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Modern coatings in high performance cutting applications

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Abstract

Modern, state-of-the-art, PVD coatings are required to fulfill a variety of different applications. Each metal cutting operation requires an optimal combination of various film parameters to achieve a high end cutting performance. Especially, Al-based coatings such as AlTiN- and AlCrN-coatings show very good results in high performance metal cutting applications.

Wear resistance, thermal stability such as oxidation resistance and hardness at elevated temperatures are key issues within these cutting operations. In this paper the influence of these properties on Al-based nitride coatings in relation to metal cutting tests such as milling and drilling will be discussed.

Keywords: PVD; Hard coatings; AlCrN; TiAlN; Cutting tools

1. Introduction

The keyword for manufacturers of cutting tools and coatings for cutting tools is productivity: a 30% reduction of tool costs, or a 50% increase in tool lifetime results only in a 1% reduction of manufacturing costs. But an increase in cutting data by 20% reduces manufacturing costs by 15%. In order to achieve higher productivity different approaches – high performance cutting (HPC) and high speed cutting (HSC) [1] can be chosen.

Advances in manufacturing technologies (increased cutting speeds, dry machining, etc.) triggered the fast commercial growth of PVD coatings for cutting tools. On the other hand, technological improvements in coating technologies (TiAlN, AlTiN, AlCrN and nanocomposite coatings) enabled these advances in manufacturing technologies.

Twenty five years ago TiN started the success story of PVD coatings in cutting tool applications. Recently, a new generation of coatings were introduced, based on the Al–Cr–N system. This system is characterized by superior abrasive wear resistance and improved oxidation resistance – promising results in cutting tool application have been reported [2,3].

This paper reports the results of a comparative investigation of state-of-the-art coatings and high-aluminum AlCrN coatings, particularly relative to high temperature behavior. Oxidation tests at elevated temperatures have been performed to rate their chemical stability in a high temperature environment. These are then related to coated tool performance in several metal cutting tests.

2. Experimental

Standard Balzers coatings were used for the comparisons of the various nitride films. All coatings were deposited by a standard Balzers RCS cathodic arc coating machine. A schematic view of this coating system is shown in Fig. 1. The coatings were done by using pure Ti-targets for TiCN, TiAl-targets with two different compositions for (Ti,Al)N-coatings and high aluminum content (Al,Cr)-targets for AlCrN-coatings.

Prior to deposition the substrates were chemically cleaned, heated and plasma etched using an Argon-ion-etching process. In the cases of (Ti,Al)N and CrAlN, a pure

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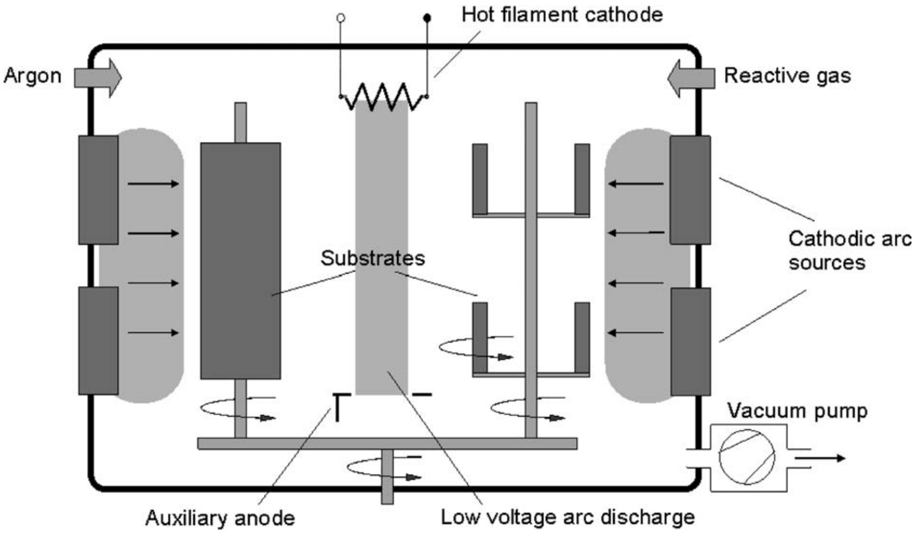

Fig. 1. Schematic illustration of the coating device used for the film deposition.

reactive nitrogen atmosphere was used while for TiCN a mixture of nitrogen and acetylene was used during the deposition. The pressure during deposition was in the range of 0.5–3.5 Pa at a temperature of approximately 500 °C. For all coatings the DC-substrate bias voltage was in the range of −50 to −150 V. The thicknesses of the coatings were in the range of 4–5 μm for the evaluation of mechanical properties and 2–3 μm for the oxidation tests. The thicknesses for the cutting tests were in the range of 3.5–4.5 μm.

The coatings deposited onto cemented carbide inserts were characterized using standard scanning electron microscopy (LEO 1530). The X-ray diffraction measurements were carried out using a Siemens Diffractometer D500 equipped with a Cu Kα X-ray source. Here, the glancing incidence (GI) mode was used. A Fischerscope H100C was used for measuring the Vickers microhardness. For this measurement the load was varied from 0.4 mN to 1 N. The load for the hardness measurements was held at 50 mN.

The abrasive wear test is comparable to a standard calotte wear test. A suspension is used to grind a spherical crater into the coating. From measurements of the ball wear scar the wear volume can be calculated. This volume is taken as a measure of resistance against abrasive wear behavior of the coating [4].

The annealing experiments for the hardness measurements were performed in a high-vacuum furnace PVA MOV 64 (Pfeiffer GmbH, Germany) using Al_2O_3 crucibles. After evacuation of the furnace to a pressure of $P_{\mathrm{vac}} < 2 \times 10^{-6}$ mbar the temperature was increased to the required temperature at a heating rate of 50 °C/min in a protective argon atmosphere by increasing the argon pressure from 100 to 400 mbar. A constant argon pressure of $P_{\mathrm{Ar}} = 400$ mbar was kept during the whole annealing time. After annealing for 2 h, the sample was cooled down in argon atmosphere to room temperature at a cooling rate of 50 °C/min. The oxidation experiments were performed in a programmable furnace PEO-601.This furnace can be heated up to 1100 °C in vacuum, air or other atmospheres. The oxidation tests were performed at several temperatures in air for duration of 30 min. After heating, the samples were continuously cooled down to a temperature of 100 °C before they were taken out of the furnace. The cutting tests were performed either in the Balzers internal cutting laboratory using a MIKRON VCP600 CNC milling machine or at external customers' machine shops.

3. Results and discussion

3.1. Comparison of coating properties

In Fig. 2a the *abrasive wear* coefficient of the various coatings is shown. The abrasion resistance of TiAlN- and AlTiN-coatings was in the range of 3–5. In comparison to the TiAl-based hard coatings the abrasion resistance of the harder and more brittle TiCN-coating was better by a factor two of while that of the AlCrN-coating was

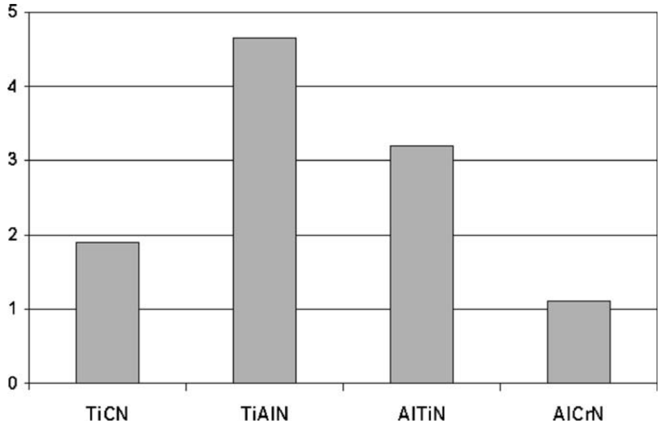

Fig. 2a. Abrasive wear resistance of TiCN, TiAlN, AlCrN coatings measured by calo wear test.

better by a factor of 3–5. As all coatings were deposited by the cathodic arc technology all of them showed a very dense compact structure. No columnar growth which is more typical for sputtering technology was evident.

Fig. 2b represents the *thermal conductivity* of TiN, TiCN, TiAlN, AlTiN and AlCrN. This property defines (besides surface properties and coefficient of friction), which amount of heat goes into the tool and which amount of heat goes into the chips. As comparison thermal conductivity of cemented carbide is around 80 W/mK. Thermal conductivity is itself depended on temperature. It is interesting to note that the thermal conductivity of AlCrN decreases above 250 °C, whereas the thermal conductivity of AlTiN coatings increases with temperature.

The *oxidation resistance* is an important property of hard coatings particularly for cutting tool applications. Mainly, during dry and high speed machining operations high temperatures are created in the cutting zone area. Higher oxidation resistance is one of the motivating factors to replace the existing coatings such as TiAlN, TiCN or TiN by a new generation of cutting tool hard coatings.

All samples were heated up to the chosen temperature, held for 30 min in air and cooled down to room temperature. The thickness of the oxidized layer formed at the coating surface was measured in fracture-cross-sections of the samples in the SEM. The TiCN-coating was stable up to a temperature of 600 °C, above this temperature the coating starts to decompose. Glancing incidence X-ray diffraction measurements were done at 600, 700 and 800 °C. At 600 °C the first signs of tetragonal TiO_2-phase beside the TiN-phase could be detected. At 800 °C the film was completely oxidized and only the tetragonal structures of TiO_2 could be found in the XRD pattern.

The TiAl-based nitrides such as TiAlN and AlTiN were stable against oxidation up to temperatures of about 800 °C. This corresponds to the investigations of Tanaka et al. [6], where oxidation temperatures of 830 °C for TiAl-based nitride coatings were reported. At 900 °C an oxidized layer thickness of about 350 nm for TiAlN and 250 nm for AlTiN were measured. Due to the high temperature the segregation of titanium and aluminum atoms is probable. Evidently, high temperature oxidation involved diffusion of aluminum atoms to the surface to form a very thin aluminum oxide top layer while the remaining titanium underlayer formed titanium dioxide. At 950 °C, the whole coating was decomposed and pure titanium dioxide was formed. No crystalline aluminum oxide could be found in the XRD-measurements.

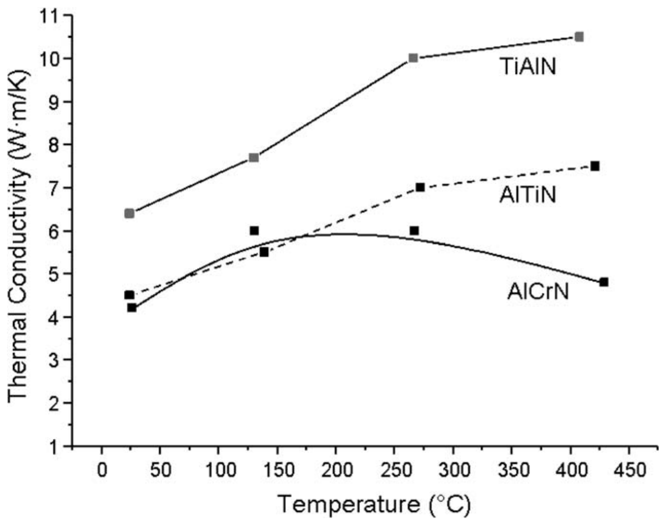

Fig. 2b. Temperature dependence of thermal conductivity of various hard coatings, measured by picosecond thermal reflection method [5] (Source: University of Illinois).

The coating with the best oxidation resistance was AlCrN. Even at 1100 °C only a thin oxidized layer of about 150 nm in thickness could be observed. At these elevated temperatures oxidation problems with the cemented carbide substrate occurred. The substrate itself started to decompose and formed tungsten and cobalt oxides. In Fig. 3, the SEM fracture-cross-section pictures and the corresponding XRD-patterns of the annealed samples at 900, 1000 and 1100 °C are shown. Initial oxide formation at the coating surface can be seen on the SEM-picture at 1000 °C although in the XRD-patterns no oxide compounds are evident. For all temperatures strong peaks of the cubic AlN-phase could be found. At 1100 °C the oxidized top layer was thick enough to be detected and indexed as Al_2O_3-peaks having a rhombohedral structure (corundum). Similar results on the thermal stability in oxidized atmosphere of high aluminum content AlCrN-coatings were also reported by Kawate et al. [7].

3.2. Comparison of cutting tests

In Fig. 4, the metal cutting performance in a *high speed machining operation in carbon steel* is shown. Various coated carbide end mills (∅8 mm, 3-flute) were tested in milling medium carbon steel Ck45 (DIN 1.1191, AISI 1045). The milling operation was done under wet conditions using the following cutting parameters: $f_z = 0.1$ mm, $a_p = 10$ mm and $a_e = 0.5$ mm. A high cutting speed v_c of 400 m/min was chosen. The wear criterion was a maximum flank wear $V_B = 0.18$ mm. Under these cutting conditions a high thermal stability of the coating along with good abrasion resistance are needed for increased coated tool performance. TiCN-coated, TiAlN-coated and AlCrN-coated carbide tools were compared in this test.

As already shown in the stationary oxidation tests, TiCN is not as stable at elevated temperatures relative to the other coatings. At high cutting speed the thermal load on the cutting edge of the TiCN-coated tool gave low tool life of around 30 m at a flank wear criterion of 0.1 mm. In this case, the good abrasive wear resistance at room temperature of the TiCN-coating (see also Fig. 2a) was less dominating for the tool life. Hence, the higher temperature wear resistance of TiCN seems to be insufficient if high temperatures are induced in cutting processes. This property would be more important for lower cutting speeds

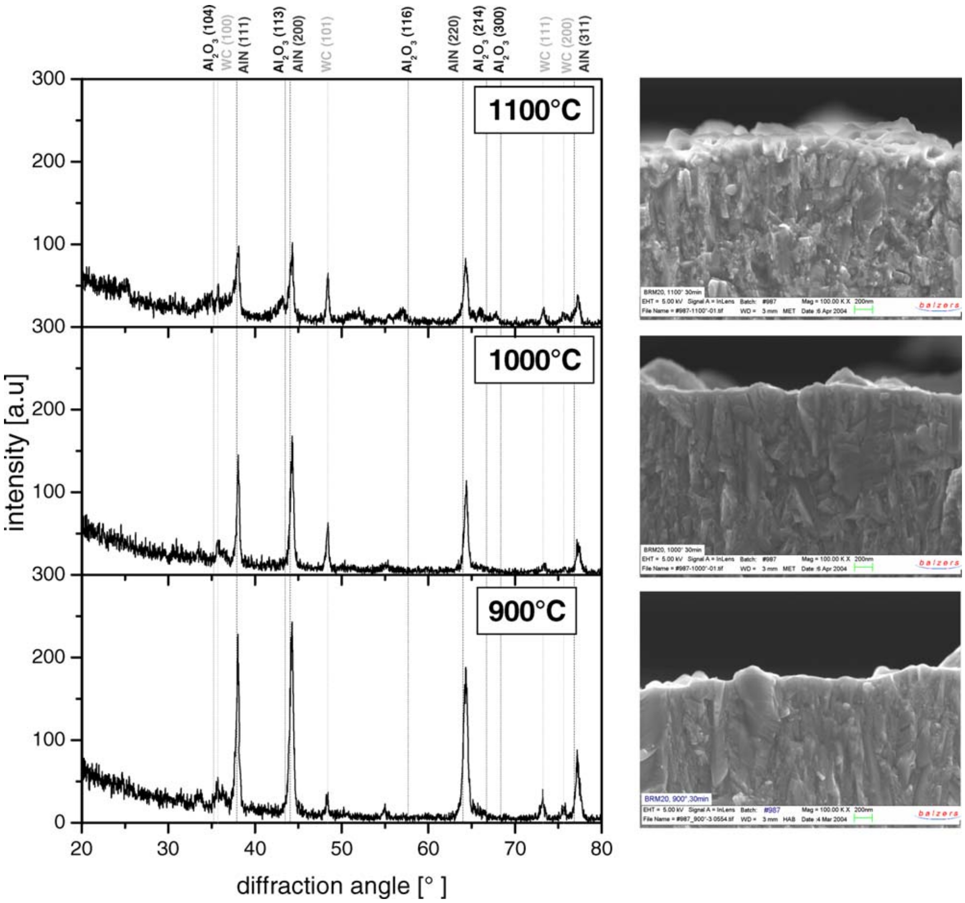

Fig. 3. Oxidation resistance of AlCrN at 900, 1000 and 1100 °C. SEM cross-section and XRD after oxidation tests.

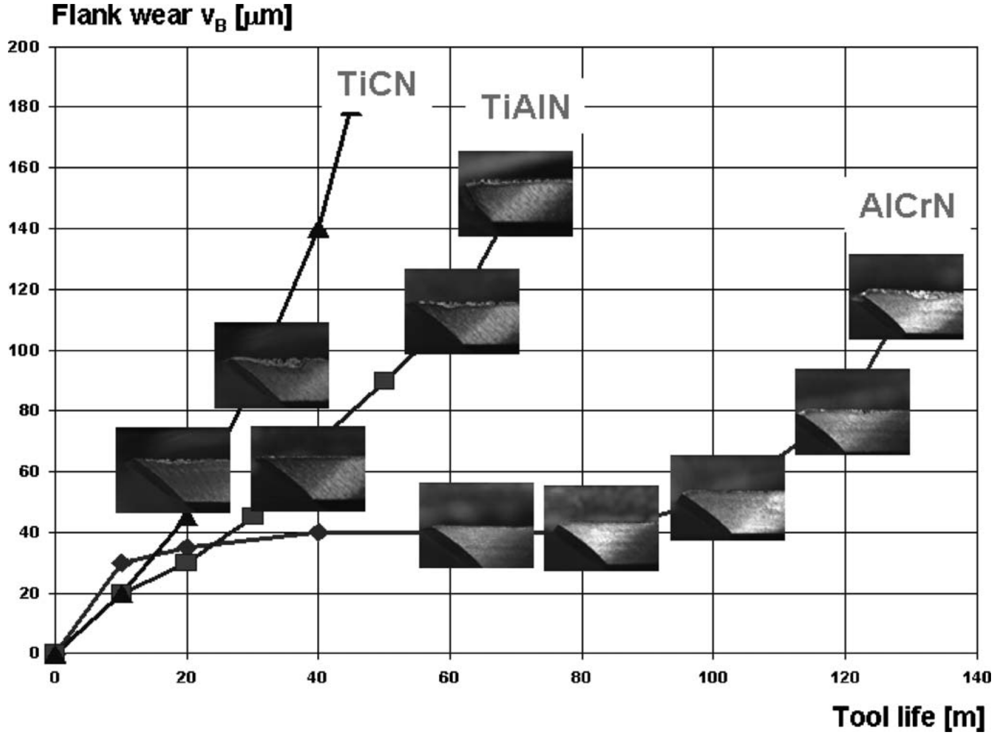

Fig. 4. Milling (finishing) test in carbon steel (AISI 1045) (carbide end mill (∅8 mm, 3-flute), $v_c = 400$ m/min, $a_e = 10$ mm, $a_p = 0.5$ mm, $f_z = 0.1$ mm, emulsion 5%).

e.g. 200 m/min. In the case of the TiAlN-coated tool the tool life increased to about 60 m. Here, the higher oxidation resistance of the TiAlN-coating in comparison to the TiCN-coated tool is the key issue for the better performance in this high speed cutting application. But if the oxidation resistance and abrasive wear resistance of the coating can be optimized simultaneously a significant increase in the tool life can be achieved.

By using an AlCrN-coating both properties are combined in one coating (see Figs. 2a and 3) and a performance increase by a factor of two to a tool life of about 130 m in this cutting test could be reached. Looking on the wear curve it can be seen that this coating has a very nice running-in phase, followed by a stabilized wear rate. This can be easily observed on the light microscopy photographs at 60, 80 and 100 m tool life. Nearly, no flank wear could be detected up to a tool life of around 100 m. After this lifetime a controlled progressive wear could be found until the end of the tool life at 130 m.

Interrupted turning tests are used for determining the toughness, wear and breakage behavior of carbide inserts, but may also be used for a fast analysis of coatings. In this case, the test was performed at cutting speeds of 200 and 315 m/min (42CrMo4V, $a_p = 1.6$ mm, $f = 0.32$). At lower cutting speed all tested coatings (TiCN, TiAlN, AlTiN, AlCrN) reached the end of the test (8000 strokes), however the wear picture was depended on the coating. In a schematic drawing (Fig. 5) the differences are presented. TiAlN shows a pronounced flank wear and a larger greater, whereas AlCrN shows almost no flankwear, but a deeper craterwear. The lower flank wear of AlCrN is explained by the higher abrasive wear resistance (Fig. 2a). The differences in crater may be explained by the different thermal properties of both coatings. Thermal conductivity (Fig. 2b) and coefficient of friction influences chip formation, therefore also the position and the width of the crater may be different.

At higher cutting speed (315 m/min) using AlCrN 6000 strokes could be done, before breakage of the inserts. This is explained by the higher thermal stability (oxidation resistance, hot hardness and thermal conductivity), whereas TiAlN reached 4000 strokes, TiCN coated inserts failed after 2500 strokes.

In Fig. 6, tool life time in a *gear cutting application* result is presented. In this application, an AlCrN-coated high speed steel hob was compared to an AlTiN-coated hob. This test was done in dry conditions at a cutting speed v_c of 200 m/min in a case-hardening steel (AISI 5115, DIN 17131). The wear criterion was a maximum wear V_B of 0.3 mm. The state-of-the-art AlTiN coating normally produced 2300 parts. By coating this hob with the high aluminum content AlCrN-coating the lifetime of the tool could be increased nearly by a factor of two. About 4100 parts could be produced in this gear cutting operation.

It is known that oxidation resistance and thermal conductivity are the dominating coating properties for especially dry gear cutting applications [8]. Kleinjans has shown that crater wear is caused by a high thermal load on the tool material, and therefore either a low thermal conductivity or a high coating thickness can protect the tool from early failure. In Fig. 2b it is shown that AlCrN based coatings show a low thermal conductivity, and even more important, the thermal conductivity does not increase (measured for temperatures up to 500 °C).

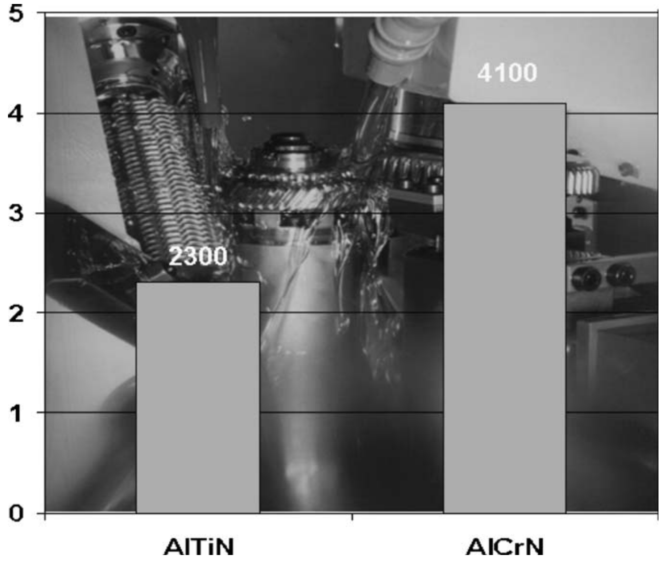

Fig. 6. Hobbing operation in case-hardening steel (AISI 5115, PM HSS-Hob), $v_c = 200$ m/min, dry, $v_B = 0.3$ mm.

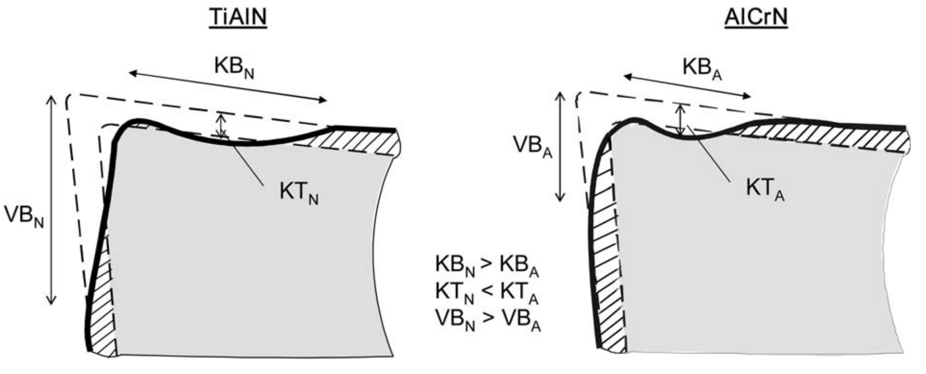

Fig. 5. Schematic drawing of wear pattern after interrupted turning test (42CrMo4V, $v_c = 200$ m/min, $a_p = 1.6$ mm, $f = 0.32$).

Besides this example, additionally positive results have been reported for AlCrN coating on high speed steel hobs in wet applications as well as on cemented carbide hobs in both wet and dry applications.

4. Conclusions

Ti-based coatings represent the state-of-the-art for PVD hard coatings used in industrial machining applications. However, new challenges mainly in the field of metal cutting as well as in stamping and forming applications need continuous improvements. Besides mechanical and physical properties, oxidation resistance and the affinity between the workpiece material and the tool are very important for further developments. These properties can be influenced on the one hand by various deposition parameters and coating technologies but also by a certain chemical composition of the elements used for the coatings.

This paper gives a comparison between state-of-the-art Ti-based PVD hard coatings and a Ti-free AlCrN-coating. Besides coating properties also machining applications in various cutting tests are compared. It could be shown that due to the excellent oxidation and wear behavior of high aluminum content AlCrN coating big steps in improvement in machining applications could be achieved. Mainly, in machining of medium carbon and heat-resistant steels excellent results in tool life for a wide range of cutting speeds could be found. As this coating is quite new in the cutting tool market further machining tests have to be done to define the potential for this type of coating.

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