



nc-AlTiN/a-Si₃N₄ and nc-AlCrN/a-Si₃N₄ nanocomposite coatings as protection layer for PCBN tools in hard machining

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ABSTRACT

The cutting material polycrystalline cubic boron nitride (PCBN) is ideally suited for machining of difficult-to-cut materials. It exhibits properties such as high hardness and high chemical stability at elevated temperatures. However, due to the occurrence of tribo-oxidation and abrasion during machining of hardened steels abrupt tool failure is common. The deposition of coatings offers a possibility to protect the PCBN substrate. Initial research results indicate that nanocomposite coated cutting tools show a significantly improved tool life and process behavior in hard machining. This paper describes the results of machining tests with uncoated and nc-AlTiN/a-Si₃N₄ and nc-AlCrN/a-Si₃N₄ nanocomposite coated PCBN tools with regard to the tool life and wear form. Additionally, the wear mechanisms abrasion and tribo-oxidation were investigated in model wear experiments. Furthermore, FEM cutting simulations were used to investigate the thermal interaction between substrate and coating.

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1. Introduction

To improve the mechanical properties of highly stressed steel components, such as crank shafts and gearbox parts, a heat treatment process by e.g. quenching and tempering is used. The components reach hardness values of more than 50 HRC. The machining of such materials belongs to the field of hard machining. The finishing process of hardened cylindrical components is carried out by grinding or hard turning. However, due to the higher flexibility, the possibility to cut complex geometries with a single machine setup and reduced machining time, hard turning is gaining increasing importance. Additionally, the achievable surface roughness (R_a up to 0.1 μm) and dimensional tolerance (IT3) are similar to that which can be realized in grinding processes. For this purpose polycrystalline cubic boron nitride (PCBN) and mixed ceramics, such as $\text{Al}_2\text{O}_3 + \text{TiC}$, are used as turning tools. PCBN shows in comparison to ceramic a higher hardness and higher process reliability. Furthermore, due to its high temperature resistance combined with a high bending strength, PCBN is particularly suited for hard turning applications [1–5].

The properties of PCBN tools strongly depend on the one hand on the type and proportion of the binder phase (ceramic, metallic) as well as the particle size of the CBN grains, and on the other hand on the production process. For this reason the range of possible applications for PCBN tools extends from hardened steels and cast irons to difficult-to-cut materials, e.g. the nickel-based alloy Inconel 718, in both continuous and interrupted cutting [3,6,7].

Therefore, the selection of the appropriate PCBN type is of considerable practical importance. For machining of hardened steels in continuous cutting, PCBN types with low CBN content and ceramic binder are preferred. This is due to the higher toughness resulting in an improved compressive strength and edge stability at elevated temperatures. In contrast, tools with high CBN content and metallic binder are more suitable for applications with significantly alternating thermal loads such as interrupted turning or milling processes [3,8]. Important and expanding fields of application for PCBN tools are the tool and mold making as well as automotive industry [9,10]. Table 1 shows the properties of cubic boron nitride along with the properties of PCBN tools depending on the CBN content.

Despite the outstanding mechanical properties of PCBN, considerable crater wear and flank wear commonly occur during steel machining. This is mainly caused by the wear mechanisms tribo-oxidation and abrasion. The development of crater wear is particularly critical, as it weakens the cutting edge. The high thermal and mechanical loads in hard machining may therefore lead to abrupt tool failure [15,16].

The effect of coatings to prevent tribo-oxidation in the form of diffusion has successfully been established in the industrial application of cemented carbide tools. The wear reducing effect is well studied in several publications [12,17]. However, when looking at PCBN the situation is entirely different. Coatings and in particular nanocomposite coatings on PCBN tools have been investigated to a significant lower extent.

According to Veprek and Jilek [18] the fabrication of nanocomposite coatings is based on the immiscibility of two compounds causing a thermodynamically driven (spinodal) segregation during deposition and ultimately resulting in a spontaneous self-organization of a stable nanostructure. Nanocomposite coatings consist of a hard crystalline phase

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Table 1

Properties of different PCBN grades and CBN [3,8,11–14].

		PCBN with 40...60% CBN	PCBN with 80...90% CBN	CBN
Density ρ	g/cm ³	–	–	3.48
Thermal expansion α	10 ⁶ /K	–	–	4.8...5.8 (430...1160 °C)
Hardness	GPa	24...33	26...43	65...70
Fracture toughness K_{IC}	MPa m ^{1/2}	2.7	6.3	3...6
Bending strength σ_{bb}	GPa	0.6...1.2	1...1.4	0.36...0.45
Thermal conductivity λ	W/mK	35...50	100...120	1300

(e.g. AlTiN, AlCrN grains) embedded in an amorphous phase (a-Si₃N₄, a-C). Due to their unique nanostructural design nanocomposite coatings exhibit hardness levels of >40 GPa and thermal stability up to temperatures of 1200 °C [18,19]. Hence, they show a high hardness and oxidation resistance in combination with a low thermal conductivity [20]. These properties are essential requirements to improve the performance of tools, particularly in the field of hard machining where high thermal and mechanical loads act on the cutting edge. Moreover, as a result of their unique structure these coatings provide a high resistance against crack propagation. For these reasons, they are well suited to protect the PCBN substrate. The operational performance of this coating concept on cemented carbide tools for high performance workpiece materials and dry cutting operations has been verified in numerous studies [19,21]. First fundamental studies also indicate the potential of nanocomposite coatings on PCBN tools [22]. Thereby, it could be proven that nc-AlTiN/a-Si₃N₄ coated PCBN cutting tools lead to improved tool life behavior in machining of hardened AISI 52100 with 60 HRC. The wear progress could be reduced. In this work it is intended to investigate the coatings regarding mechanical properties and tribological as well as application behavior. The aim is to detect the mechanisms of action in contact with hardened steel AISI H13 in order to identify the suitability of nc-AlTiN/a-Si₃N₄ and nc-AlCrN/a-Si₃N₄ coatings on PCBN cutting tools. Additionally, finite element method (FEM) cutting simulations were conducted to investigate the thermal interaction between substrate and coating during the machining process.

2. Experimental details and simulation model

2.1. Nanocomposite coated PCBN tools

The coatings were deposited on fine-grained PCBN types with a CBN content of 50 to 60% and a TiN binder phase. The geometry of the indexable inserts was ISO code CNGA120408 with a chamfer width of $b_\gamma = 0.14$ mm and a chamfer angle of $\gamma_f = 25^\circ$. Measurements of the cutting edge radius revealed a radius of approx. $r_\beta = 25$ μ m. As a result of pre-treatment and deposition of the nanocomposite coatings, the radius increased to approx. 30 μ m. In order to compare the nanocomposite coatings with coatings which are commercially available, a PVD coating based on TiAlN was used. The reference tools had the same ISO geometry and a cutting edge radius of approx. 20 μ m. The selected tools are specifically designed for machining of hardened steels with regard to edge geometry and coating.

The nanocomposite coating process was performed by the Society for Production Engineering and Development (GFE), Schmalkalden, Germany, using the Arc-PVD method on a coating machine by PLATIT, Grenchen, Switzerland. The deposition procedure involved the process steps: alkaline and Ar⁺ ion precleaning; ion beam etching with Ti⁺ respectively Cr⁺ ions using a high bias voltage of 1000 V; deposition of different intermediate layers (see Table 3) and deposition of nanocomposite coatings with a total coating thickness of 2.2...2.4 μ m. As major deposition conditions, a substrate temperature of 430...460 °C, a substrate bias of 40...110 V and a deposition pressure of 0.7...4 Pa were used. The elemental compositions of the nanocomposite coatings, as determined by glow discharge optical emission spectroscopy (GDOES), are summarized in Table 2.

The used nanocomposite coatings consist of AlTiN grains or AlCrN grains, each embedded in an amorphous Si₃N₄ matrix. These nanostructures and the resulting high numbers of grain boundaries lead to a high hardness. According to the different mechanical and thermal properties of the different phases, the coatings show higher residual stresses compared to conventional hard coatings. To compensate the stress differences between the PCBN substrate and the nanocomposite top layer, different intermediate layers have been used. The adjustment of the residual stress behavior and the properties of the intermediate layer were done for each nanocomposite coating (nc-AlTiN/a-Si₃N₄ and nc-AlCrN/a-Si₃N₄) with different architecture and thicknesses. It is supposed that a combination of metallic layers (Ti, Cr) and gradient structures influences the ductility of the intermediate layer system and allows the modification of residual stresses. The differences of the used intermediate layers are shown in Table 3.

Table 4 shows the most important physical properties of the two different nanocomposite coatings which were measured at IWF and GFE. The values are mean values of the different coatings with the three different interlayers, as the variation of the properties within the nc-AlTiN/a-Si₃N₄ and nc-AlCrN/a-Si₃N₄ coatings is low.

The specimen with nc-AlCrN/a-Si₃N₄ coating showed higher hardness and residual stresses than the specimen with nc-AlTiN/a-Si₃N₄ coating. The stress measurements only showed a small influence of the adhesion layer structure on the residual stresses of the nanocomposite coatings. Furthermore, the nc-AlCrN/a-Si₃N₄ coating showed a lower Coulomb friction coefficient with the contact partner hardened AISI H13. The coefficients were measured using a cylinder-plate-tribometer at a frictional speed of 50 m/min. First coating delaminations were observed in scratch tests at loads of 39 N for the nc-AlTiN/a-Si₃N₄ coating and 42 N for the nc-AlCrN/a-Si₃N₄ coating, respectively, indicating a slightly lower adhesion of the nc-AlTiN/a-Si₃N₄ coating to the PCBN substrate.

2.2. Analysis of tribological behavior

2.2.1. Calo test

In order to analyze the resistance against abrasion, calo tests were conducted. A hardened steel ball of AISI 52100 (62 HRC) with a 30 mm diameter rotating in a polishing medium (slurry) was pressed into the specimen with a defined load. The used slurry was a lapping suspension consisting of alcohol and diamond with an average grain size of $D_p = 1$ μ m. Tests were carried out with a rotational frequency of $n = 800$ rpm and a grinding time of $t_g = 300$ s. Once the film had been abraded off, the resulting impression was evaluated. For the calo test indexable inserts with the geometry ISO code TBGN060104B were used.

2.2.2. Annealing test

Uncoated, nc-AlTiN/a-Si₃N₄ (Ti-2) and nc-AlCrN/a-Si₃N₄ (Cr-2) coated inserts were heated in a furnace at standard atmospheric conditions in order to determine their oxidation behavior. The cutting inserts were

Table 2

Elemental composition of the nanocomposite coatings.

	Al [at.%]	Ti [at.%]	Cr [at.%]	Si [at.%]	N [at.%]
nc-AlTiN/a-Si ₃ N ₄	17.5	16	–	3.5	60
nc-AlCrN/a-Si ₃ N ₄	14	–	32	4	51

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