased friction decreased the shear angle. According to [16], the higher shear angle increased the chip thickness. The higher coefficient of friction of the TiAlCrSiN and CrAlN+Mo:S coated tools compared to the CrAlON coated tool might therefore cause the higher chip thickness of those coated tools.

**Analysis of the coated tools after performing the planing tests**

After performing the planing tests, the tools were investigated by SEM and EDS. Independently of the cutting speed, the coated tools showed similar damage characteristics. Fig. 9 exemplarily shows the rake face of the coated tools after performing a planing operation at \( v = 150 \text{ m/min} \).

There are darker and brighter areas near the cutting edge of the CrAlN+Mo:S coated tool. The TiAlCrSiN coated tool showed brighter areas and the surface of the CrAlON coated tool remains unchanged compared to prior the planing test. Table 4 shows the chemical composition at the marked areas in Fig. 9 measured by EDS. The EDS measurement reveal that there was iron adherent on the CrAlN+Mo:S and TiAlCrSiN coated samples in both, the brighter and darker areas. Since light elements like carbon, oxygen and nitrogen cannot be quantified reliably by the EDS detector used for the investigation, Table 4 does not show the content of those elements. However, due to the material contrast caused by the back scattered electrons (BSE), it can be assumed that the darker areas show a higher carbon or oxygen content compared to the brighter areas. Therefore, they might contain more carbides or oxides. Due to the higher density of iron compared to the elements containing the coating material, it appeared brighter than the coating material. Only small amounts of the substrate material tungsten and cobalt were detected by EDS, indicating that no substrate is exposed due to abrasive wear. There were no steel adhesions nor abrasive wear observed for the CrAlON coated tool. The oxinitride CrAlON coating therefore seemed to show a lower adhesi-

**TABLE 4: Chemical composition at the marked areas in Fig. 9 measured by EDS.**

| Coating       | CrAlN+Mo:S - Pos. 1 | CrAlN+Mo:S - Pos. 2 | CrAlON | TiAlCrSiN |
|---------------|---------------------|---------------------|--------|-----------|
| Cr [at.-%]    | 75                  | 66                  | 77     | 5         |
| Al [at.-%]    | 12                  | 5                   | 23     | 9         |
| Ti [at.-%]    | 0                   | 0                   | 0      | 15        |
| Mo [at.-%]    | 9                   | 14                  | 0      | 0         |
| S [at.-%]     | 0                   | 0                   | 0      | 0         |
| Si [at.-%]    | 0                   | 0                   | 0      | 1         |
| Fe [at.-%]    | 4                   | 11                  | 0      | 67        |
| W [at.-%]     | 0                   | 4                   | 0      | 2         |
| Co [at.-%]    | 0                   | 0                   | 0      | 1         |
Conclusion

Within the scope of this article, a special planing test setup was presented, which is equipped with a highspeed camera and a dynamometer to measure the process forces. This enables a comprehensive investigation of the chip formation and of the friction during planing. Using the planing test setup, the contact length at the rake face, the chip thickness and the coefficient of friction could be measured simultaneously during the continuous cutting operation. The planing test setup was developed for the qualification of PVD coatings for cutting tools and was exemplarily used to investigate three different coating systems in the scope of this article. For this purpose, indexable inserts made of cemented carbide were coated by the three different coating systems CrAlN+Mo-S, CrAION and TiAlCrSiN by means of a hybrid process using an industrial coating unit. Subsequently, the coated tools were investigated using the special planing test setup. The oxyxinitride CrAION coated tools showed a lower adhesion tendency against the steel workpiece material during planing compared to the nitride CrAlN+Mo-S and TiAlCrSiN coated tools at all cutting speed investigated. This prevented adhesive wear and reduced friction of the CrAION coated tools. The reduced friction decreased the chip thickness during cutting. Moreover, the CrAION coated tools showed a reduced contact length, which is advantageous to increase the tool performance. In further investigations the present results will be used in order to calculate the influence of the coating on the mechanical and thermal load by FEM. In order to analyse higher cutting speeds, the planing test rig is currently being extended by a new linear direct drive, which enables cutting speeds of up to $v_c = 500 \text{ m/min}$.

Acknowledgement

The authors gratefully acknowledge the financial support of the German Research Foundation, Deutsche Forschungsgemeinschaft (DFG), within the project BO 1979/48-1 “Influence of HPPMS pulse parameters on stoichiometry and the formation of reaction layers on nitridic hard coatings for cutting” and within the project BR 2967/7-1 “Simulation-optimized coating development for dry machining”.

Open Access funding enabled and organized by Projekt DEAL.

References

[1] B. Denkena, H. K. Tönshoff: Spanen, 3., bearb. u. erw. Aufl., Springer, Heidelberg, New York, 2011
[2] E. Huber, S. Hofmann: Oxidation behaviour of chromium-based nitride coatings, Surf. Coat. Technol., 68-69, (1994) 64–69. 10.1016/0257-8972(94)90339-2
[3] J. Vetter et al.: CrAION coatings deposited by the cathodic vacuum are evaporation, Surf. Coat. Technol., 98 (1998) 1233–1239. 10.1016/S0257-8972(97)00238-7
[4] A. Albert et al.: Preparation and properties of MoSx films grown by d.c. magnetron sputtering, Surf. Coat. Technol., 41 (1990) 127–134. 10.1016/0257-8972(90)90336-2
[5] K. Bobzin et al.: Tribological studies on self-lubricating (CrAION+Mo-S) coatings at elevated temperature, Surf. Coat. Technol., 333 (2018) 282–291. 10.1016/j.surfcoat.2018.06.067
[6] K. Bobzin et al.: Entwicklung neuer PVD-Beschichtungen in Umweltverträgliche Tribosysteme: Die Vision einer umweltfreundlichen Werkzeugmaschine, Hrsg.: H. Murrenhoff, Springer-Verlag Berlin Heidelberg, (2010) 83–136
[7] A. Rö ethic: Structural and mechanical properties of Cr–Al–O–N thin films grown by cathodic arc deposition, Acta Mater., 60 (2012) 6494–6507. 10.1016/j.actamat.2012.08.010
[8] S. Vepřek et al.: Superhard nanocrystalline composite materials, Appl. Phys. Lett., 66 (1995) 2640–2642. 10.1063/1.113110
[9] N. Jiang et al.: Nanocomposite Ti–Si–N films deposited by reactive unbalanced magnetron sputtering at room temperature, Materials Science and Engineering: B, 106 (2004) 163–171. 10.1016/j.mseb.2003.09.033
[10] D. Yu et al.: Microstructure and properties of TiAlSiN coatings prepared by hybrid PVD technology, Thin Solid Films, 517 (2009) 4950–4955. 10.1016/j.tsf.2009.03.091
[11] K. Bobzin et al.: Mechanical properties and oxidation behaviour of (AlCrN) and (AlCrSiN) coatings for cutting tools deposited by HPPMS, Thin Solid Films, 517 (2008) 1251–1256. 10.1016/j.tsf.2008.06.050
[12] F. Klauz, W. König: Stand der Kenntnisse über die Zerspanbarkeit der Stähle, Stahl und Eisen, 85 (1995) 1669
[13] B. Bergmann, T. Große: Basic principles for the design of cutting edge roundings, CIRP Annals, 67 (2018) 73–78. 10.1016/j.cirp.2018.04.019
[14] M. Carlet et al.: Qualification of PVD coatings for machining using a planing test setup, Accepted for publication in Production at the leading edge of technology - Proceedings of the 11th Congress of the German Academic Association for Production Technology (WGP), Springer-Verlag, Heidelberg.
[15] W. C. Oliver, G. M. Pharr: An improved technique for determining hardness and elastic modulus using load and displacement sensing indentation experiments, J. Mater. Res., 7 (1992) 1564–1583. 10.1557/JMR.1992.1564
[16] M. E. Merchant: Mechanics of the Metal Cutting Process, I. Orthogonal Cutting and a Type 2 Chip, J. Appl. Phys., 16 (1945) 267–275. 10.1063/1.1707586
[17] K. Bobzin et al.: Nanocomposite TiAION+MoS coatings for high performance cutting tools, Surf. Coat. Technol., (2019). 10.1016/j.surfcoat.2019.07.071
[18] K. Bobzin et al.: Wear behavior and thermal stability of HPPMS (Al,Ti,Cr,Si)ON, (Al,Ti,Cr,Si)N and (Ti,Al,Cr,Si)N coatings for cutting tools, Surf. Coat. Technol., (2020) 125370. 10.1016/j.surfcoat.2020.125370

AUTHORS

Prof. Dr.-Ing. Kirsten Bobzin is the head of the Surface Engineering Institute of the RWTH Aachen University.

Dr.-Ing. Tobias Brügellmann is the former chief engineer of the department PVD technology at the Surface Engineering Institute of the RWTH Aachen University.

Dr.-Ing. Nathanael Kürpel is the former team leader of the department PVD technology (Tools) at the Surface Engineering Institute of the RWTH Aachen University.

Marco Carlet, M. Sc. is the team leader of the department PVD technology (Tools) at the Surface Engineering Institute of the RWTH Aachen University. He has a master’s degree in Production Technology and focuses on coating development for high performance cutting tools.

Dennis Hoffmann, M. Sc. is a scientific assistant of the department PVD technology (Tools) at the Surface Engineering Institute of the RWTH Aachen University.

Apl. Prof. Dr. rer. nat. habil. Bernd Breidenstein is leader of the analytics department at the Institute of Production Engineering and Machine Tools of the Leibniz University Hanover.

Dr.-Ing. Alexander Krödel-Worbes is leader of the department Manufacturing Processes at the Institute of Production Engineering and Machine Tools of the Leibniz University Hanover.

Dipl.-Ing. Sascha Beblein is a former scientific assistant at the Institute of Production Engineering and Machine Tools of the Leibniz University Hanover.

Marco Carlet, M. Sc., Surface Engineering Institute, RWTH Aachen University, Kackertstr. 15, 52072 Aachen, Germany, Email: carlet@iot.rwth-aachen.de, www.iot.rwth-aachen.de