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FINAL DEGREE PROJECT

Materials Engineering Degree

WEAR AND FRACTURE MECHANISMS OF COATED PC-BN INSERTS: *Literature review and identification of critical design parameters from a materials science viewpoint*

Report and Annexes

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Abstract

In the last years, the interest in polycrystalline cubic boron nitride (Pc-BN) as a tool material has significantly grown, especially for turning operations involving difficult-to-cut materials. This is related to the fact that it is the second hardest material, behind diamond, while also exhibiting high-temperature strength, thermal stability and chemical inertness. Within this context, Pc-BN makes possible the use of extreme cutting conditions; thus, reducing the production costs. Moreover, the employment of hard thin film ceramic layers deposited on Pc-BN substrates extends the tool life, yielding it an eco-friendly attribute, as it opens the possibility of reducing or even eliminate the use of lubricant and coolants in the machining operations.

The aforementioned high mechanical properties are intrinsically linked to its microstructure. Pc-BN is a composite material consisting of cubic boron nitride (c-BN) particles embedded in a ceramic (e.g. TiC, TiN, WC, AlN, etc.) or metallic matrix (e.g. Co-based alloys). In general, ceramic matrices are found in low and medium c-BN content substrates, whereas metallic ones are employed for binding high c-BN content materials. Accordingly, ceramic matrices are commonly used in turning operations, where continuous contact with high temperatures generated are present. On the other hand, metallic matrices with high c-BN content are implemented in milling operations, where higher toughness is required due to the interrupted-cutting nature (multiple impacts) involved in this machining operation.

The main objective of this project is to review and analyse the wear and fracture mechanisms of coated Pc-BN inserts. Within this framework, critical microstructural design parameters, such as coating chemical nature, Pc-BN microstructure and chemical nature, will be analysed. The machined work-material and cutting operation involved will be also studied. Finally, identification and setting of correlations among the different variables will be attempted. In order to achieve these objectives, an in-depth literature research will be conducted. The results indicate that flank wear is the main contact-related degradation mechanism for the coated Pc-BN systems studied. It is followed by crater wear, and less extended notch wear. Moreover, the use of coatings in Pc-BN tools allows to subject these tools to more extreme conditions compared to other tool materials. Unfortunately, specific correlations among coating-substrate-workpiece have not been identified. Main reasons behind is the extremely large number of variables involved in the different studies as well as the limited amount of literature in this subject.

One main conclusion of the literature search and critical analysis done is that interest in Pc-BN composite has prominently grown over the last two decades, particularly because it has proven to be a reliable competitor for cemented carbides as tool materials in the referred applications. Although production cost is still a variable in favour of cemented carbides, as compared to Pc-BN based tools, the fact that the latter can be used under more extreme conditions is considered a key attribute.

Resum

Durant els últims anys, l'interès pel nitrur de bor cúbic policristal·lí (Pc-BN), com a material per a eines, ha augmentat significativament, especialment en operacions de tornejat de materials difícils de mecanitzar. Aquest fet es deu a que és el segon material més dur, darrere del diamant, fins i tot a altes temperatures; a part de ser inert químicament, i també presentar bona resistència a altes temperatures i estabilitat tèrmica. Sota aquest context, el Pc-BN fa possible el mecanitzat sota condiciones extremes, reduint així els costos associats a la producció. Així mateix, l'ús de capes fines de ceràmiques dures allarga la vida útil de l'eina i fa que les operacions de mecanitzat siguin més sostenibles mediambientalment, degut a que obre la possibilitat de reduir, i fins i tot eliminar, l'ús de lubricants i refrigerants en el mecanitzat.

Les propietats mecàniques que s'han mencionat prèviament, estan intrínsecament relacionades a la seva microestructura. El Pc-BN és un material compost format per partícules de nitrur de bor cúbic (c-BN) lligades en una matriu ceràmica (com per exemple TiC, TiN, WC, AlN, etc.) o en una matriu metàl·lica (com per exemple una basada en un aliatge de Co). En general, les matrius ceràmiques es troben en substrats amb un contingut de c-BN Baix o mitjà, mentre que les matrius metàl·liques es troben en substrats amb alts continguts de c-BN. Degut a aquest fet, les matrius ceràmiques generalment s'utilitzen en operacions de tornejat, on hi ha un contacte constant i on es generen altes temperatures. Per altra banda, normalment les matrius metàl·liques amb alt contingut de c-BN es troben en aplicacions interrompudes on la tenacitat és un dels principals requeriments, degut a l'alta generació d'impactes durant el mecanitzat.

L'objectiu principal d'aquest projecte és fer una revisió i analitzar els mecanismes de desgast i fractura de plaquetes recobertes de Pc-BN. Per altra banda, també s'analitzaran els paràmetres crítics de disseny microestructural, com ara la composició química dels recobriments, la microestructura del Pc-BN o la seva naturalesa química. Els materials mecanitzats i les operacions de tall involucrades també s'estudiaran al llarg d'aquest projecte. Finalment, s'intentaran relacionar diferents variables relacionades amb el mecanitzat amb aquestes eines. Per tal d'aconseguir aquests objectius, es realitzarà una recerca literària. Els estudis indiquen que el principal mecanisme de desgast pels diferents sistemes recoberts estudiats, és el conegut com a *flank wear*, seguit pel *crater wear*, i finalment, en menor mesura, *notch wear*. A més a més, s'ha comprovat que l'ús de recobriments en el Pc-BN permet mecanitzar en condicions més extremes, comparat amb altres materials d'eines. Malauradament, no s'han pogut identificar relacions específiques entre els recobriments-substrats-materials mecanitzats. Les raons principals són que el número de variables en les publicacions revisades és molt gran i que la informació existent en aquest tema és relativament escassa. En tot cas, una conclusió important de la revisió, és que l'interès en aquest compost ha crescut de forma rellevant

durant les últimes dues dècades, període en el qual s'ha consolidat com a una alternativa molt competitiva dels carburs cementats.

Resumen

En los últimos años, el interés por el nitruro de boro cúbico policristalino (Pc-BN) como material para herramientas ha aumentado significativamente, especialmente en operaciones de torneado de materiales difíciles de cortar. Esto se debe a que es el segundo material más duro, por detrás del diamante, incluso a altas temperaturas; además de ser químicamente inerte, y presentar buena resistencia a altas temperaturas y estabilidad térmica. En este contexto, el Pc-BN hace posible el mecanizado bajo condiciones extremas, rediciendo así los costes asociados a la producción. Asimismo, el empleo de capas finas de cerámicas duras prolonga la vida útil de la herramienta, además de hacer este material más sostenible medioambientalmente, debido a que abre la posibilidad de reducir, e incluso eliminar, el uso de lubricantes y refrigerantes en las operaciones de mecanizado.

Las propiedades mecánicas previamente postuladas están intrínsecamente relacionadas a su microestructura. El Pc-BN es un material compuesto formado por partículas de nitruro de boro cúbico (c-BN) ligadas en una matriz cerámica (por ejemplo, TiC, TiN, WC, AlN, etc.) o metálica (por ejemplo, basada en una aleación de Co). En general, las matrices cerámicas se encuentran en sustratos con contenido de c-BN bajo o medio, mientras que las matrices metálicas se encuentran en sustratos con alto contenido de c-BN. Debido a esto, las matrices cerámicas generalmente se usan en operaciones de torneado, donde hay contacto constante y se generan altas temperaturas. Por su parte, las matrices metálicas, con alto contenido de c-BN, se usan para el fresado de materiales donde la tenacidad es uno de los requerimientos más importantes, debido al corte interrumpido (impactos) que ocurren durante esta operación de mecanizado.

El objetivo principal de este proyecto es hacer una revisión y analizar los mecanismos de desgaste y fractura de plaquitas recubiertas de Pc-BN. Por otro lado, se analizarán diversos parámetros críticos en el diseño microestructural de estas herramientas, como la composición química de los recubrimientos, la microestructura del Pc-BN o su naturaleza química. Los materiales mecanizaos y las operaciones de corte involucradas también se estudiarán en este proyecto. Finalmente, se intentará correlacionar distintas variables asociadas con las herramientas recubiertas de Pc-BN. Con el fin de alcanzar estos objetivos, se realizará una búsqueda literaria. Los resultados indican que el principal mecanismo de desgaste, por los sistemas recubiertos estudiados, es el conocido como *flank wear*, seguido por *crater wear*, y en menor medida notch wear. Además, el uso de recubrimientos en el Pc-BN se ha visto que permite el uso de condiciones más extremas, comparado con otros materiales de herramientas. Desafortunadamente, no se han podido identificar relaciones especificas entre recubrimientos-sustratos-materiales mecanizados. Las razones principales de ello son que el número de variables en las publicaciones revisadas es muy grande y que la información existente en este tema es relativamente escasa. En todo caso, una conclusión importante de la revisión es que el interés en este

compuesto ha crecido de forma relevante durante las dos últimas décadas, período en el cual él se ha consolidado como una alternativa muy competitiva de los carburos cementados.

Acknowledgements

Firstly, I would like to thank to my supervisors, Luis Miguel Llanes Pitarch and Sandra Gordon Pozuelo, for trusting on me and letting me be a part of this project. I would like to express my generous gratitude to them for guiding me during these challenging times. Thanks for restructuring this project in such a short time, and for all the dedicated hours. Sandra, thank you for your guidance and patience during these months.

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Glossary of terms

Al	Aluminium	**g**	Grams
Al_2O_3	Alumina	**GPa**	Gigapascals
AlB_2	Aluminium diboride	**h-BN**	Hexagonal boron nitride
AlCrN	Aluminium chromium nitride	**HCP**	Hexagonal close-packed
AlCrO	Aluminium chromium oxide	**HPHT**	High pressure - high temperature
AlN	Aluminium nitride	**HRC**	Rockwell C hardness
a_p	Depth of cut	**HSS**	High speed steel
BUE	Built-up-edge	**HV**	Vickers hardness
BUL	Built-up-layer	**K**	Kelvin degrees
c-BN	Cubic boron nitride	**K_{Ic}**	Fracture toughness
Co	Cobalt	**m**	Meters
CrN	Chromium nitride	**MMC**	Metal matrix composite
CVD	Chemical vapor deposition	**MnS**	Manganese sulfide
EDM	Electrical discharge machining	**MoC**	Molybdenum carbide
f	Feed rate	**MoS_2**	Molybdenum disulfide
FCC	Face centered cubic	**MPa**	Megapascals
FIB	Focused ion beam	**MQL**	Minimum quantity lubricant

nc	Nanocoating
Ni	Nickel
ºC	Celsius degrees
Pc-BN	Polycrystalline cubic boron nitride
PCD	Polycrystalline diamond
PMMC	Particle metal matrix composite
PVD	Physical vapor deposition
SEM	Scanning electron microscopy
Si_3N_4	Silicon nitride
SiC	Silicon carbide
Ti	Titanium
TiAlN	Titanium aluminium nitride
TiC	Titanium carbide
TiCN	Titanium carbonitride
TiN	Titanium nitride
TiOCN	Titanium oxide carbide nitride
TiSiN	Titanium silicon nitride
TRS	Transverse rupture strength
v_b	Flank wear
v_c	Cutting speed
w-BN	Wurtzite boron nitride
WC	Tungsten carbide
WRA	Whisker-reinforced alumina
µm	Micrometres

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1. Preface

The actual increase in globalization has also led to a rise of industrialization, where the manufacture process has an important role in terms of productivity. Moreover, the constant development of new materials or modifications of those widely used nowadays lead to improve industrial efficiency and reduce manufacturing costs/time. Apart from that, other requirements such as quality is commonly considered. In order to satisfy the requirements of industries, it is important to have enough knowledge of the used material in manufacturing processes. This knowledge allows the engineers to do different forecastings, resulting in an increase of the industrial efficiency.

In this project, coated Pc-BN tools have been studied to increase the knowledge of these tools. Although it is a material known from long time ago, compared with other tools iPc-BN tools are still emerging, and remain in constant development. A notable growth of the knowledge of coated Pc-BN could allow industries to improve their efficiency, while also reducing their residues and being more sustainable, since coated Pc-BN tools exhibit a satisfactory performance in dry conditions.

An in-depth literature review is needed, since the number of works published in this field is not large. Furthermore, trends about the use of Pc-BN tools are not completely defined. In this regard, analysis of the gathered information will require comparison of the different parameters of coated Pc-BN systems addressed in the open literature. Following this approach, it is expected to identify and establish guidelines for improving the microstructural design of coated Pc-BN, on the basis of a better understanding of the corresponding microstructure-properties relationship, as a function of work-material and machining operation involved.

2. General introduction

2.1. Pc-BN as a super-hard material

In the late 1950s, the first cubic boron nitride (c-BN) was synthesized by Wentorf in General Electric's laboratories with the name of Borazon™ [1]. Since 1969, the c-BN has been commercially available [2]. c-BN is known for being the second hardest material, also at high temperatures, after diamond. Moreover, its development was motivated by the demand of an alternative super-hard material to diamond, due to the fact that this graphitizes when reacts with ferrous materials during cutting operations [3].

c-BN is commonly used as a polycrystalline aggregate (Pc-BN) which is indeed a composite material consisting of c-BN particles embedded in a matrix with metallic (e.g. Ni, Co, Al) or ceramic (e.g. nitrides, carbides and/or carbonitrides) nature. Consequently, it may exhibit a wide range of properties depending on its microstructure and the chemical nature of the matrix elements used [1,4].

Pc-BN is widely employed as a cutting tool material of difficult-to-cut materials, such as hardened steels, high speed steels, die steels, bearing steels, alloys steels, case-hardened steels, white cast irons and alloyed cast irons among others [5]. Polycrystalline diamond (PCD), cemented carbides, high speed steels (HSS) and other ceramics (mainly based on Al_2O_3 or Si_3N_4) are also used as a cutting tool material. The implementation of hard materials as cutting tools allows the possibility of greater process flexibility, reducing the machining time, and consequently decreasing energy consumption and final cost [6].

In the particular case of Pc-BN as a cutting tool, an improvement on hard machining applications is attributable to its excellent mechanical properties: high-temperature strength, thermal stability, chemical inertness, and as previously stated above, high hardness [7]. Some of these properties are shared with several conventional ceramic tools, which have a lower cost but at expenses of a much shorter tool life. Main reason behind it is the high concentration of heat generated in hard machining, which causes temperature gradients and concentrated tool wear [8]. Although PCD presents the highest thermal conduction, it is known that Pc-BN materials have a thermal conductivity 4-5 times higher than conventional ceramic tools [9]. On the other hand, the major advantage of Pc-BN tools over diamond tools lies on the machinability of hard ferrous metals, due to diamond graphitization of the latter [10]. In order to evidence the specific advantages of using Pc-BN, a comparison between the most employed materials for these applications is shown in **Figure 2.1,** and summarized in **Table 2.1**.

Cemented carbides are the most used materials in turning operations, due to its excellent combination of toughness and hardness as well as its low cost compared to Pc-BN tools. However, Pc-BN tools are preferred in hard turning operations due to its higher hardness and abrasive wear resistance. In addition, such machining operation can be done without coolants due to their high thermal conductivity, which can be translated in more efficient cutting [11]. Therefore, Pc-BN tools can be placed in milling operations, replacing conventional ceramics or steels, and in many turning operations, as an alternative to ceramic, cemented carbides or cermets [12].

*Table 2.1 Properties exhibited by different tool materials. *Typical composition in vol.% unless indicated* [1].

Tool material **Property**	**Tungsten carbide**	**Alumina**	**Mixed alumina**	**Whisker reinforced alumina**	**Silicon nitride-based**	**Pc-BN**	**PCD**
Typical composition*	94 wt.% WC + 6 wt.% Co	90-95% Al_2O_3 + 5-10% ZrO_2	Al_2O_3 + 30% TiC + 5-10% ZrO_2	75% Al_2O_3 + 25% SiC	77% Si_3N_4 + 13% Al_2O_3 + 10% Y_2O_3	98% c-BN + 2% AlB_2/AlN	PCD + 0-18% Co
Density [g·cm^{-3}]	14,8	3,8-4,0	4,3	3,7	3,2	3,1	3,4
Hardness at RT [HV]	1700	1700	1900	2000	1600	4000	8000-10000
Hardness at 1000ºC [HV]	400	650	800	-	900	1800	-
Fracture Toughness [MPa·m$^{1/2}$]	10	1,9	2	8	6	10	7,9
Young's Modulus [GPa]	630	380	420	390	300	380	925
Thermal conductivity [W/(m·ºC)]	100	8-10	12-18	32	23	100	120

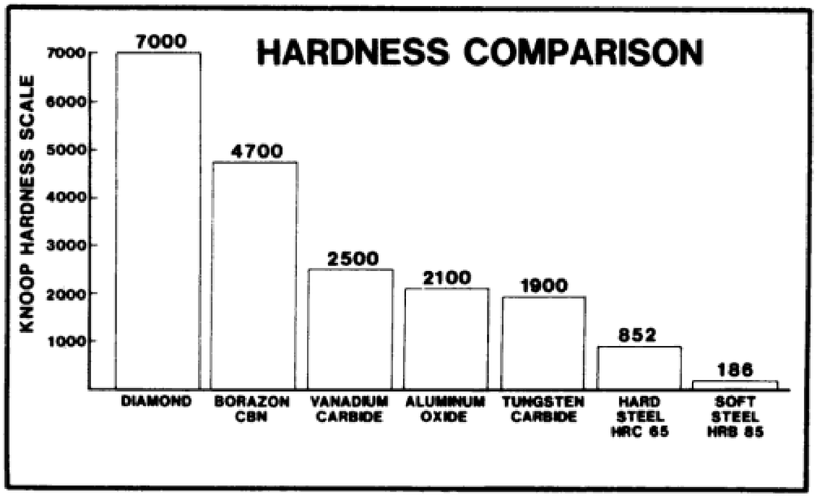

***Figure 2.1** Comparison of Knoop Hardness for different tool materials* [13].

Figure 2.2 shows an example of a cutting tool insert typically used in hard machining operations. It is mainly composed of two parts: *i)* the tip, placed in the cutting edges, and *ii)* the base (parts A and B in **Figure 2.2**, respectively). The base material may be a cemented carbide, cermet, ceramic or a ferrous material, being the first one the most common, due to its combination of relatively high toughness (from 5 to 25 MPa·m$^{1/2}$) and hardness (from 7 to 24 GPa). The Pc-BN substrate is located in the cutting edges of the insert, which are the regions subjected to major mechanical and thermal service conditions. Within this context, Pc-BN can be placed in one, two (as seen in **Figure 2.2**) or four of the edges of the insert [14–20].

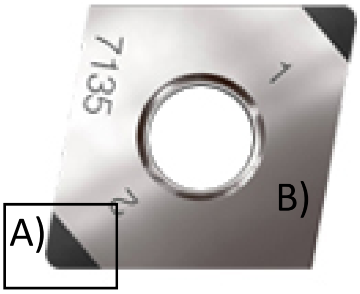

***Figure 2.2** Commercial twice-tipped edge Pc-BN insert, where A) is one of the two Pc-BN tips and B) the base material* [14].

2.1.1. Microstructural characteristics of Pc-BN

2.1.1.1. Crystallographic structure

The chemical bounds of boron nitride (BN) are isoelectronic with carbon, which means that they have the same number of valence electrons. The BN could appear in different crystallographic structures: hexagonal, cubic (also called zinc blende structure) and wurtzite. The hexagonal boron nitride (h-BN) is more stable and is the precursor of the other two structures. For instance, c-BN and w-BN are obtained by submitting h-BN to high pressure and temperature. While w-BN is favoured at temperatures lower than 300 K, c-BN is found at temperatures higher than 2500 K [21]. Furthermore, BN is comparable to carbon, where h-BN and c-BN are similar to graphite and diamond, respectively, in terms of crystallographic structure [22][23].

In general terms, the cubic structure is one of the seven possible crystallographic structures, and stands out for having the same lattice parameters of the unit cell, (i.e. $a = b = c$ and $\alpha = \beta = \varphi = 90º$). According to the fourteen Bravais Lattices, this structure can be found in three different ways: primitive, face-centered and body-centered, as it is depicted in **Figure 2.3** [24].

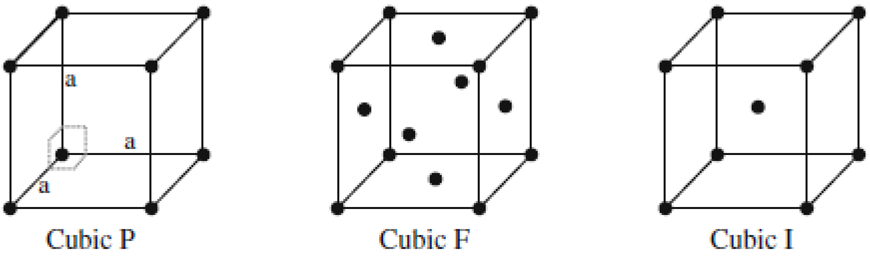

Figure 2.3. *Cubic form in the primitive lattice (Cubic P), the face-centered lattice (Cubic F) and in the body-centered lattice (Cubic I)* [24].

Moreover, the unit cell of the FCC is characterized for having four ions. Both FCC and HCP has the highest atomic factor and present octahedral and tetrahedral interstices, which allow cation implementation in the net. As a consequence, the net tends to stabilize incorporating cations in the tetrahedral or octahedral voids. The eight tetrahedral voids can be found midway between each corner and the centre of the unit cell. On the other hand, three of the four octahedral voids are located at the midpoint of each edge of the cell, whereas the other one is found in the center of the cell, as depicted in **Figure 2.4**. According to the positions of the atoms, the coordination number for a FCC structure is equal to twelve [24,25].

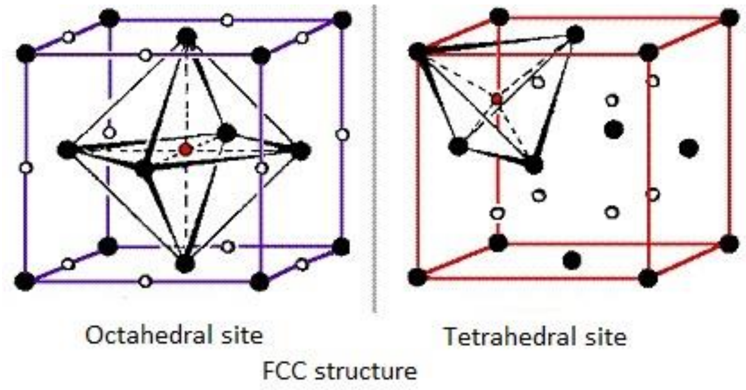

Figure 2.4 *Octahedral and tetrahedral sites of a FCC structure* [26].

According to the literature, FCC has six cleavage planes (as seen in **Figure 2.5**) in the lattice plane (110) [22]. A cleavage or glide plane is characterised for being the highest atomic density plane of the crystallographic structure, besides having both Burgers vector and dislocation line on it. Due to this high planar atomic density, the distance between atoms is lower and the dislocation movement is favoured in this direction. Thus, deformation and fracture tend to occur along cleavage planes [24,25].

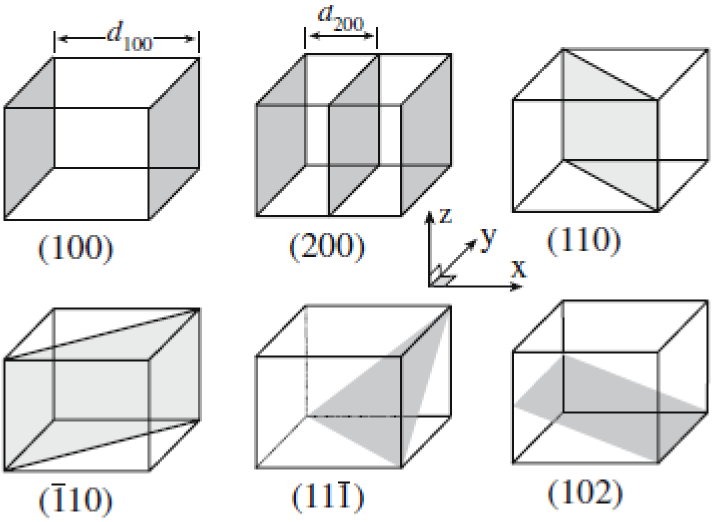

Figure 2.5. *Different lattice planes available in the cubic structure* [24].

As stated above, the c-BN is akin to diamond in terms of consisting of two interpenetrating face-centered lattices shifted by ¼ <1 1 1> respect each other. One consists of boron atoms placed in the tetrahedral holes, while the other includes nitrogen atoms that define the FCC lattice [23,24]. The lattice constant a is 3,615 Å, and the density is approximately 3.45 $g \cdot cm^{-3}$ [22].

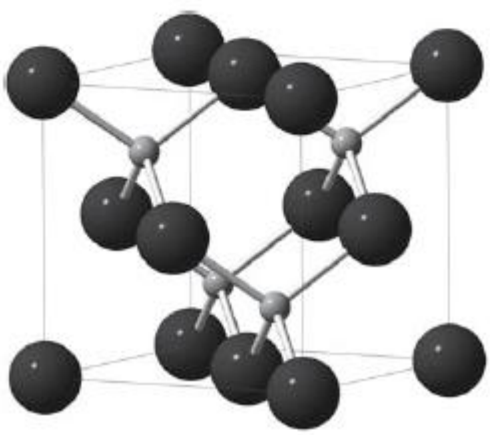

Figure 2.6 *Crystal structure of the c-BN* [24]*, where the big and small spheres represent N and B atoms, respectively.*

The unit cell of a c-BN structure is shown at **Figure 2.6**, where the bonds between B and N atoms are strongly covalent and tetrahedrally coordinated with and hybridization [22].

The differences between the properties of h-BN and c-BN can be explained in terms of crystal structure. The h-BN is a soft phase built by sp^2-bonded B_3N_3 hexagonal planar layers, whereas the c-BN is a hard sp^3-bonded phase. Both structures could be described as a stacking of layers of atoms, where the stacking sequence is ABABAB along the [001] direction and ABCABCABC along the [111] direction in the case of h-BN and c-BN, respectively. Furthermore, atoms are linked by covalent (sp^2) bonding within the layers in h-BN, whereas bonding between the layers is of Van der Waals type. These leave a high interplanar spacing, which is translated into a lower compacity in the c-axis. As a consequence, h-BN presents an anisotropic behaviour due to the higher compressibility in the c-axis. On the other hand, bonding is covalent along all directions in the c-BN, yielding then higher mechanical properties [22,27,28].

The hexagonal structure of BN is characterised by its low density and hardness, while c-BN and w-BN ones exhibit higher densities due to the tetrahedral arrangement. In the c-BN and w-BN structures, each atom is in a three-dimensional lattice in a sp^3 hybridization, with four strong covalent bonds (σ), where weak bonds (π) are no longer available. It explains the higher compacity in the c-axis, see **Figure 2.7**, of these structures; and in consequence, their higher hardness. The differences between c-BN and w-BN lie in the fact that the tetrahedral structure is obtained [27,28].

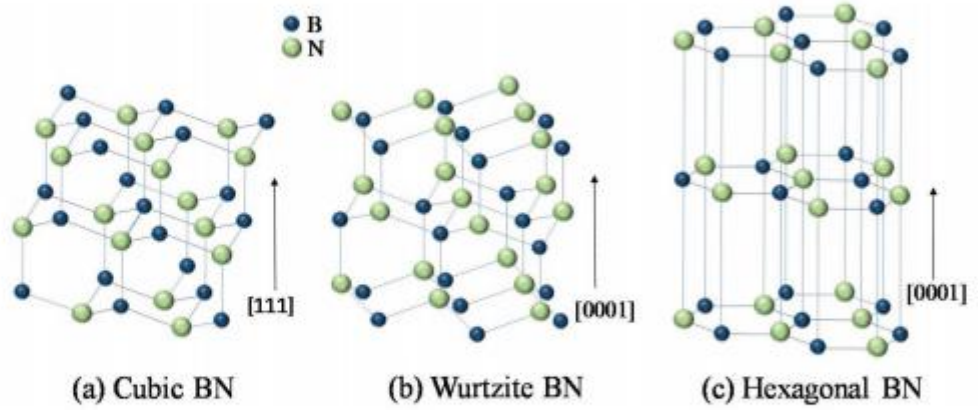

Figure 2.7 *Different forms of the BN compounds: a) c-BN, b) w-BN and c) h-BN* [28].

2.1.1.2. Pc-BN as a composite material

As mentioned before, c-BN is mostly employed as Pc-BN when used as a cutting tool. The polycrystalline cubic boron nitride is a composite material consisting of c-BN grains dispersed in a matrix with metallic (e.g. Ni, Co, Al) or ceramic (e.g. carbides, nitrides and/or carbonitrides) nature, in proportions from 5 to 90 vol.% [29,30].

Pc-BN can be classified according to c-BN content in: *i)* low c-BN content for c-BN volume percentages below 50%, *ii)* medium c-BN content for c-BN vol.% in the range of 50 to 70% vol.% and *iii)* high c-BN content when this is higher than 70 vol.% [31]. Furthermore, ceramic binders are usually preferred for low and medium c-BN contents, whereas the high c-BN content is employed together with metallic binders [32].

According to the literature, metals of the groups IV, V and VI of the periodic table, their compounds (i.e. carbides, nitrides, carbonitrides, borides or silicates) and other elements such as aluminium (Al), cobalt (Co) or nickel (Ni), may compose the matrix [29,33]. Although the most common matrix is Ti-based, some other binders are widely used, i.e. TiC, TiN, Al, WC-Co, Ti, TiN-Al, Al_2O_3, Co and Ni [30,34].

Ceramic binders improve the density ratio and the surface finish, in terms of lower roughness, of the composite. However, due to its characteristic brittleness its use is limited to the low and medium c-BN content [35,36]. On the other hand, metallic binders are used for the high c-BN content, in order to improve the fracture toughness of the composite while maintaining the wear resistance that provides the c-BN phase [37].

The sintering of c-BN is difficult because it requires high pressures and temperatures (around 4-6 GPa and over 1100ºC [29,38]), as shown in **Figure 2.8** due to the covalent bonding (more information about the sintering process could be found in **Section 2.1.3**). In that context, the use of binders is an alternative to reduce those parameters of the sintering process as well as to improve some drawbacks of the binderless c-BN. A high purity Pc-BN, also known as binderless Pc-BN, exhibits excellent mechanical and thermal properties, but is extremely brittle [4,39]. Binders are usually softer than c-BN grains; thus, they decrease the composite hardness. However, binders may affect positively other properties. For instance, it is reported that TiN and TiC improve thermal stability and wear resistance [39]. It is demonstrated that addition of metals, such as Al or Ni, enhances the interface bonding between cBN particles and binder phase [40].

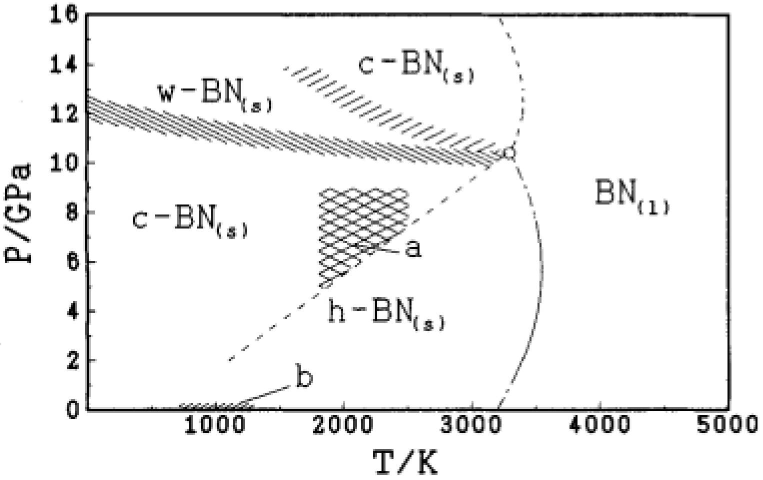

Figure 2.8 *P, T diagram of BN: a) catalytic conversion of h-BN into c-BN, b) metastable region for the vapor-phase formation of c-BN* [41].

Another important role of binders is to prevent the formation of B_2O, which hinders the diffusion between the c-BN grains. Al compounds are usually used for this purpose, by protecting the inner surface from chemical attack [38,42–44]. Nevertheless, it is reported that Pc-BN hardness can be reduced when Al content exceeds 20 wt.% of the total binder [45]. Besides the chemical attack protection, aluminium also gives thermal stability and is used to reduce the sintering temperature of the Pc-BN, due to its low melting point. In c-BN-Al systems, TiN is often added to reduce grain growth of AlN and AlB_2 (i.e. its thermal expansion coefficient is midway between c-BN and Al) as well as to improve strength and wear resistance [38,45,46].

Although the presence of WC in the binder phase is rather avoided, it can only be minimized. WC binder particles comes from the milling attrition process, which is one of the first steps of the Pc-BN manufacture process, where the balls are made of WC. Given that c-BN is harder than tungsten carbide, c-BN powders can pick impurities as a result of the crashed process that usually takes place at this stage. Consequently, WC impurities are not easy to be controlled, and the final Pc-BN microstructure could contain different amounts of WC with distinct size distributions. It leads to unpredictable performance of the tool [29].

2.1.2. Mechanical properties of Pc-BN

Although Pc-BN is generally defined for being constituted of BN particles in its cubic phase, some h-BN grains can also occasionally appear in the microstructure. The retained h-BN as well as other factors (e.g. particle grain size distribution, binder chemical nature, etc.) are reported to affect the mechanical properties of the final Pc-BN product.

2.1.2.1. Effect of h-BN

An excess of compressed h-BN retained in the microstructure deteriorates the bonding strength of the c-BN grains in the Pc-BN. As a consequence, h-BN fractions higher than 0.5 vol.% results in a hardness decrease (**Figure 2.9**) [4].

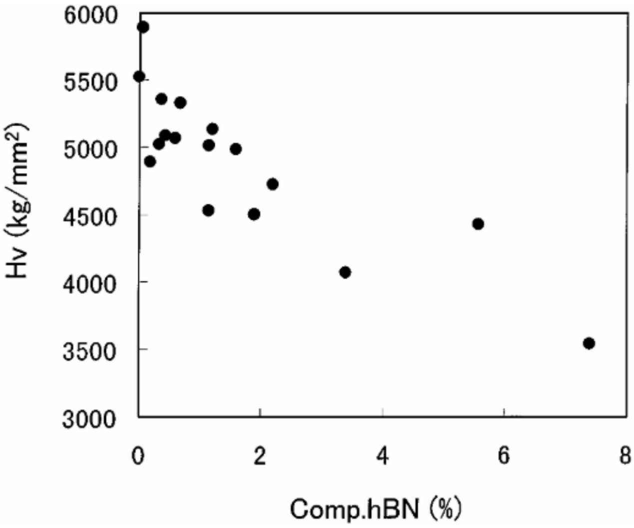

Figure 2.9 *Hardness at room temperature of Pc-BN as a function of the amount of retained compressed h-BN* [4].

2.1.2.2. Effect of c-BN grain size

It is known that the mechanical properties of polycrystalline materials are dependent on the grain size, which can be explained on the basis of a Hall-Petch relationship, i.e. hardness increases as grain size decreases [25]. Within this context, as grain size is reduced, the fraction of grain boundaries gets higher. Hence, slip between grains is reduced because grain boundaries act as obstacles to dislocation movement, and the applied stress needed to cause plastic deformation gets higher. Hence, when coarse grains are used, more plastic deformation may occur, and hardness is decreased. Finer grains also improve chemical bonding between the different phases of the final material, leading to higher strength. Thereby, the hardness is increased by reducing the grain size, as shown in **Figure 2.10** [38,45].

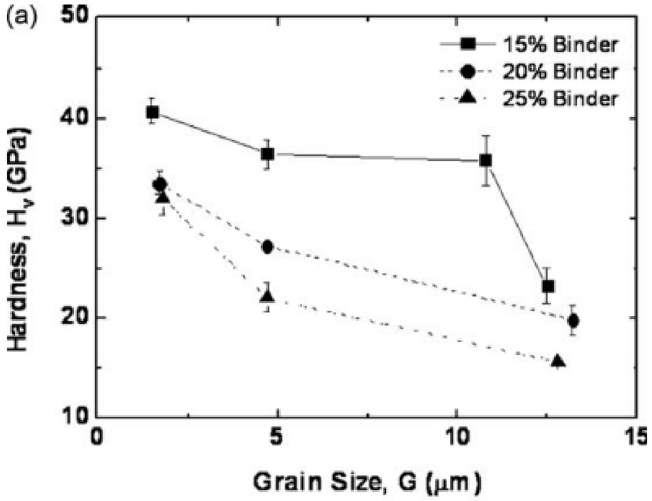

Figure 2.10 Hardness dependence on the grain size and the binder content of Pc-BN with Al binders [38].

Considering Pc-BN applications, the variation of the mechanical properties with temperature is another effect to take into account. At high temperatures (above 500 ºC), hardness is less affected by finer grains, due to the greater degree of grain boundaries, which implies less deformations. The flexural strength or transverse rupture strength (TRS) of high purity Pc-BN with fine grain size increases as the temperature rises, which is related to the relaxation of the localized stress at crack tip given by microplastic deformation, see **Figure 2.11**. Additionally, TRS is improved by grain refinement at room temperature, while it is barely affected by temperature until 800ºC [4].

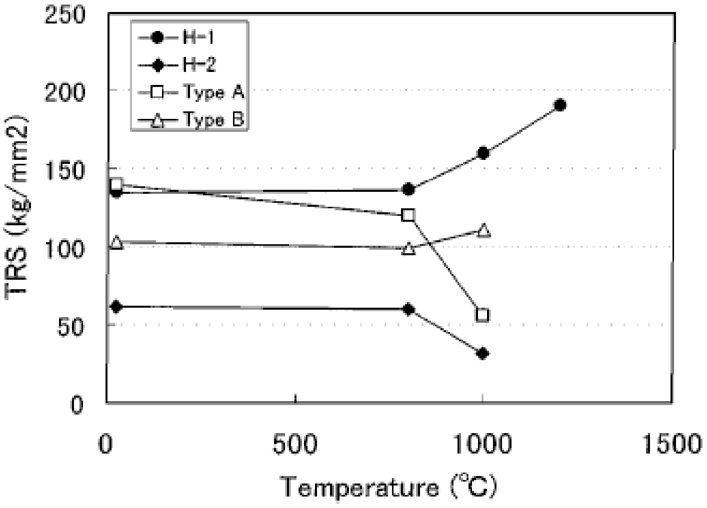

Figure 2.11 Temperature dependence of TRS of high purity Pc-BN sintered bodies (H-1: fine grained with c-BN vol% > 99,9%, H-2: coarse grained with c-BN vol% > 99,9%, Type A: with c-BN vol% > 85-90% and Type B: with c-BN vol% > 50-55%) [4].

Fracture toughness is another mechanical property clearly affected by grain size, although its dependence is opposite to the one exhibited by hardness. When the grain size decreases, fracture toughness gets also lower, contrary to hardness. This can be explained by an increasing c-BN – c-BN particle contact, which raises brittleness of the material and consequently reduces fracture toughness, although combined by an increase of the Young's modulus, see **Figure 2.12** [39]**.**

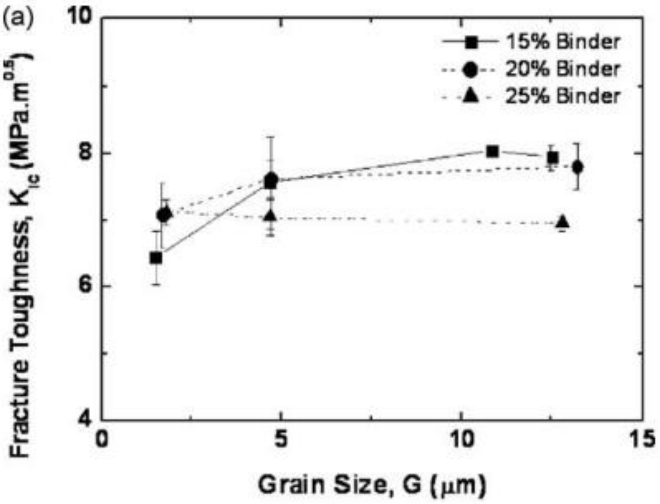

Figure 2.12 *Fracture toughness dependence on the grain size and binder content of Pc-BN with Al binders* [38].

Furthermore, particle shape of the c-BN grains can also have influence on the final properties. During the sintering process, the higher pressure and temperature values used cause local deformations, which lead to the formation of residual stress fields around individual particles. Thus, spherical c-BN particles have more homogeneous stress distributions than irregular ones [45].

2.1.2.3. Effect of the binder content

Since it its known that binderless Pc-BN would exhibit excellent properties, the binder content is another parameter which must be taken into account. In this regard, fracture toughness increases as the binder amount rises. Meanwhile, as expected, other properties such as hardness, transverse rupture strength and Young's modulus are adversely affected, as it is depicted in **Figure 2.10**, **Figure 2.11** and **Figure 2.12**. Such microstructural effect could be explained by the weaker character of the binder, which yields larger plastic deformations. Another consequence is the rise in crack deflection. As stated above when discussing grain size effects, it can also be explained by the decreasing number of c-BN – c-BN particle contacts [38,45].

Hardness shows a strong dependence on c-BN content, and consequently on binder content. Since high hardness is given by the ultra-hard phase (c-BN phase), when the binder content is increased, the c-BN content is decreased. Thus, hardness is lowered whereas fracture toughness is rised for higher binder contents.

The effect of grain size on fracture toughness is larger for grades with high c-BN content. However, when binder content increases, sensitivity of this property to grain size changes and is reduced due to the fact that binder starts controlling toughness of the final material [38] [47]. In **Table 2.2**, some mechanical properties of different Pc-BN grades, as reported in the literature, are summarised.

Table 2.2 *Summary of mechanical properties of different Pc-BN materials* [1,47,48].

Material	%c-BN	Binder	E (GPa)	Hv (GPa)	K_{IC} (MPa·$m^{1/2}$)	TRS (MPa)
BZN 8100	60	TiC	650	30	7.8	846
BZN 7000	80	AlN	709	34	7.7	512
BZN 6000	90	Ni/Co alloy	737	37	10.8	747

2.1.2.4. Effect of the manufacturing process

Manufacturing process is essential in order to control the final microstructure, in terms of density, homogeneity and grain size. Thus, it indirectly defines the mechanical properties of the sintered Pc-BN. In the HPHT process, as it is the case in many other manufacturing processes, the sintering temperature plays an important role. Within this context, low sintering temperatures cause a weak union between the powder particles, leaving a low-density final product which deteriorates the mechanical properties. Thereby, high sintering temperatures enhance better unions and promote densification, but also grain growth [38,45].

It has been observed that at low temperatures the c-BN-binder interface is weak, reducing density and hardness, as in the case of c-BN-Cr_3C_2 under 1600ºC (**Figure 2.13**). As far as the temperature does not exceed approximately 1850ºC, the interphase boundaries do not achieve enough strength. However, it has been observed that temperatures higher than 2000ºC also affect mechanical properties due to grain growth, see **Figure 2.12** and **Figure 2.13** [49]. Poor sintering temperatures lead to porosity which has been reported to decrease strength, because pores act as crack-initiating sites [45].

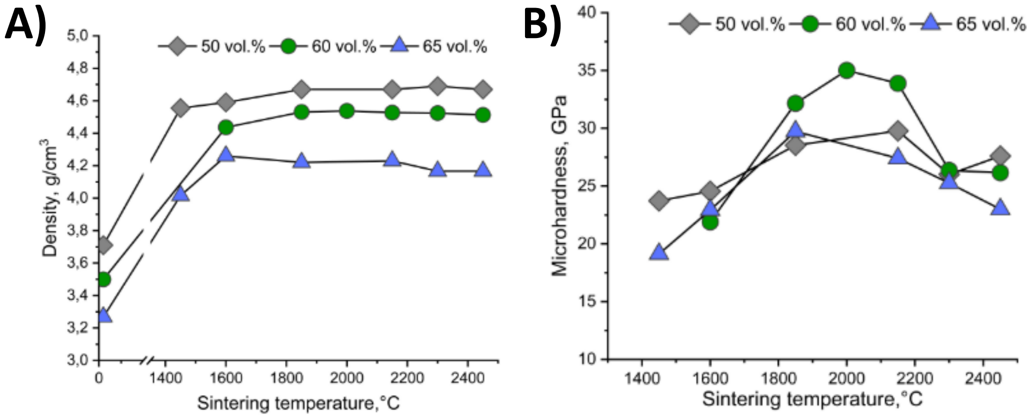

Figure 2.13 Dependence of the A) density and B) the microhardness with the sintering temperature of Pc-BN materials with Cr_3C_2 as a binder phase [49].

The amount of retained h-BN in the final material also depends on the sintering temperature of the material; and thus, it also induces changes on the mechanical properties of the material. Thus, at higher sintering temperatures, the final material has lower amount of compressed h-BN and better mechanical properties, see **Figure 2.14** [4].

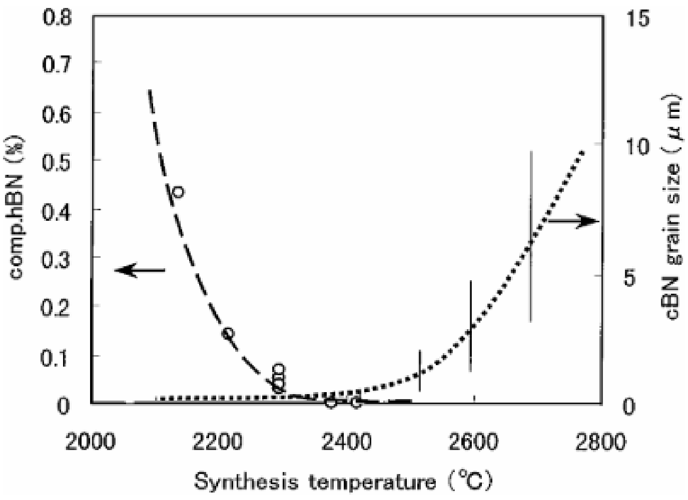

Figure 2.14 Amount of compressed h-BN and c-BN grain size of Pc-BN with the synthesis temperature [4].

It is of utmost importance to have a homogeneous microstructure in the final material, because the presence of agglomerates acts as a defect and consequently as a crack-initiating site, decreasing the strength of the material. The homogeneity is mainly controlled during milling and mixing processes, where the use of ultra-fine particles is reported to decrease the mixing efficiency, because they have high tendency to form agglomerates in the matrix [45].

2.1.3. Manufacture of Pc-BN

The Pc-BN manufacture process could be divided in two different steps: *i)* the high pressure high temperature (HPHT) direct conversion process for obtaining the c-BN through the h-BN; and *ii)* the binder assisted sintering for achieving the final Pc-BN product. The sintering of c-BN is difficult and expensive, as it needs high pressures and temperatures (around 7 GPa and 2000ºC) as presented before (**Figure 2.8**), due to the covalent bonding [29,50]. Within this context, the use of binder is an alternative for reducing those sintering parameters (i.e. down to 4-6 GPa and 1200-1500ºC) and obtaining a more uniform Pc-BN, as binder aids to fill out the pores [21], [30], [41], [42].

The HPHT direct conversion process could be done with or without the presence of catalysts (e.g. alkaline compounds, ammonium borates, inorganic fluorides or silicon alloys). The use of catalysts reduces the sintering parameters of the process. Furthermore, the resulting c-BN powder is usually of a small grain size with some catalysts residues as inclusions. In the case of producing c-BN grains without catalysts, higher pressure and temperature are needed, depending on the particle size and the degree of crystallinity of the starting h-BN material [15], [41]. Once HPHT process has been completely done, c-BN particles are separated by chemical or physical methods in order to remove flux precursors, inclusions, by-products and unreacted h-BN [22].

Afterwards, the obtention of the final Pc-BN may start. One method used is adding c-BN with a grain size between 0.5-15 µm on a pre-mixed, heat treated and sieved matrix powders with a grain size between 1-10 µm. Then, an attrition milling process is done for breaking down the precursor powders and intimately mixing them. The resultant mixed powder is dried under vacuum or low pressures at 600 ˚C, in order to remove solvents and passivate metallic surfaces (such as aluminium). and then sieved again. Finally, the powders are assembled into a capsule, and HPHT-sintered such that matrix is melted. **Figure 2.15** summarizes this processing route.

During the attrition milling, WC balls are used as milling mean. Hence, the powders could pick up milling impurities (up to 8 wt.%) which may have detrimental effects on the final Pc-BN properties, especially in the application of hard turning [29,45,51]. In order to remove these milling impurities, the matrix can be milled before adding the c-BN. Then, mixing of powders could be done by dispersing them in a solvent with an ultrasonic mixer or by dry acoustic mixing (i.e. without solvent). In the case of ultrasonic mixing, the solvent has to be removed when the powders are intimately mixed. Following this alternative method, c-BN is not submitted to attrition milling. As a result, low content of impurities from the milling media are found in the final material, and more reactions between matrix and c-BN particles occur due to the smaller grain size of matrix powders [29].

In addition, Pc-BN could be assembled in the form of disks which can be sliced in tips by EDM or laser machining. In this way, the cost of Pc-BN tools is reduced. Pc-BN tips are then joined to a substrate structure (e.g. cemented carbide) and brazed into a base material (e.g. cemented carbide, complex alloy) resulting in the final Pc-BN insert, as shown in **Figure 2.16** [52,53].

Figure 2.15 *Flow diagram of a general process for producing Pc-BN.*

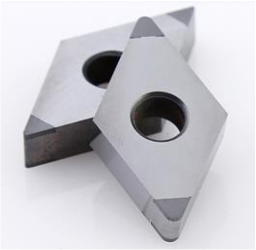

Figure 2.16 *Example of a Pc-BN inserts for hard turning* [54].

2.2. Use of coatings in tools

In the field of cutting tools, the application of advanced work materials and dry machining operations are some of the factors which have challenged working conditions during recent years. Moreover, high hardness and wear resistance, with good toughness and chemical stability are properties that must be present in an ideal cutting tool. Unfortunately, no material has shown the combination of all these properties. For this reason, use of coatings is a good alternative, in order to improve tool life while maintaining the outstanding properties of the substrates [55–58].

Environmental and economic factors contribute to the increasing demand of machining under dry or minimal lubrication conditions. In these operations, where is characteristic to have high-cutting speeds and temperatures, tools are exposed to high thermal stresses which contribute to reduce the tool life. The use of coatings is expected to reduce chemical wear, offering better surface finishes in dry cutting operations and during longer periods of time, and to improve machining performance and reduce power consumption; thus, enhancing productivity [55–57,59,60]. Furthermore, the use of coatings expands the range of both tool materials to be used in dry machining as well as work-materials to be shaped.

2.2.1. Physical vapour deposition (PVD) and chemical vapour deposition (CVD)

Nowadays more than 80% of the cutting tools are coated by either physical vapour deposition (PVD) or chemical vapour deposition (CVD) techniques (see **Figure 2.17**) [57,59–61]. PVD consists on melting, evaporating (or sputtering) and ionizing a solid metallic precursor, which reacts with an ionized gas. Both components, in a plasma-like state, are deposited in a substrate with a polarized surface. High vacuum with high purity gases, together with a good preparation of the substrate, are required in order to obtain satisfactory results. On the other hand, CVD method consists of a coating formation from the chemical reaction of volatile precursors in an activated environment (by heat, light or plasma). The main disadvantage is the high temperature required in the substrate to promote chemical reaction, which may lead to residual stresses, changes in surface and/or distortion of the substrate when it is cooled down. As a consequence, the resulting film tends to be less uniform than the obtained by PVD [23,62,63]. According to the literature, Al_2O_3, Ti(C,N), TiC and TiN are coatings usually obtained by CVD, whereas TiAlN, TiSiN, AlCrO, MoS_2 are rather produced by PVD [62].

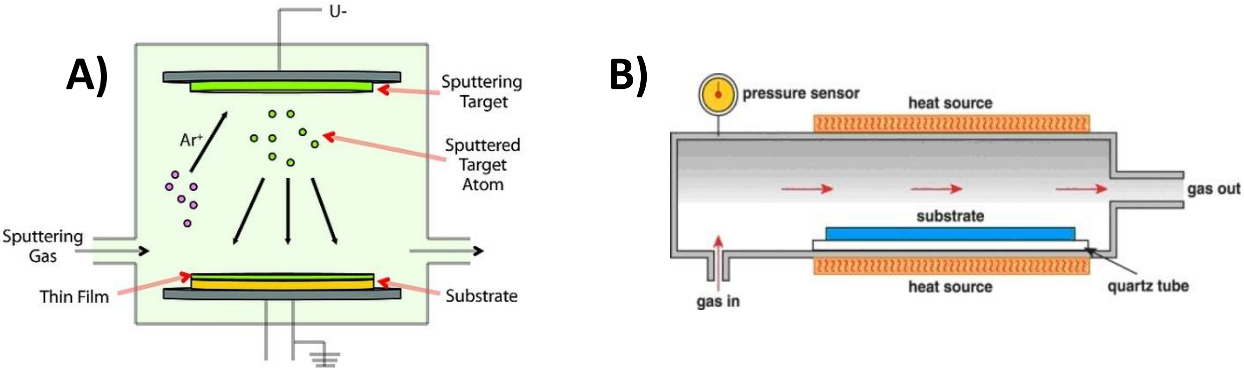

Figure 2.17 *A) Physical vapor deposition process (sputtering process) B) chemical vapor deposition process* [64,65].

2.2.2. Coatings

Technology of hard coatings might be classified in five different groups: *i)* titanium-based coating materials, *ii)* ceramic coatings, *iii)* super-hard coatings, *iv)* solid lubricant coatings, and *v)* soft coatings [55]. They are described below.

Titanium-based coatings (e.g. TiC, TiN, TiCN, (Ti,Al)N) - the most popular group - are expected to improve wear resistance by reducing friction, adhesion and diffusion phenomena. They also exhibit good deposition rates during the coating process and shows strong bonding with most of the substrates. While TiC provides high properties for wear resistance and have good chemical stability, TiN offers a low friction coefficient. TiC and TiN are outperformed by TiCN coatings, which have excellent hardness and abrasive wear resistance, with high chemical stability too [55,57,59,60,66].

Although ceramic coatings have high thermal stability and good wear resistance, they are not extensively used due to their brittleness and poor bonding with substrates, except in the Al_2O_3 case. Al_2O_3 is often compared to TiC, because it also exhibits high properties for wear resistance and good chemical stability [55,59,60].

The other three groups are the newest ones in the coating tools list. Super-hard coatings (e.g. PCD, Pc-BN) reduce friction and adhesion wear due to ultra-high hardness and high wear resistance. Solid lubricant coatings (such as amorphous metal-carbon) are hard films with a very low friction coefficient. Finally, **soft coatings** (e.g. MoS_2, graphite) are deposited on top of hard coatings to reduce friction and wear at early stages [55,58,67,68].

Given the excellent properties of c-BN materials, it may seem unnecessary an extra protection by means of coating. However, the application of thin films can enhance some drawbacks, such as [68–70]:

- Easiness to distinguish worn tip.
- Capability to machine a wider range of materials, regarding hardness.
- Improve wear resistance by reducing crater, flank and notch wear formation.
- Decrease diffusion wear.
- Extending high precision during machining, as a direct consequence of preventing the above-mentioned wear mechanisms.
- Protect tools against high temperatures (due to thermal barrier properties exhibited by the coating).
- Decrease friction and cutting forces, which permits the use of higher cutting speeds; thus increasing machining performance and productivity.

Commercial Pc-BN cutting inserts are often coated by TiN, TiC and/or TiCN with a metallic phase, such as Al and/or Cr. The most widely used is TiN, because it provides tribological resistance, high-performance machining, wear resistance, hardness and toughness. Moreover, it shows good adhesion and compatibility with Pc-BN substrates. Coatings with a similar thermal expansion coefficient as Pc-BN are preferred in order to reduce internal stresses caused by the deposition process. TiAlN is extensively used as inner layer, since its high adhesion with Pc-BN, good wear, oxidation resistance and chemical inertness. Another compound that may be used as adhesion layer is CrN. On the other hand, TiN and TiCN are rather used as outer layers, owing to the light colour of the former, which helps to identify when the wear appears, and the improvement of toughness of the latter, reducing inner stressed at the tool and preventing crack diffusion. However, titanium degrades at temperatures higher than 600ºC producing TiO_2 and negatively affecting the coating properties. However, aluminium and chromium are added in coatings composition, due to their oxidation in high temperatures (around 850ºC for aluminium and 1000ºC for chromium) producing Al_2O_3 and Cr_2O_3. These hard by-products are reported to improve thermal stability, oxidation resistance and chemical inertness [55,68,71–76].

2.3. Difficult-to-cut materials

In the last decades a new generation of materials has been introduced, characterised with some of the following properties: high strength-weight ratio, high stiffness and toughness, high strength and hardness at high temperatures, wear and fatigue resistance, corrosion and oxidation resistance, heat resistance, etc. [77–79]

During machining processes, these materials may lead to high cutting forces, temperatures and friction between the tool-chip and tool-workpiece interfaces. These high temperatures and stress generated are responsible of the rapid deterioration of the cutting tools used during machining. For these reasons, these materials are referred to as “difficult-to-cut materials”. Unfortunately, despite their excellent combination of properties, the application of these materials is not growing as expected because conventional methods for machining are uneconomical, and half of the final price of the product is associated with machining [77–79].

Hard to cut materials might be classified under one of the following families: *i)* steels (e.g. hardened alloys steels, high-speed steels, tool steels, cast iron, etc.), *ii)* titanium and its alloys, *iii)* superalloys (nickel, iron-nickel and cobalt alloys), *iv)* metal matrix composites (known as MMCs) and *v)* ceramics (e.g. mullite, zirconia, alumina, silicon nitride) [77,78]. In general, all of them are characterised by relatively high hardness, usually above 45 HRC. These materials are well known as difficult-to-cut materials due to the short tool life and instability of the machining process, as a consequence of its abrasiveness which is mainly related with the carbide formation. For example, the large number of alloying elements in steels together with high carbon concentration promotes the formation of many carbides (e.g. M_xC_y). In the case of superalloys, TiC, CrC, MoC are the most common ones. Advanced structural ceramics are also found to be difficult-to-cut materials owing to its high wear resistance [77–80].

In order to withstand mechanical and thermal stresses generated at high temperatures during machining, different types of cutting materials are employed, such as ceramics, coated carbide, PCD and Pc-BN, the one studied in this bachelor's thesis [77,78]. In particular, Pc-BN is widely employed for machining hardened steels (such as the Cr-based H01, H10 and the W-based H20 and H30), cast irons (e.g. white, grey, nodular), sintered Fe-base alloys, valve seat rings and super-alloys (Ni- and Co-based) among others. In this regard, scientific research have focused on studying the performance of Pc-BN tools in machining of Inconel 718, chromium white cast iron and some hardened steels such as AISI D2, 90MnCrV8, 16MnCr5.

2.4. Continuous vs. interrupted cutting

Hard cutting operations (such as turning, milling, drilling, grooving, threading and boring) are applied on materials with hardness values higher than 45 HRC. They may be roughly classified as processes involving continuous or interrupted cutting. In continuous operations, the contact between tool and workpiece is constant, while in interrupted ones such a contact is not steady [11,14,31,81]. In terms of dry machining, the interrupted cutting is preferred as it only requires air cooling [77].

In continuous operations, where abrasion is the principal wear mechanism, tools are required to have properties like wear resistance, low friction coefficient, hardness and chemical stability at high temperatures. Chemical stability is needed due to the exposition of the tool to high temperatures for long periods, which could lead to diffusion wear [9,82,83]. On the other hand, in interrupted operations, where mechanical and thermal impact conditions are severe, four main features must be considered: tool entry into workpiece, tool exit, cyclic loading/unloading and heating/cooling (as shown in **Figure 2.18**). Tool entry is considered the major harmful issue, due to the requirement of high initial cutting forces, which can be translated into higher mechanical impact. Although in this case saturation temperatures are not reached (unlike in continuous cutting), the presence of gradient temperatures as a result of heating and cooling cycles lead to thermal shocks. As a consequence of the mentioned aspects, the main requirement for tools in interrupted cuttings is fatigue resistance [9,82–84].

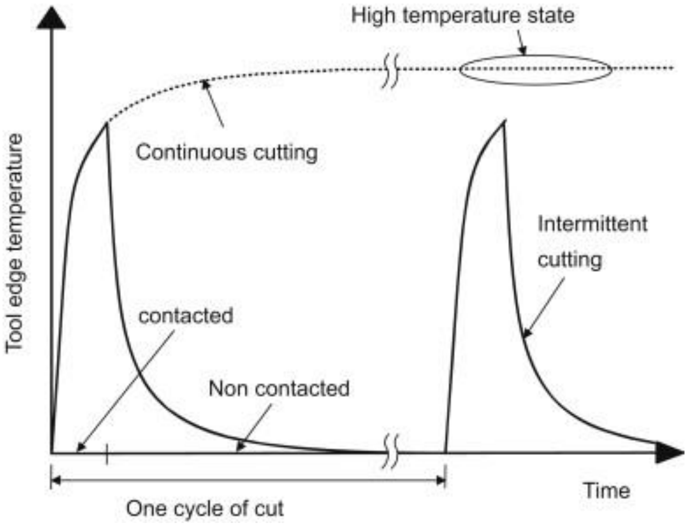

Figure 2.18 *Cyclical variation of tool edge temperature for interrupted cutting compared with continuous cutting* [85].

Among the different options available, HSS tools would then be the main candidate for interrupted cutting, because their relatively high toughness. Nevertheless, they are not used because their hardness is decreased when temperature exceeds 500˚C. On the other hand, ceramic tools are not widely used in interrupted cutting because its brittle behaviour, which cause catastrophic failure. On the other hand, Pc-BN tools have demonstrated a good performance in both continuous and interrupted cutting, providing longer tool lifes. Main reasons for this are their high hardness, also at high temperatures, great wear resistance and thermal stability. Within this context, high c-BN content with metallic binder is preferred for interrupted cutting, owing to its relatively high hardness - fracture toughness combination, whereas low c-BN content with ceramic binders is mainly used in continuous operations, where higher chemical stability is desired [9,77,83,84].

2.5. Wear and fracture mechanisms of inserts under service-like conditions

Tool life is a determining factor for cost-effective cutting processes. In the inserts, the cutting edge is the region subjected to higher stresses, temperatures and friction. The combination of these factors leads to different wear situations. Generally, crater, flank and notch wear are different kind of degradation mechanisms involved in cutting operations (**Figure 2.19**). Crater wear, on the rake tool face, is considered for evaluating reliability of the tool and can lead to chipping and catastrophic failure (by weakening the cutting edge). Flank wear, on the flank tool surface, is used to define tool life owing to its large influence on the quality of the machined surface. Finally, notch wear is a combination of both flank and rake face wear [5,17,86–94].

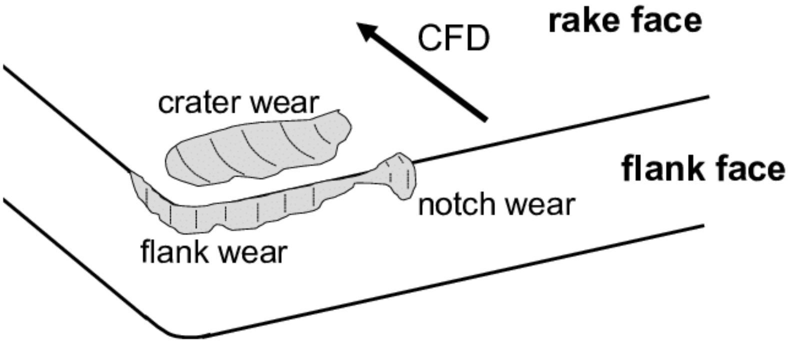

Figure 2.19 *Crater, flank and notch wear in an insert* [62].

These three wear patterns are cause by one or a combination of the following wear mechanisms: abrasion, adhesion, diffusion and tribo-chemical reactions [86,90,91,95].

- Abrasion is produced when hard particles contained on the workpiece abrade the binder of the Pc-BN (as it is the softest part) and lead c-BN particles to detach. Abrasive wear can be reduced by employing ceramic binders instead of metallic ones.
- Adhesion occurs when part of the workpiece or the generated chip during machining melt (i.e. due to high temperatures) and attaches to the tool.
- Diffusion is also promoted by the high temperatures reached and depends on the chemical stability of the tool and its affinity with the workpiece material. As a result, the tool material could suffer chemical changes on its microstructure and became less wear resistant.
- Tribo-Chemical reactions among tool, work-material and atmosphere could create a layer called built-up-layer (BUL). Unless the reaction occurs at the cutting edge, the high forces involved in the process expelled it to the surrounding areas of the tool.

Workpiece material, tool geometry (i.e. rake angle, edge chamfer and edge radius, as depicted in **Figure 2.20**), environmental conditions and thermo-mechanical loading, are factors which directly affect wear mechanisms [5,23].

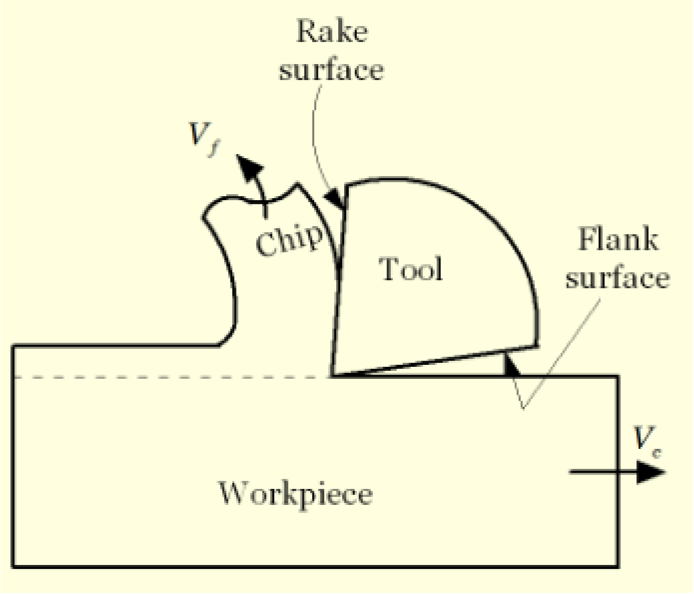

Figure 2.20 *Schematic drawing of a cutting operation, with tool surfaces* [96]**.**

Although flank, crater and notch wear are the most recalled wear modes in cutting operations, other phenomena such as chipping, thermal shock, built-up-edge (known as BUE), nose and tool breakage are also observed.

- Chipping is caused by abrasion, which commonly occurs along the cutting edge when it intermittently removes chips due to cyclic impact and thermal loads [17,89,91,93,97].
- Thermal cracks, which often appear perpendicular to the cutting edge, are related to interrupted cuts and thermal fatigue wear [89,90].
- BUE formation is a dynamic process caused by adhesion, where layers from the chipped-off particles are welded on the rake face and became a part of it (see **Figure 2.21**). This process affects wear in terms of either fracture or alteration of the geometry. Fracture occurs when shear loads are high enough and the formed bond is temporary, because it is pull-out from the tool surface. As a result, the fracture of this generated layer removes tool particles with the adhered material. In the case that BUE remains on the cutting edge, i.e. it is not fractured and removed due to chip motion, it alters the geometry of the edge, changing the shear angle. This causes instabilities in chip formation and damage the machined surface. Although BUE implies some negative aspects, it also has some advantages, particularly in terms of the formation of an additional layer between the tool and the workpiece, as it increases tool protection. It can

be minimized by working under lubricated conditions and might be beneficial in rough cutting, owing to the additional layer formed [17,87,89,93,95].

- Plastic deformation may also occur when tool material is softened due to excessive high cutting temperatures and stresses [89,90].

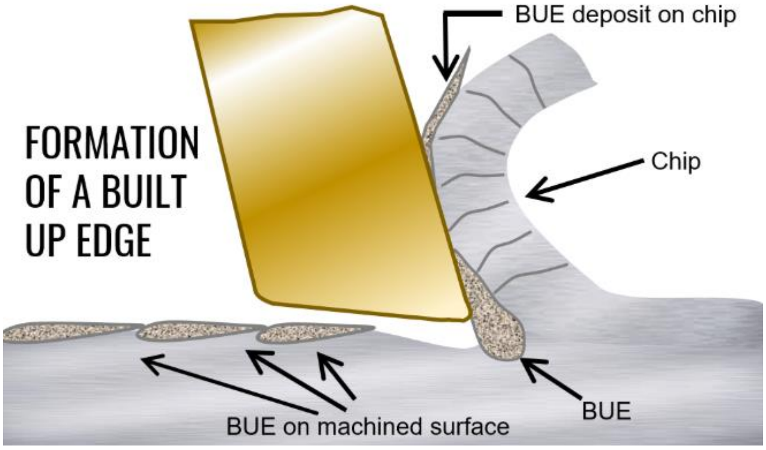

Figure 2.21 *Formation of a built-up-edge while machining* [98].

Although some researchers have investigated wear experienced by Pc-BN tools in hard operations, general trends are difficult to discern. In this case, not only tool geometry and cutting parameters influence tool wear mechanisms; but also c-BN content, binder chemical nature (which is more susceptible to suffer wear mechanisms), chemical stability and composition of the workpiece affects tool life. In all the cases abrasion, adhesion and diffusion are usually considered as the main tool wear mechanisms, and flank wear as the tool life criterion [90,91].

In addition, in cutting operations two types of loads are recalled: *i)* direct mechanical loading in the cutting edge, which may induce fracture if load exceeds the tool material strength, and *ii)* frictional loading at the rake and flank faces, when chips are produced in front of the tool by continuous shearing. As far as cutting tool is used properly, and tool materials are also selected correctly, edge fracture should not occur. Under these conditions, continuous wear dominates. This must be taken into account as excessive tool wear leads to unacceptable surface tool finish or out-of-tolerance dimensions on the machined product [5,17,90,91,95,99].

3. Objectives

The main scope of this Bachelor's project is to review and analyse the wear and fracture mechanisms of coated Pc-BN inserts. It will be done by conducting an in-depth literature review to identify the critical design parameters from a materials science point of view. In order to reach the main objective, the following secondary objectives may be defined:

- To provide an overview of Pc-BN as a composite material for tool applications, cutting operations, work-materials (also referred to as difficult-to-cut materials=, and the wear/fracture mechanisms involved in cutting operations.
- To understand Pc-BN microstructure and the mechanical properties of these composites, as well as and the correlation among them.
- To determine the benefits of using a coated Pc-BN tool instead of other tool materials when machining difficult-to-cut materials.
- To identify and understand main wear/fracture mechanisms of coated Pc-BN.
- To review the coatings commonly employed for commercial Pc-BN tools, as well as the ones under study in the literature.
- To investigate the most suitable conditions of the different machining operations where the coated Pc-BN inserts could be properly used.
- To identify production process of Pc-BN inserts, regarding surface modification technologies, pre and/or post coating stages of the tools.

4. Analysis of data base

The aim of this chapter is to collect, classify and analyse all data found and gathered within the open literature regarding coated Pc-BN tools. Detailed information might be found in **Table 0.1** in **Annex A. Database**. Main goal behind it is to identify critical microstructural design parameters of coated Pc-BN tools from the materials science point of view on the basis of observed wear/fracture mechanisms.

4.1. Advantages of using coated Pc-BN as compared with other tool materials for machining difficult-to-cut materials

Literature review

As stated in previous chapters, carbides, ceramic and Pc-BN based tools are widely used to machine difficult-to-cut materials. Their good combination of mechanical properties (mainly regarding hardness and wear resistance) makes them optimal options for sustaining the high cutting forces and temperatures reached during the operation. Depending on the cutting conditions and parameters (e.g. cutting speed) some are more suitable than others, since their mechanical properties are not exactly the same. For example, carbides are restricted to low cutting speeds (between 30 to 70 m/min) owing to their poor thermochemical stability. However, by using a metallic binder or by increasing the binder content they can be employed at high feed rate values due to their improved fracture toughness. Similarly, alumina-based materials are often used as ceramic tools, where the combination of alumina with TiC enhances thermal properties, enabling an increase of cutting speed (between 120 to 140 m/min), while the improvement in thermal and mechanical shock resistance is symbolic. The use of whisker-reinforced alumina ceramic tools ($Al_2O_3 + SiC_w$, known as WRA) permits achieving even higher cutting speeds (between 200 to 750 m/min), as they present higher toughness. Additionally, silicon nitride (Si_3N_4) tools can be implemented at higher speeds and feed rates than alumina, because their low thermal expansion and elevated toughness. Although PCD tools present the highest values of hardness and thermal conductivity, i.e. they are excellent candidates for being used under the most extreme conditions; they are not employed with ferrous workpieces, due to the graphitization of diamond. Finally, Pc-BN coated tools, whose properties have been mentioned in the previous chapters, may reach cutting speed values up to 350 m/min, overcoming the negative fact that their price is 3 to 4 times higher than that of carbides [100–103]. Several investigations have shown coated Pc-BN to be the best option when machining difficult-to-cut materials, as compared to other tool materials. This will be presented and explained now.

Several studies have focused on comparing the performance of Pc-BN with respect to that of cemented carbide tools. Andersson and Berg [104] analysed the machining of chromium alloyed steels, with different grades of TiN coated Pc-BN and cemented carbides. Longer tool life (3.5 times) was found for all Pc-BN tools. The importance of c-BN content was also demonstrated as the results showed tool life longer than 50 min for high content c-BN tools, 15 times higher than for those with low content c-BN. The addition of MnS improved life of all the used tools. Higher surface quality was obtained for all Pc-BN tools, independently of the different depths of cut used. Furthermore, many studies have also been performed on machining Inconel 718 with TiAlN or TiN coated Pc-BN and carbide tools, where the cutting speed was higher for Pc-BN than carbide tools. Inconel 718 has shown excellent roughness and more homogeneous surface finish, when it was machined with Pc-BN tools instead of tungsten carbide tools. In addition to this, Pc-BN tools showed longer tool life than carbide tools in dry cutting conditions [101,102]. However, Criado *et al.* [100] reported that when machining Inconel 718 under coolant cutting conditions, tungsten carbide tools showed longer tool life than TiN-coated Pc-BN ones [100]. Similar trend has been shown by Ezugwu *et al.* [105] who analysed the performance of TiAlN/TiN-coated Pc-BN tools when turning Ti-6Al-4V alloys. In this case, different Pc-BN tools showed lower tool life than carbide ones. Moreover, it was reported that high c-BN content in Pc-BN leads to a decrease in tool life, owing to the acceleration of notch wear when c-BN content is increased. Regarding wear mechanisms, adhesion and flank wear are found to be predominant when machining chromium alloy steels [104]; while crater wear was dominant at first stages of machining Inconel 718 with medium c-BN content, and flank wear predominated in final stages. Apart from these wear mechanisms, chipping, notch and BUE wear were also observed in TiAlN or TiN coated Pc-BN tools with medium c-BN content [100–102]. Moreover, notch and chipping wear are found to be predominant when machining Ti-6Al-4V alloys [104].

Partial conclusions

Figure 4.1 shows tool life differences among cemented carbide and coated Pc-BN tools when turning a cold-work steel. Although it is extracted from a single paper [103], it is depicted here as an example of the general trend of almost all of the papers gathered in the database. It can be observed how coated Pc-BN tools present, as a tendency, longer tool life than coated cemented carbides. Additionally, coated Pc-BN tools showed longer machined surface per unit of time and per cutting edges in almost all cases (except at low v_c, around 35 m/min), and above all, in very high v_c values (around 300 m/min) [100–102,104]. Moreover, from the different works found, coated Pc-BN tools performed better in dry conditions than in wet conditions, opposite to the results observed for cemented carbides.

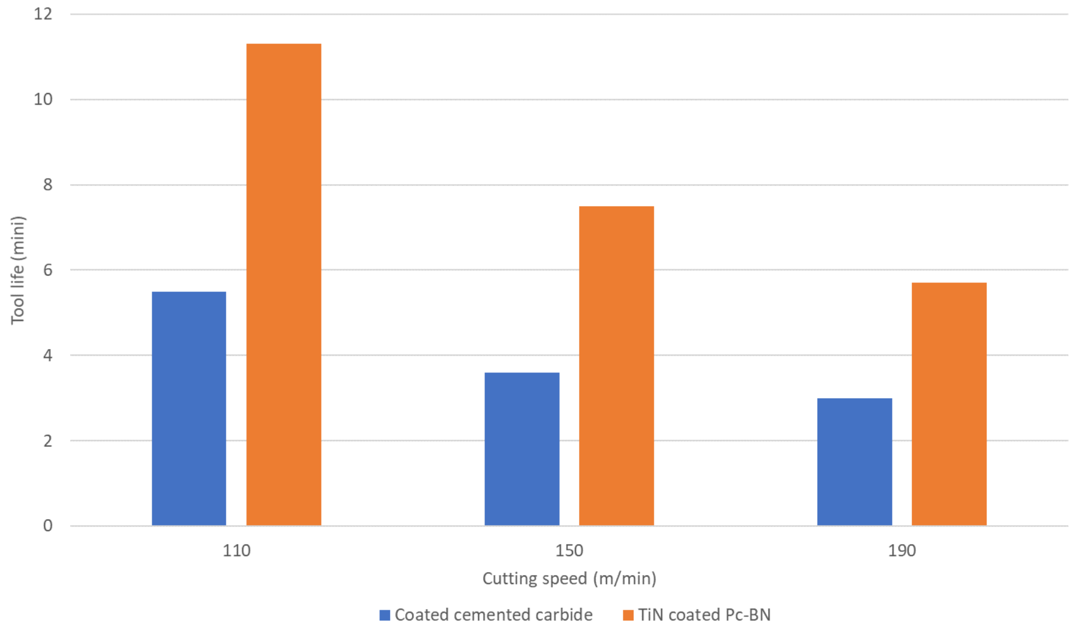

Figure 4.1 *Tool life of coated cemented carbide and Pc-BN tools at different* v_c *when machining cold-worked steel (f=0.05 mm/rev;* a_p*=0.1 mm; dry conditions).* [103] *Modified.*

4.2. Review of studied/employed coating-Pc-BN systems

The aim of this section is to have an overview of the coatings most commonly used in coated Pc-BN tools. Taking into consideration the studies where life of coated Pc-BN tools is addressed, it may be pointed out that the capability of the coating to retain its mechanical properties under high temperatures is the main factor that controls its effectiveness. Thus, thermal stability and mechanical strength may be defined as the most important factors to account in the selection of the appropriated coating in these systems [74,75].

The bibliographical review done permits to confirm the suitability of coated Pc-BN as inserts for machining difficult-to-cut materials. As it is shown in **Figure 4.2**, it may be evidenced that Pc-BN is a novel material that has attracted an increasing interest recently. This is supported by the fact that the number of publications of scientific studies has been increasing almost exponentially in the last 20 years. In this regard, it should be highlighted that since the first paper published on coated-Pc-BN, around 2001, the number of papers involving coated systems has increased more rapidly than those just reporting issues of uncoated Pc-BN (see **Figure 4.2 B**).

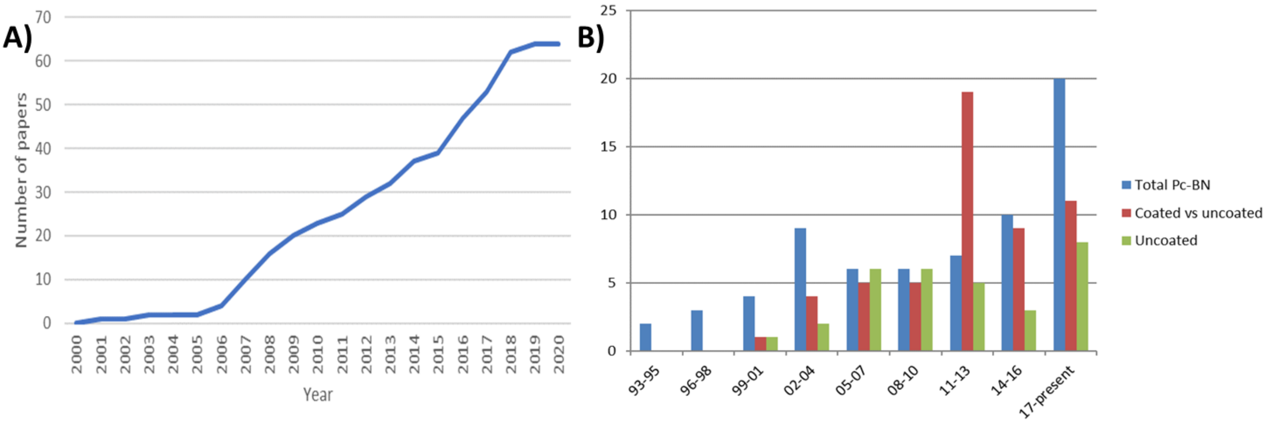

Figure 4.2 *Number of papers published per year of A) coated Pc-BN systems and B) coated, un-coated and papers comparing coated with un-coated Pc-BN.*

Literature review

From the gathered database it may be confirmed that, as expected from information commented in **section 2.2**., TiN is the most commonly coating deposited on PcBN tools. This is particularly true in low to medium Pc-BN grades with Ti-based binders (mostly TiN or TiCN). However, it is observed that it is also employed in high c-BN content substrates with metallic binders. In general, it is reported that TiN has a speed-limited effect, as it degrades producing TiO_2 when the temperatures reached during the operations exceed its thermal stability (i.e. in the range of 450 to 600ºC). The same tendency might be observed with TiCN. However, this coating is mostly employed as a multilayer coating (i.e. with TiAlN) rather than as a single layer; where TiAlN is usually found as the inner layer in contact with the Pc-BN substrate and TiCN as the outer layer [32,68,72,73,76,86,100–104,106–130].

TiAlN is also widely applied for coating Pc-BN inserts. Herein, it is also preferred for low cBN content and ceramic binders Pc-BN. However, it is also reported in some medium to high cBN with either ceramic or metallic binders. Wada and Hanyu [131] indicated less tool wear progress when TiCN-Al binders were used with low c-BN content Pc-BN tools, instead of TiN-Al binders with medium or high c-BN contents tools. These coatings presented higher thermal stability, because it oxidizes up to 850 ºC producing an oxide protective layer of Al_2O_3. Moreover, it has been found that TiAlN shows higher mechanical properties (such as higher toughness) when compared to TiN, TiSiN or AlCrN coatings [58,68,100–102,106,123,131–134].

In some publications, these coatings are not used separated, but are rather implemented as multilayer architectures, as the previously mentioned TiCN/TiAlN coating. Hence, they are strengthened due to such layer assemblage. Analysing the database, we can observe that the most often combinations used are TiAlN/TiCN, Al_2O_3/TiCN, Al_2O_3/TiN and TiAlN/TiN coatings.

Some works, although in lower quantity, are also found focusing on TiSiN and AlCrN coatings. TiSiN coatings are mainly used in low content c-BN tools with ceramic binders, such as TiCN. However, they are more brittle than the others, leading to surface crack and, as a consequence, more prone flank and crater wear than the coatings aforementioned. In the case of AlCrN coatings, apart from low c-BN content, they are also employed with medium c-BN grades. These coatings are well known to exhibit high thermal stability, since there is an intense chromium-diffusion to the surface, generating the oxide protective layer Cr_2O_3. Furthermore, these coatings show high hot hardness and less flank and crater wear than the mentioned above [58,68,133,135,136].

Some researchers analysed the performance of solid lubricant coatings, such as amorphous BN. This kind of coatings are characterized for having a low friction coefficient; thus, they increase the tool life by reducing the temperature generated during machining. They differ from the conventional solid lubricant materials (i.e. graphite, disulfate of molybdenum or tungsten) because they present superior thermal stability [74,137].

Nanocomposite systems have been recently introduced. These novel coatings have shown higher mechanical properties and better performance than micron-scale films. In order to rationalize such enhanced behavior, Hall-Petch relation together with grain-boundary creep rate, when the grain size is decreased, have to be considered. Although mechanical properties are favoured when the grain size is decreased, it may lead to a change in deformation mechanism, owing to the increment of grain boundaries. Thus, both effects have to be considered in order to choose the optimal grain size. The most accepted structure for these systems is a nanosized nitride phase in an amorphous matrix (nc-MeN/intercrystallite binder), which usually is made of Si_3N_4. The amorphous matrix is characterised for suppressing grain growth of the nitride phase while maintaining the good adhesion and high strength. However, the introduction of silicon in the matrix phase could deteriorate the mechanical properties for contents higher than 20% due to the formation of an interlayer. The most studied systems gathered in the database are nc-AlTiN/α- Si_3N_4 and nc-AlCrN/α- Si_3N_4, which show higher performance and less crater wear than conventional TiAlN coatings [58,74,75,138]. Furthermore, Uhlmann *et al.* [75] reported that nc-AlCrN/α- Si_3N_4 coatings present less abrasion and flank wear than nc-AlTiN/α- Si_3N_4 ones, due to their higher hardness, higher thermal stability and better adhesion. The same authors in another study [135] stated that hardness of nanostructured coatings are twice the one of conventional films, such as TiAlN. **Figure 4.3** shows a graph summarising tool life values for different coating-Pc-BN systems [74]. It can be concluded that nanostructured systems had higher tool life than conventional ones.

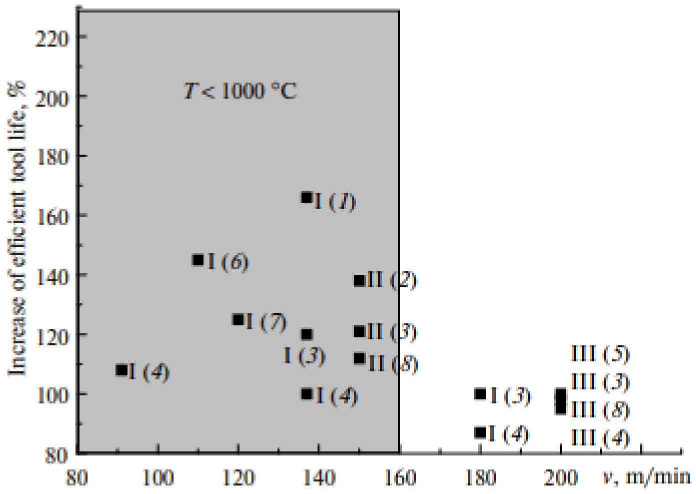

Figure 4.3 *Influence of tool life in machining various workpiece materials: I- AISI 51200 (62 HRC), II-AlSi330 (52 HRC), III-AISI 5115 (60 HRC); the tool coating composition: 1- nc-AlTiN/α- Si_3N_4, 2- nc-TiAlN, 3- TiAlN, 4- TiN, 5- TiSiN, 6-Al_2O_3-NbN, 7- α-BN and 8- AlCrN* [74].

Partial conclusions

It is clearly noticeable that nearly all of the works conducted involve the use of low/medium c-BN content with ceramic binders whereas, the less studied high c-BN content is used together with metallic binders (see **Figure 4.4 A**). Within this context, **Figure 4.4 B** shows that the most popular ceramic binders are TiN, TiC and TiCN, being them also the first ones introduced. Nevertheless, it should be underlined that even though these binders are referred to as TiN, TiC and/or TiCN, these are the main components of the binder. Hence, binder also includes other elements product of second reactions between the raw materials (such as TiB_2 or WC, see **section 2.1.2.4,**). For instance, a binder named TiN means that ceramic phase where c-BN particles are embedded consists of TiN as main compound but together with TiC and/or TiCN, TiB_2 etc. This occurs since there are not many researches that specifies this topic. Meanwhile, other elements such as Al have been recently introduced as binder compound. Moreover, the employment of metallic matrices is much more recent than ceramic Ti-based and Al-based binders, and the interest in them has been growing over the last 5 years.

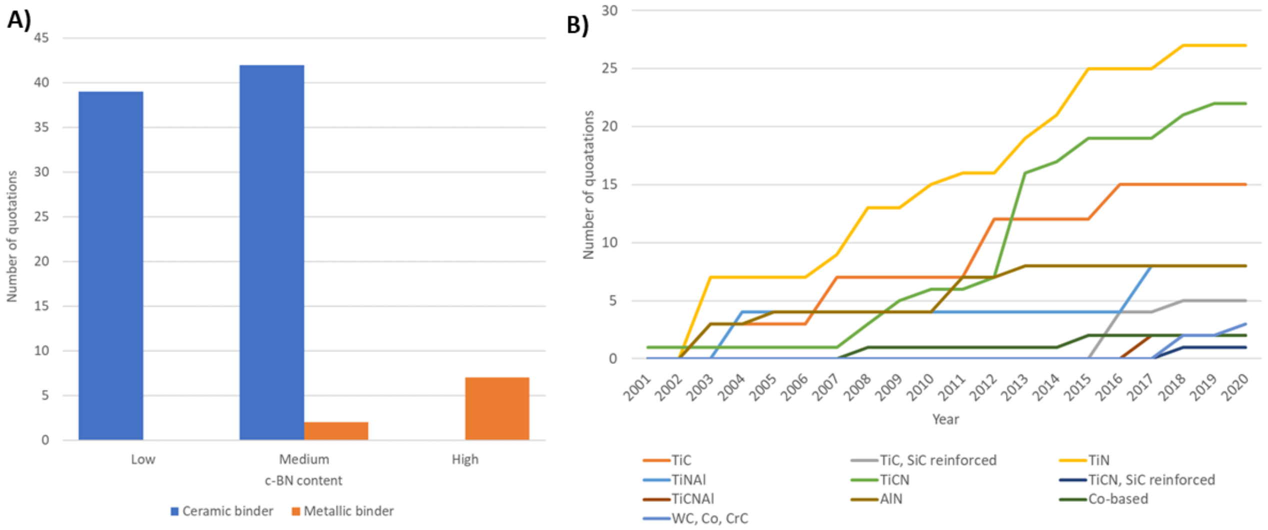

__Figure 4.4__ Number of quotations published as a function of A) c-BN content and B) binder chemical nature.

Concerning the chemical nature of the coating, it can be concluded (**Figure 4.5**) that Ti-containing coatings are the preferred ones. It is expected that these coatings enhance wear resistance by reducing friction, adhesion and diffusion phenomena. However, over the years other elements (e.g. Si, Al and Cr) had been introduced to the popular TiN to counteract some drawbacks of it, such as thermal stability, oxidation resistance and chemical inertness. Finally, the two most implemented options, as stated above, are TiN and TiAlN. It is important to take into account that in recent years, the interest of the possibility to use nanocoatings has growth significantly.

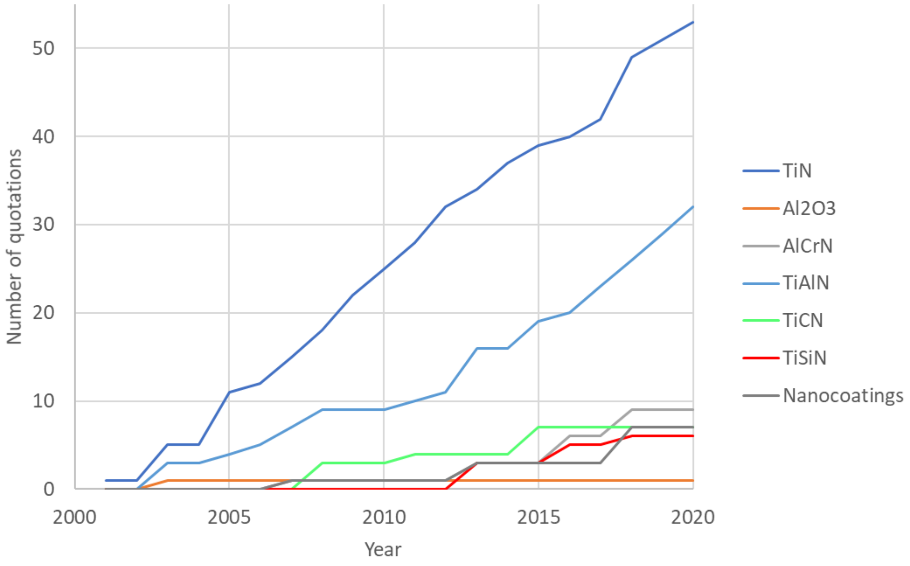

__Figure 4.5__ Number of quotations regarding the different coatings used in Pc-BN systems during the last two decades.

When studying whether there are differences in coating chemical nature depending on the substrate c-BN content (**Figure 4.6**) and binder chemical nature (**Figure 4.7**), no correlations have been identified. However, it seems that coating selection is somehow related to chemical composition of Pc-BN binder. In addition, there are three “popular” combinations binder-coating: TiCN-TiN (the most), TiN-TiN and TiN-TiAlN, as observed in **Figure 4.7**. Similar comment may be done when considering the machined material (**Figure 4.8 A and B**), where clear trends are not identified.

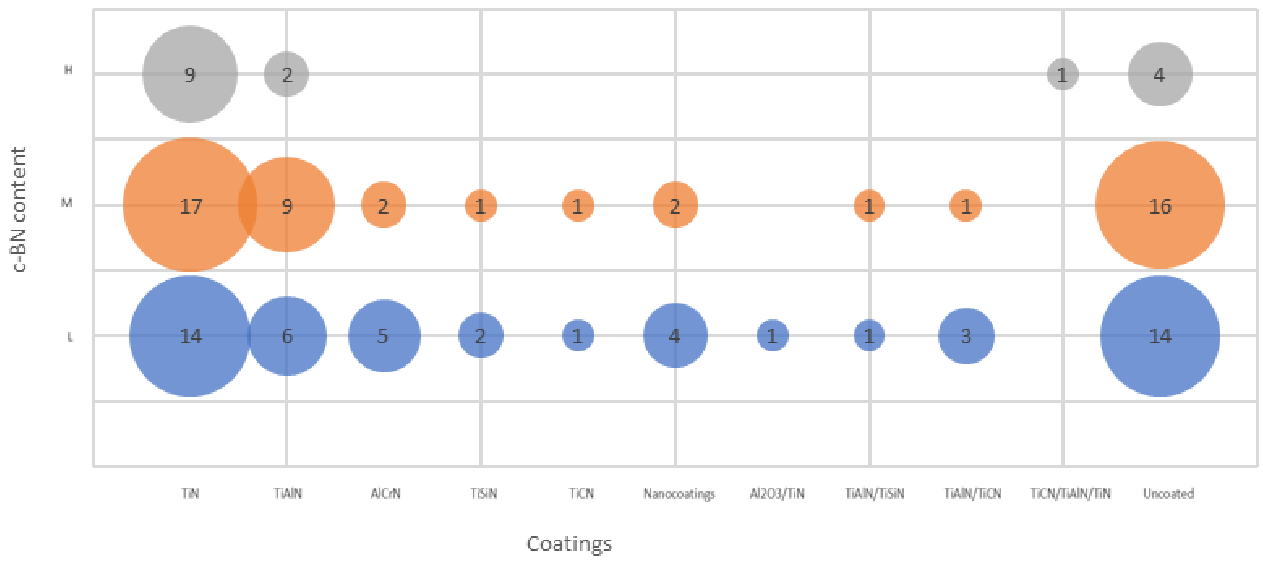

Figure 4.6 *c-BN content depending on the coatings used. Bubble size is proportional to the number of quotations written inside.*

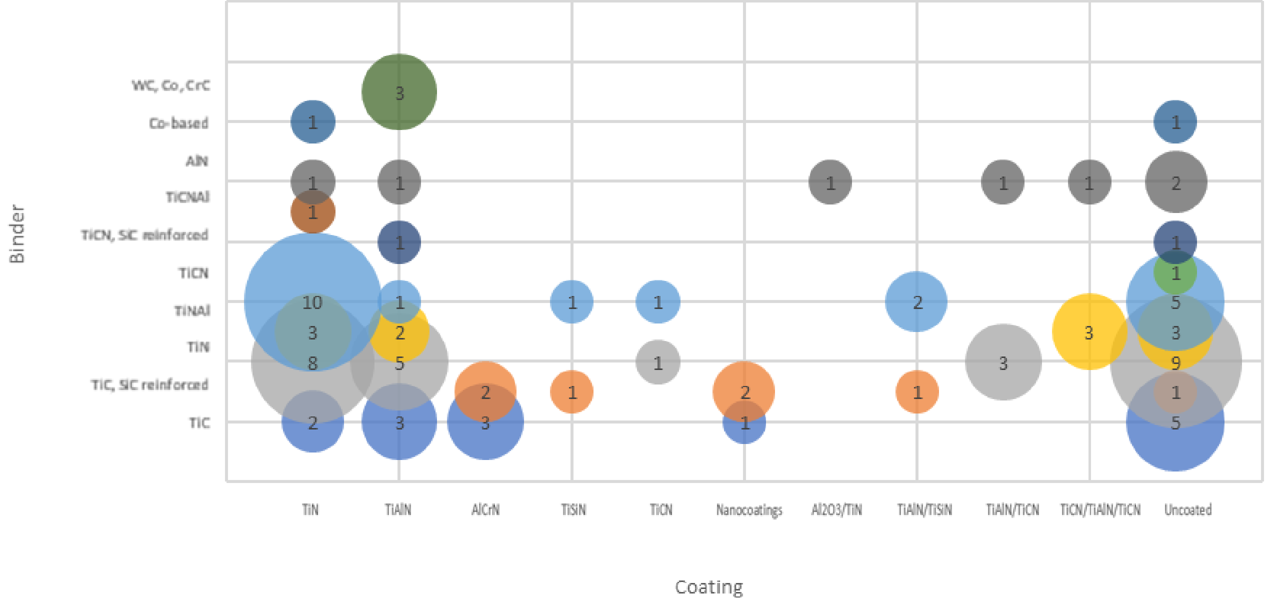

Figure 4.7 *Combinations of binders and coatings used in the literature found. Bubble size is proportional to the number of quotations written inside.*

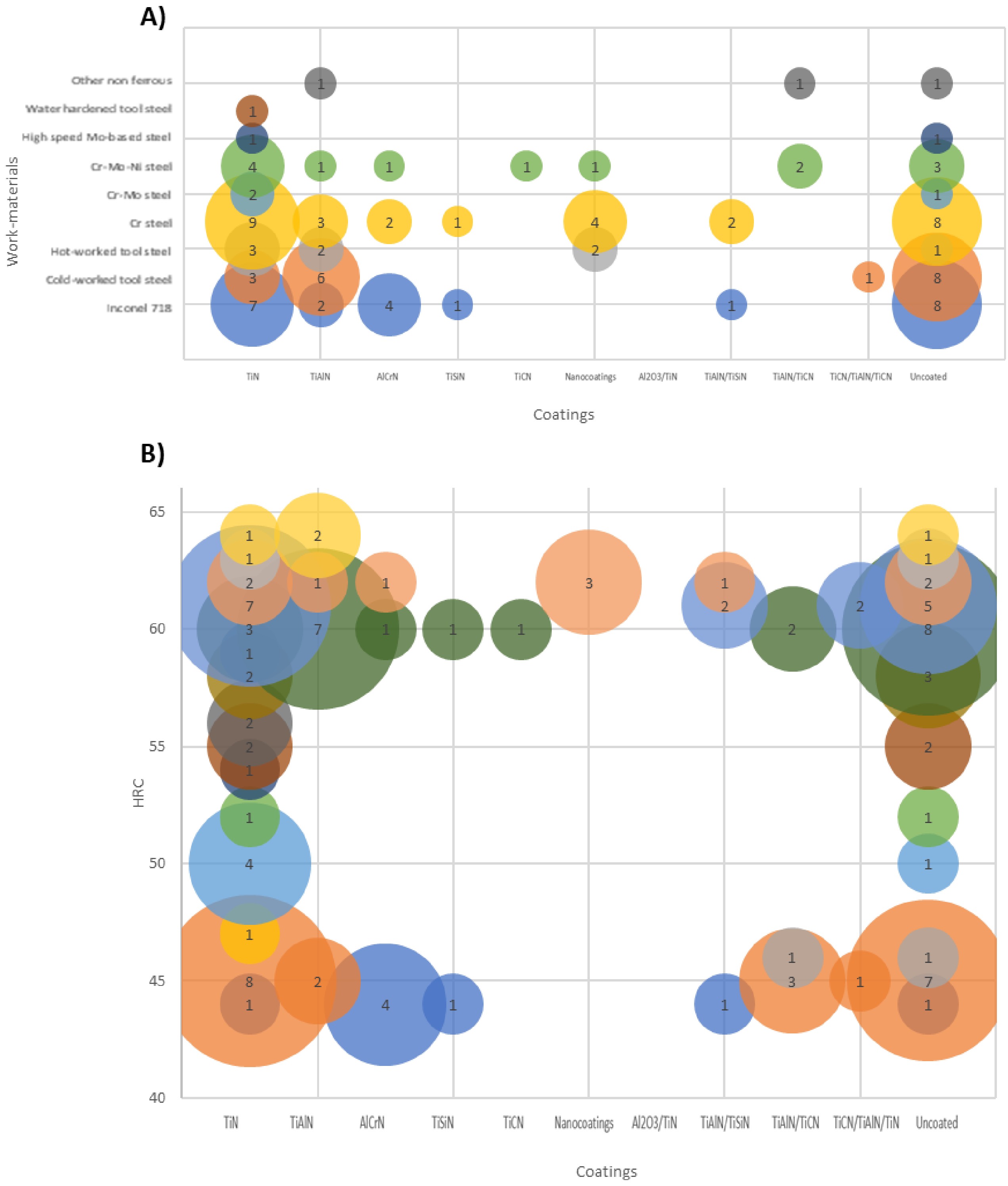

Figure 4.8 *Combinations of coatings used with the different A) work-materials machined B) HRC of the work-materials machined. Bubble size is proportional to the number of quotations written inside.*

4.3. Coated Pc-BN wear/fracture mechanisms depending on the work-material

As it was explained in **section 2.5**, different types of wear may appear during cutting operations. In this section, the information gathered in the database will be analysed to study aspects linked to the damage observed as a function of the work-material.

Literature review

Regarding the workpiece to be machined, most of the studies address material removal operations in high-hardness materials (i.e. from 44 to 64 HRC). This is particularly true concerning steels containing Cr and those used as tools. However, the second most relevant implementation of coated Pc-BN inserts is related to a non-ferrous material, i.e. Ni-base superalloys, as it may be observed in **Figure 4.9** and **Figure 4.10**.

The relevance of these materials within the aeronautical/aerospace industry increases the added-value of coated Pc-BN as insert option. Moreover, regarding the values of hardness of the workpieces machined, most of the work-materials, which are related to Cr steels, had a hardness higher than 60 HRC, as depicted in **Figure 4.11**. However, there is another important value of hardness to highlight, which is 45 HRC. It is related to the second most studied workpiece, i.e. Inconel 718.

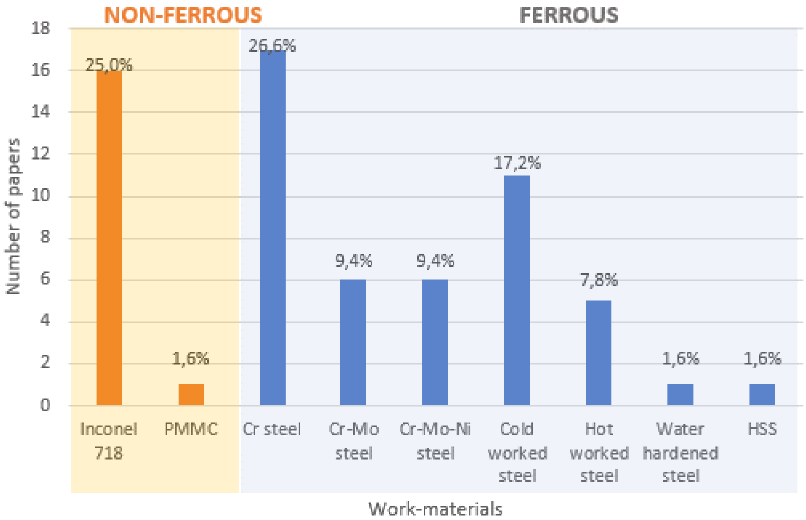

Figure 4.9 *Number of papers published and gathered in the database, depending on the work-materials machined.*

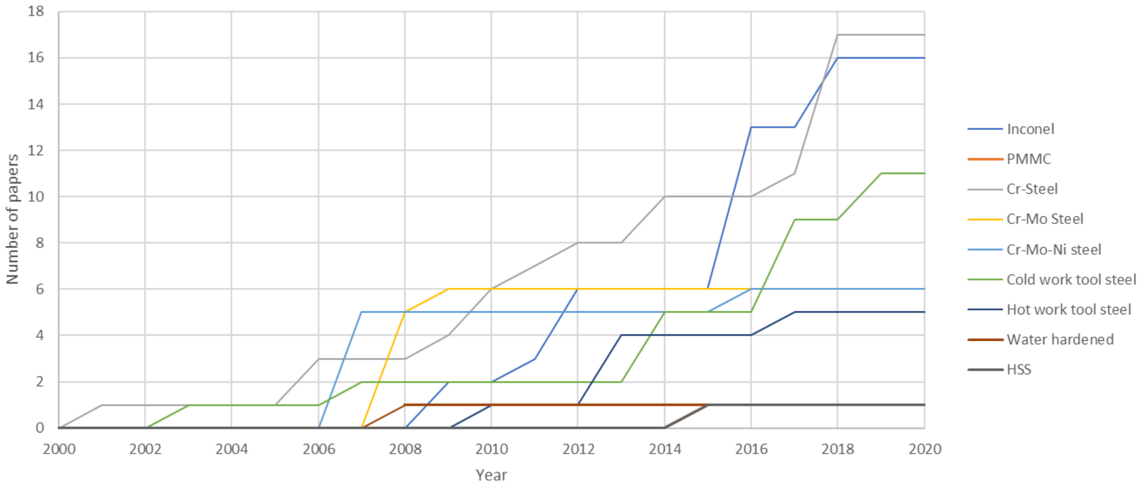

Figure 4.10 *Number of quotations regarding the different work-materials machined with Pc-BN systems during the last two decades.*

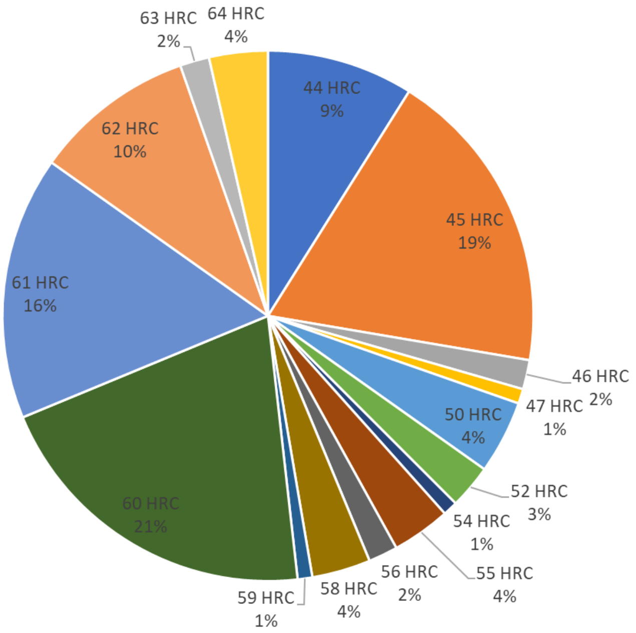

Figure 4.11 *Values and percentages of hardness of the different work-materials machined.*

Operations conducted with non-ferrous work-materials (e.g. Inconel 718 or the PMMC Al 2124 SiC) generally resulted in a combination of flank, notch and crater wear, due to appearance of abrasion, chipping, adhesion or thermal cracks. In the case of Inconel 718, researchers studied coated Pc-BN tools by TiN, TiSiN and (Ti,Al)N with low (50 %) or medium (65 %) c-BN content and with ceramic binders (such as TiN, TiC, TiCN, TiC whisker-reinforced SiC). Very interesting, almost all studies were carried out under coolant conditions. Flank and notch wear were observed as the main contact-related degradation mechanism, caused by abrasion and chipping phenomena (the abrasive chips observed were segmented which induced variable forces and it results in fatigue wear). In addition, crater and

BUE wear were also observed in some cases (i.e. at low feed rates of around 0.1 mm/rev), where the unstable BUE formation led to chip formation [93,100,102,107,129,136,139,140]. Khan *et al.* [141] reported that at high cutting speed conditions (up to 400 m/min) chipping wear was observed with thermal cracks leading to fracture. On the other hand, Njuguna and Gao [142,143] studied the performance of TiAlN/TiCN coated and uncoated Pc-BN tools in turning Al 2124 SiC PMMC. In this case, abrasion (due to SiC hard particles) followed by adhesion were observed as the main wear mechanisms with chipping and fracture phenomena. The generated chips were discontinuous and dull, and with increasing speed, it presented a granular form.

Other researchers have focused their works in turning bearing chromium steels (e.g. AISI 51XX, 50XXX and 52XXX grades) with low and medium content coated Pc-BN tools. All these works have been conducted in dry conditions. The used tools were commonly coated with one or a combination of the following compounds: TiN, TiAlN, TiSiN, AlCrN. Flank wear was observed as the main degradation mechanism, along with abrasion, and crater wear which might be attributed to the presence of carbides (i.e. chromium carbides) leading to c-BN grains detachment from the bond. However, it was stated that the use of coatings could delay wear, owing to crater wear in coated Pc-BN tools does not appear until the coating has been completely removed by cracking. In this case, chips were generated in a saw-tooth and segmented form (as observed in **¡Error! No se encuentra el origen de la referencia.**) with carbides embedded and white layers on them. Moreover, chip breakage was observed with crater wear progression. It was also concluded that an increase in temperature, due to high cutting speeds or high coefficient of friction, may result in enhanced wear and consequently, in a degradation of surface quality [32,68,75,106,110,113,116,122,123,125,127,133,137,144]. This is opposite to the findings of Saoubi *et al.* [68] who reported less flank and crater wear on uncoated Pc-BN than on TiN, TiSiN, TiAlN or AlCrN coated Pc-BN tools. It was attributed to the higher cutting conditions (V_c = 200 m/min and f = 0.15 mm/rev) used in this study. Secondly, chromium-molybdenum steels (AISI 41XX grade) have also been investigated with medium or high c-BN content Pc-BN TiN coated tools under dry conditions. In this case, crater wear was observed as the main degradation mechanism, and it has been shown that a rise in cutting speed, feed rate or in c-BN content may lead to higher chemical wear. This occurs due to the fact that Fe diffuses into Pc-BN binder, weakening the binder and thus promoting c-BN particles to be pull-out from the tool; and consequently, the workpiece surface roughness is increased [112,124]. Finally, turning of nickel-chromium-molybdenum steels (AISI 43XX grade) with coated Pc-BN tools has also been evaluated. The coatings used were commonly the following ones: TiN, TiAlN, AlCrN, TiCN or TiAlN/TiCN. Flank wear with chipping were observed as the main degradation mechanisms. Moreover, it has been shown that the use of coatings might decreases flank wear, as also happens when c-BN content is increased [58,118,126,145].

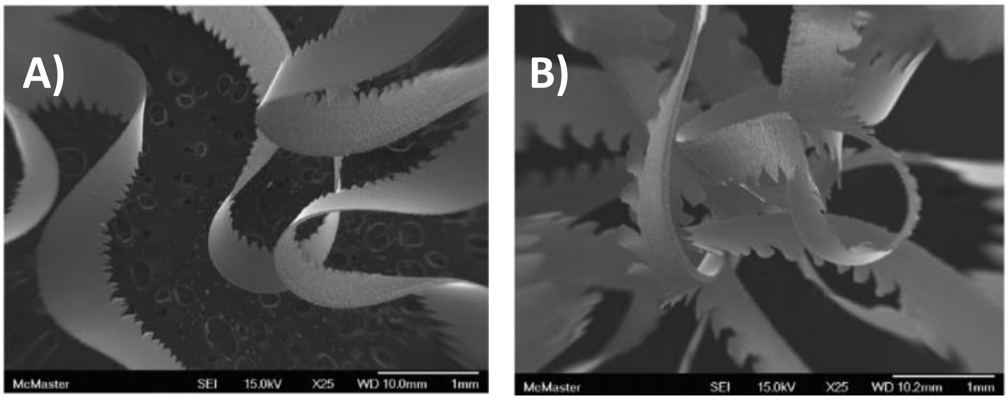

Figure 4.12 *SEM micrographs of the produced chips when machining cold-worked tool steel (v_c = 100 m/min, a_p= 0.06 mm, f=0.05 mm/rev) uncoated Pc-BN and B) TiN coated Pc-BN* [111].

The cutting of different tool steel grades has been analysed by several researchers. One main group refers to cold-worked tool steels - AISI D and O grades, machined with low/medium and high c-BN content coated Pc-BN tools, respectively. In the case of D grade steels, where TiN and TiAlN coatings were used, abrasion was observed as the main wear mechanism, as a consequence of rubbing of hard carbides of the workpiece, expressed in the form of crater wear. Here, adhesion was reported as a secondary wear mechanism. At low cutting speeds, crater wear was expressed together with grooving, also the produced chips were discontinuous. A steady plastic flow on the workpiece was present on the tool face, generating tangled chips at high cutting speeds (as shown in **Figure 4.12**). The generated chips were more intense in the case of TiN coated tools than uncoated Pc-BN tools, due to higher adhesion [76,103,111,114,123,131]. Although in most of the studies it has been shown that the use of coatings improves tool life, owing to less contact between tool and workpiece, there are works reporting opposite effects [111]. However, correlations are complex as indicated by the findings of Wada and Hanyu [131] who showed a decrease in tool's wear when c-BN content is lowered or when TiCN-Al binder is used instead of TiN-Al binder. On the other hand, chipping was observed as the main wear mechanisms when O grade steel was machined, with tools coated with multilayer TiCN/TiAlN/TiN coatings [69]. Additionally, some researchers have studied the machining of hot worked chromium-based tool steels (AISI H1X grades) with low and medium c-BN content tools, coated with TiN or TiAlN. As it has been observed on the other workpieces, abrasion was determined as the main wear mechanism, expressed in the form of flank and crater wear as consequence of the rubbing of the present martensitic grains of the workpiece. At high cutting speeds, adhesion with BUE wear were also observed. In this case, the produced chips had a saw-tooth form with white layers on their bases (as shown in **Figure 4.13**) [75,117,121]. In addition to this, Dureja *et al.* [121] stated that Pc-BN tools are not economical for machining these steels when the hardness of workpieces is under 47 HRC, since excessive adhesion and plastic flow are revealed. In the case of machining water hardened tool steels (AISI W grade) with high content TiN coated Pc-BN tools, abrasion and adhesion were observed and expressed in the form of chipping [109]. Finally, flank and crater wear were observed as the main contact-related degradation mechanisms when machining high-speed molybdenum-based tool steels (AISI M grade) with low c-BN content TiN coated Pc-BN tools with ceramic binder [119]. In **Table 4.1** the different wear mechanisms found for each studied work-material are summarised.

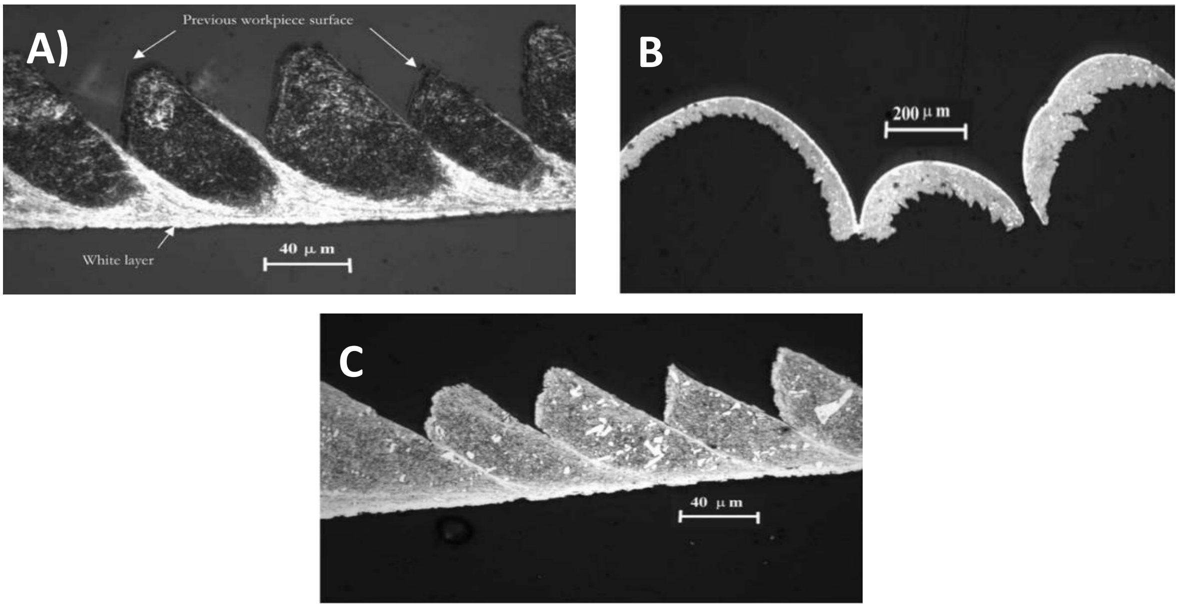

Figure 4.13 *Chips generated when machining hot worked chromium-based tool steels with an uncoated low content Pc-BN tool: A) white layer on the basis, B) segmented form of the chips and C) carbides embedded on the white layers* [7].

Partial conclusions

Although the systems considered in this investigation are coated; the mechanical properties of the underneath Pc-BN substrate are known to play an important role in the final coated tool performance. In that sense, as mechanical properties are intrinsically linked to the microstructure parameters, c-BN content and binder chemical nature are also included in this study for work-material/wear mechanisms correlations.

As stated in **section 444.2**, clear correlations between coating and workpiece were not identified. Nevertheless, some observations may be done when considering the Pc-BN substrate employed as a function of the work-material. On the one hand, regarding binder chemical nature, TiCN is extensively used when machining Cr-steel, whereas TiC is preferred for Ni-base superalloys and TiN for cold-work tool steels (see **Figure 4.14 A)**. Moreover, from **Figure 4.14 B**, it can be observed how binary coatings are used for “low” HRC values, while ternary or quaternary coatings are preferred to machine higher HRC work-materials. On the other hand, **Figure 4.15 A** shows low content Pc-BN to be the most chosen option for all workpiece materials, except for cold-worked tool steels where the medium one is preferred. Moreover, from **Figure 4.15 B**, it can be concluded that low c-BN content is used for work-materials with “low” hardness, whereas medium c-BN content is more versatile.

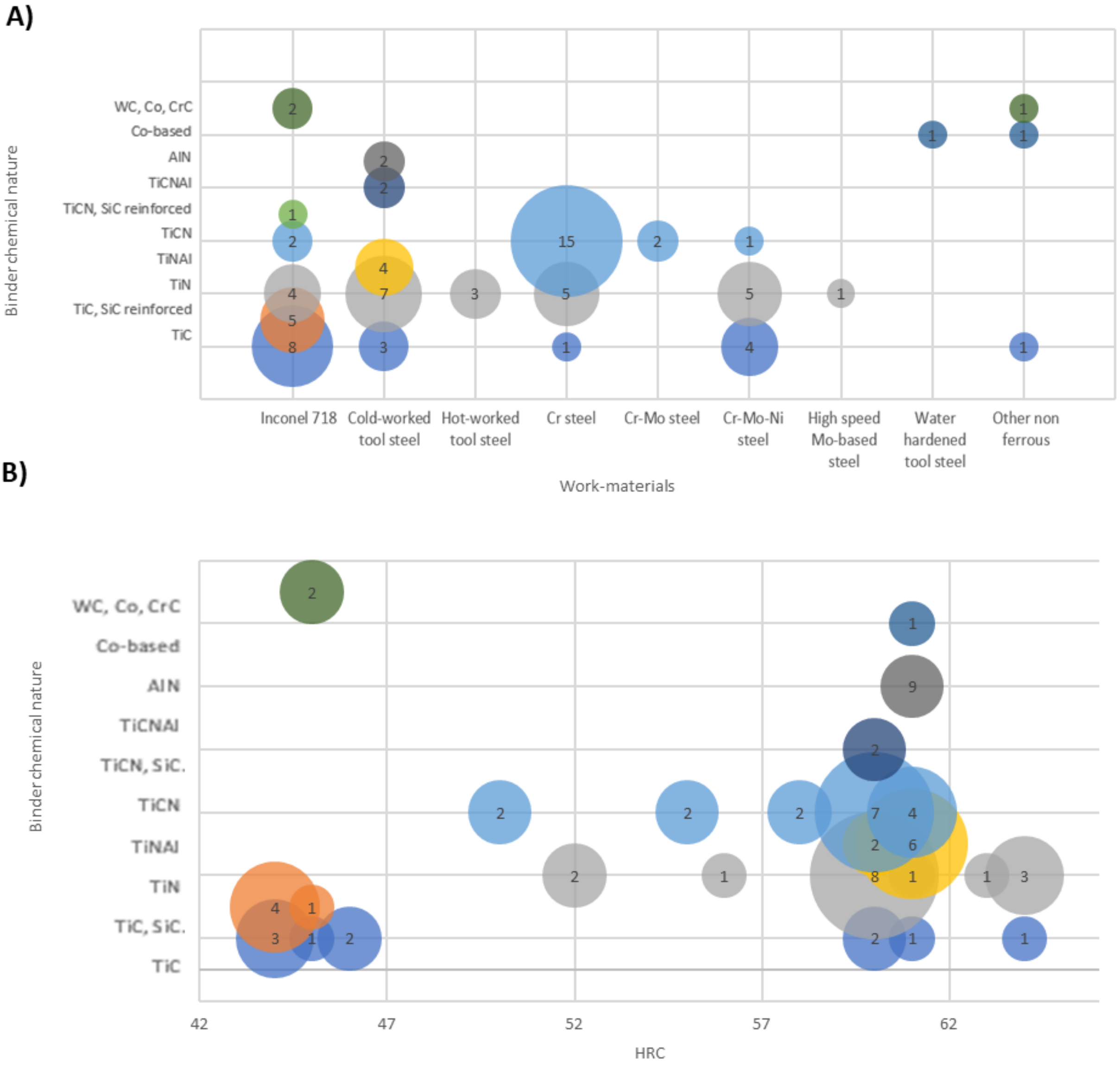

***Figure 4.14** Combinations of binder chemical nature and A) work-materials and B) values of hardness of the machined workpieces. Bubble size, and the number on it, are proportional to the number of quotations.*

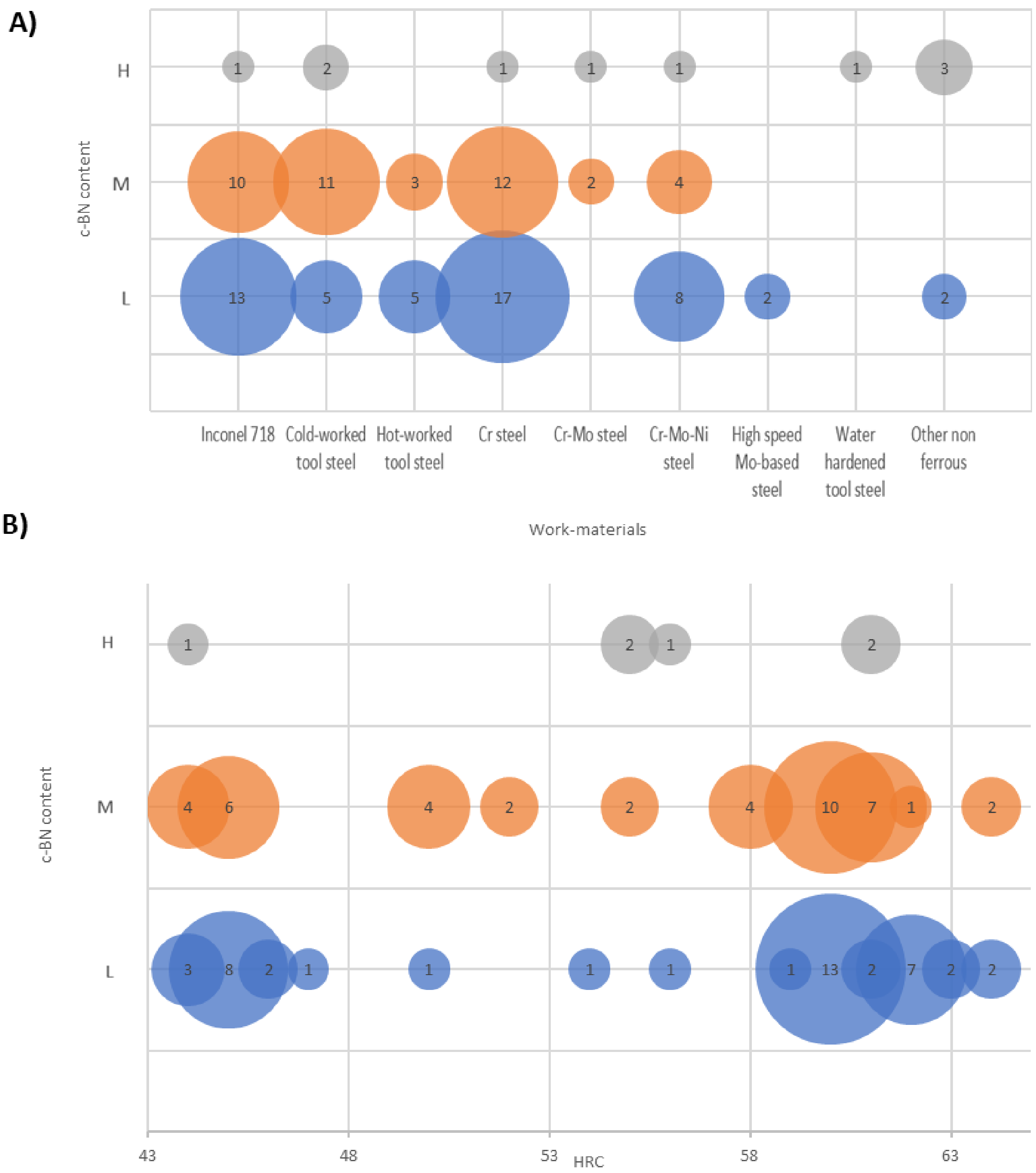

__Figure 4.15__ c-BN content depending on the A) machined work-materials and B) values of hardness of the machined workpieces. Bubble size, and the number on it, are proportional to the number of quotations.

As depicted in **Figure 4.16 A**, flank wear is identified as the main wear mechanisms for coated Pc-BN tools, followed by crater and less common notch wear. They are produced by the following damage/fracture mechanisms (**Figure 4.16 B**): chipping (23%), abrasive wear (23%) and adhesion wear (20%), together with adhesion related BUE phenomena (12%).

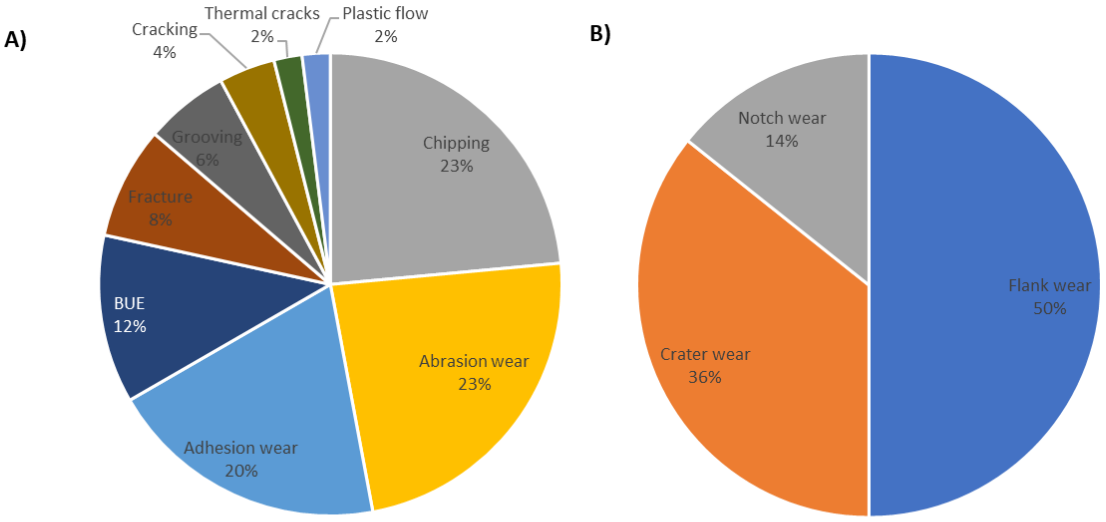

Figure 4.16 *A) Fracture mechanisms and B) wear mechanisms found for the studied coated Pc-BN systems.*

In more detail, flank wear is the main contact-related degradation mechanism found for almost all coated Pc-BN systems (as seen in **Figure 4.17**). Moreover, chipping has been observed more frequently in coated Pc-BN tools containing high and medium c-BN content. Meanwhile, adhesion mechanisms seems to be more prominent in high c-BN metallic binder tools, while abrasion one are dominant in low c-BN substrates, as observed in **Figure 4.18**.

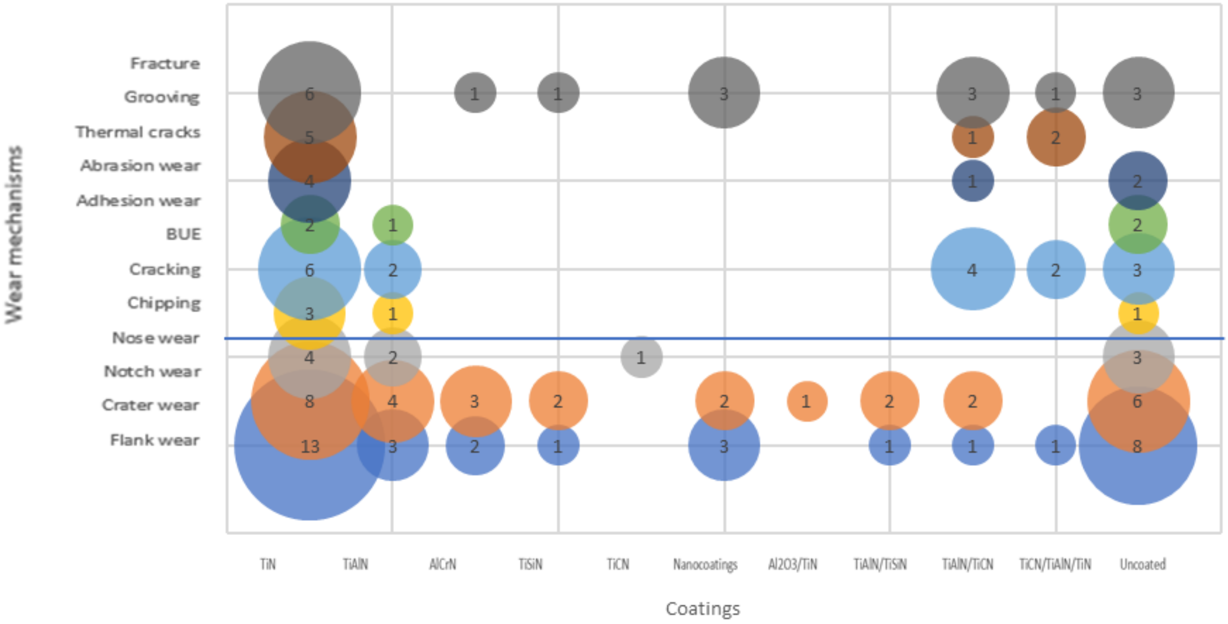

Figure 4.17 *Combinations of wear mechanisms observed and coatings used in the literature found. Bubble size, and the number on it, are proportional to the number of quotations.*

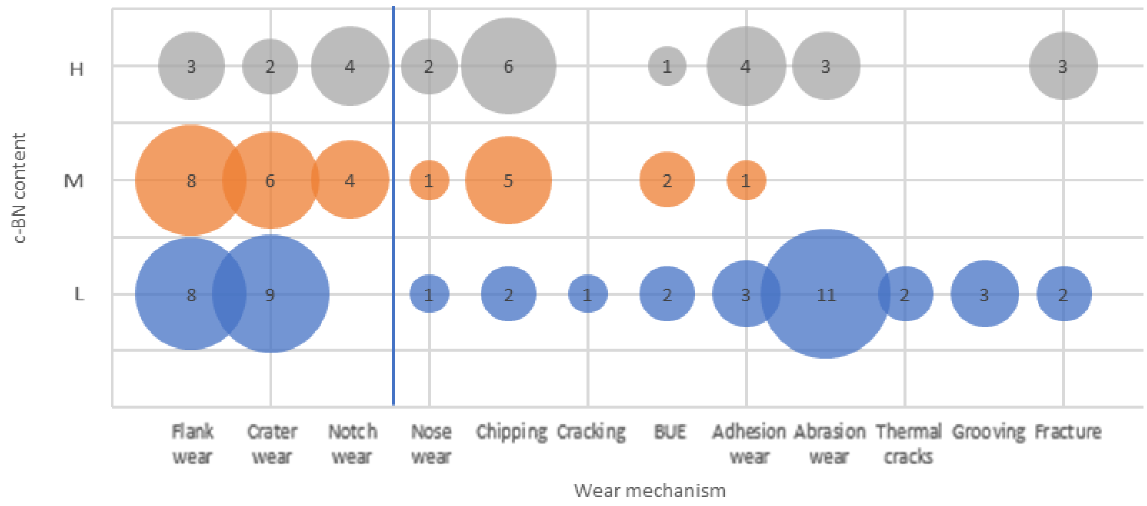

Figure 4.18 *c-BN content depending on wear and fracture mechanisms observed. Bubble size, and the number on it, are proportional to the number of quotations.*

To conclude, **Table 4.1** summarises the different wear and fracture/damage mechanisms reported by some authors depending on the machined material.

***Table 4.1**. Wear and damage mechanisms for each work-material studied.*

WORKMATERIAL		**WEAR MECHANISMS**			**OBSERVED DAMAGE/FRACTURE MECHANISMS**
		Flank	**Notch**	**Crater**	
Non-ferrous	*Inconel 718*	✓	✓	✓	Chipping, BUE, abrasion, adhesion, thermal cracks and fracture
	PMMC	✓	-	✓	Chipping, abrasion, adhesion and fracture
Ferrous	*Cr steels*	✓	-	✓	Abrasion
	Cr-Mo steels	-	-	✓	Chemical wear
	Cr-Mo-Ni steels	✓	-	-	Chipping
	Cold worked tool steels	-	-	✓	Abrasion, adhesion, grooving, chipping
	Hot worked Cr-based tool steels	✓	-	✓	BUE, abrasion, adhesion
	Water hardened tool steels	✓	-	✓	Abrasion, adhesion, chipping
	High-speed Mo-based tool steels	✓	-	✓	-

4.4. Review of machining operations and conditions for coated-Pc-BN

The aim of this section is to analyse, from the information gathered in the database, the type of machining operations and conditions where coated Pc-BN tools are implemented.

Literature review

Concerning machining operations, it is quite clear that coated Pc-BN is an attractive candidate for facing the challenge of dry machining, as about half of the review works consider these service conditions, as shown in **Figure 4.19**.

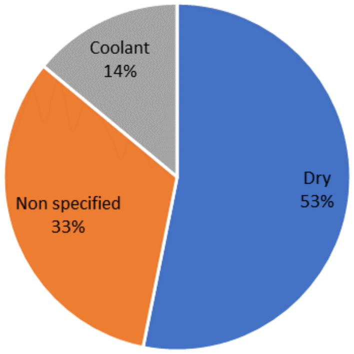

Figure 4.19 *Percentages of dry/coolant conditions in machining operations.*

From the literature, it can be observed that the most used machining operation is turning. Although many different conditions have been tested by researchers, coated Pc-BN tools are normally used in the following conditions: v_c = 150 to 250 m/min, f = 0.1 to 0.15 mm/rev and a_p = 0.2 to 0.3 mm in dry and interrupted conditions. However, some researchers also studied the behaviour of coated Pc-BN tools in milling or grinding operations. Taylan *et al.* [69] reported that the high friction generated in hard milling makes coated Pc-BN tools not useful in this type of operations. On the other hand, Teramoto *et al.* [126] as well as Derakshan and Akbari [124] stated that turning with coated Pc-BN tools might be compared with grinding in terms of final workpiece surface roughness. Additionally, it could be a good option for replacing grinding so that electric power consumption, environmental impact and costs would be reduced.

As stated in the previous sections, coated Pc-BN systems are speed-limited, owing to the thermal stability of the coatings. However, when they are used at low cutting speeds (i.e. below 150 m/min), the cutting forces reached are higher; thus, increasing the tool wear and reducing tool life. Moreover, cutting forces are also increased when rising either feed rates or depth of cut, being the last one the factor which more influences the tool life. It is also observed that tool wear is usually reduced by using minimum quantity lubrication (known as MQL) or dry conditions, since the BUE protective layer generated is observed to not appear under coolant conditions.

Finally, it has been reported that surface roughness is adversely affected by feed rate and depth of cut. For example, by increasing feed rate, the final surface roughness of the workpiece could be reduced, owing to BUE layer formation. However, when higher feed rates and/or cutting speed are used, the surface/cutting edge machined is increased, resulting in higher surface roughness. Furthermore, higher surface roughness is found when machining operations are made in dry conditions instead than when using coolant [93,100,102,116,118,124,129,144].

Partial conclusions

Independent of dry/coolant condition in turning, in most of the cases the use of coated Pc-BN yields relatively high levels of machining performance, in terms of cutting speed (v_c), feed rate (f) and depth of cut (a_p). However, once again dispersion of values obtained for variable microstructures of Pc-BN substrate (**Figure 4.20** and **Figure 4.21**), coatings (**Figure 4.22**) and workpieces (**Figure 4.23** and **Figure 4.24**) is quite large and overlap each other along the whole range of conditions studied. Nevertheless, as shown in **Figure 4.24 A**, it seems that when the hardness of workpiece increases, the cutting speed used in turning is decreased. Moreover, Si-containing coatings are also used in higher cutting speeds than the other coated systems.

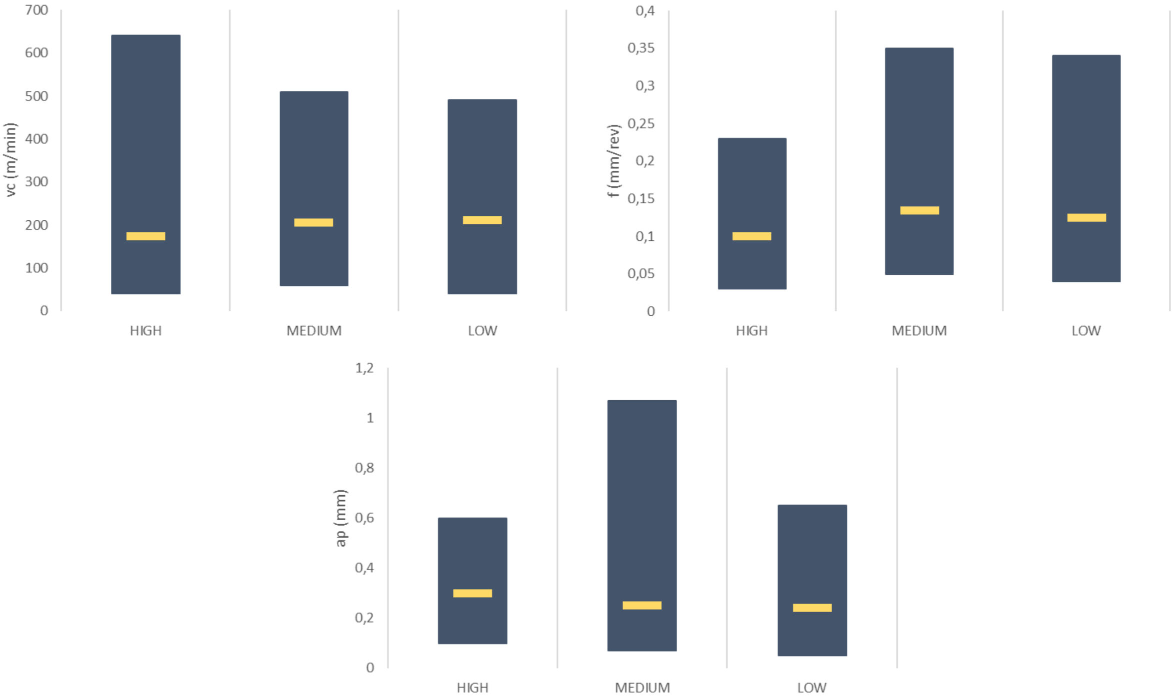

Figure 4.20 *Range of machining parameters used as a function of c-BN content: A) v_c vs c-BN content; B) f vs c-BN content and C) a_p vs c-BN content. Yellow lines represent the mean value of all the database considered.*

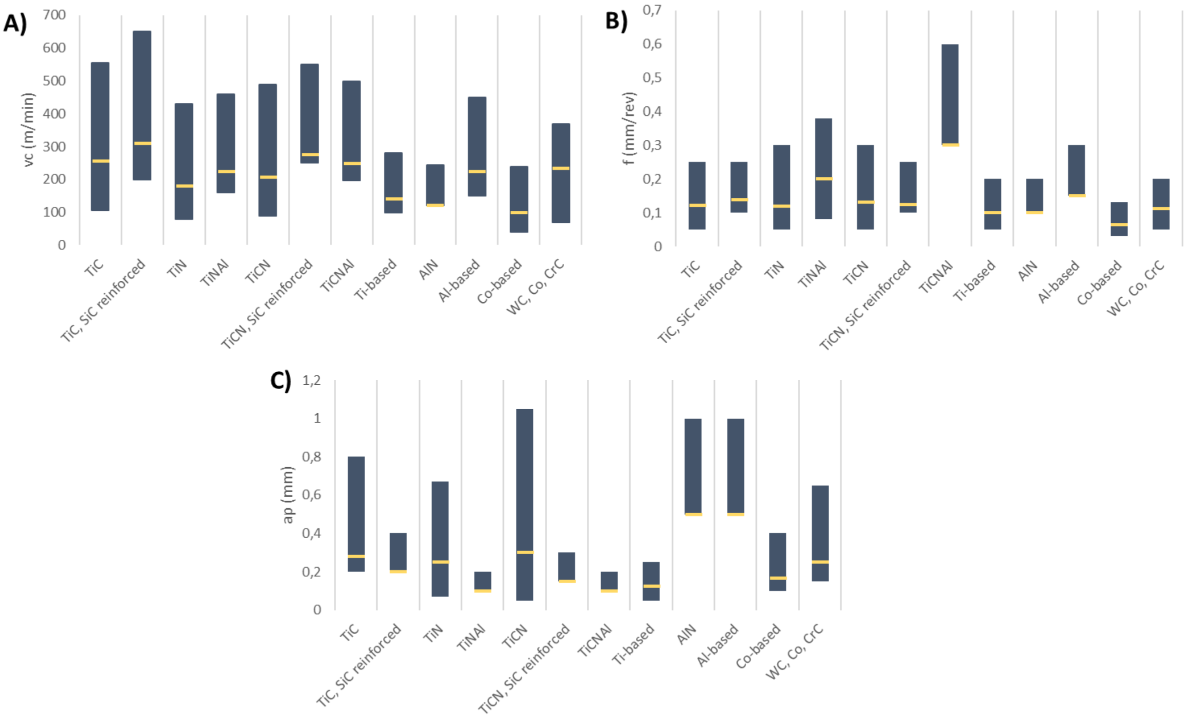

Figure 4.21 *Range of machining parameters used as a function of binder chemical nature: A) v_c vs binder; B) f vs binder and C) a_p vs binder. Yellow lines represent the mean value of all the database considered.*

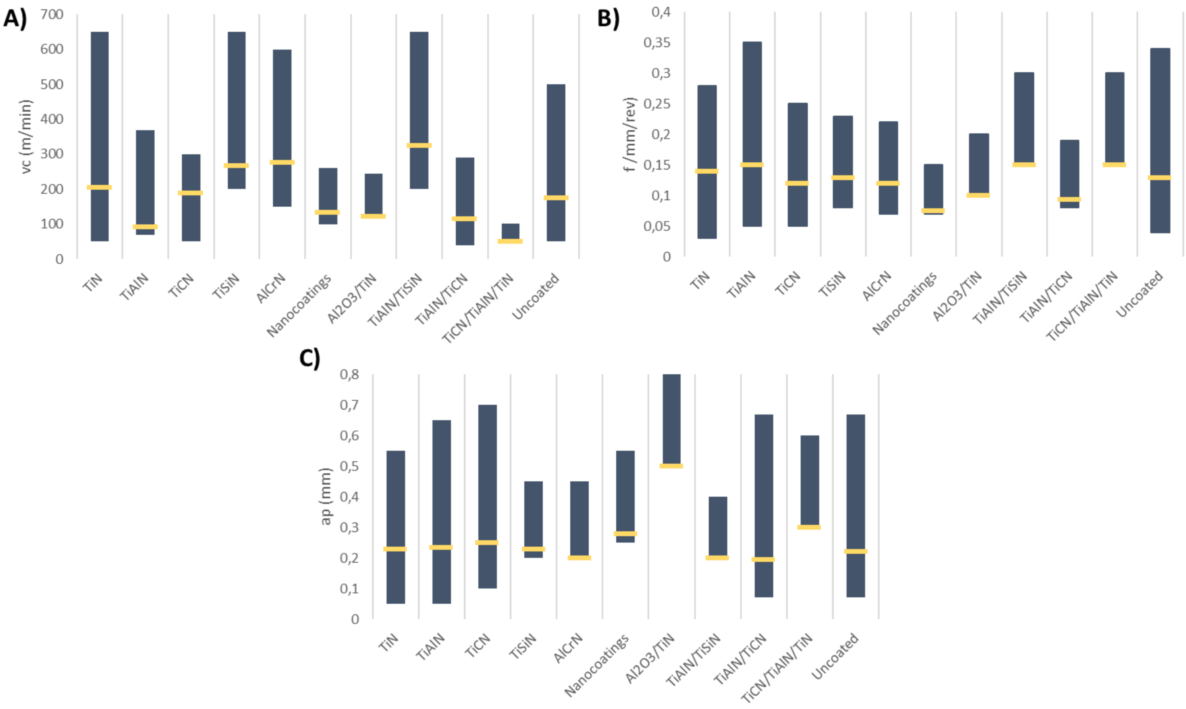

Figure 4.22 *Range of machining parameters used as a function of coating chemical nature: A) v_c vs coatings; B) f vs coatings and C) a_p vs coatings. Yellow lines represent the mean value of all the database considered.*

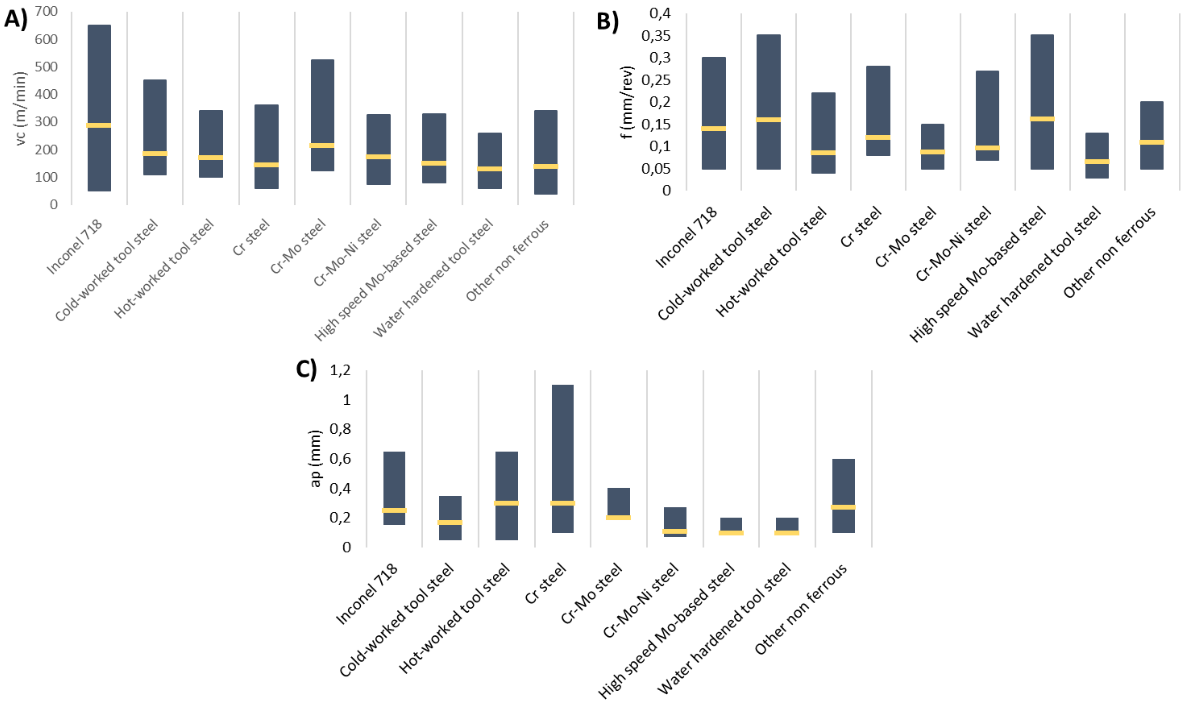

Figure 4.23 *Range of machining parameters used as a function of work-materials: A) v_c vs work-material; B) f vs work-material and C) a_p vs work-material. Yellow lines represent the mean value of all the database considered.*

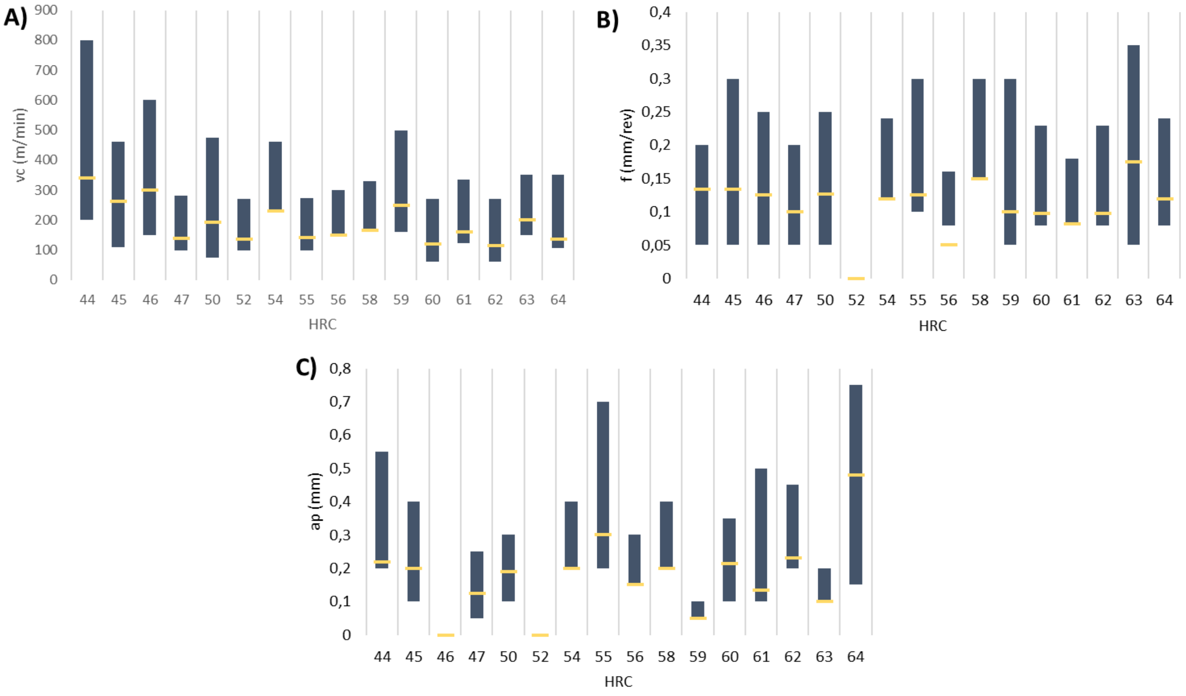

Figure 4.24 *Range of machining parameters used as a function of work-materials hardness: A) v_c vs HRC of work-material; B) f vs HRC of work-material and C) a_p vs HRC of work-material. Yellow lines represent the mean value of all the database considered.*

4.5. Additional information about surface modification technology

In this section, additional information about pre and post coating technology will be given. Unfortunately, information about these subjects is quite scarce in open literature, possibly because of property rights issues. The following treatments may be an example of surface modification technology in Pc-BN coated systems [73,123,146–148]:

- Previous cleaning of the substrate, to remove impurities. This is proposed because remnant impurities may result in lower mechanical adhesion during coating process. Moreover, impurities could react with the targets and gases used during coating processes, which could lead to the deposition of unwanted components.
- Roughening of the substrate's surface (for example by ion etching), to improve the adherence and the durability of the coating.
- Coating process might be done by PVD (processes such as sputtering or arc-ion plating) or CVD. Arc-ion plating coating processes are preferable to form smooth layers.
- Application of underlayers to prevent notch wear and improve the adherence. The underlayers may contain compounds such as: TiN, TiC, TiCN, TiAlN, TiOCN, Al_2O_3, CrN, among others. The choice of Ti-based coatings as underlayers is related to their affinity to most of the Pc-BN binders.
- Blasting treatments (as shot peening) may be applied as post coating processes to reduce or change stresses generated during the coating process. These treatments might be applied locally, such as in the rake face. The application of shot peening treatments can change the tensile stresses generated during coating process to compressive stresses, which is important for reducing excessive stresses that may result in delamination.

5. Further work

During this project, a theorical-base analysis of wear and fracture mechanisms of coated Pc-BN inserts has been done and several conclusions have been drawn from it. However, it would be interesting to check the experimental concordance of the trends here observed.

A microstructural and mechanical characterization at different length scales should be done in order to check or prove the general trends identified in this project. In this regard, it should be interesting to do a microstructural characterization before the mechanical one, aiming for an optimized microstructural design. Subsequent mechanical characterization opens the possibility to assess the influence of substrate microstructure and coating chemical nature on the mechanical contact response of coated Pc-BN systems. Mechanical contact response assessment could be done by spherical indentation, simulating service-like conditions, and micro-scratch tests, for studying the adhesion of the coating in the substrate. Moreover, it would be interesting to inspect the different damage and fracture micro-mechanisms observed in coated Pc-BN systems by using scanning electron microscope (SEM) and focused ion beam (FIB). With these inspections, it would be possible to compare experimental results with the ones found in literature under real machining conditions, including validation of trends discerned from the literature review done here.

Conclusions

From the critical review of the literature published on the use of coated Pc-BN as cutting tools, the following conclusions may be drawn:

- The amount of scientific papers addressing coated Pc-BN is rather limited. Within this context, most than the 50% of the publications deal with mechanical performance, whereas those following a materials science and engineering approach are quite scarce.
- The suitability of coated Pc-BN inserts for machining difficult-to-cut materials is confirmed.
- Metallic binders are used with high c-BN contents, while ceramic binders are present in low/medium c-BN contents. Furthermore, low/medium Pc-BN grades are used in 86.67% of the studies revised.
- Three “popular” combinations of coating and binder are found: TiCN-TiN, TiN-TiN and TiN-TiAlN. However, specific correlations between coating-substrate-workpiece are difficult to be discerned.
- Tools with low c-BN content are used for work-materials with “low” hardness, whereas medium c-BN content tools are more versatile. Moreover, low c-BN contents are chosen for almost all workpieces, except for cold-worked tool steels, where the medium one is preferred.
- Ti-based coatings are the most preferred ones for Pc-BN tools, especially TiN and TiAlN films.
- Flank wear is the main contact-related degradation mechanism (50%) for coated Pc-BN inserts, followed by crater wear (36%) and notch wear (14%).
- Regarding the fracture mechanisms, abrasion wear is the most common one, normally in the form of chipping, while adhesion wear (considering BUE) is the second most prominent.
- Chipping has been observed to be more prone to occur in high and medium c-BN content tools.
- Coated Pc-BN inserts seem to be a good candidate for dry machining operations. Replacing well-established tool materials, which need the use of coolants, for coated Pc-BN inserts would increase the sustainability of these operations, making industries to follow more eco-friendly paths and removing other problems related with the use of coolants.
- Implementation of coated Pc-BN allows the use of more extreme conditions compared to other tool materials.
- Finally, Pc-BN seems to be a good option as a substitute of cemented carbides in some specific operations, as the ones in which the use of coolant must be avoided, or in interrupted operations.

6. Environmental impact

The environmental impact caused during the realization of this project is related with the electrical energy consumption.

Approximately, 500 h of electrical consumption with a laptop have been accounted for carry out his project. Considering that consumption of the laptop is 0.88 kWh/day and the emitted emissions related with this energy are 0.343 kg CO_2/kWh, the total emissions would be worth around 18.9 kg of CO_2.

Economic analysis

The aim of this section is to estimate the costs associated with resources invested in this project. In **Table 0.1** the prices associated with the time spent by each of the members are broken down.

Table 0.1 *Hours dedicated by each member of the project, associated with their cost.*

Member	Hours	Price (€/h)	Cost (€)
Head of project	20	50	1000
PhD Investigator	100	30	3000
Final Degree Student	400	20	8000
Total cost			12000

In **Table 0.2** the price related to electricity is depicted. In this case, the price of electricity has been estimated to 0.1 €/kWh.

Table 0.2 *Hours and cost related to electricity.*

	Hours	Price (€/kWh)	Cost (€)
Total cost	500	0.1	5.5

Thus, the total cost estimated for this project would be **12005,5** €.

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Annex A. Database

Table 0.1 *Information gathered for the database. Operating parameters: [v_c] = m/min; [f] = mm/rev; [a_p] = mm; [v_c] = mm.*

Authors	Coating details	Substrate	Workpiece / Operating parameters	Key results
G. Poulachon *et al.* [5]	1. TiN (2 µm)	-Medium c-BN content (57%). -TiCN binder.	Cr steel (38-60 HRC) Turning: v_c=120-300 f=0.08-0.2 a_p = 0.1-0.3 Dry conditions.	-Coating has improved tool life (owing to lower diffusion). -An increasement of Vc leads to rapid coating removing (major exposition of coating to higher temperatures and abrasion). -Flank wear is the first one observed. When it is constant, with higher Vc, crater wear is observed. Finally, tool failure is observed.
E. J. Oles et al. [123]	1. TiAlN (3-3.5 µm) 2. Al_2O_3/TiN double coated (5.5/1.5 µm) 3. TiN (2 µm)	1/4. Low c-BN content (50 %) with TiC binder. 1/4. Medium c-BN content (70 %) with TiN binder.	Cold-worked tool Steel (60-64 HRC) Turning: v_c=106-122 f=0.1-0.12 a_p = 0.5-0.6	-TiAlN improved tool life by 80 % when compared with an uncoated tool, due to lower crater wear. -The double coating provided the necessary thermal barrier to improve crater wear

	4. Uncoated	1/4. Medium c-BN content (65 %) with TiN binder. 2/3/4. High c-BN content (90 %) with AlN binder.	Dry conditions.	resistance, giving higher tool life than the uncoated tool. TiN coating offered lower protection against crater wear than the double coating.
Z. Zurecki *et al.* [128]	1. TiN (2 µm) 2. Al_2O_3/TiCN *Both PVD coated.*	1. Medium c-BN content (60-65 %) with TiN binder. 2. Alumina-based black ceramic	<u>Cold-worked tool steel (61 HRC)</u> Turning: v_c = 122, 213 f = 0.1 a_p = 0.4 Dry conditions and cryogenic cooling (LIN)	-The use of LIN cooling controls the thickness of white/dark layers. Preventing workpiece softening and improving residual stress distribution. -Thinner white layers and more acceptable when machining with alumina-based tools and LIN cooling than in dry operations with Pc-BN tools.
S. Berg [104]	1. TiN *(PVD coated)* 2. Uncoated 3.TiCN/Al_2O_3/TiN *(CVD coated)*	1. High c-BN content with metallic binder. 1/2. Medium c-BN content (57 %) with TiCN binder. c-BN grain size = 0.5-2 µm.	<u>Bainitic and martensitic PM steel</u> Turning: v_c = 150 f = 0.2 a_p = 0.15 Dry/coolant conditions.	-Longer tool life was observed with c-BN TiN coated Pc-BN tools than cemented carbides, up to 583 %. -High c-BN content TiN coated Pc-BN tools showed higher tool life than medium c-BN content tools, because

		3. Cemented carbides.	With/without additives (MnS and MnX).	of their higher toughness. -BUE elimination was observed when cutting fluid was used, decreasing tool life. Thus, higher tool life was observed in dry conditions. -Wear mechanisms observed in bainitic steel: adhesion with BUE formation. In martensitic steel: flank wear. -The addition of MnS extended tool life. -Pc-BN coated tools provided higher surface quality and higher productivity than cemented carbides.
E. O. Ezugwu *et al.* [105]	1. TiAlN/TiN (3.5/0.5 µm) 2. Uncoated	1. High c-BN content (90 %) with Al ceramic binder.	Ti-6Al-4V Turning: v_c = 150-300 f = 0.15 a_p = 0.5 With coolant.	-Pc-BN tools showed lower performance than tungsten carbide tools. -Pc-BN tool life: low c-BN content (uncoated)

	2. Low c-BN content (50 %) with TiC binder. 2. High c-BN content (90 %) with Al ceramic binder. 2. Tungsten carbide.	> high c-BN content (uncoated) > high c-BN content (TiAlN/TiN coated). It may be explained because when c-BN content is increased, notch wear is accelerated. -Low c-BN content tools are observed to be more sensitive to coolant pressure, improving tool life by 150 %. -In low c-BN content tools and tungsten carbides nose wear is the predominant failure mode. However, in high c-BN content tools (coated/uncoated) the predominant wear modes observed are notch and chipping wear. -No adverse effect on surface finish is observed with Pc-BN tools.

G. de Siquiera Galoppi *et al.* [106]	1. TiAlN 2. TiN 3. Uncoated	Not specified	Cr steel (62 HRC) Turning: v_c = 91-183 f = 0.08-0.15 a_p = 0.2	-Higher tool life observed when cutting speed or feed rate are decreased. -Crater wear similar in coated and uncoated tools. -Coated Pc-BN tool extended tool life owing to crater wear was observed when coating was completely removed.
R. T. Coelho *et al.* [58]	1. TiAlN nanocoating 2. TiAlN 3. AlCrN 4. Uncoated	-Low c-BN content (50 %) with TiC binder.	Cr-Mo-Ni steel Turning: v_c = 150 f = 0.07	-Coatings improved Pc-BN tool life: TiAlN nanocoating by 38 %, TiAlN by 21 % and AlCrN by 12 %. The improvement of tool life with the nanocoating is related its hot hardness. -Uncoated Pc-BN tools had higher cutting forces than the coated tools, leading to higher flank wear.

H. Bouchelaghem *et al.* [114]	1. TiN	-Medium c-BN content (57 %) with TiN binder. c-BN grain size = 0.5-2 µm.	Cold-worked tool steel (60 HRC) Turning: v_c = 85-310 f = 0.08 a_p = 0.5 Dry conditions.	-Abrasion was observed as the predominant wear mechanism. -When v_c is decreased grooving and crater wear were found, leading to nose tool collapse. At higher v_c it was observed to occur during the first minute.
A. E. Diniz and A. J. de Oliveira [145]	1. TiN *(PVD coated)*	1. Low c-BN content with TiN binder. 1. High c-BN content with metallic binder.	Cr-Mo-Ni steel (56 HRC) Turning: v_c = 150 f = 0.08 a_p = 0.15 Dry conditions.	-Low c-BN tools offered better performance than high c-BN tools in continuous and semi-interrupted operations in terms of tool life. -Interrupted operations were observed to improve tool life. Moreover, no chipping or breakage were observed because they had enough toughness.
W. F. Sales *et al.* [109]	1. TiN	-High c-BN content with Co-based binder.	Water hardened tool steel Turning:	-Chipping, abrasion and adhesion wear and also brittle fracture were observed.

			v_c = 60-200 f = 0.03-0.1 a_p = 0.1	-Diffusion was observed with an increasement of v_c due to an increasement of temperatures (mainly at 150-200 m/min).
F. Mahfoudi *et al*. [112]	1. TiN (2 µm)	-Medium c-BN content (57 %) with TiCN binder.	Cr-Mo steel (50 HRC) Turning: v_c = 300-400 f = 0.05-0.1 Dry conditions.	-Higher surface roughness results were found when v_c was increased and f decreased. -Crater wear controlled hard turning process (mainly caused by BUL formation at rake face by oxidation). -With an increasement of v_c, chemical wear on tool rake must be considered. Moreover, this increasement also gave results similar to finishing by grinding.
M. Teramoto *et al.* [126]	1. TiAlN/TiCN (2 µm) 2. TiCN (2 µm) 3. TiN (2 µm)	1./2. Low c-BN content (40-45 %) with TiN binder. c-BN grain size = 1-2 µm	Cr steel (58-62 HRC) Turning: v_c = 250 f = 0.08-0.1 a_p = 0.07-0.1	-Medium c-BN content tools: lower flank wear was observed with TiAlN/TiCN coating than TiN coating. It also gave higher wear resistance than TiN coating. It could be

	4. Uncoated *All PVD coated*	1./3. Medium c-BN content (60-65 %) with TiN binder. c-BN grain size = 3 µm 4. Low c-BN content (40-45 %) with TiCN binder. c-BN grain size = 3 µm.	Dry conditions.	used to replace grinding with cutting (↓ electric power used = ↓ environmental impact = ↓ total cost). -Low c-BN content tools: TiAlN/TiCN coated tool showed less flank wear width than TiN coated tool. Also chipping resistance was improved by 30%, and when compared with uncoated it was improved by 50 %, due to its coarse microstructure.
E. D. Derakhshan and A. A. Akbari [124]	1. TiN (*PVD coated)* 2. Uncoated	-Medium c-BN content (57 %) with TiCN binder. c-BN grain size = 0.5-2 µm. -High c-BN content with metal binder.	Cr-Mo steel (45-65 HRC) Turning: v_c = 125-173 f = 0.1 a_p = 0.3 Dry conditions.	-Best surface quality was observed with high c-BN content tools. -Turning may be compared/replaced with and instead of grinding. -A variation in v_c affected the resulting surface roughness.

M. A. Yallese *et al.* [125]	1. TiN *(PVD coated)*	-Medium c-BN content (57 %) with TiCN binder. c-BN grain size = 0.5-2 µm.	Cr steel (60 HRC) Turning: v_c = 90-180 f = 0.08-0.2 a_p = 0.2-0.6 Dry conditions.	-Pc-BN inserts showed satisfactory wear resistance for high v_c. However, they are not industrially recommended at v_c > 280 m/min, the optimal v_c = 120 m/min. -When $v_{c\ was}$s increased higher tool wear was found and there is a degradation of the surface quality. The temperature generated was dissipated through chipping. -Turning may be an alternative to grinding, because of they roughness results. Thus, reducing the production cycle and the final costs.
L. R. Silva and C. B. Soares [129]	1. TiN *(PVD coated)*	1. High c-BN content Pc-BN insert with a metallic binder. 2. Aluminia-based ceramic	Inconel 718 (44 HRC) Turning: v_c = 300-600 f = 0.05-0.15	-Higher surface roughness results found in dry conditions than in MQL conditions.

		tool with SiC (25 %) whisker reinforcement. 3. Alumina-based ceramic tool with 28 % of TiC.	a_p = 0.35 Dry and MQL conditions.	-Notch wear as the predominant type of wear in alumina-based ceramic tools. Additionally, in Pc-BN tools flank wear was also observed. -In MQL conditions lower cutting forces were observed. -Ceramic tools produced better surface finish than Pc-BN tools.
K. Bouacha *et al.* [144]	1. TiN	-Low c-BN content with TiN binder.	Cr steel (64 HRC) Turning: v_c = 124-246 f = 0.08-0.16 a_p = 0.15-0.45 Dry conditions.	-Higher cutting forces were observed with an increasement of f or a_p or a decreasement of v_c. -Surface roughness was observed to be highly affected by f.
J. S. Dureja *et al.* [121]	1. TiN	-Low c-BN content (50 %) with TiN binder.	Hot worked tool steel (42-52 HRC) Turning: v_c = 100-180 f = 0.05-0.15	-Abrasion wear was found to dominate at low values of v_c and f. At higher values of v_c it was observed with BUE, which reduced tool wear.

			a_p = 0.05-0.2 Dry conditions.	-At high f, TiN oxidation was observed, leading to the exposition of c-BN on flank wear. -At high values of a_p lower values of friction were generated, due to BUE formation. Thus, lower wear was observed.
A. Zawada and B. Storch [127]	1. TiN (1 µm) *PVD coated* 2. Uncoated	-Medium c-BN content (57 %) with TiCN binder. c-BN grain size = 0.5-2 µm. -Medium c-BN content with TiN binder.	Cr steel (58 HRC) Turning: v_c = 165 f = 0.15 a_p = 0.2 Dry conditions.	-Wear started to develop form the point in which the cutting-edge cuts through a deformed layer (which is determined by a_p). -Flank wear was observed in early stages and it was very developed due to c-BN abrasive grains.
J. Zhou *et al.*	1. TiN (5 µm) 2. Uncoated	-Low c-BN content with TiN binder.	Inconel 718 Turning: v_c = 200-350 f = 0.1-0.25 a_p = 0.3 With coolant.	-The use of coatings in Pc-BN increased tool life at v_c < 300 m/min. However, this effect was neglected in higher v_c. -BUE generation was observed with a decreasement of f.

				-Cracking and breakage of NbC and TiC were observed on Inconel 718.
F. Taylan *et al.* [69]	1.TiCN/TiAlN/TiN (2-4 µm) *PVD coated* 2. Uncoated	-High c-BN (90 %) with Al ceramic binder. c-BN grain size = 22 µm.	Cr steel (61 HRC) Milling: v_c = 50.87 f = 0.05-0.15 a_p = 0.3	-Coated Pc-BN tool was not useful for hard milling due to braking (friction). -The failure was found to be by the fracture of the cutting edge. -Macrochipping was observed as the main tool wear (it was promoted by low v_c or high f).
D. Bhaduri and A. K. Chattopadhyay [113]	1. TiN *(PVD coated)* 2. Uncoated	Not specified.	Cr steel Grinding: v_c = 22-45 Dry conditions.	-Uncoated Pc-BN underwent fracture wear. -Higher voltage in PVD process led to denser and compacter microstructure in TiN.
V. Bushlya *et al.* [107]	1.TiN (2 µm) *PVD coated* 2. Uncoated	-Low c-BN (50 %) with TiC-based binder. c-BN grain size = 0.5-2 µm.	Inconel 718 (45 HRC) Turning: v_c = 250-350 f = 0.1-0.2	-Tool life was found to be highly sensitive to v_c. -Abrasive wear was observed together

			a_p = 0.3 With coolant.	with rake cratering (chemical wear). -Higher surface quality was observed when machining with uncoated Pc-BN than when machining with coated Pc-BN. However, thermal cracks were observed. -Delamination of the coating was observed.
S. Khamel *et al.* [116]	1. TiN *(PVD coated)*	-Medium c-BN content (57 %) with TiCN binder. c-BN grain size = 0.5-2 µm.	Cr steel (60 HRC) Turning: v_c = 100-200 f = 0.08-0.16 a_p = 0.2-0.6	-Surface roughness was found to be highly affected by f.
V. Bushlya *et al.* [140]	1.TiN 2. Uncoated	-Low c-BN (50 %) with TiC-based binder. c-BN grain size = 0.5-2 µm.	Inconel 718 (45 HRC) Turning: v_c = 250-350 f = 0.1-0.2 a_p = 0.3 With coolant.	-Higher cutting forces were observed in coated Pc-BN insert (10 % higher) than the uncoated one. -Tool life was 20 % longer for the coated system than the uncoated one in v_c = 250 m/min. However, it was decreased by

				250 % when v_c = 350 m/min. -Tool life was found to be highly sensitive to v_c, due to coating has a cutting-speed limited effect (because at higher temperatures it is rapidly oxidized).
S. A. Khan *et al.* [141]	1. TiAlN/TiN (1.5/0.5 µm) 2. Uncoated	-Low c-BN (50 %) with TiC binder. c-BN grain size = 2 µm.	Inconel 718 (46 HRC) Turning: v_c = 150-450 f = 0.05-0.2 With coolant.	-Flank wear was found to be the dominant type of wear, because of abrasion. However, grooving and BUE were also present at low v_c. At high values of v_c (450 m/min), fracture, chipping and thermal cracks were also observed. -The use of coatings didn't provide any significant benefit in terms of tool life.
R. M'Saoubi *et al.* [68]	1. TiN (2 µm) 2. TiSiN (2 µm) 3. TiAlN (2 µm)	-Low c-BN (50 %) with TiCN binder. c-BN grain size = 2 µm.	Cr steel (58-62 HRC) Turning: v_c = 200 f = 0.15 a_p = 0.25	-Less flank and crater wear were observed in the uncoated insert. -The coated systems may be classified in terms of flank and

	4. AlCrN (2 µm) 5. Uncoated *All PVD coated*			crater wear: TiSiN (owing to its brittle fracture and surface crackings) > TiAlN > TiN > AlCrN (due to its high hot hardness and oxidation resistance).
S. Asaithambi and S. Gowri [149]	1.TiN (4 µm) *PVD coated* 2. Uncoated	Not specified.	CFRP Turning: v_c = 100-200 f = 0.05-0.15 a_p = 0.25-1.25	-The coated insert showed less surface roughness, cutting temperatures, wear rate and higher performance than the uncoated one.
E. Uhlmann et al. [75]	1. TiAlN 2. nc-AlTiN/α-Si_3N_4 3. nc-AlCrN/α-Si_3N_4 *All PVD coated*	-Medium c-BN content (55 %) with TiN binder.	Hot worked tool steel Turning: v_c = 160 f = 0.08 a_p = 0.3 Dry conditions.	-Nanocomposite coated systems showed higher performance and lower crater depth than TiAlN coated PcBN tools. - nc-AlCrN/α-Si_3N_4 were observed to have higher adhesion than the other coatings, together with high abrasion resistance, hardness and thermal stability.
S. Sveen *et al.* [150]	1. TiAlN/TiSiN *(PVD coated)*	-Low c-BN content (50 %)	Cr steel (58-64 HRC)	-Crater and flank wear were observed. Also,

	2. Uncoated	with TiCN binder. -Medium c-BN content (60 %) with TiCN binder.	Turning: $v_b = 0.3$	micro-edge chipping was observed. -Coating with spalling tendency because of poor adhesion. -Higher content of TiCN in binder led to smooth polished morphologies.
S. Sveen *et al.* [133]	1. TiAlN (5 µm) *PVD coated*	-PM HSS. -Cemented carbide. -High c-BN content (90 %) with AlN binder. c-BN grain size = 22 µm.	Scratch test: 10 mm; 10 m/min Hardness test: 0-100 or 100-200 N	-Adhesion of TiAlN coating increases in the following order: Pc-BN – HSS – Cemented carbide. -Major adhesive fracture is observed in Pc-BN.
M. A. Shalaby *et al.* [151]	1. TiN (2 µm) *PVD coated* 2. Uncoated	1. Medium c-BN content (60 %) with TiN binder. c-BN grain size = 3 µm. 2.1. Medium c-BN content (57 %) with TiN binder.	Cold-worked tool steel (52 HRC) Turning: $v_c = 100\text{-}170$ $a_p < 4$ $v_b < 0.2$	

		2.2. Mixed alumina ceramic (Al_2O_3 + TiC).		
J. Kundrák *et al.* [152]	1. TiN	-Low and medium c-BN content (50-70 %) with ceramic binder.	Cr steel (62 HRC) Turning: v_c = 60-210 f = 0.12 a_p = 0.1	-Higher tool wear when v_c is increased.
Ł. Ślusarczyk and G. Struzikiew [120]	1. TiN *(PVD coated)* 2. Uncoated	-Medium c-BN content (60 %) with TiCN binder. c-BN grain size = 1-3 µm. -High c-BN content with metallic binder.	Cr steel (55 HRC) Turning: v_c = 150, 100 f = 0.2, 0.1 a_p = 1, 0.5 Dry conditions.	-The cutting parameters that were found to be highly influent in surface roughness were the insert material and a_p. -Uncoated systems generated unacceptable form of chips.
M. J. Njuguna and D. Gao [143]	1. TiAlN/TiCN (2 µm) 2. Uncoated	-Low c-BN content (40-45 %). -High c-BN content (90 %) with Co-W-Al binider. -PCD.	Al 2124 SiC (PMMC) Turning: v_c = 40-100 f = 8.3 m/min a_p = 0.1-0.3 Dry conditions.	-Abrasion, adhesion, flank wear, chipping and fracture were observed. -PCD machined workmaterial showed better surface finish than when machined with Pc-BN. However, coated Pc-BN systems

				gave better surface finish than the uncoated ones.
S. Girishankar and M. Omkumar [119]	1. TiN 2. Uncoated	-Low c-BN content (50 %) with TiN binder.	High speed tool steel (62-64 HRC) Turning: 1); 2) v_c = 150-250; 80-120 f = 0.05-0.3; 0.1-0.2 a_p = 0.1	-TiN broke free in coating system, leading to higher tool life due to lower c-BN exposure. -Pc-BN coated system produced better surface finish and was capable to produce 300 % more number parts than the uncoated system, being more cost effective, by 400 %.
Y. Matsuda *et al.* [153]	1. TiCN (1.5 µm) 2. TiAlN/TiCN (2 µm) 3.TiAlN (2 µm) *All PVD coated*	1. Medium c-BN content (55 %) with TiCN binder. c-BN grain size = 2 µm. 2. Low c-BN content (40 %) with TiN binder. c-BN grain size = 1 µm. 3. Medium c-BN content (70 %) with TiN binder.	Hardened steel Turning: v_c = 130 f = 0.11 a_p = 0.6 Dry conditions. Interrupted and	-Interrupted cutting: tool life values were twice as large in TiCN coated systems than in TiN coated inserts, owing to less notch wear and better surface roughness were observed in TiCN coated inserts. However, TiAlN coated inserts offered the longest tool life, due to its high toughness and

		c-BN grain size = 5 µm.	continuous operations.	excellent coating peeling resistance. -Continuous operations: less notch wear and better surface roughness were observed than in interrupted operations, because coating was maintained, and it worked to supress notch wear.
A. Zawada and B. Storch [122]	1. TiN *(PVD coated)* 2. Uncoated	-Medium c-BN content with TiN binder. -Medium c-BN content (57 %) with TiCN binder. c-BN grain size = 0.5-2 µm.	Cr steel (58 HRC) Turning: v_c = 165 f = 0.15 a_p = 0.2	-Hard turning with Pc-BN was observed to give very smooth and uniform surface. -Crater and flank wear were observed. Edge strength and reliability was preserved during the test.
S. L. Soo *et al.* [136]	1. TiSiN (1.5 µm) 2. TiSiN/TiAlN (2 µm) 3. AlCrN multilayer (2.25 µm)	1/2/3/4. Medium c-BN content (65 %) with TiC binder (with SiC whiskers reinforcement).	Inconel 718 (44 HRC) Turning: v_c = 200-450 f = 0.15 a_p = 0.2	-Life advantage of 40 % was observed in TiSiN coated inserts over the uncoated ones. The other coatings presented poor coating integrity.

	4. CrAlN multilayer (5.5 µm) *All PVD coated* 5. Uncoated	5. Low c-BN content (50 %) with TiC binder.	With coolant.	-No benefit was observed, except at $v_c >$ 300 m/min. At 200 m/min notch wear was observed and when v_c was increased crater wear was the dominant wear mechanism.
S. Kumar *et al.* [118]	1. TiN (6 µm) 2. Uncoated	-Medium c-BN content (65 %) with ceramic binder.	<u>Cr-Mo-Ni steel (40-60 HRC)</u> Turning: v_c = 75-150 f = 0.1-0.2 a_p = 0.2	-Coated systems gave better surface quality (10-15 % better). Less surface roughness when f is decreased.
S. A. Klimenko *et al.* [137]	1. α-BN (6 µm) *PVD coated* 2. Uncoated	Not specified.	<u>Cr steel (50-60 HRC)</u> Turning	-The coating reduced the contact between the tool and the workpiece. Thus, it acted as a solid lubricant, reducing coefficient of friction and the generated temperatures and as a result, it reduced tool wear and increased tool life.

T. Wada and H. Haynu [131]	1. TiAlN (*PVD coated*) 2. Uncoated	-Low c-BN content (45 %) with TiCN-Al binder. c-BN grain size = 5 µm. -Medium c-BN content (65 %) with TiN-Al binder. c-BN grain size = 3 µm. -Medium c-BN content (75 %) with TiN-Al binder. c-BN grain size = 5 µm.	Cold-worked tool steel (60 HRC) Turning: v_c = 180-300 f = 0.3 a_p = 0.1 Dry conditions.	-The coated system had smaller contact area than the uncoated one at the rake face-chip interface, which resulted in less tool wear (even at high v_c). -Less tool wear was observed when TiCN-Al binder was used instead of TiN-Al binder.
K. B. Rathod and D. I. Lalwani [117]	1. TiN	-Low c-BN content (50 %) with ceramic binder.	Hot worked tool steel (60 HRC) Turning: v_c = 140-220 f = 0.06-0.18 a_p = 0.15 Dry conditions.	- v_c was found to be the dominant factor in flank wear. -Best surface roughness obtained with the increasement of v_c and the decreasement of f and workpiece's hardness.

M. Junaid Mir and M. F. Wani [103]	1. TiN 2. Uncoated 3. TiC/TiCN/Al$_2$O$_3$	1. Pc-BN with TiN binder. 2. Mixed alumina ceramic (Al$_2$O$_3$ + TiC) 3. Cemented carbide	Cold-worked tool steel (45 HRC) Turning: v_c = 110-190 f = 0.05 a_p = 0.1 Dry conditions.	-Pc-BN coated inserts showed higher wear resistance for all v_c, and as a result higher tool life and better surface roughness than the others. Less flank wear was also observed (owing to its ability to retain its hot hardness and its higher thermal conductivity). -At low v_c abrasion, adhesion and crater wear were observed in coated Pc-BN tools. In mixed alumina ceramic tools abrasion and adhesion were observed, while in cemented carbide abrasion, adhesion, chipping, and failure were observed. -No premature failure by chipping was observed.
E. Uhlmann *et al.* [138]	1. nc-AlTiN/α-Si$_3$N$_4$/TiN (1.9 µm)	-Low c-BN content (50 %).	Cr steel (62 HRC) Turning:	-Coatings gave life advantage of 38% and a thermal insulator effect.

	2. nc-AlTiN/α-Si_3N_4/TiN/TiAlN (1.6 µm) 3. n-AlTiCr/CrN/AlCrN (1.5 µm) 4. AlTiN-ML/AlCrN/TiN (1.8 µm) 5. TiSiN/TiN/ nc-AlTiN/α-Si_3N_4 (1.5 µm) 6. AlCrON/CrN/AlCrN (1.7 µm) 7. Uncoated		$v_c = 100$ $f = 0.08$ $a_p = 0.25$	-Bests results obtained with coatings 2 and 3, due to their high hardness and abrasive resistance. Together, with coating 5, were the coatings which showed the highest tool life.
B. Ozlu *et al.* [154]	1. TiAlN 2. Uncoated	-Low c-BN content (50 %) with ceramic binder.	<u>Cr steel</u> Turning: $v_c = 120\text{-}240$ $f = 0.04$	-Higher cutting forces and surface roughness were observed in the coated insert. The surface roughness obtained with TiAlN coated Pc-BN was 130

			$a_p = 0.6$ Dry conditions.	% higher than in the uncoated Pc-BN.
J. Díaz-Álvarez *et al.* [102]	1. TiAlN/TiN 2. TiAlN (6 µm) 3. TiN (2 µm) 4. Uncoated (x2)	1. Tungsten carbide. 2. Medium c-BN (65 %) in WC, Co, CrC binder. 3. Low c-BN (50 %) in TiCN binder. 4. Medium c-BN (60 %) in TiCN SiC reinforced binder. 4. Medium c-BN (65 %) in TiCN SiC reinforced binder.	<u>Inconel 718 (45 HRC)</u> 1. Turning: $v_c = 50\text{-}70$ $f = 0.1\text{-}0.15$ $a_p = 0.25$ 2/3/4.Turning: $v_c = 250\text{-}300$ $f = 0.1\text{-}0.15$ $a_p = 0.15$ In all cases in dry conditions.	-Wear observed in carbide: chippinig, notch and flank wear and BUE. Wear evolution led to catastrophic breakage by chipping. An increasement in v_c or f decreased tool life and surface quality. -Wear observed in Pc-BN systems: chipping, notch and flank wear and BUE. Flank wear was dominant in the final stages and crater was observed after the first 5 minutes. An increasement in v_c decreased tool life. -Less chipping and notch wear were observed with the decreasement of c-BN content (owing to toughness is increased). Thus, tool life was longer.

V. Criado *et al.* [100]	1. TiAlN/TiN 2. TiN (2 µm) *All PVD coated*	1. Cemented carbide. 2. Low c-BN content (50 %) with TiN binder.	Inconel 718 (45 HRC) 1. Turning: v_c = 50-70 f = 0.1-0.15 a_p = 0.25 2.Turning: v_c = 250-300 f = 0.1-0.15 a_p = 0.15 In all cases in coolant conditions.	-Less tool life was observed for Pc-BN tools. However, the used v_c, was up to 4-6 times higher than the used for cemented carbide. -Higher machined surface/edge was obtained when f was increased. -Best combination of machining parameters was when f was increased and v_c decreased.
J. L. Cantero *et al.* [101]	1. TiAlN/TiN 2. TiAlN (6 µm) 3. TiN (2 µm) *All PVD coated* 4. Uncoated (x2)	1. Tungsten carbide. 2. Medium c-BN (65 %) in WC, Co, CrC binder. 3. Low c-BN (50 %) in TiCN binder. 3. NTK JP2.	Inconel 718 (45 HRC) 1. Turning: v_c = 35-50 f = 0.1-0.15 a_p = 0.25-0.5 2,3,4.1 Turning: v_c = 300 f = 0.15	-With an increasement of a_p lower tool life was observed (less effect was observed with f). -Most frequent wear in Pc-BN tools was notch wear and chipping. Adhesion and crater wear were also present. Together with NTK JP2, they were not industrially viable.

		4. Medium c-BN (60 %) in TiCN SiC reinforced binder. 4. Medium c-BN (65 %) in TiCN SiC reinforced binder.	a_p = 0.15-0.15 4.2 Turning: v_c = 200-300 f = 0.5 a_p = 0.15-0.5 In all cases in dry conditions.	-Although carbides operated in lower v_c, f and a_p, their industrial viability was confirmed. -All were negatively affected with the increasement of v_c.
M. Mandú *et al.* [76]	1. TiN *(PVD coated)*	-Low c-BN content (50 %) with TiN+Al_2O_3 binder.	Cold-worked tool steel (59 HRC) Turning: v_c = 160-340 f = 0.05-0.25 a_p = 0.5 Dry and MQL conditions.	-Abrasion and adhesion were the dominant wear mechanisms. -Lower tool wear was obtained when f or v_c were decreased or when MQL conditions were applied.
E. Kaya and I. Kaya [134]	1. TiAlN *(PVD coated)* 2. Uncoated	1. High c-BN content (90 %) with WC, Co, CrC binder. c-BN grain size = 1-2 µm.	NiTi Turning: v_c = 70-250 f = 0.05 a_p = 0.2	-PCD outperformed Pc-BN at any v_c. -Longest tool life was obtained at v_c = 130.

	2. PCD.	-Flank, notch, nose, crater and chipping wear were observed. -Wear mechanisms are v_c sensitive. At higher v_c, higher temperatures were generated, which led to higher diffusion, chemical and oxidation wear.