Wear of coated and uncoated PCBN cutting tools used in turning and milling

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Abstract

This licentiate thesis has the main focus on evaluation of the wear of coated and uncoated polycrystalline cubic boron nitride cutting tool used in cutting operations against hardened steel. And to exam the surface finish and integrity of the work material used. Harder work material, higher cutting speed and cost reductions result in the development of harder and more wear resistance cutting tools. Although PCBN cutting tools have been used in over 30 years, little work have been done on PVD coated PCBN cutting tools. Therefore hard turning and hard milling experiments with PVD coated and uncoated cutting tools have been performed and evaluated. The coatings used in the present study are TiSiN and TiAlN. The wear scar and surface integrity have been examined with help of several different characterization techniques, for example scanning electron microscopy and Auger electron spectroscopy.

The results showed that the PCBN cutting tools used displayed crater wear, flank wear and edge micro chipping. While the influence of the coating on the crater and flank wear was very small and the coating showed a high tendency to spalling. Scratch testing of coated PCBN showed that, the TiAlN coating resulted in major adhesive fractures. This displays the importance of understanding the effect of different types of lapping/grinding processes in the pre-treatment of hard and super hard substrate materials and the amount and type of damage that they can create. For the cutting tools used in turning, patches of a adhered layer, mainly consisting of $\mathrm{Fe_xO_y}$ were shown at both the crater and flank. And for the cutting tools used in milling a tribofilm consisting of $\mathrm{Si_xO_y}$ covered the crater. A combination of tribochemical reactions, adhesive wear and mild abrasive wear is believed to control the flank and crater wear of the PCBN cutting tools. On a microscopic scale the difference phases of the PCBN cutting tool used in turning showed different wear characteristics. The machined surface of the work material showed a smooth surface with a Ra-value in the range of 100-200 nm for the turned surface and 100-150 nm for the milled surface. With increasing crater and flank wear in combination with edge chipping the machined surface becomes rougher and showed a higher Ra-value. For the cutting tools used in milling the tendency to micro edge chipping was significant higher when milling the tools steels showing a higher hard phase content and a lower heat conductivity resulting in higher mechanical and thermal stresses at the cutting edge.

Keyword: PCBN, PVD coating, Wear mechanisms, Tool wear, Metal cutting

Preface

This licentiate thesis is based on my work done between April 2010 and January 2014, including 1 year of maternity leave. My work has been performed at Dalarna University at the material technology group and Linköping University at the group of nanostructured Materials. It is also a collaboration with SECO, Uddeholm, Element Six and SKF.

I would like to thank my supervisor at the Dalarna University, Mikael Olsson, my supervisor at Linköping University, Magnus Odén, my co-PhD student at Linköping, Robert Pilemalm and all of the persons involved in the project.

A large thank you to all of my grate colleagues and former colleagues at Dalarna University, not only for theirs support but also for all the laughs and practical jokes.

And last but absolutely not least, a big hug to my loving family, especially Stefan and my son Hugo who have been my support through good and bad times!

Included papers

Paper I

S. Sveen, J. M. Andersson, R. Msaoubi, M. Olsson, Scratch adhesion characteristics of PVD TiAlN deposited on high speed steel, cemented carbide and PCBN substrates, *Wear*, 308 (2013) 133-141

Paper II

Susanne Sveen, Rachid M'Saoubi, Ulf Bexell, Mikael Olsson, PCBN hard turning of ball bearing steel – Influence of PVD coating deposition on tool wear and surface finish / surface integrity of machined surface, In manuscript

Paper III

S. Saketi, S. Sveen, S. Gunnarsson, R. M'Saoubi, M. Olsson, Wear of a high cBN content PCBN cutting tool during hard milling of powder metallurgy cold work tool steels, In manuscript

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Contents

Chapter 1

Introduction

Metal cutting is today involved in many different processes in the industry, in engines for example many parts are manufactured with help of metal cutting. A cutting process starts with a raw material and ends up with a finished product, the process can involve several steps that remove the work material in form of chips, by using for example turning, milling, drilling or grinding. The methods used in the present study are hard turning and hard milling. These are processes involving work materials with hardness from 45 HRC and upwards, like for example the hardened ball bearing steel used in the present study. These will put high demands on the cutting tool, due to for example the high temperatures and forces involved in the cutting process.

The most important demands on the cutting tool are wear resistance, toughness and hot hardness [1]. To fulfill this high demands set on the cutting tool, a coating can be at help, the deposited coating must have a high hardness, low chemical reactivity and low affinity to iron [2]. The most common cutting tool materials used today are high speed steels, cemented carbides and super hard materials such as Polycrystalline Cubic Boron Nitride (PCBN) and diamond. To coat these material Physical Vapour Deposition (PVD) and Chemical Vapour Deposition (CVD) are often used. The most common coatings deposited by PVD in cutting applications are TiN, Ti(C, N), (Ti, Al)N and PVD oxides and the most common CVD coatings are Ti(C, N), Al_2O_3 and TiN [3].

Due to the request of harder material and higher cutting speed, new tool materials have been developed. In the 1950s the first synthesized cubic boron nitride (cBN) was developed from hexagonal boron nitride, in the 1970s the cBN was first introduced as a cutting tool material and since then it has developed into many different grades, aimed for different work materials [4].

The PCBN material is known for its high hardness, its ability to keep the hardness at higher temperatures and its chemical inertness to iron [5]. Therefore PCBN cutting tools are a good candidate for cutting in hardened steels. The usage of PCBN cutting tools can also eliminate grinding, due to the ability to create a smooth surface topography on the machined part in the turning process. The cutting tools made of PCBN are more expensive to purchase but the higher cost is compensated with for example longer cutting times and higher cutting speeds. Also the advantage of cutting steel in its hardened state, into a finished product and the ability to eliminate steps in the cutting process is time and cost saving.

The knowledge of wear of cBN cutting tools used in hard machining of hardened steels are today not adequate. Little work have been done involving the coated PCBN cutting tools, therefore this thesis is focused on the wear of the cutting tool and the surface of the work material for both coated and uncoated PCBN cutting tool. A better knowledge of the tribological behaviour of the cutting tools will save money for the industries in form of for example longer cutting times, more reliable cutting processes and better surface finish, fewer process steps and dimensional accuracy on the machined part [6].

1.1 Aim of the work

The aim of the present study is to evaluate the wear of different PCBN cutting tools, both coated and uncoated, used in hard machining of hardened steel. And to exam the surface finish and integrity of the work material used. The aim is also to compare the mechanisms of the coated tool against the uncoated tool and to see if a coating on top of the tool can give any beneficial properties such as a prolonged tool life or a better surface finish of the work material.

Chapter 2

Metal cutting

In metal cutting the desired geometry of a raw metal piece can be achieved by removing metal from the piece in form of chip formation. There are a large number of different cutting processes and in the present work two different processes have been used i.e. hard turning and hard milling. The usage of hard machining can in some cases eliminate the use of grinding operations. This will lead to cost reductions of the produced product and an increased productivity [7]. The most common tool materials in metal cutting are cemented carbide, ceramic, super hard materials such as diamond and PCBN [8].

2.1 Hard turning

Hard turning is a single cutting edge operation, in which work materials with a hardness between 45 HRC and 65 HRC is turned [9]. The temperature of the hard turning process is higher compared to the temperature of an ordinary turning process. The higher temperature is caused machining of a harder work material. This higher temperature of the hard turning process increases the wear of the cutting tool. In turning there are three different cutting parameters to consider, feed (f), depth of cut (a_p) and cutting speed (v). The wear of the tool can in many ways be controlled by these parameters, the feed and cutting speed are the most usual parameter to adjust due to the requirements on the finished product which will influence the depth of cut. According to E.M Trent et al. [8] the cutting speed can be explained as the speed in which the uncut material passes the cutting edge, the feed is the distance that the tool moves in axial direction every revolution and the thickness of removed work material is called the depth of cut.One positive advantage with the hard turning process is that in some cases the process can be used instead of a grinding process. This will decrease the machining time, the work material can be turned in its hardened state instead of first turning the product into its desired form and shape and then harden the finished product. Tool, bearing and case-hardened steels are often turned in a hard turning process due to theirs high hardness [8, 9].

2.2 Hard milling

In hard milling the material is milled in its hardened state, the hardness of the material starts at 45 HRC. As for hard turning the temperature is higher in hard milling compared to ordinary milling, this will lead to higher wear rates of the cutting tool. In milling, the cutting tool is rotated and the work material, which is mounted on a table, is moved under the cutter. The cutter in a milling operation have various numbers of cutting edges, which are called teeth, the variation can range from one cutting teeth up to hundreds. In milling there are a number of different parameter influencing the cutting process, such as cutting speed (v_c), depth of cut (a_p), cutting width (a_e) and cutting feed (f). Cutting width is the width of the material that the cutting tool can cover [1].

Chapter 3

Wear and wear mechanisms

There are three different macroscopic wear mechanisms that are involved in the cutting operations, these are crater, flank and notch wear. Also there are three different microscopic wear mechanisms involved in the process thought to be the main wear mechanisms of the cutting operations, these are adhesive, abrasive and tribochemical wear [10]. Depending on the combination of cutting tool material, coating material, work material and the cutting parameters, the influence of each wear mechanism will vary in range. The parameter which mostly influences the tool life, in form of time it takes to reach a predetermined wear, is the cutting speed of the process [9]. The adhesive and abrasive wear mechanisms are most common at the flank of the cutting tool where the temperature is lower compared to the rake face of the cutting tool where the chemical wear is the most common mechanism.

3.1 Macroscopic wear of a cutting tool

In Figure 3.1 a schematic figure of the chip, work piece and cutting tool interface is shown. At the chamfer and flank of the tool the dotted line represents a worn cutting tool. The crater wear of the worn tool is located at the chamfer of the cutting tool while the flank wear of the worn cutting tool is located at the flank of the tool as.

Figure 3.2 show a LOM image of a TiSiN coated cutting tool used until it reached a flank wear of 0.3 mm. In this image the tip consisting of Grade 2 can be seen as well as the wear of the cutting tool.

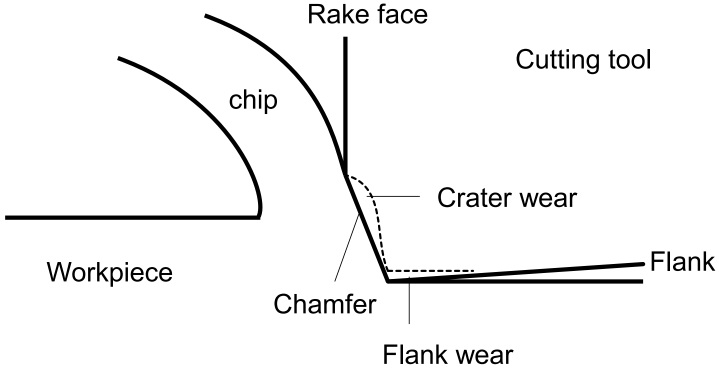

Figure 3.1: Schematic figure of the chip, workpiece and cutting tool. The dotted line represents a worn cutting tool.

In the Scanning Electron Microscopy (SEM) image of Figure 3.3 a larger magnification of the cutting tool can be seen, in this magnification the crater, flank and notch wear are clearly visible.

The crater and flank wear are the two macroscopic wear mechanisms that are most commonly seen on the cutting tools used in the present study. The crater wear appears on the rake face or the chamfer of the cutting tool while the flank wear appears on the flank of the tool.

The crater wear of a tool are often reported to be of a tribochemical nature, caused by a reaction between the rake face of the tool and the chip from the work material. The crater wear is influencing the reliability of the machining process in form of catastrophic failure [11].

The flank wear of a cutting tool is caused by abrasive and adhesive wear of the tool, when it is being rubbed against the work material. It is the surface of the flank that is controlling the surface finish of the work material, which in the end will end up as the surface finish and dimensional accuracy on the machined part [6,9,12–14]. The flank wear can be formed early in the machining process, it is therefore a large concern in the reliability of the machining process. It is also important, as variations in wear can cause dimension problems on the machined part.

The notch wear of the cutting tool is caused by the contact between the machined surface and the cutting tool at the edge of the tool where the chip and the cutting tool no longer are in contact [15].

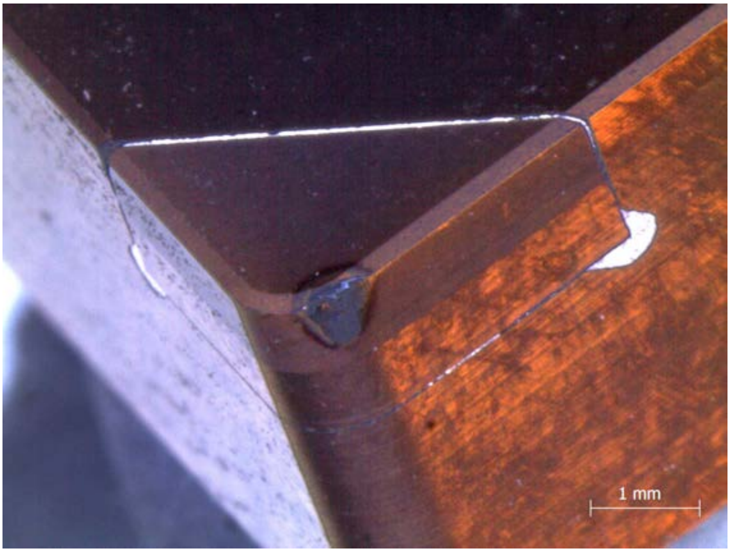

Figure 3.2: LOM image of an used TiSiN coated cutting tool.

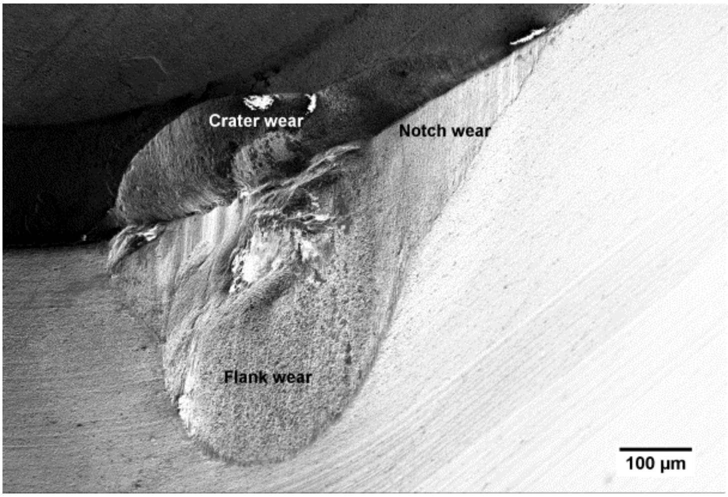

Figure 3.3: Crater wear, flank wear and notch wear of a cutting tool.

A cutting tool used in milling operations often experiences chipping as a wear mechanism, the chipping is observed along the cutting edge of the tool and are a loss of tool fragments [5].

The flank wear of a cutting tool used in turning can be divided into three different regimes. The first regime is where the cutting edge is worn rapidly and is in a running-in period, in the second regime the cutting tool has reached a steady state and the wear is slowly increasing. In the last regime, the wear of the cutting tool is high and if the tool is not replaced it will soon experience catastrophic failure. The cutting tool is not supposed to be used in the third regime, it should be replaced in the end of regime two [9, 16, 17].

3.2 Adhesive wear

Adhesive wear comes from a shearing between the asperities of two counter materials that are in relative motion. The surface of a material in a microscopic scale is almost never perfectly smooth, it is consisting of asperities. When a cutting tool slides against a work material, a shearing of the material takes place due to the deformation of asperities. When forces of the shearing reaches values high enough, micro welds will form, the tangential motion of the two surfaces will cause separation of the junction. The separation of the micro weld either occurs in the formed interface, in the cutting tool or in the counter work material. The adhesive wear occurs when the separation is in one of the counter materials and not in the formed interface and there by removes material. The different properties, such as hardness, of the materials will play an important part in which material the separation will occur, but the chemical reactivity between the materials will affect the probability for adhesive wear to occur. The adhesive wear is often found at the rake face of the cutting tool where the temperature is higher compared to the temperature on flank face of the cutting tool [2, 18].

3.3 Abrasive wear

The abrasive wear is divided into two classes i.e. two body abrasion and three body abrasion. The two body abrasion can be explained by a counter body that scratches and thereby deform and peel off material from the work material or tool. This will lead to scratches or grooves in the material. In three body abrasive wear, a third body is present between the two sliding bodies. The third body will deform or peel off material from both or one of the bodies. Which body that will be deformed depends on the hardness of the abrasive material and the two counter bodies. To be able to deform another material, it must be harder compared the scratched material. The two body abrasion can develop out of a three body abrasion, if the third body is being depressed into the softer body and then scratches the counter body. The abrasive wear can be divided in different categories i.e. micro cutting, micro fatigue, micro chipping and micro ploughing. The abrasive wear is often found at the flank face of the cutting tool which has a lower temperature than the rake face of the tool. Metal cutting is a form of abrasive wear but in a very large scale [2,15].

3.4 Tribochemical wear

Tribochemical wear means that the wear is of a chemical nature, where reactions take place in the contact between the cutting tool and the work material and perhaps the chips. In metal cutting the temperature is often high which is contributing for a reaction to take place. The temperature at the rake face of the tool is higher than the temperature at the flank, this makes the rake face more favorable for a chemical reaction to take place. In metal cutting new unaffected material is exposed to the atmosphere in a continuously flow which is contributing to the tribochemical wear to take place. A thin layer of oxidized material is often formed on the surface of the material, these oxide layer can often easily be removed from the surface and new oxides can be formed on the unaffected underlying material which again is removed, this process can lead to high wear rates [2,15,18].

3.5 Wear of polycrystalline cubic boron nitride

According to Y. Huang et al. [12] the three main wear mechanisms for a PCBN cutting tool in hard turning are abrasion, adhesion and diffusion. In which extent each mechanism influences the wear of the tool in a specific case is dependent on a numerous of factors such as for example the cBN grade used, work material and cutting condition.

J. Angseryd and H.-O. Andrén [19] discussed that the wear of a PCBN cutting tool is mostly due to a chemical degradation of the cBN grains in the tool. One suggestion is that oxidized iron [19,20] adhered on the wear scar, penetrates into the cutting tool and degrades the cBN grains. Cross sections of a crater revealed an adhered layer, with a thickness of 50 - 100 nm, that mostly covered the wear scar. J Angseryd and H.-O. Andrén saw that the adhered layer interacted with the PCBN material below the surface of the wear scar. According to SEM/EDX analysis the adhered layer consisted of large Fe-rich areas, some of these areas where oxidized on the surface and other were heavy oxidized areas. To get a better understanding of the adhered layer, the authors used Transmissions Electron Microscopy (TEM) studies on the samples. In these studies the authors could see Fe-rich areas penetrating into the cBN grains.

The discussion of the main wear mechanism being chemical degradation is not accepted from all directions, in an article written by Poulachon et al. [7] they discussed that the main reason for wear of PCBN cutting tools was due to abrasion of the binder phase, caused by hard carbide particles in the work material. The abrasion of the binder phase caused detachment of the cBN grains.

Some other authors [21] think that the main reason for wear of the PCBN cutting tool is caused by adhered work material. The adhesion between these two is not strong, leading to a non-constant layer on the surface of the cutting tool, rather than a layer that are built up and then continuously removed in the cutting process. When the adhered layer is removed from the cutting tool the cBN grain will be plucked-out and thereby removed from the cutting tool, leaving holes at the surface of the wear scar. In an article written by J. Angseryd et al. [22] they stated that no indication of pluck-outs of cBN grains could be seen in the wear scar of the cutting tool. They concluded that the pluck-outs of cBN grains could not be a major degradation mechanism of the cutting tool in their case.

How the degraded cBN is removed from the tool is not confirmed, this could be due to the difficulties to detect such a low amount of material. There are suggestions that the material could be found in the adhered work material [22] or that the cBN material is dissolved or diffused into the chips [20]. J. Angseryd et al. [22] also describes that the Ti(C,N) phase in the binder is somewhat less worn than the cBN grains and are therefore protruding from the cBN grains in the wear scar of the cutting tool. When J. Barry and G. Byrne [23] investigated the wear of PCBN cutting tools with a TiC binder they could also see that the cBN was more worn than the binder phase. Their suggestion to this phenomenon was that the reaction between the cBN and the work material causes a reaction product that acts as a protector to the binder phase, against diffusion.

Chapter 4

Materials

In the present study different grades of PCBN are used as cutting tools, in two cutting operations, turning and milling. As reference, coated Cemented Carbide (CC) and coated High Speed Steel (HSS) are also included. Three different hardened materials, hardened ball bearing steel 100Cr6, Vancron 40 and Vanadis 4 E are used as work materials.

4.1 Cutting tool material

4.1.1 Polycrystalline cubic boron nitride

PCBN is a composite material consisting of cBN grains in a metallic or ceramic binder. The cBN material is the second hardest material known today, after diamond. It is produced at high temperature and high pressure from hexagonal boron nitride (hBN), which is a very soft material often used as lubrication. After the production of cBN the binder is added and the material is once again subjected to high temperature and pressure and is sintered together into a cutting tool [5].

cBN have unlike diamond a good chemical inertness to steel [12], a better resistance against oxidation compared to diamond [24] and a high hot hardness [5].

PCBN materials can be divided into two different groups, low content cBN and high content cBN, by adding between 50 -70 % of cBN into a binder a low content PCBN (L-cBN) material is created. A ceramic binder is often used in L-cBN. By adding approximately 90 % of cBN into a metallic binder a high content PCBN (H-cBN) material is created [6, 12]. Comparing L-cBN and H-cBN in form of cutting performance in hard turning, C. Lahiff et al. [6] say that the L-cBN give a longer tool life and contribute to a better surface finish. While, according to G. Poulachon et al. [7], the L-cBN performs better in hard materials without hard carbide grains and H-cBN performs better when it comes to abrasive wear in hard material.

In the present study four different tool materials are used. In Table 4.1 the cBN content and binder matrix of these materials can be seen.

Table 4.2 shows some physical, thermal and mechanical properties of a typical cBN material and of the binder materials used in the present study.

In Figure 4.1 the microstructure of an unworn polished Grade 2 cutting tool is shown. Three phases can be seen in the SEM micrograph, one dark and two lighter areas. The dark area is the cBN grains and the two lighter areas are the binder matrix and can be distinguished with one smooth phase and one mixed phase. The smother phase contains TiCN and the mixed phase contains Al_2O_3, AlN and Co.

In Figure 4.2 the hot hardness and abrasion resistance is plotted against the toughness and bending strength for different cutting tool materials. In the figure it can be seen that the PCBN have a high hot hardness and abrasive resistance compared to other material but the toughness and the bending strength is quite low. According to S. Hogmark and M. Olsson is the preferable cutting tool material a material with higher hot hardness, abrasion resistance, higher toughness and bending strength compared to the materials existing today [36].

The cutting tools used in turning in the present study all have a chamfered edge of 25° and 0.15 mm. According to hardness measurements done in the present study the Grade 1 and Grade 2 have a Vickers hardness of 3500 ± 400 HV and 4000 ± 200 HV respectively. The milling tools in the present study have a rake angle of $-28°$.

Table 4.1: cBN content and binder matrix of the cBN materials used.

	Tool material	cBN content [%]	Binder matrix
Low content cBN	Grade 1	50	TiCN, Al_2O_3, AlN and TiB_2
	Grade 2	60	TiCN, Al_2O_3, AlN, TiB_2 and Co
High content cBN	Grade 3	85	Co,W and Al
	Grade 4	90-95	AlN and AlB_2

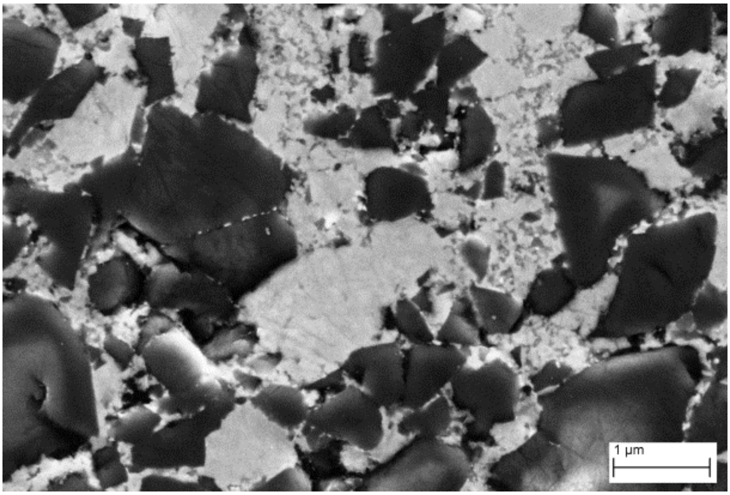

Figure 4.1: SEM image of a unworn Grade 2 cutting tool.

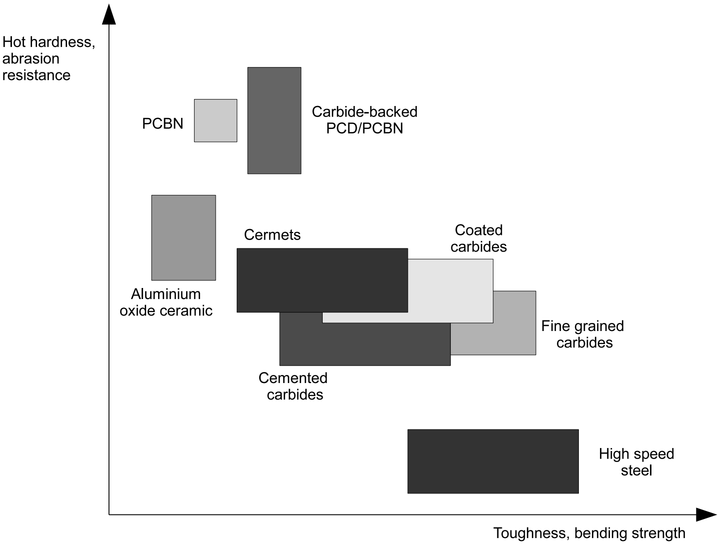

Figure 4.2: Hot hardness and abrasion resistance verses toughness and bending strength for different cutting tool materials [36].

Table 4.2: Physical, thermal and mechanical properties of cBN and the binder materials [25–35].

	Density [g/cm^3]	Melting point [°C]	Hardness (Hv) [GPa]	Elastic modulus [GPa]	Thermal conductivity [W/m·K]
cBN	3.48	2973	75	850	13
TiCN[a]	4.90-5.44	2950-3257	27-31	251-450	43
Al_2O_3	3.9	2043	14-19	210-390	25-35
AlN	3.25	2250	12	308	82-170
TiB_2	4.52	3225	25-35	560	60-120
Co	8.9	1495	1	209	100
W	19.3	3422	3.4	411	174
Al	2.7	660	0.2	70	235
AlB_2	3.17	-	-	240-270	-

[a] TiCN is a solution of TiC and TiN which means that the properties is dependent on the proportion of the added materials.

4.1.2 Cemented carbide and high speed steel

Cemented carbide is a sintered product of hard carbide particles in a binder matrix. The carbides are often made of tungsten, titanium, tantalum or niobium with a binder matrix consisting of cobalt or nickel. The carbides are often in the size of 1 - 10 µm and are often between 60 – 95 vol% of the cutting tool material [1, 24].

The hardness of a high speed steel is often around 850 HV, this is lower compared to the hardness of cemented carbide. High speed steel has a martensitic matrix with 10 - 15 vol% of carbides, often in form of $Fe_3(W, Mo)_3C$ and V_4C.

In the present study cemented carbide and high speed steel are used as reference material for the cBN cutting tools. In Table 4.3 the chemical composition and the hardness of these two material are shown. Both of these materials were used coated with TiAlN.

Table 4.3: The chemical composition and hardness of the cemented carbide and high speed steel used.

Material	C [wt%]	V [wt%]	Cr [wt%]	Co [wt%]	Mo [wt%]	W [wt%]	WC [wt%]	Hardness $HV_{0.5}$
CC	-	-	-	6	-	-	94	1710
HSS	1.3	3.1	4.2	8.5	5	6.4		830

4.1.3 PVD coatings

In the present study some cutting tools are coated, the coatings used are TiAlN or TiSiN. The TiAlN have an outermost layer of TiN. The TiAlN coating has a chemical composition of Ti(0.34)Al(0.66)N and the TiSiN coating has a chemical composition of Ti(0.8)Si(0.2)N. Both of the coatings are PVD coatings, deposited with cathodic arc evaporation technique and are approximately 2 µm thick. The TiSiN coating has a high hardness and high thermal stability, due to this it exhibits a good wear resistance. One drawback is that it is brittle, this could cause surface cracking [37]. The TiAlN coating has a higher chemical stability but it has a lower hardness compared to TiSiN. G.Poulachon et al. [7] concludes that when depositing a coating on top of a PCBN cutting tool, it will decrease the wear mechanisms due to a reduction of diffusion between the work material and the rake face of the cutting tool.

4.1.3.1 PVD - process

The PVD process is a coating process in which the coating material is evaporated from solid material inside a chamber and then condensed on the substrate. Due to this the process is generalized as a gaseous state process, which also includes the CVD process. Depending on how the atomization of the source material is being done, the process is categorized under different names. The deposition process used in the present study is cathodic arc evaporation, which is an evaporative vaporization of the coating material [2]. Cathodic arc evaporation can be performed either with a pulsed or a continuous arc.

The advantage of the cathodic arc evaporation is that it has a higher vaporization rate compared to the sputtering process, but not as high as the thermal process. The drawback with this method is that droplets formed in the coating due to a large amount of coating material being sprayed on to the surface at ones can form macro particles [2, 38]. These droplets are causing a rougher surface of the cutting tool, which can shorten the life length, it also has a negative effect on the tribological behaviour of the coating [39]. If there are higher demands on the tool due to the cutting process, the droplets are removed from the surface [9].

4.1.3.2 Adhesion coating to substrate

The adhesion between a coating and the substrate is according to K. Holmberg and A. Matthews [2] defined as the molecular attrition between bodies in contact. When the bonds, that is between the coating and the substrate, brakes, it is called coating delamination, spalling or flaking of the coating. The breaking of the bonds results in crack formation in the interface and is propagating until the coating is detached from the substrate. The resistance for a crack to grow in the interface until fracture of the coating is called, interfacial fracture toughness, K_c. The interfacial fracture toughness of the coating is measured with help of scratch testing in article II. The adhesion between the coating and the substrate, except the chemical bonds, is depending on the elasticity, hardness and ductility of both the coating and the substrate, it is also dependent on the thickness of the coating.

4.2 Work material

In the present study three different work material are used i.e. through hardened ball bearing steel 100Cr6, Vancron 40 and Vanadis 4 E.

4.2.1 Through hardened ball bearing steel

The through hardened ball bearing steel used in the present study is of the type 100Cr6, with a chemical composition according to Table 4.4. The material is used in form of rings with a diameter of 180 mm, a width of 60 mm and a material thickness of 14 mm.

According to hardness measurements made in the present study the material has a Vickers hardness of $655 \pm 15\,\mathrm{HV}$.

Table 4.4: The maximum and minimum wt% of the chemical composition of 100Cr6.

	C	Si	Mn	P	S	Cr	Ni	Mo
Min. value	0.95	0.20	0.20			1.35		
Max. value	1.00	0.35	0.40	0.025	0.015	1.60	0.25	0.08

4.2.2 Cold work tool steels

Two different cold work tool steel have been used for milling in paper II, these two are Vancron 40 and Vanadis 4E.

Vancron 40 is a nitrated powder steel, with the chemical composition according to Table 4.5 while Vanadis 4E is a powder metallurgical cold work tool steel, with the chemical composition also according to Table 4.5.

Vancron 40 has a matrix of tempered martensite with hard particles of carbonitrides of V(C, N) and carbides of (Mo, W)6C. Vanadis 4E also has a matrix of tempered martensite but with hard particles consisting of carbides (V, Mo, Cr)C.

The hardness of the cold work tool steels are 790 ± 30 HV for the Vancron 40 and 810 ± 30 HV for the Vanadis 4E.

Table 4.5: Chemical composition of Vancron 40 and Vanadis 4E.

	C [%]	N [%]	Si [%]	Mn [%]	Cr [%]	Mo [%]	W [%]	V [%]
Vancron 40	1.1	1.8	0.5	0.4	4.5	3.2	3.7	8.5
Vanadis 4E	1.4	-	0.4	0.4	4.7	3.5	-	3.7

Chapter 5

Surface characterization

In order to understand the wear mechanisms controlling the cutting process different surface analysis and microscopic techniques have been used. In this chapter Light Optical Microscopy (LOM), Scanning Electron Microscopy, Auger Electron Spectroscopy (AES) and white light interferometry are briefly described.

5.1 Light optical microscopy

Due to its simplicity the first study of a specimen is often performed with LOM. LOM offers a lateral resolution of 0.3 µm and a small depth of field. Thus, the sample preparation is of importance in order to get a flat surface. If a larger depth of field is needed a stereo ocular can be used with the drawback of a restricted lateral resolution. LOM is a fast and technique and combined with e.g. etching important information can be extracted of the investigated surface.The LOM used in the present study is a Leica DRM light optical microscope.

5.2 Scanning electron microscopy

SEM has two major advantages compared to conventional LOM, i.e. higher resolution and greater depth of focus. A higher resolution makes it possible to study a surface at a higher magnification while the greater depth of focus makes it possible to study topographical objects at low magnifications. When an electron beam strikes a surface a variety of signals are generated, see Figure 5.1. It is from the detection of a specific signal that an image can be produced or the elemental composition of a sample can be determined. The most important signals, which provide valuable information, are the secondary electron, backscattered electrons, characteristic X-ray photons and Auger electrons. The primary electrons interact with the atoms in the sample and can be elastically or inelastically scattered. Due to the scattering, the primary electrons travel down to a limited depth in the sample material resulting in an activated, pear-shaped, volume, see Figure 5.1. Electrons emitted from the sample with energy less than 50 eV is called secondary electrons and because their low energy only electrons originating within a few nanometers from the surface are able to escape from the sample. An incident electron being deflected more than 90 degrees and leaving the sample surface is called a backscattered electron. The backscattered electrons have energies up to the primary electron energy which means their escape depth can be substantially larger than for the secondary electrons [40–42].

5.3 Energy dispersive X-ray spectroscopy

When the atoms in the specimen are bombarded with the primary electron beam, many of the atomic inner-shell electrons are ejected, thus ionizing atoms of the specimen. The vacancies are filled by other outer-shell electrons. The energy difference of the transition is emitted either

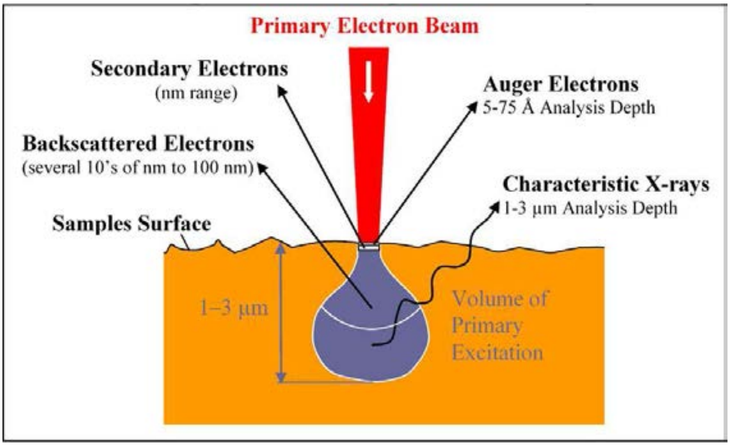

Figure 5.1: The different emitted electrons and what depth they can emit from [43].

as X-ray photons or it can be given to a second, emitted, electron, an Auger electron. Both the photon and the Auger electron are characteristic for the element from which they are emitted [42, 43].

For detection of emitted characteristic X-rays the SEM is commonly equipped with an energy dispersive X-ray spectrometer, EDS. The EDS gives valuable information about the elemental composition of the sample down to a depth of 0.5-5 µm, depending on accelerating voltage, average atomic mass and specimen orientation.

5.4 Auger electron spectroscopy

Auger electron spectroscopy is a very surface sensitive analyzing method. This is due to the relatively short inelastic mean free path for the Auger electrons, i.e. transportation of emitted electrons generated in the sample to the surface, can only occur from a certain depth typically 50 Å. Thus, AES is used to obtain information from the outermost surface layers of a sample. AES can be combined with ion sputtering in order to extract depth information [40].

5.5 White light interferometry

The technique uses the interference of white light to analyze surface topography. By scanning a moveable objective vertically above a sample surface the topography for each point on the sample surface can be extracted and in this way the surface topography is measured. The topographical data can easily be transformed to 3D images, i.e. surface maps in 3D of the sample surface. The technique has a depth resolution of 5 nm and the surface must be reflective and is sensible for porosity and sharp peaks [44,45].

5.6 Mechanical properties

5.6.1 Hardness

The hardness of the substrates of the cutting tools and the work material are in the present papers measured with two different methods, Micro Vickers hardness and Micro Combi tester. In Micro Vickers hardness measurements a diamond tip is pressed down into a material with a predetermined load. Afterward the diagonals of the plastic deformed impression are measured and the hardness is calculated. The calculation of the hardness involves the mean value of the diagonals and the predetermined load. When measuring the hardness of a coating it is important to measure only on the coating without the contribution of the substrate. To avoid this contribution the depth of the impression should be less than 1/10 of the coating thickness [2]. In these cases the Micro Combi tester is a more preferable method to be used, due to the ability to use lower loads which decreases the penetration depth of the indenter. The Micro Combi tester register the depth and displacement of the indenter, as in nanoindentation, during loading and unloading, and calculates the hardness of the material with help of a method described by Oliver and Pharr [46]. If the geometry of the indenter is known the hardness can be calculated with help of the depth of the plastic deformation by removing the elastic contribution from the total depth and the Young's modulus (E) can be calculated by analyzing the unloading curve since the initial slope is direct related to the elastic modulus. The hardness of the material is related to the projected area corrected by the indenter constant for the used tip [46].

5.6.2 Coating adhesion

The adhesion between the substrate and the coating has in the present study (article II) been measured with help of scratch testing. The scratch test is according to Kenneth Holmberg and Allan Matthews [2] the most common way to measure the adhesion between a coating and a substrate. In the conventional scratch test a Rockwell C diamond stylus (120° cone with 200 µm radius) is drawn across the coated substrate surface under an increasing normal load until a well-defined coating failure occurs, frequently associated with localized chipping or spalling. The corresponding normal load is termed the critical normal load and is often used as a measure of the coatings mechanical strength or "practical adhesion". The critical normal load can be detected by on-line monitoring of the friction force and acoustic emission signals and/or by post-test examination using optical or scanning electron microscopy. The scratch test is a fast and simple way to estimate coating adhesion but can only be regarded as semi-quantitative since the results (critical normal loads) are affected by various intrinsic and extrinsic parameters [47]. The critical normal load can be divided into two critical normal loads, one for the initiation of continuously cracking ($F_{N,C1}$) and one for the continuously substrate exposure ($F_{N,C2}$).

Chapter 6

Summary of included papers

6.1 Paper I

In the present paper the adhesion between a cathodic arc evaporated TiAlN coating deposited on high speed steel, cemented carbide and PCBN, respectively, are measured by using of scratch testing. Two critical normal loads, $F_{N,C1}$ and $F_{N,C2}$, were measured and defined as the coatings cohesive and interfacial adhesive strength. The hardness of the coatings, substrates and the coating-substrate composites were also measured.

The results show that the practical adhesion corresponding to the critical normal load of the substrate exposure increases in the order of PCBN - HSS - CC. The TiAlN coating deposited on the PCBN was the only coating that showed major adhesive fracture. All the specimens experience different coating failure mechanism although they all can be regarded as hard substrate materials. This shows that the coating/substrate deformation mechanisms during scratching and the critical normal loads obtained are strongly dependent on the mechanical properties of the substrate material. A soft surface will promote plastic subsurface deformation and cracking of the coating at normal loads lower than the continuous substrate exposure while a hard and stiff substrate will cause sub-surface deformation and coating cracking unless interfacial cracking resulting in spalling will occur.

The only coating/substrate composite showing adhesive fracture is the TiAlN coated PCBN substrate. The SEM analyze reveals a low inter atomic bonding between the cBN phase and the coating. This is a combination of high stress concentration and the presence of microcracks at the matrix/cBN phase interface. The defects will serve as stress concentrators and promote high local stresses which will decrease the cohesive strength of the substrate surface and subsurface regions causing bulk fractures in connection to the interface.

This explains the importance of understanding the effect different lapping and grinding processes have on the pretreatment and what damage they can create. Surface and sub-surface damage caused by the lapping/grinding process may have a significant importance on the practical adhesion and therefor in the case of metal cutting the tool life.

6.2 Paper II

In paper II, two different PCBN cutting tools are used, one with 50 % of cBN and one with 60 % cBN in a binder matrix, both are used coated and uncoated and the coatings used are TiAlN and TiSiN. The cutting tools are used in hard turning tests against tough hardened ball bearing steel with different cutting times, 43 seconds, 20 minutes and until the cutting tool reached a flank wear of 0.3 mm, this in order to evaluate the flank and crater wear over time. Posttest evaluations were made on the cutting tools and the work material with help of SEM, AES and 3D optical surface profilometry. The SEM was used in order to evaluate the wear mechanisms on the crater and flank of the cutting tool and to exam the work material surface. AES depth profiles were made in order to characterise the interface between the adhered work material and the cBN grains and binder matrix. 3D optical surface profilometry were used in order to evaluate the crater and flank wear of the cutting tool and to measure surface features of the work material.

The results from the SEM analyses showed that the PCBN cutting tools displayed crater wear, flank wear and micro edge chipping and that the coating showed a high tendency to spalling which could be a result of poor adhesion to the substrate material.

All results pointed on a small influence of the coating on the crater and flank wear, this could be a result from the poor adhesion mentioned above.

On a micro scale the different phases in the PCBN material showed different wear characteristics. The worn cBN phase displays a micro scratched morphology, the Ti(C,N) rich binder phase regions display a smooth polished morphology and the Al_2O_3 rich binder phase regions display a rough fragmented morphology.

An adhered layer covered both the crater and the flank of the cutting tool, in form of patches of adhered work material, that according to AES analysis consisted of iron and iron oxide.

According to 3D optical surface profilometry the machined surface showed a smooth surface with a R_a-value in the range of 100-200 nm. However, with increasing crater and flank wear in combination with edge chipping the machined surface topography becomes rougher showing R_a-values in the range of 300-400 nm.

6.3 Paper III

High cBN content PCBN cutting tools are in paper III used in milling operations against two different hardened cold work tool steels, Vanadis 4 Extra (V4E) and Uddeholm Vancron 40 (V40), the milling operation is performed using two different cutting speeds, 100 and 150 m/min. The PCBN cutting tools used have a cBN content of 85 % and a binder phase consisting of Co, Al and W. Comparing the two work materials showed a higher hard phase content and lower heat conductivity of V40 compared to V4E. The flank and crater wear of the cutting tool, the surface finish and integrity of work material and the chips was post-test evaluated using SEM, AES and 3D optical surface profilometry.

The exam of the tools showed crater wear, flank wear and edge micro chipping increasing with higher cutting speed. The continuous wear rate as well as the tendency for micro chipping were higher when milling V40 compared to the V4E. This was due to a higher hard phase content and a lower heat conductivity for the V40 resulting in thermo-mechanical stresses acting on the cutting tool during milling.

The wear of the milling tool is believed to be a combination of tribochemical, adhesive and abrasive wear, both on the flank and in the crater. The abrasive wear shown on the flank and crater are believed to be caused by cBN grains in the cutting tool which have been pulled out from the cutting edge. Due to the smooth wear of the crater and flank and that no signs of preferential wear of the PCBN material phase constituents could be seen indicated on a tribochemical wear affecting both phases in a similar way.

The AES depth profile revealed that the crater of the milling tools is covered with an adhered layer with a thickness of 50 - 300 nm, somewhat ticker on the binder phase compared to the cBN grains, the adhered layer is Si_xO_y rich.

The machined surfaces show a relatively smooth surface (Ra $<$ 100-150 nm) with a superficial plastic deformation limited to the extreme surface. However, a high tendency to edge chipping will have a negative impact on the machined surface topography.

Chapter 7

Conclusions of the present work

The results in the present work show that the influence of the coating on the crater and flank wear of the cBN cutting tool is small. This could due to spalling of the coating, which also could be seen in scratch tests performed in the present work, where the coated PCBN experiences a lower practical adhesion compared with the HSS and CC. Cutting tools used in the present study showed crater wear, flank wear and edge micro chipping. The tendency to micro edge chipping was significantly higher when milling the tool steel showing a higher hard phase content and a lower heat conductivity resulting in higher mechanical and thermal stresses at the cutting edge.

The main wear mechanisms of both the turning and milling tools is a combination of tribochemical, adhesive and abrasive wear, both on the flank and in the crater. Although the different phase of the PCBN material used in turning show different wear characteristics. The worn cBN phase displays a micro scratched morphology, the Ti(C,N) rich binder phase regions display a smooth polished morphology and the Al_2O_3 rich binder phase regions display a rough fragmented morphology.

For the cutting tools used in turning, patches of adhered layer mainly consisting of Fe_xO_y were shown at both the crater and flank. For the cutting tools used in milling a tribofilm consisting of Si_xO_y covered the crater.

All of the machined surfaces showed a smooth surface with R_a-value in the range of 100 - 200 nm and with a superficial plastic deformation limited to the extreme surface.

Chapter 8

Sammanfattning på svenska

Skärande bearbetning är idag en vanligt förekommande process inom många industrier som till exempel bilindustrin. Skärprocessen innebär många olika steg, där material avverkas i form av spånor. De olika metoderna kan till exempel vara svarvning, fräsning, borrning eller slipning. De processer som undersökts i denna studie är svarvning och fräsning. I dessa processer uppkommer höga temperaturer och krafter vilket medför höga krav på de skär som användas. För att kunna leva upp till dessa höga krav kan en beläggning vara till hjälp, dock måste även dessa beläggningar klara av att leva upp till vissa krav.

De vanligaste materialen som används i skären till skärande bearbetning är hårdmetaller, keramer samt superhårda material så som diamant och polykristallin kubisk bornitrid (PCBN). Belagda PCBN skär har inte funnits länge på marknaden, därför finns inte tillräckligt med forskning inom detta område. Syftet med denna avhandling är att öka förståelsen för de mekanismer som styr nötningen av obelagda och belagda PCBN verktyg i samband med skärande bearbetning av härdade stål, samt se vilken inverkan det resulterande verktygsslitaget har på den bearbetade ytans egenskaper. En ökad förståelse av det tribologiska beteendet skulle kunna ge en besparing för industrin i form av längre skärtider, minskade byten av skär, tillförlitligare skärprocess och bättre yta och dimensioner på den färdiga produkten.

PCBN är känd för sin höga hårdhet, förmågan att behålla den höga hårdheten upp till höga temperaturer samt den låga reaktiviteten till järn, dessa egenskaper gör PCBN till en bra kandidat för skärande bearbetning av stål i dess härdade tillstånd.

Undersökningarna visar att beläggningen gjort lite eller ingen påverkan på förslitningen av skäret, vilket kan komma av att vidhäftningen mellan skär och beläggning kan vara undermålig, detta har även framkommit i undersökningar gjorda i den aktuella studien. Det har även framkommit att förslitningen på både svarv och fräs skären är täckta av påkletat arbetsmaterial i fallet med svarvning är detta arbetsmaterial påkletat i form av högar med oxiderat järn medan i fallet med fräsning är påkletningen ett jämnt lager av oxiderat kisel.

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