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Wear Protection in Cutting Tool Applications by PACVD (Ti,Al)N and Al_2O_3 Coatings

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Abstract

Various (Ti,Al)N-, Al_2O_3-, and (Ti,Al)N/Al_2O_3 multilayer coatings were deposited onto cemented carbide cutting tool inserts by a plasma assisted chemical vapour deposition (PACVD) technique. Al_2O_3 coatings were deposited using the gaseous mixture $AlCl_3$, Ar, H_2, and O_2. (Ti,Al)N intermediate layers were deposited in the same device using the process mentioned and the gases $AlCl_3$, Ar, H_2, $TiCl_4$ and N_2. The unique properties of (Ti,Al)N/Al_2O_3 multilayer coatings result in superior wear protection for cutting inserts applied in severe multifunction cutting processes. The influence of different deposition temperatures on structure and properties of the coatings like crystallographic phases, chemical composition, mechanical and technological properties is shown.

PACVD (Ti,Al)N/Al_2O_3 coated cutting inserts with fine grained crystalline α/κ-Al_2O_3 offer performance advantages which are superior with respect to coatings deposited by chemical vapour deposition (CVD) due to the low deposition temperature applied.

Keywords:

PACVD, (Ti,Al)N, Al_2O_3, Multilayer, Cemented Carbide , Wear

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1. Introduction

Changes in economical and technological developments in the cutting market show an impact on the requirements in the design of coated cemented carbide cutting tools. Wear resistance was mostly considered as the main criteria for cutting operations during the last 20 years. Modern automatic machining process facilities created additionally a demand in process stability. The appropriate fatigue properties of cemented carbide substrate materials and cermets attract a considerably higher amount of attention for highly reliable machining.

It is well known that the mechanical properties of powder metallurgical substrates may suffer from the high process temperatures of a common CVD process [1,2,3]. The superior performance of PVD TiN, TiCN, and (Ti,Al)N based coated tools in interrupted cutting applications, such as milling, grooving, threading, and drilling led to a considerable development of commercial PVD coatings. Nevertheless, the wear resistance of CVD crystalline α-Al_2O_3 or κ-Al_2O_3 is still superior in many cutting applications.

Plasma Assisted Chemical Vapour Deposition (PACVD) allows both to obtain the excellent properties of CVD coatings and the advantages of the low PVD substrate temperature. This creater a new approach to meet the required wear behaviour of modern cutting tools, such as multifunctional cutting tools (e.g., for drilling and turning).

Additional advantages of the PACVD process are:

- the possibility to deposit crystalline Al_2O_3
- the possibility to deposit (Ti,Al)N
- the deposition of Al_2O_3 directly onto cemented carbide, cermets, and steel substrates without using bonding layers
- substrate rotation is not required to obtain homogeneous coating thickness
- only low amounts of process gas are required
- relatively high pressure of 100...500 Pa are used
- the process is highly economical

In this study, cutting of steel with the multifunctional tool Tizit EcoCut® was chosen to demonstrate these special advantages.

Wear and failure of cutting tool inserts involve a complex interaction between various mechanisms. The most important wear and failure modes can be seen in Fig. 1 and are summarized as follows:

Using EcoCut® tool inserts, drilling operation with perpendicular plain hole ground as well as turning (plain and parallel) is realised within one tool. Damage on the main cutting edge are attributed to cracking due to stress and thermal fatigue of coating and substrate material in position 1 during drilling and abrasion and crater wear in position 2 during turning (see Fig. 1). In general, insert life may be enhanced by geometric factors (e.g., governing stresses, chip formation, thermal gradients), processing conditions (e.g., cutting parameters, lubricants), substrate, coating, and surface conditions.

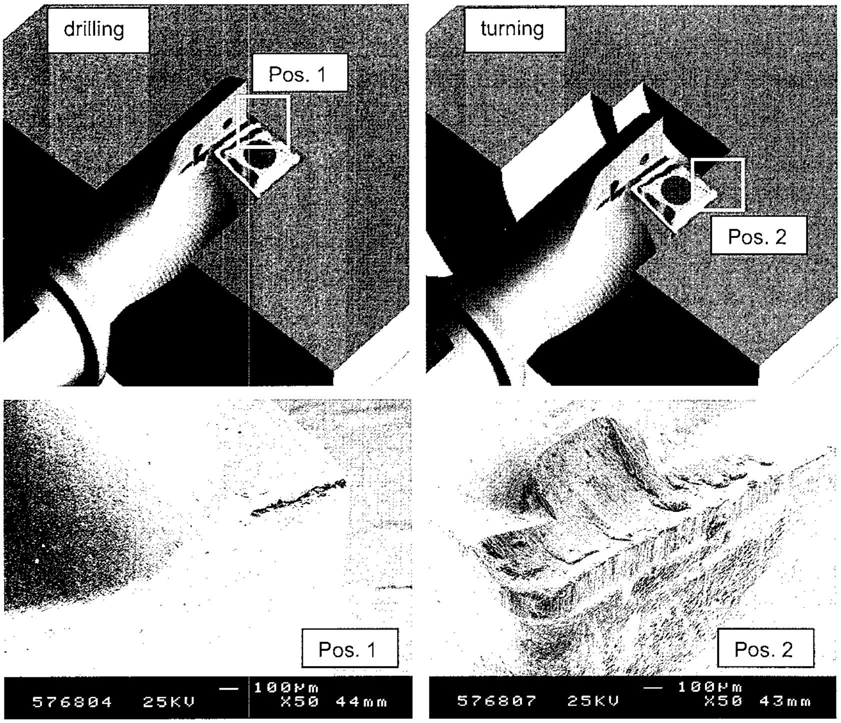

Fig. 1. SEM micrographs of damage mechanisms on EcoCut® cutting tool inserts in drilling (left) and turning (right)

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It is the aim of this paper to present and discuss the results obtained with new PACVD (Ti,Al)N/Al_2O_3 multilayer coatings on cutting tool inserts. For this investigation, two goals are focused: (i) the performance of PACVD coatings in cutting and (ii) the interpretation of analytical methods related to the wear mechanisms observed.

2. Experimental Details

2.1. Coating Deposition

Deposition experiments were carried out using a PACVD system, which consists of an inductively heated vertical reactor with parallel plate-type electrodes (diameter, 500 mm), powered by a unipolar pulsed dc power supply for deposition of (Ti,Al)N and a bipolar pulsed dc power supply (MAGTRON) for deposition of Al_2O_3 [4]. The electrodes are connected to the pulse power supply and isolated from each other and the reactor wall. The plasma was generated using a DC pulse power supply (unipolar, bipolar) with frequencies up to 33.3 kHz. The reactor size was 400 mm in diameter and 600 mm in height.

The gas inlet system consists of a tube with a perforated gas ring distributor positioned between the plate electrodes. As process gases, H_2, Ar, O_2, N_2, $TiCl_4$ and $AlCl_3$ (formed by reaction between HCl and Al chips) were used. The total gas flow, the total pressure and the pulse frequency during deposition were kept constant. In addition to further process parameters, the substrate temperature was varied as shown in Table 1. (Ti,Al)N and Al_2O_3 single layered coatings as well as (Ti,Al)N/Al_2O_3 multilayered coatings were deposited in the same reactor. Multilayered coatings were produced in the same run.

Table 1. Deposition process parameters for (Ti,Al)N and Al_2O_3

deposition parameter	(Ti,Al)N	Al_2O_3
total pressure [Pa]	200	200
substrate temperature [°C]	500 ... 600	500 ... 700
total gas flow [l/h]	500	500
discharge voltage [V]	440	280
power supply	unipolar	bipolar

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The substrates used for the coating experiments and cutting tests were cemented carbides (11 wt% Co, 8 wt% Ta/NbC, 4 wt% TiC, rest WC). Silicon was used as substrate for stress measurements.

2.2. Coating Characterisation

The coatings deposited were characterised by scanning electron microscopy (SEM, JEOL JSM 6300), X-ray diffraction (XRD, Siemens C09 585), and standard metallographic techniques. The composition of the coatings was investigated using energy dispersive X-ray analysis (EDX). For evaluation of the coating adhesion on the substrate, a scratch test was employed. The biaxial stresses in the coatings were characterised by using the deflection method with silicon samples sized 20 × 7 × 0.3 mm^3 using the Stoney formula [5]. The deflection was measured using two parallel laser beams reflected from the sample surface. During the measurement, the sample was heated in vacuum (pressure $\leq 10^{-2}$ Pa) up to 700°C at a rate of 5°C/min and cooled down afterwards.

2.3. Cutting Tests

The wear properties of the coated inserts were evaluated in a metal cutting test. The specific cutting experiments were carried out using WC/Co based cemented carbide cutting tools (Tizit EcoCut®, insert style XCNT080403EN). A HEID FMS 530 turning machine was used to realize lubricated cutting with coolant. The coated inserts were evaluated in the machining of special parts shown in Fig. 2 with the operation steps drilling (first step) and turning of nine segments (the shoulder on the inner side of the part). To create appropriate cutting conditions, a Ck60 steel (DIN 1.1221) was used as test material. The detailed cutting conditions for drilling and turning as well as the main goal of these cutting operations are listed in Table 2.

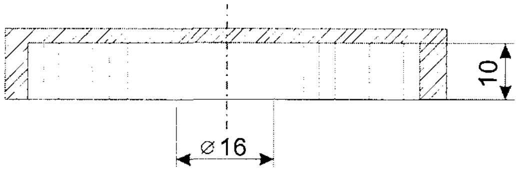

Fig. 2. Schematic drawing of one part used for cutting tests

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Table 2. Cutting test parameters

cutting method	cutting conditions		purpose of testing
continuous drilling of Ck60 steel	speed depth of cutting feed rate wet	v_c = 150 m/min a_p = Ø 16 mm f = 0.04 mm/rev	fracture resistance
continuous turning of Ck60 steel	speed depth of cutting feed rate wet	v_c = 200 m/min d = 2.0 mm f = 0.15 mm/rev	wear resistance

3. Results and Discussion

3.1. Coating Characterisation

3.1.1. Coating Thickness

Coating thickness depends on various factors like process parameters (position in the chamber, core construction of reactor, process gas mixture, gas flow, plasma discharge, pressure, deposition temperature, etc.), the substrates used, and the deposition time. The individual film thickness of the various coatings shown in Fig. 3 are typical examples for the coating thickness used in the cutting tests and for stress measurements.

3.1.2. Coating Composition

The coating composition was investigated qualitatively and quantitatively using EDX. For the (Ti,Al)N coatings, the Ti:Al atomic ratio was adjusted to be about 1:1. An expected slight shift towards a higher Al content was observed for higher process temperatures, as already reported in [6]. A very small amount of Cl was detected, which increases for lower process temperatures. The different Al_2O_3 coatings showed a constant Al:O atomic ratio. A comparable small amount of Cl (similarly increasing with declining process temperature) and traces of Ar were detected in the coatings.

3.1.3. Coating Structure

The structure of the (Ti,Al)N intermediate layers is characterised by fine-grained columns and a smooth surface morphology (see Fig. 3) with sub-micron sized crystals. Higher deposition temperatures result in an increase of the size of the column or grain diameter.

The crystalline Al_2O_3 coatings deposited showed very fine-columnar grain structure. The coatings show a very smooth surface with crystals in the sub-micron range. Typical morphology of amorphous Al_2O_3 coatings were detected by SEM cross-section as featureless and glass-like structure, with an extremely smooth surface. It is interesting to note the well-matched crystal size of both the (Ti,Al)N and Al_2O_3 layers shown as sample 2 in Fig. 3 indicating advantages with regard to adhesion in the interface structure as compared to samples 1, 3, and 4.

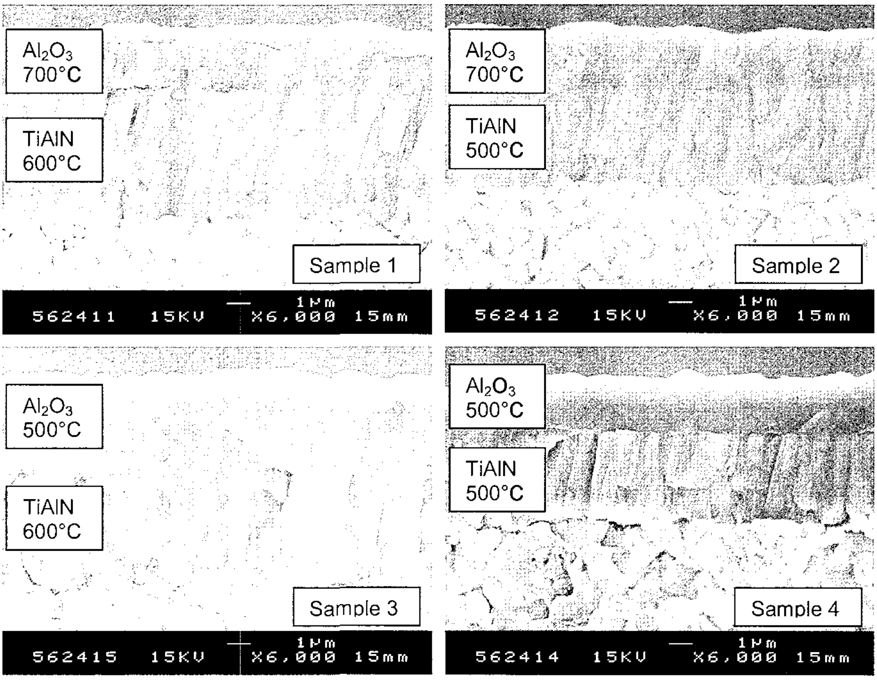

Fig. 3. SEM cross-sections of (Ti,Al)N/Al_2O_3 multilayer coatings on cemented carbide substrates

XRD patterns of the typical crystalline and amorphous Al_2O_3 coatings, respectively, are shown in Fig. 4. Both the α-Al_2O_3 and κ-Al_2O_3 phase were identified in the crystalline coatings deposited at higher substrate temperature. For the amorphous Al_2O_3 coating deposited at lower temperature, no diffraction peaks were detected.

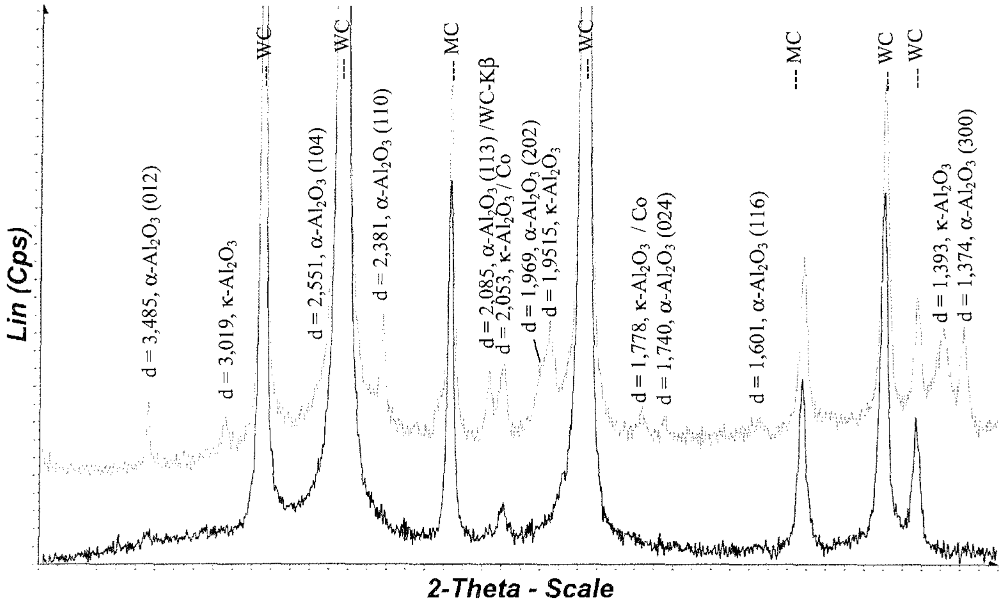

Fig. 4. XRD pattern for a crystalline α/κ-Al_2O_3 (top) and an amorphous Al_2O_3 coating (bottom)

3.1.4. Coating Adhesion

The adhesion of the coatings was evaluated using acoustic emission during scratch tests. For the samples 1 to 4 shown in Fig. 3, the critical loads obtained were 19 N, 12 N, 52 N, and 5 N, respectively. Deposition conditions, coating thickness, structure, and intrinsic stresses are known to affect the scratch test results. In general, adhesion may be further enhanced using chemical, mechanical, or thermal pre-treatment of the uncoated cutting inserts.

3.1.5. Biaxial Coating Stresses

For adhesion and formation of thermal fatigue cracks, the dependence of stresses on the temperature is assumed to be crucial [7]. An example for this dependence of coating stresses is shown in Fig. 5 for the coatings used in this work deposited onto silicon substrates as single layers. Because of the low thermal expansion coefficient of silicon (3×10^{-6} K^{-1} [8]) with respect to the coatings investigated, all coatings show biaxial stress close to zero or even tensile stresses in the as-deposited condition. However, coating stress can be assumed to shift to the advantageous compressive region for cemented carbide substrates with higher thermal expansion coefficients (for the cemented carbide used in this work, the thermal expansion coefficient increases from 5.6×10^{-6} to 5.8×10^{-6} K^{-1} in the temperature range between 20 and 700°C [9]).

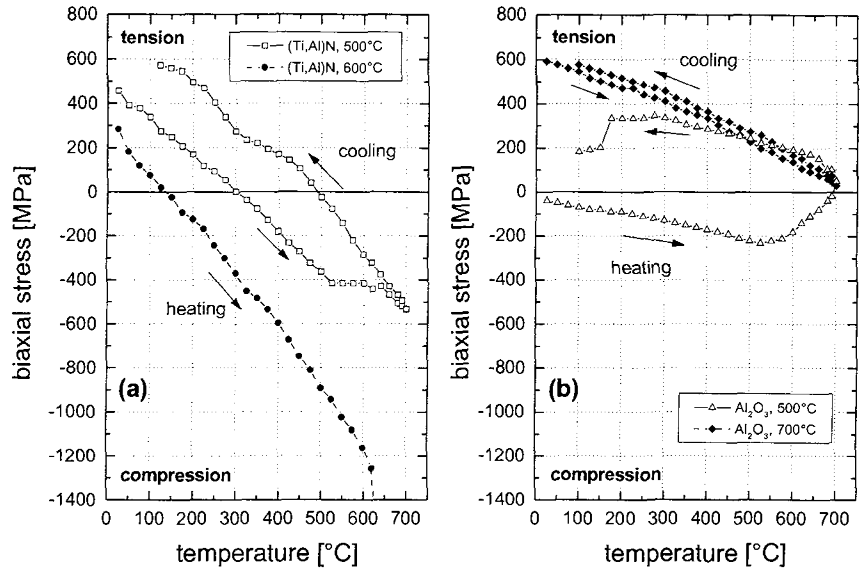

Fig. 5. Dependence of the biaxial film stress on the temperature for different coatings on silicon substrates

As the coating-substrate composite is heated, the tensile stress component is relaxed and the system follows a thermoelastic line to increasing compressive stresses. The lower mismatch in the thermal expansion coefficients of Al_2O_3 and Si with respect to that for the (Ti,Al)N/Si system is also visible by the lower slope of the thermoelastic line for the Al_2O_3 coatings. Temperatures exceeding the deposition temperature lead to a relaxation of the stress as a result of recovery of coating defects [10]. In the case of extremely high stresses (as observed for the (Ti,Al)N coating deposited at 600°C, solid

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circles in Fig. 5a), an apparent further increase of the coating stress for increasing temperatures was observed which is attributed to softening of the substrate (and thus coating stress relaxation by increasing substrate bending [11]). During the cooling phase, tensile cracks may be formed in the coating as a result of tensile stresses, leading to a lower slope in the curve.

In general, the stress-temperature curves reveal the beneficial effects of a higher deposition temperature, as shown in the case of the Al_2O_3 coating deposited at 700°C (solid circles in Fig. 5b). In this case, no recovery effect at high temperatures and no tensile crack formation was observed.

3.2. Cutting Test Results

The cutting tests were carried out according to the test parameters summarised in Fig. 2 and Table 2 using the coated samples shown in Fig. 3. In Fig. 6 the flank wear of the coated EcoCut® inserts are plotted versus the number of parts machined. The life time criteria was dictated by the wear mechanisms occurring, i.e. substrate failures, chipping of the coating, and flank wear.

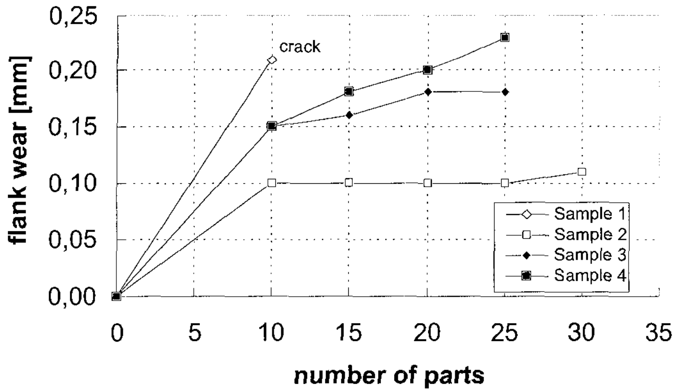

Fig. 6. Cutting test results obtained for the samples shown in Fig. 3 (for details of the machined part see Fig. 2)

For sample 1, the shortest tool lifetime of 10 machined parts was obtained. A very rapid wear progress was observed in this case. This was caused by chipping of the whole multilayer coating from substrate and resulting damage of the cutting edge named as position 1 in Fig. 1. Sample 2 showed superior wear resistance and tool life (more than 30 parts machined). For samples 3 and 4, a tool life of 25 parts was obtained. However, sample 4 showed a faster wear progress compared to sample 3 due to lower coating thickness of the Al_2O_3 layer.

3.3 Failure Analysis and Wear Mechanisms

As shown in Fig. 6, remarkable differences in the wear behaviour were detected for the different samples. The wear mechanisms observed are summarised in Fig. 7 and can be classified according to Table 3. The classification refers to the failure mode observed on the cutting edge.

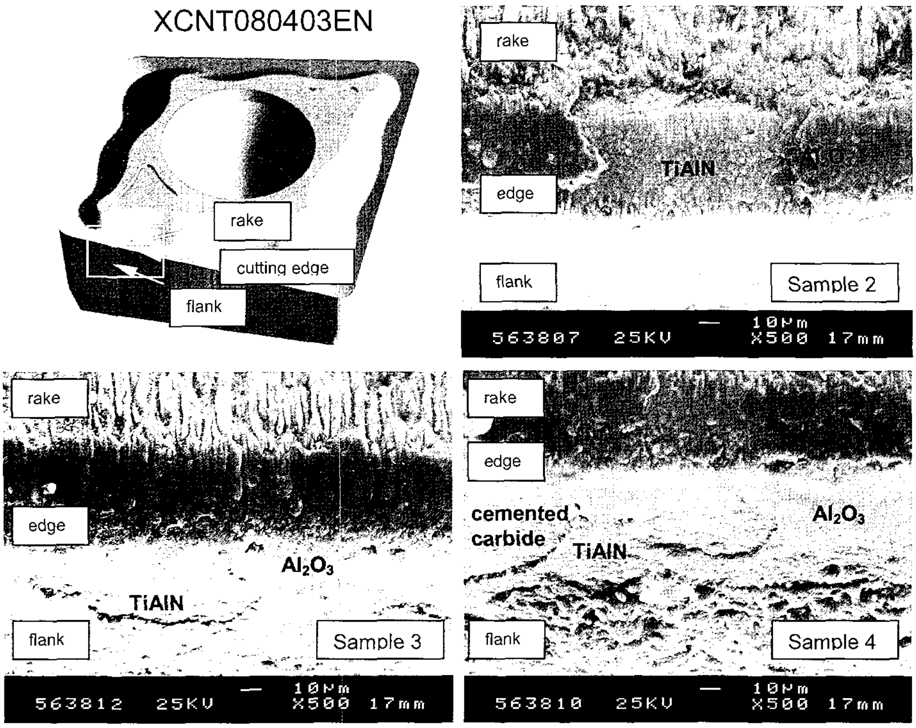

Fig. 7. SEM micrographs of the wear mechanisms observed during cutting tests using the samples shown in Fig. 3 (the number of parts machined is given in Table 3)

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It is obvious, that higher deposition temperature of the Al_2O_3 coating has an advantageous effect on the abrasion resistance. The dominating damage mechanism of sample 1, i.e. failure of the interface between cemented carbide and (Ti,Al)N coating seems to be in good agreement with the high intrinsic compressive coating stresses (see Fig. 5, the intrinsic stress component can be seen when the temperature reaches the deposition temperature of 600°C for the (Ti,Al)N intermediate layer). Lower intrinsic stress values (which can be assumed to be compressive if the curves shown in Fig. 5 are shifted to the compressive region according to the higher thermal expansion coefficient of the cemented carbide substrate compared to Si) seem to be related to lower interfacial stresses and, consequently, less pronounced interfacial failure. According to the Coffin-Manson relationship for low cycle fatigue [12], where the plastic strain amplitude applied during thermal cycling governs the number of cycles to failure, those coatings showing the lowest compressive stresses have proven to perform in a superior manner.

Table 3. Tool life limiting wear mechanisms and cutting performance of the samples shown in Fig. 2 depending on deposition parameters

sample	**deposition temperature (Ti,Al)N/Al_2O_3**	**number of parts machined**	**dominating wear mechanisms**
1	600°C/700°C	10	• interface failure (cemented carbide/(Ti,Al)N) • crack formation
2	500°C/700°C	>30	• partial interface failure ((Ti,Al)N/Al_2O_3)
3	600°C/500°C	25	• significant abrasive wear of Al_2O_3 • partial interface failure ((Ti,Al)N/Al_2O_3)
4	500°C/500°C	25	• significant abrasive wear of Al_2O_3 • partial interface failure ((Ti,Al)N/Al_2O_3) • partial interface failure (cemented carbide/(Ti,Al)N)

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4. Conclusions

Hard coatings based on (Ti,Al)N/Al_2O_3 deposited by PACVD have proven to increase the lifetime of cemented carbide cutting tools. Using the PACVD technique, a direct deposition of hard coatings like TiN, Ti(C,N), (Ti,Al)N, (Ti,Al)(C,N) and Al_2O_3 onto cemented carbide, cermet, and steel substrates is possible. 700°C crystalline Al_2O_3 coatings could be deposited which show excellent wear resistance. Coatings deposited at 500°C were amorphous. (Ti,Al)N coatings deposited in the same run serve as highly suitable intermediate layer.

In applications with severe cutting conditions, the lifetime of cemented carbide inserts depends besides a variety of different mechanisms on the toughness of the substrate material and the coating properties as well. Cracking of substrates and coatings has been considered to be caused by higher stresses induced by higher deposition temperatures. The tool life limiting wear mechanisms of crack formation in the substrate material, abrasion and chipping due to adhesion problems are determining the tool performance.

Although the properties of (Ti,Al)N/Al_2O_3 multilayers are not known sufficiently well until now, biaxial stress measurements of the individual single layers seems to be an appropriate additional method to characterize and improve the required coating properties.

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