

Review

# Recent Advances in Turning Processes Using Coated Tools—A Comprehensive Review

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**Abstract:** Turning continues to be the largest segment of the machining industry, which highlights the continued demand for turned parts and the overall improvement of the process. The turning process has seen quite an evolution, from basic lathes using solid tools, to complex CNC (Computer Numerical Control) multi-process machines, using, for the most part, coated inserts and coated tools. These coatings have proven to be a significant step in the production of high-quality parts and a higher tool life that have captivated the industry. Continuous improvement to turning coated tools has been made, with many researches focusing on the optimization of turning processes that use coated tools. In the present paper, a presentation of various recently published papers on this subject is going to be made, mentioning the various types of coatings that have recently been used in the turning process, the turning of hard to machine materials, such as titanium alloys and Inconel, as well as the interaction of these coatings with the turned surfaces, the wear patterns that these coatings suffer during the turning of materials and relating these wear mechanisms to the coated tool's life expectancy. Some lubrication conditions present a more sustainable alternative to current methods used in the turning process; the employment of coated tool inserts under these conditions is a current popular research topic, as there is a focus on opting for more eco-friendly machining options.

**Keywords:** machining; turning process; turning tools; solid tools; cemented carbide; coated tools; coated cemented carbide; Physical Vapor Deposition (PVD); Chemical Vapor Deposition (CVD); multilayered coatings; nanolayered coatings; wear mechanism; tool life; minimum quantity Lubricant (MQL); cutting forces

## 1. Introduction

The machining industry has seen a significant growth in the past 5–6 years, and it is projected to be a 100 billion USD industry by 2025 [1]; this is primarily due to the high demand for higher quality products and computer numerical control machines (CNC), that enable manufacturers to develop these high quality and complex products at higher speeds [2]. Nowadays, there are 6-axis CNC machines, capable of turning feedstock bars into a complete product, which are quite appellative to the machining industry [3]. Moreover, the lathe and milling segment are still leading the market. In 2018, the lathe segment was leading the market, valued at 17.65 billion USD, followed by the milling segment [4]. The lathe market has grown significantly and is expected to keep growing in the following years [5].

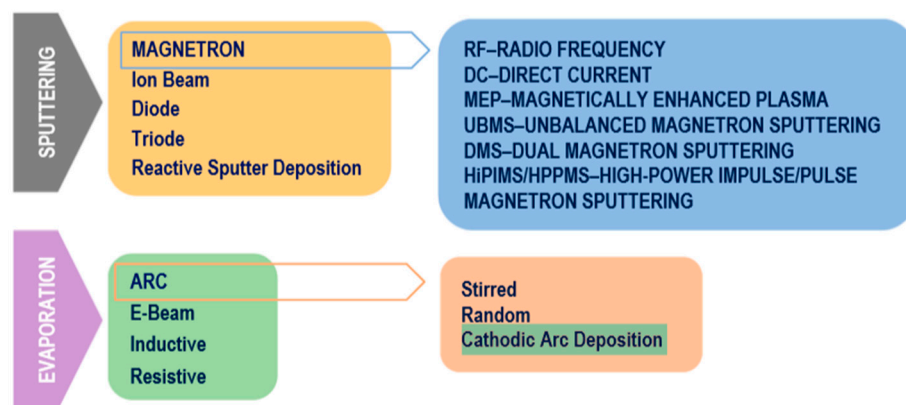
The turning process can be described as the machining of a piece of material that is rotating, using a single pointed tool that is stationary, to produce a smooth and straight outside or inside radius on the piece. When turning, some considerations need to be taken into attention, such as the type of turning that is being made, for example longitudinal turning, and external or internal turning; quality demands, such as surface finish or tolerance must also be taken into consideration, because these are factors that depend on the material that is being machined, as well as the tools and the machine that is being used [6]. As previously stated, the tools used for turning are single-pointed, and can be

categorized into solid tools and insert tools; these tools can be coated to improve the process. Turning was initially carried out on a lathe, but the processes have seen significant evolution, particularly due to the development of computer numerical control (CNC) machines from the 1980s onwards, as well as turning centers, and later machining centers that could employ different processes such as turning and milling. This led to an increase in their use in the manufacturing industry [7], evolving from basic lathes, to multiple-process machining centers.

As the machines for turning evolved, so did the tools that were being used in the process, from solid tools with simple geometries, usually made out of steel, to coated cemented carbide tools, that make up to 80% of all tool inserts used in today's machining. These coated cemented carbide tools have improved the machining process significantly by enabling the machining of materials at faster rates than using conventional, uncoated tools [8,9]. These coatings are deposited on the surface of the tool to provide more wear resistance or a lower friction coefficient—in summary, these coatings provide a way to machine materials at higher speeds, while maintaining overall good surface quality and, especially, improving tool life, by reducing cutting forces, temperature and tool wear. There have been recent developments in cemented carbide tools, fabricating these tools with gradient layers, where the outer layers are, for example, harder than the substrate [10]. The fabrication of these gradient composite tools will provide tools with more versatility, as the desired properties can be applied on the base tool and improved on the surface, increasing their performance. Studies have been made to analyze the way the thickness of these gradient layers affect the properties of these tools [11]. A study carried out by Zhou et al. [12], tested different gradient cemented carbides, with layers of differing thicknesses, and has tested these with different coatings in the high speed cutting of a titanium alloy. Thus, Zhou et al. found that the thickness of the gradient layer's influences cutting performance, and that this thickness can be controlled by altering the contents of the cemented carbide constituents. Additionally, the authors concluded that the carbide with the thickest layer had the best cutting performance, making the control of these thicknesses very appealing when dealing with this type of substrate.

Coatings can be obtained using two different processes, either by Chemical Vapor Deposition (CVD), or by Physical Vapor Deposition (PVD). CVD films are achieved by having a precursor pumped inside a reactor; this precursor is regulated by control valves. The precursor molecules pass by the substrate and are deposited on its surface, achieving a thin, hard coating. This process runs at high temperatures, reaching temperatures of up to 900 °C and, additionally, the film thickness is usually uniform throughout the substrate surface. PVD consists of different methods, such as evaporation, sputtering and molecular beam epitaxy (MBE). In the sputtering technique, the applied coating is achieved by placing a magnetron near the target, in a vacuum. Then, an inert gas is introduced, then a high voltage is applied between the target and the substrate, releasing atomic size particles from the target. These particles are projected onto the substrate and they start to form a solid film. In the evaporation technique, the target acts as an evaporation source, having the material to be deposited, which works as a cathode. The material is heated at a high vapor pressure, which causes the release of the particles. The pumped gas, inserted in the reactor, clashes with the nano particles, which causes the acceleration of these particles, which in turn creates a plasma. This plasma proceeds through the deposition chamber, thus depositing the coating's layers onto the substrate. Usually, PVD processes, when compared to CVD, run at a lower temperature (under 500 °C), and are more environmentally safe due to the type of precursors used in the CVD process, which are toxic. Additionally, the energy consumption of the PVD process is considerably lower than that of the CVD process [13–16].

Regarding the PVD process, there are various methods that can be used to obtain different coatings, either in composition or with different properties. Some of these methods are quite novel, or are seeing a new use in order to obtain certain coatings. As previously mentioned, the various methods that are applied in the coating industry are either sputtering or evaporation methods. Magnetron sputtering and arc evaporation methods have seen recent use in the deposition of coatings. Figure 1 shows the various PVD methods.



**Figure 1.** Different physical vapor deposition (PVD) techniques that are used currently in the production of advanced coatings [16].

The most used method, for magnetron sputtering PVD coating, is the direct current method (DC), however there are many more (as seen in the previous image), such as unbalanced magnetron sputtering (UBMS) and the novel high-power impulse/pulse magnetron sputtering (HiPIMS/HPPMS). Regarding these sputtering methods, there is a recent paper, that presents a method on how to control the boron-to-titanium ratios of  $TiB_x$  thin films. The authors show, in this paper, that the addition of an external magnetic field during the strongly magnetically unbalanced magnetron sputtering of a  $TiB_2$  target in Ar, enables the ability to control the ratio of B/Ti. This research paves the way for synthesizing stoichiometric single-crystal transition-metal diborides [17]. Still regarding magnetron sputtering, a paper by Romero et al. [18] studies the properties of  $TiAlN/TaN$  nanostructured coatings deposited by DC magnetron sputtering. These coatings were deposited at different substrate rotation speeds. These different rotation speeds enable the control of the coating's architecture and mechanical properties. Recent studies on the HiPIMS reveal interesting results, such as having better coating adhesion or even having better coating mechanical properties. This paper by Zauner et al. [19], studies the influence of HiPIMS parameters on the properties of  $Ti-Al-N$  thin films, by using a  $Ti-Al$  composite target in mixed  $Ar/N_2$ - atmospheres. The parameters that were studied were both the pulse frequency and duration, and the  $N_2$  flow ratio, substrate bias voltage and target composition. The optimal parameters for obtaining good values of hardness and moderate compressive stresses were determined, and it was found that the regulation of these parameters enables the control of the coating's structure. These variations can promote the formation of a highly preferred cubic phase, though altered gas-to-metal ratios arriving at the film surface.

Regarding evaporation methods, the arc evaporation has seen some use in recent research, especially the cathodic arc deposition method. In this paper, coatings obtained by this method will be mentioned. In a recent paper by Zhirkov et al. [20], a stable and reproductible arc plasma generation from a  $TiB_2$  cathode is presented. The authors show that the use of a Mo (molybdenum) cylinder around the boride cathode limits the movement of the arc spots to within the rim. This, coupled with a  $TiB_2$  cathode containing 1wt% of carbon, generated a stable arc with high reproducibility. These borides are not usually synthesized using DC arc evaporation, although the authors show with these results that the cathodic arc is an efficient method for the synthesis of these metal borides

When selecting the type of coating desired for a tool, the machining process being implemented must be taken into consideration, as there are some advantages and disadvantages to coatings that are applied to cutting tools. For example, in the paper presented by Hovsepian and Ehiasarian [21], the production of coatings using different PVD techniques is explored, namely the conventional DC magnetron sputtering and the HiPIMS technique. The produced coatings were tailored for the applications that were chosen, while investigating the properties of the produced coatings. Studies such as these highlight the necessity of good planning when choosing the right coating for the right application. Furthermore, some parameters, such as coating properties (i.e., chemical composition,

hardness or coating design), influence tool performance when applied to different machining processes (for example, roughing or finishing), but the deposition method also influences the cutting behavior of these coatings. CVD coatings are usually applied to cemented carbide cutting tools due to the good behavior of these materials under elevated temperatures, whereas, due to the overall low temperature of the PVD process, this also means that this method can be used to coat tool steel, with some studies having been done on the preparation and evaluation of these coatings [22]. However, there are some studies that propose an approach to solve the problem of diamond deposition on steel substrates using the CVD process. The authors propose a Ni/Cu/Ti interlayer for the diamond coating to adhere. The coating showed good adhesion to the multi-metal interlayer, and good wear resistance [23,24]. The study by Silva et al. [25] evaluates the wear resistance of Ti–Al–Si–N coatings deposited by PVD on a steel substrate; the coating was evaluated, including the adhesion of the coating, and the authors reported that a good adhesion of the coating to the tool steel was achieved. PVD, being a line-of-sight process, has some disadvantages, for example, it is harder to apply PVD coatings on complex geometries, although this can be achieved by using, for example, pulsed high-power sputtering [26]. Another disadvantage of PVD is that the coating thickness is harder to control throughout the substrate surface, however, using the mentioned pulsed high-power sputtering, the thickness distribution of the PVD films is more homogenous [26]. PVD coatings are usually thinner than CVD coatings. A thin PVD coating is more suited for finishing operations, as the thinner PVD coatings, confer the tool with a sharp cutting edge (when compared to thicker CVD coatings), also, the compressive stresses exhibited by PVD coatings (CVD coatings exhibit tensile stresses, contrary to the PVD coatings) are favorable; these stresses, coupled with the small layer thickness, make for a stronger and sharper cutting edge, making these coatings ideal for finishing operations [27–29]. Still regarding coating thickness, although generally PVD coatings are thinner than CVD coatings, there is a novel method that enables the deposition of thick PVD coatings, using a state of the art arc-evaporated PVD technique, that can grow coatings up to 24.5  $\mu\text{m}$  [30].

As previously stated, coatings provide tools with properties that best fit machining applications, and, as in the case of gradient cemented carbide tools, that have different layers with different properties; coatings can use the same principle as these tools. This means that a coated tool may have a multi-layered coating, in which, for example, the outer layer has elevated wear resistance and the subsequent layer has a main thermal dissipation function. This versatility makes coated tools very appealing.

Tool coatings are classified by their architecture type (number of layers/layer arrangement) and by their chemical composition (layer composition). They are also characterized by their mechanical properties, such as hardness, indentation modulus and their stress state (stresses induced during the deposition of these coatings). Additionally, the microstructures of these coatings are often analyzed, as these are linked to the mechanical properties of the coatings. There is recent research that studies the altering of the microstructures of some coatings, in order to improve their performance.

Coatings can have various designs, from single layer to multi-layered coating. The types of coating architecture are as follows:

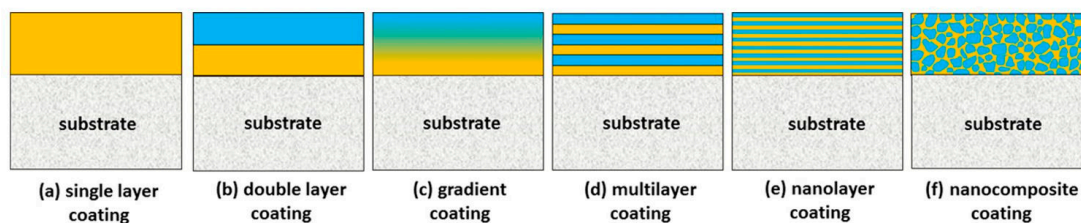
- (a) Single layer coating;
- (b) Double layer coating;
- (c) Gradient coating;
- (d) Multilayer coating;
- (e) Nanolayered coating;
- (f) Nanocomposite coating.

Different coatings with different designs have different types of architecture; the coating can have, for example, a multilayered architecture. The architecture of the coating is linked to coating design, meaning different architectures are chosen to deal with different problems.



Multilayer coating is a type of coating that shows more application in the industry by combining more than one appealing characteristic of each layer of coating. The higher number of layers also contributes to a hardness increase and to a higher crack propagation resistance. In this way, the tool performance can be enhanced, making this type of coating very attractive [14,18,30,31]. Additionally, in a study carried out by Kainz [32], multilayered CVD coating (TiN/TiBN) is compared to single-layered TiN and TiBN, concluding that performance is better with the multilayered coating.

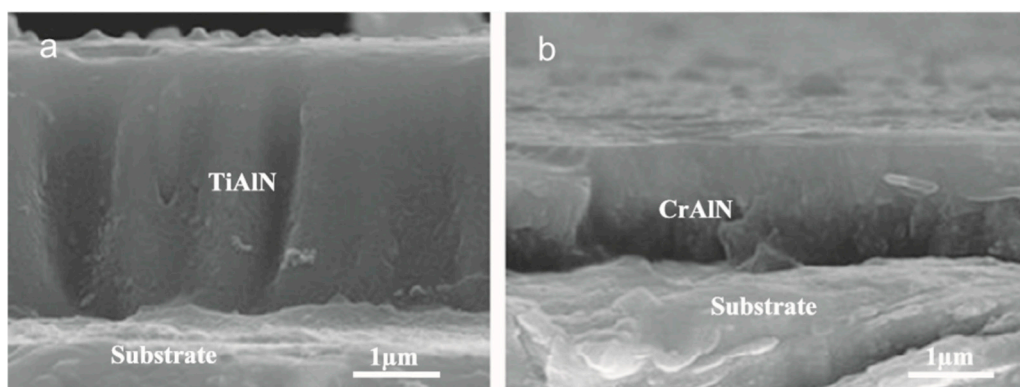
Figure 2 shows, in a scheme, how the different types of coating look when applied on the substrate.



**Figure 2.** Different designs of hard coatings. Reproduced from [14], with permission from Elsevier, 2017.

Coatings are also characterized by their chemical composition, for example, different types of coatings with different chemical compositions are obtained through different deposition processes. The most common coatings obtained by PVD processes are TiN, Ti(C, N), (Ti, Al)N, while the most common coatings obtained by CVD are Ti(C, N),  $\text{Al}_2\text{O}_3$ , and TiN. Notice that these coatings are employed in different types of architecture, in order to obtain a better-suited cutting tool for a certain machining operation [27]. It is important to note that the chemical composition is important, as different chemical compositions have different hardnesses, friction coefficients and different thermal conductivities, which directly influences coating wear patterns. Regarding coating microstructure, it varies with the coating's chemical composition. Images will be presented regarding the microstructure of various coatings, especially those that have recently been researched. There are various studies regarding coating microstructure, either analyzing coatings obtained by a novel process or analyzing microstructural changes that might occur after machining. In a study by Longt et al. [33], the cutting performance of TiAlN- and CrAlN-coated silicon nitride inserts is analyzed in the dry turning of cast iron (Figure 3). The microstructure of these coatings is also analyzed and is displayed in the following images.

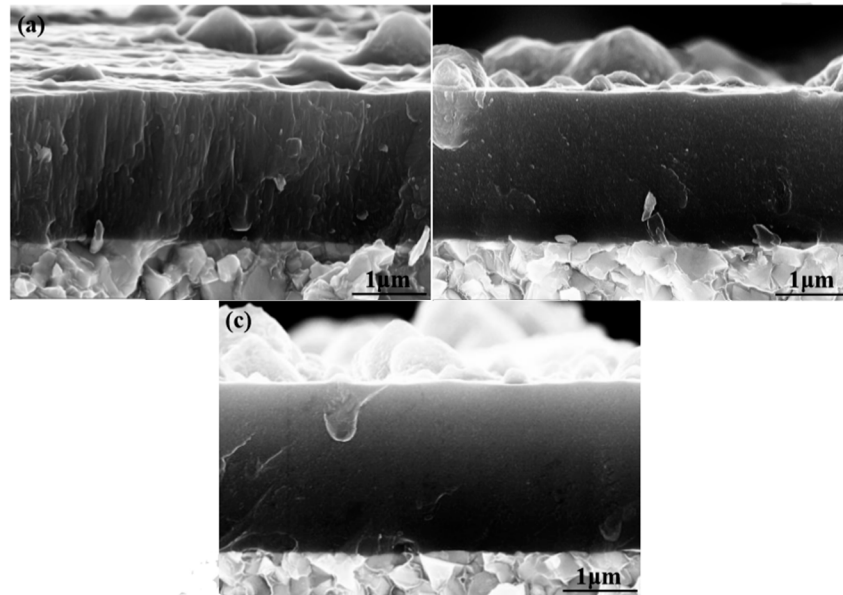
The mentioned coatings were obtained by PVD cathodic arc evaporation, and their thickness were about  $4\ \mu\text{m}$  for the TiAlN coating and about  $2\ \mu\text{m}$  for the CrAlN coating.



**Figure 3.** (a) TiAlN coating microstructure (b) CrAlN coating microstructure. Reproduced from [33], with permission from Elsevier, 2014.

The authors reported that the TiAlN coating had a dense and smooth structure with small grains, while the CrAlN coating's structure had formed columnar crystallites.

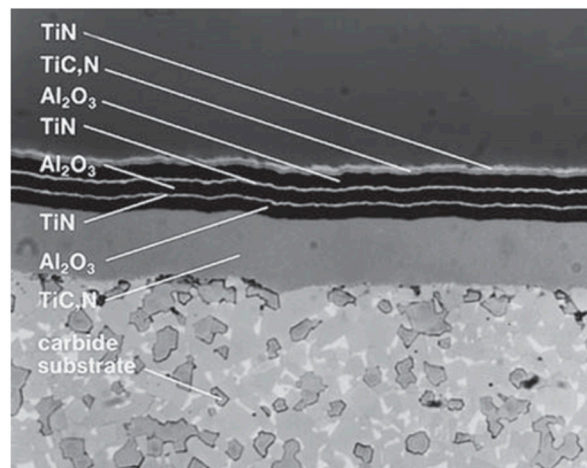
Still regarding coating microstructure, another study [34] analyzes the influence of Ni on the microstructure of a PVD cathodic arc evaporation obtained using AlTiN coating (Figure 4). The cutting performance is also analyzed in this study. Three samples were analyzed, one coating composed of AlTiN, another with 1.5% Ni and the third one with 3% Ni content. The following images are of the microstructures of these coatings.



**Figure 4.** (a) AlTiN coating microstructure with 0% Ni; (b) AlTiN coating microstructure with 1,5% Ni (c) AlTiN coating microstructure with 3% Ni. Reproduced from [34], with permission from Elsevier, 2019.

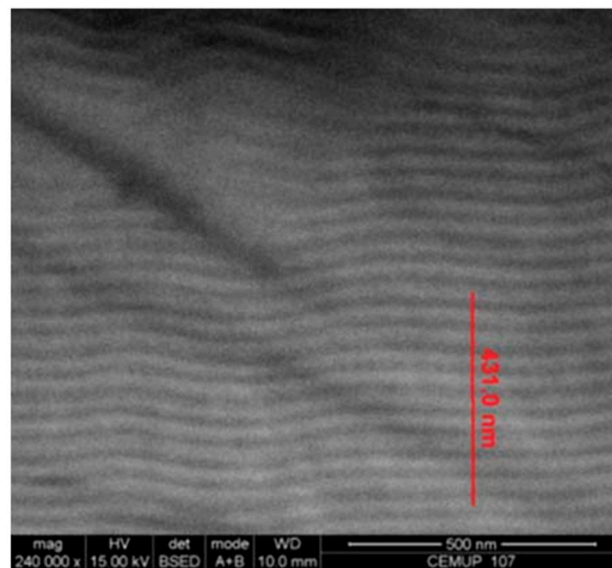
Notice the microstructural change that is occurring: while the coating with 0% Ni (a) exhibits a columnar microstructure, the addition of Ni promotes a more compact nanocrystalline structure. Although the nanohardness and elastic modulus for the AlTiN coatings had the highest values (26.2 GPa and 315.8 GPa respectively), the authors report that the coating with 1.5% Ni (b) has the best cutting performance. The lowest hardness values and elastic modulus came from the coating with 3% Ni (c) (20.9 GPa and 300.5 GPa respectively). It was also reported that the coating adhesion was worst for the 3% Ni (c) coating, while the 1.5% Ni (b) coating was practically tied with the AlTiN coating in terms of adhesive strength. However, the 1.5% Ni (b) coating was the coating with the greatest toughness, improving tool life by 160%.

Regarding multilayered coatings, these are very appealing to the machining industry, as they confer tools with various properties that can be combined in order to achieve a satisfactory machining process. The trend seems to be reducing layers' thickness, in order to achieve a greater combination of various properties, such as high hardness, a low friction coefficient, thermal conductivity, diffusion barrier and corrosion resistance [35]. Figure 5 shows the overall structure of multilayered coatings.



**Figure 5.** Example of a complex CVD-obtained multilayer coating microstructure. Reproduced from [35], with permission from John Wiley and Sons, 1969.

The nanolayered coatings are a type of multilayered coating, the difference being the layer thickness, which is in the nanometer range. Figure 6 shows the structure of a nanolayer TiB<sub>2</sub> coating.



**Figure 6.** TiB<sub>2</sub> nanolayer coating structure. Reproduced from [35], with permission from John Wiley and Sons, 1969.

The coating's structure influences the overall coating strength and adhesion to the substrate. It is an important aspect of fabricating new coatings or finding the correct application to a certain coating.

As previously mentioned, the coatings are also characterized by their mechanical properties, such as hardness, indentation modulus and the stress state of the coated tool (residual stresses that were induced during the deposition process). These mechanical properties can be altered by changing the coating's microstructure, as seen in the previous study [34], or by changing the coating's architecture or structure. As previously mentioned, a multilayered coating has more compressive stresses (e.g., a thin PVD coating); this will make for a stronger and more tough cutting edge. Additionally, their high number of interfaces confers coating strength. However, these residual stresses may provoke coating adhesion problems. In a study by Dai et al. [36], the properties of TiB<sub>2</sub>/Cr multilayered coatings with double periodical structures are studied. Various multilayered architectural structures were studied, changing the thickness of the Cr layer in order to see the changes to the microstructure and

mechanical properties. It was reported that this double periodical multilayer structure can refine the growth structure of the  $TiB_2$  grains, resulting in a betterment of the coating's mechanical properties. The authors also reported that the residual stresses can be decreased through the deformation of the metallic Cr layers, which, in turn, causes a dramatical improvement to the coating adhesion. Additionally, keeping these residual stresses low can also boost the peel resistance of the coatings [37].

Coatings are applied depending on the machining process and based on the process's pre-requisites, since their performance is heavily tied to the coating's properties (chemical composition, architecture, microstructure and mechanical properties). Because of this, coating design is very important [21,38]. To know which coating to apply and where to apply it, studies have been conducted to evaluate cutting tool behavior. There are many parameters able to affect the cutting performance of a tool, such as cutting speed, feed, depth of cut and lubrication regimen, and tool performance issues which affect the tool's life and the overall finish quality of the workpiece. Cutting tool behavior knowledge has proven to be key in optimizing the turning process. By changing these parameters accordingly, a process can be optimized to meet the expected results [39], such as in the study performed by Krishnan [40], which used the Taguchi method to predict the best parameters to attain the lowest surface roughness when turning IS2062 E250 Steel. The parameters that were varied (input parameters) were the cutting speed, depth of cut and feed rate. The Taguchi loss function was used to compare the experimental values to the desired ones and to predict the output results (surface roughness and material removal rate (MRR)). An analysis of variance (ANOVA) method was used to determine the parameters that most influenced the desired result or the output parameters, in this case the surface roughness and MRR. The process could then be optimized to achieve the good surface roughness that was desired. Similarly, a study conducted by Durga [41], used the Taguchi method to predict the best machining parameters for turning AISI 304 stainless steel with a  $TiAlN$  nano-coated tool. The variable parameters of this study were the cutting speed, depth of cut and feed rate, then the authors developed regression equations based on the results for the surface roughness and material removal rate obtained from the empirical tests to develop equations to determine the surface roughness and material removal rate when using coated or uncoated tools for this type of experiment. Recently, studies on the parameters that influence tool performance are focusing on the minimum quantity lubricant (MQL), studying the effect of using this method in the machining of various materials using different tools. The study performed by Khan and Maity [42], which employs MQL using vegetable oil and compares it to dry cutting and flood cooling when turning commercially pure titanium, obtained satisfactory results, reducing cutting forces and cutting temperature when using this approach. Tool geometry also affects the cutting performance, because, by analyzing the cutting tool behavior more adequately, geometries can be created to achieve the desired results. Regarding the study carried out by Harisha et al. [43], cutting tool geometry is analyzed in order to minimize the cutting force when turning hardened steels, this is because tool geometry, when incorrect, leads to energy loss which results in loss of productivity.

In this paper, the recent advances in coated turning tool behavior are analyzed, looking at the different coatings that have been used in recent years. The different wear mechanisms which the coated turning tools are subjected are also going to be analyzed and presented, relating the different wear mechanisms to the coated tool life. There is also a chapter in this paper that will be reserved to the behavior of coated tools under advanced lubrication or cutting conditions, such as, turning using MQL conditions or using cryogenic conditions. Finally, the paper will conclude with a summary of each chapter and there will be mention of what are the recent trends in the turning process using coated tools.

## 2. Coatings for Turning Tools

In coatings applied to tools, or hard coatings, generally, nitrides, carbides, borides and oxides of transition metals are used. The nitrides used as coatings for cutting tools are  $TiN$ ,  $TiAlN$ ,  $CrN$ ,  $ZrN$ ,  $TiSiN$ ,  $TiAlSiN$ ,  $CrAlN$ ,  $TiAlCrN$ , and  $cBN$  [8,9,14,41]; carbides for coatings are  $TiC$ ,  $CrC$ , and  $WC$ . For boride coatings,  $TiB_2$  is used due to its chemical inertness, high hardness and good wear resistance.



Additionally, they can be deposited in tool steel with good adhesive capabilities [44,45]. One of the most widely used oxide coatings is the  $\text{Al}_2\text{O}_3$ . Other somewhat common coatings for cutting tools are DLC,  $\text{MoS}_2$  and WC-C [13,15].

Due to the drastic tool life reduction, and overall unsatisfactory surface roughness values of the workpiece when using high speed steel (HSS) as a tool material, the industry has been using tool coatings to overcome the issues arising from the use of HSS. In a study by Gupta et al. [46], the cutting characteristics of PVD-coated turning tools were analyzed. The test involved the turning of C45 steel using solid tools coated with TiN, AlCrN and TiAlN. Cutting forces were measured, while cutting speed and feed rate were varied throughout the testing process. The TiAlN coating proved to be the most efficient, relative to tool life, due to its hardness and self-lubricating ability, almost avoiding the adhesion of the workpiece material to the tool surface, and therefore increasing tool life. Research like this continues to be important, as the choice of the right coating can prove to be a profitable choice for manufacturers, a fact that explains the vast amount of studies performed in this area, from finding optimal conditions to machine a certain material, to comparing various types of coatings with different structures or coating methods. In the following paragraphs, recent studies made on the comparison of various coatings, and studies that use coated tools with novel/complex geometries in the turning process, are going to be presented.

The work developed by Koyilada [47], testing the machinability characteristics of Nimonic C-263, used coated cemented carbide for turning that material under dry machining conditions. Carbides were coated with commercially available CVD bilayer coating (TiCN (bottom layer)/ $\text{Al}_2\text{O}_3$  (top layer)), and PVD multilayer coating (TiAlN/TiN), consisting of alternating layers of TiN and TiAlN on the substrate. Both these coating types were compared. The results show that the PVD coating presented a remarkable improvement in the surface finish of the workpiece when compared to the CVD-coated tool. Cutting forces measured in the tests were also lower when the PVD coating was in use. Additionally, the PVD coating outperformed the CVD bilayer coating in terms of tool life. This is due to the PVD-coated tool presenting a superior compressive strength when compared to the CVD-coated tool (due to deposition technique and multilayer configuration), making it more suitable to work under a fluctuating load. Due to the microstructure of Nimonic C-263, the tool is subjected to dynamic fatigue, even in continuous machining, which explains the underperformance of the CVD coating in this case. Although the PVD multilayer coating is preferred for higher cutting speeds, ranging from 50–90 m/min (further cutting speed augmentation would require the use of a cutting fluid paired with the coated cutting tools), the CVD bilayer coating should be used to turn this material at speeds below 60 m/min, because the top layer of  $\text{Al}_2\text{O}_3$  has a low thermal conductivity, which results in a higher machining temperature at higher cutting speeds. This eventually leads to wear problems, especially material adhesion and coating disaggregation.

Another study that compares the characteristics of CVD and PVD-coated carbide tools, is a work presented by Ginting [48] which studies the productivity of AISI 4340 hard turning using multilayered CVD (TiN (top layer)/ $\text{Al}_2\text{O}_3$ /TiCN (bottom layer)) and monolayered PVD coatings (TiCN). Productivity was characterized by the material removal rate (MRR) and volume of material removal (VMR). Otherwise, the variables analyzed in the tests were cutting speed, feed rate and depth of cut. The upper limits set to the coated tools reveal that the CVD multilayer-coated carbide can achieve a slightly higher feed rate and depth of cut value. In terms of tool life, the PVD monolayer coated tool endured for longer than the CVD-coated tool. In terms of surface roughness, the PVD coating was more effective as well. As mentioned above, PVD coatings have more sharp edges and are thinner, providing a better quality surface finish, however, in terms of productivity the CVD-coated carbide achieved values higher by about 78–125% than the monolayer PVD-coated tool. This highlights the fact that choosing the right coating method and type of coating can prove an advantage. As seen in that study, the PVD-coated tool performs better regarding tool life and overall surface finish quality, but in terms of MRR the CVD-coated tool is more effective. This is due to the coating properties: while the PVD coating (TiCN) is harder than the outer layer of the CVD coating (TiN), its friction coefficient

is also lower when compared to the TiN. This, coupled with the fact that thin PVD coatings confer the tool with sharper cutting edges and have more compressive stresses (caused during the PVD process [29]), give the PVD coating superior finishing capabilities when compared to this CVD coating.

In the work presented by Kumar et al. [49], the performances of PVD coated carbides using TiAlN, AlCrN and TiAlN (top layer)/AlCrN (bottom layer) were tested in the turning of Inconel 825, as well as uncoated carbide tools. The performance of each tool was evaluated, taking into consideration the flank wear of the tool, work-piece surface roughness, cutting force generated during the cutting process and chip formation. The optimal machining parameters were analyzed using grey relational analysis under multiple response optimization, and the results showed that the bilayer coating (TiAlN/AlCrN) outperformed the single layered coatings, TiAlN and AlCrN, in the machining of this alloy.

Still regarding the comparison between CVD- and PVD-coated tools, the study performed by Koseki et al. [50] compares TiN-coated tools obtained by different deposition methods in the continuous turning of Ni-based super-alloys. These high-strength, low-conducting alloys require higher cutting forces and temperatures than other materials during the machining process. The damage suffered during the tests was investigated, and the CVD coating proved to be more efficient in the machining of these alloys, suffering almost no change in coating hardness and overall less plastic deformation in the process.

A method that has seen some use is the coating of a textured tool in order to promote better chip removal, better adhesion of the coating to the tool and even an improved tool life. In the work developed by Mishra [51], the machining performance of laser-textured chevron shaped tools, and untextured tools was evaluated. These tools were coated with AlTiN and AlCrN using PVD. Cutting forces and tool wear were analyzed for textured and untextured cutting tools. Coating growth on textured tools was better, presenting a reduced number of microcavities and macroparticles for both coatings. The value of the cutting forces was lower for the textured tools, resulting in less tool wear, and the texture on the tools improved the tool-coating adhesion. The chips formed by the textured tools were thinner when compared to untextured tools, however, chip fragments were embedded in the textures. Thus, machining parameters need to be adjusted in order to find a balance between these two phenomena in order to produce favorable machining conditions.

As previously stated in Chapter 1, discussing developments in gradient cemented carbide tools, studies on the influence of this gradient and on how to control the grain size of the cemented carbide, have been conducted [11,12]. These gradient cemented carbides already represent a significant improvement when using uncoated cemented carbide tools. Additionally, these gradient cemented carbides may improve the quality of the coating, making it more adherent to the substrate, and even improve tool performance. A paper presented a study regarding CVD coating application on gradient cemented carbide tools of different grain sizes, where it was observed that the coating thickness is related to the carbide grain size, coating thickness increases with smaller grain sizes [52]. It was also concluded that the adhesion strength of the coating is overall better on gradient cemented carbides when compared to regular cemented carbides, however, the adhesion strength drops when the grains of the cemented carbide are finer. A thicker coating may not be ideal for finishing operations, however, for roughing operations, having a thicker coating may be beneficial.

Cutting tool coatings may also provide a sustainable eco-friendlier alternative when machining certain materials, as some of these materials, for example, nickel-based super-alloys, already mentioned in this chapter, require higher cutting speeds, which results in higher cutting forces and a higher temperature in the cutting area. To counteract these problems, lubrication is employed, sometimes by flooding the cutting area. Practices like these have proven to be unsustainable and damaging to the environment.

A recent tendency is to employ methods able to reduce the high usage of these lubricants and make the overall machining process more eco-oriented. These methods (Figure 7) sometimes use biodegradable oils, such as vegetable oils, as lubricants. Dry machining is also a sustainable option, as it removes the use of cooling fluid altogether, having as its alternative the minimum quantity

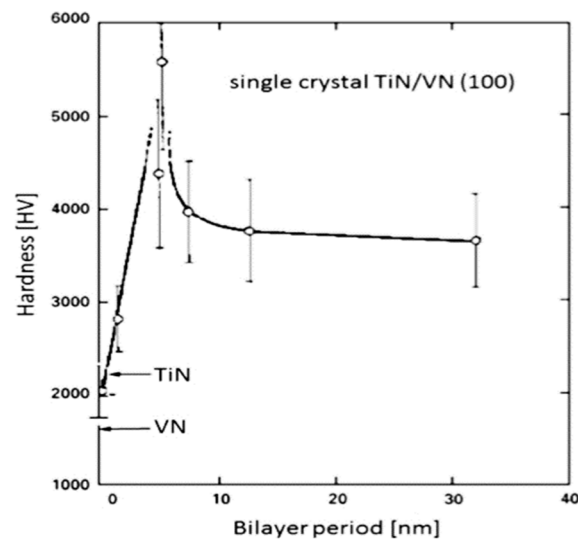
lubrication (MQL) method, in which small amounts of lubricant are employed. MQL presents itself as being a viable alternative to dry machining when having problems with cutting temperature or surface finish quality. Other sustainable methods, such as cryogenic cooling, or the use of a high-pressure coolant, in which the coolant is applied to a select area of the tool, are employed as an alternative to the conventional flood cooling method [53].



**Figure 7.** Wheel of sustainable machining. Reproduced from [53], with permission from Elsevier, 2019.

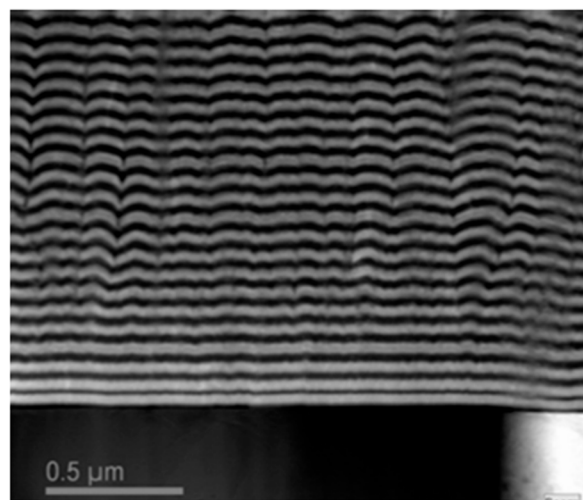
The work produced by Thakur and Gangopadhyay [54] proposes a sustainable alternative to the machining of nickel-based super alloy, by employing TiN/TiAlN PVD-coated tools and dry turning of the Incoloy 825. Tests were conducted employing different lubrication methods, such as dry machining, flood machining and MQL. Cutting forces, temperature of the cutting area, tool wear and surface integrity were evaluated. While the temperature in the cutting area was higher for dry machining when using a PVD-coated tool, the overall surface finish was of better quality when compared to flood cooling and MQL. Moreover, cutting forces also presented lower values when using a PVD coating, even in dry machining. This means that the cutting force necessary would be lower, therefore promoting a more environment-friendly alternative (dry machining); an overall better surface finish was obtained using the PVD-coated tool under an MQL environment.

Regarding nanolayered coatings, they are quite appealing, mainly due to their high hardness value, for example, research was done on nanolayer TiN/VN coatings, and results found that there was a very high hardness increment [55]. This hardness increase is related to the nanolayer thickness, as see in Figure 8.



**Figure 8.** Hardness increase of a TiN/VN coating, over the thickness of the bilayer. Reproduced from [14], with permission from Elsevier, 2017.

The reason for this hardness increase was attributed to the large number of interfaces between layers, characteristic of nanolayered coatings. In Figure 9, the structure of a CrN/TiAlN nanolayered coating deposited on steel is shown [14].



**Figure 9.** CrN/TiAlN nanolayered coating structure. Reproduced from [14], with permission from Elsevier, 2017.

The structure shown in Figure 9, characteristic of nanolayered coatings, confers the coatings a very high crack propagation resistance, as the cracks tend to not propagate as deep as in a monolayered coating, thus risking damage to the substrate. These coatings are very similar to the multilayered coatings, the main difference being the thickness of each layer and that the hardness value for a nanolayered coating is not equal to the average hardness of its constituents—however, this is the case for regular multilayered coatings [14]. A recent study about the influence of the thickness of these nanolayers in coatings found that, for hardness values at room temperature, there were no significant changes between the coatings with differing thickness layers. However, the cutting properties of the coatings were different, with the coating with the thinnest nanolayers exhibiting a higher tool life than the coating with thicker nanolayers [56].

As mentioned previously, understanding cutting tool behavior is the key to correctly optimizing a machining process. There are many studies on coatings' behavior while cutting, for example, in the study presented by Gassner et al. [57], the thermal crack network on CVD TiCN/Al<sub>2</sub>O<sub>3</sub>-coated cemented carbide cutting tools is analyzed. The theme of coating tools and coating performance is heavily researched, comparing coating methods to achieve overall better machining results, or even finding an eco-friendlier alternative to machining certain materials.

### 3. Coating Influence on Turned Surface Quality

There are many factors that influence surface quality in the turning process, as seen in Chapter 1. A turning process can be optimized in order to have the best possible surface quality, by changing certain parameters, such as rotation speed, feed rate and depth of cut. These parameters are mainly dependent on the machine, as the machine also influences cutting performance and the overall surface finish of the machined piece [58]. There have been studies that relate the chip formation thickness to the overall surface roughness of the machined piece [59]. Using a prediction method to determine chip formation thickness can serve as a monitor of the surface roughness of certain materials. However, there are more factors that influence the surface roughness of turned pieces, such as lubrication method and tool geometry, and the coating that is being employed also affects the overall surface quality of the workpiece. As previously mentioned, thin PVD coatings are very well suited to surface finish operations, and provide an overall better surface quality than thicker coatings. This is mainly due to the sharp edges that are conferred to the substrate, and compressive stresses that confer the tool edge strength [27–29].

In this chapter, the influence of coated tools on the surface quality of various materials are presented. The materials selected are mainly titanium alloys and nickel-based super-alloys, as these are very appealing for structural and engineering applications, especially due to their strength-to-weight ratio. Although these alloys have some processing problems associated with them, for example low machinability rating, their poor machinability may be attributed to material properties, such as high hardness at high temperatures, low thermal conductivity and high chemical reactivity [60]. There have been some studies conducted on the turning of hardened steels, which will also be presented in this chapter, highlighting the coating's influence on turned surface quality.

In the aforementioned study [40], a comparison of the machining performance of coated tools, using a monolayer PVD coating TiCN and a multilayer CVD coating TiN/Al<sub>2</sub>O<sub>3</sub> in the hard turning of AISI 4340 steel. The authors found that, in this case (and as elaborated above), the PVD coating would be best suited for finishing operations, especially due to the hardness values of TiCN and the lower friction coefficient (when compared to the TiN top layer of the CVD coating). The surface roughness values obtained for the PVD-coated carbide and for the CVD-coated tool, are (0.8–1.6) micron and (1.6–3.2) micron, respectively. However, for material removal rate the CVD coating is preferred, although the turned surface quality is poorer than those using PVD coatings.

The study by Fernández-Abia et al. [28], presents a comparison of four coatings (and an uncoated tool) in the turning of austenitic stainless steel, AISI 304L. The cutting behavior of these coated tools were analyzed. The authors mention that these types of PVD coatings are best suited for achieving low values of surface roughness, especially due to the sharp edges conferred by the PVD process. The coatings used were, AlTiN; AlTiSiN; AlCrSiN; and, finally, TiAlCrN. The first three coatings are nano-structured coatings. The graph of Figure 10 shows the results obtained from this study, regarding the surface roughness of the machined material.



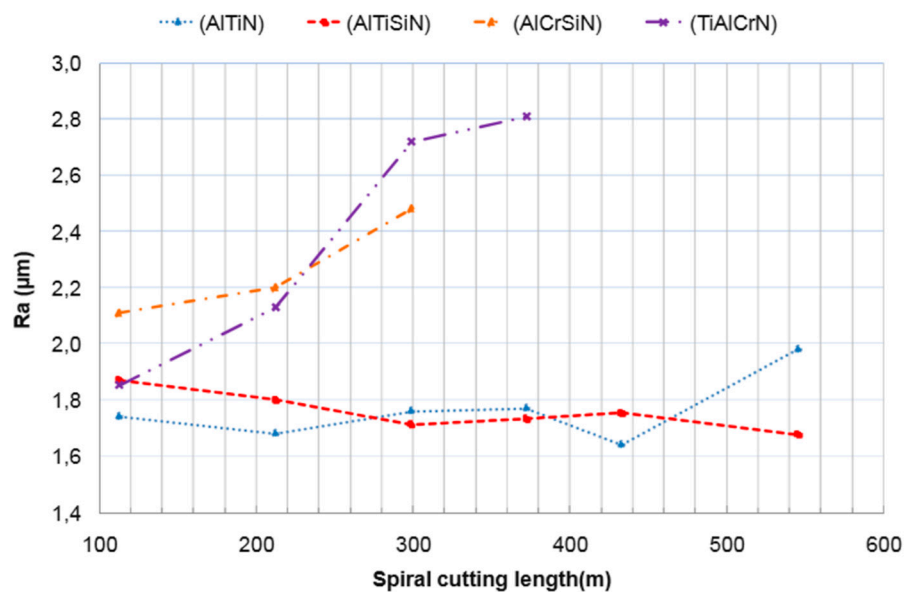


Figure 10. Graphic of surface roughness value (Ra) for different PVD coatings [28].

The best coatings for the machining of this material are the AlTiN and AlTiSiN coatings; this is due to their nano-crystalline structure. Although AlCrSiN also has this beneficial nanostructure, the presence of chromium in its chemical composition favors the creation of an oxide protective layer that is inferior to the AlTiN and AlTiSiN coatings.

Regarding the turning of nickel-based super-alloys, in this study [54], the influence of coating and lubrication/cooling method was observed in the turning performance of Incoloy 825, using a TiN/TiAlN multilayer coating. The results regarding surface roughness obtained from these tests can be interpreted from the graphs in Figure 11.

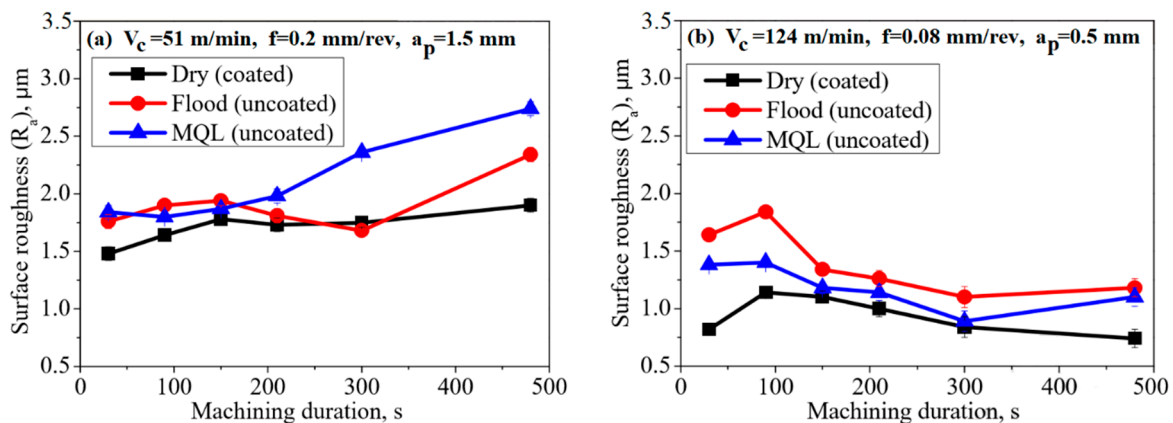


Figure 11. Different values of surface roughness for the machining duration. (a) and (b) have different cutting parameters. Reproduced from [54], with permission from Elsevier, 2016.

The coated tool provides the better surface roughness quality from the tests that were carried out. The fact that dry machining with coated tools provides a better surface quality is quite an interesting finding, as this type of machining is sustainable and eco-friendly, and these coatings enable the machining of high-quality parts at a lower price/environmental impact. The authors also added that the cutting temperature was lower for the dry machining using PVD TiN/TiAlN-coated tools. A study was also mentioned before [49], in which a PVD and CVD coating were used in the machining of Nimonic C-263; the findings of these authors report that the PVD TiN/TiAlN multilayered coated tool is better for the surface finish. Due to the sharper edges, this coating provided a 14.3% reduction

in surface roughness value when compared to the CVD TiCN/Al<sub>2</sub>O<sub>3</sub> counterpart, in which a higher edge radius contributed to the lower turned surface quality. As stated previously, the PVD coating is preferred for higher machining speeds than the CVD coating.

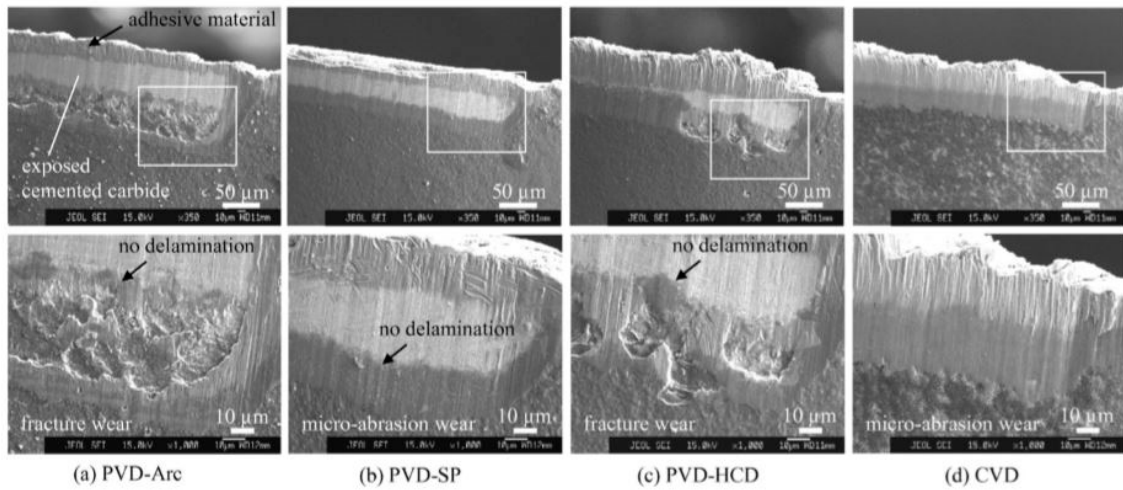
Without a doubt, coatings improve the overall surface finish quality of turned parts, however, tools with the correct geometry can rival the low roughness values obtained, especially those with thinner PVD coatings. By analyzing the literature, a trend can be seen, with thin PVD coatings usually being employed in finishing operations, explained by the residual stresses that thin PVD coatings have (compressive stresses), and by the sharp cutting edge that these coatings confer to tools. Their chemical composition is also a contributing factor, as, depending on the coating chemical composition, these will react differently with the material that is being turned, sometimes even forming hard protective layers that lower the friction coefficient, thus improving overall coated tool performance [25].

#### 4. Tool Wear Mechanisms

Coated cutting tools significantly improved the tool life of conventional tools, as coated tools suffer overall less wear in the same lifetime as an uncoated one, particularly at high machining speeds [61], however, coated tools eventually give out, due to the fact that a lot of these coated tools are used in dry machining conditions, which means that the machining temperature is overall higher. A coated tool has different wear mechanisms, such as abrasive wear, thermal cracks, adhesive wear, build up edge (BUE), or coating structure failure, resulting in spalling or cracks appearing on the coating. Understanding the different wear mechanisms for each coating type helps one make a better coating or machining parameters choice to achieve the desired results. These wear mechanisms are related to some parameters; for example, when there is an increase in the cutting force, it can be assumed that the coating is suffering abrasive wear, or that there is a problem with the coated tool's edge. Wear is also related to the coating properties, different coatings (or coating layers) have different hardnesses, friction coefficients and thermal conductivities, all factors that also contribute to the wear patterns of these coated tools. Coating microstructures can influence factors, such as coating adhesion, that might cause fracture wear later. Mechanical properties, such as hardness, indentation modulus and the stress state of the coating itself, affect the wear patterns that these will suffer. In some cases, high residual stresses can cause problems with coating adhesion, that is, the coating's adhesive strength is lower, and the coating is more likely to suffer spalling or delamination, although, as mentioned before, different coatings obtained by different deposition methods have different stress states. Hardness is primarily tied with abrasive wear, as well as the coefficient of friction (COF); the latter being related to coating design (layer thickness or layer chemical composition), as seen in the study by Dai et al. [36], where it is reported that the increase in the thickness of a Cr layer, in a multilayered TiB<sub>2</sub>/Cr coating with double periodical structures, would result in a decrease in coating hardness and an increase in coefficient of friction, which will affect the coated tool's wear rate.

In this chapter, some studies regarding different wear mechanisms and coating degradation will be addressed, presenting images for some types of wear mechanisms, as well as a summary of the findings of these studies.

In a work mentioned in the previous chapter [50], there is a study on the wear of TiN coatings obtained by different deposition methods. In addition to abrasive wear and fracture wear, a common wear mechanism is adhesive wear, where the material adheres to the coated tool. In Figure 12, the wear mechanisms for the TiN coating, obtained by different deposition methods, can be seen on the tool's cutting edge.



**Figure 12.** Wear mechanisms on TiN coating, in the continuous turning of a nickel-based super-alloy using different coating techniques: (a) PVD-arc, (b) PVD-SP, (c) PVD-HCD and (d) CVD. Reproduced from [50], with permission from Elsevier, 2015.

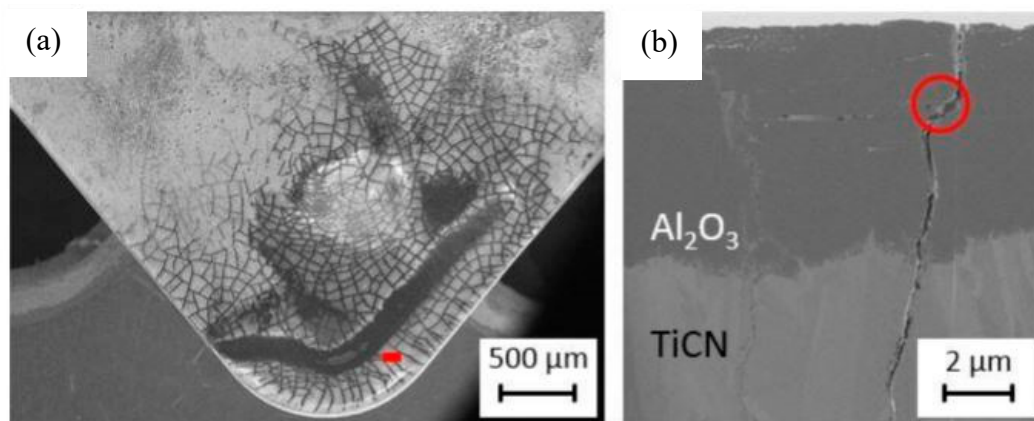
In Figure 12, in addition to noticing the adhesive material on the cutting edge, other wear mechanisms can be seen, such as fracture wear, where the cemented carbide substrate is exposed. There is also micro-abrasion wear that can be noted on all the samples.

Still regarding the same study [60], some plastic deformation can be observed in the coating (Figure 13). In this image, a broken coating area and adhesive material can also be seen.



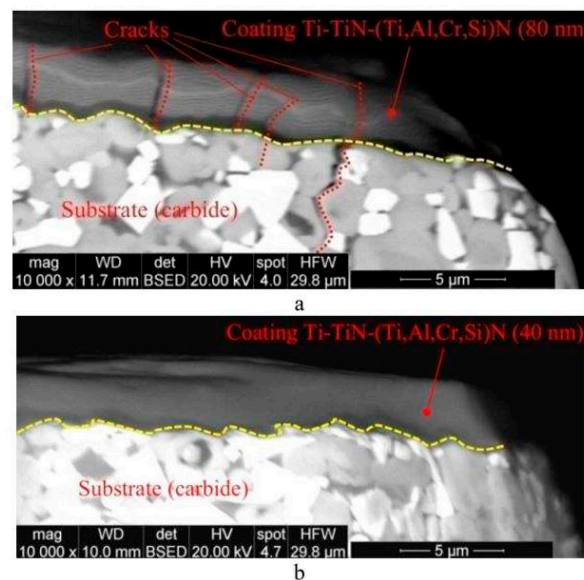
**Figure 13.** High resolution TEM image regarding a TiN coating obtained by PVD-Arc, noticing wear on the surface of the tool. Reproduced from [50], with permission from Elsevier, 2015.

Also due to temperature, thermal cracking may occur on the coating. Another study regarding thermal cracking of CVD TiCN/Al<sub>2</sub>O<sub>3</sub>-coated cemented carbides [57] analyzes various methods to close the cracks that occur due to excessive cutting temperature, such as wet blasting or filling the cracks with TiO<sub>2</sub>. This wear mechanism can be observed in Figure 14, taken from the same work.



**Figure 14.** (a) SEM image of rake face of a coated CVD insert after face turning (b) highlighted section of the rake face. Reproduced from [57], with permission from Elsevier, 2019.

Regarding crack defects on cutting tools, the study performed by Vereschaka et al. [56] highlights the influence of the PVD Ti-TiN-(Ti,Al,Cr,Si)N nanolayer coating thickness, which was tested in the turning of AISI 321 steel. The coatings differed in the number of nanolayers and nanolayer thickness; the coating with the thicker nanolayers had a total of 33 nanolayers (Coating A), and the other coating, with the thinner nanolayers, had a total of 57 of these layers (Coating B). These coatings were also tested against monolayered Ti-(Ti,Al)N-coated and uncoated tools, and both the nanolayered coatings presented a higher tool life than these last two. However, Coating A has less wear resistance and, with the increase in cutting speed, the cutting temperature also increased, inducing thermal stresses in the superficial layers of the tool. This can be observed in Figure 15, where (a) is the image regarding the thickest nanolayered coating and (b) is the thinnest one. The thinner layers provide the coating with a higher wear resistance, which means that thinner layers better resist thermal stress crack formations.



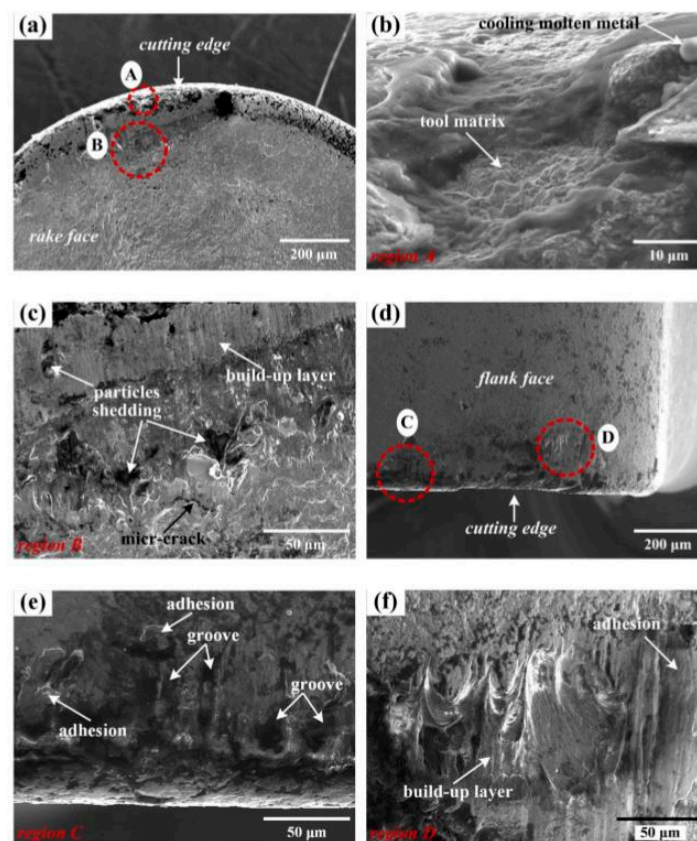
**Figure 15.** Crack formation on PVD nanolayered coating surface, area directly adjacent to the cutting edge; (a) coating with nanolayers of 80 nm and (b) coating with 40 nm nanolayer thickness [56].

Coatings, when deposited, mirror the substrate surface, resulting sometimes in an uneven coating surface, with imperfections such as cracks, and even residual stresses that may have resulted from the coating process. These superficial imperfections may cause material transfer and have a negative impact on the coated tool performance, by promoting tool wear or by not conferring the desired surface finish.



Some methods have been proposed to minimize these defects, such as a post-deposition polishing of the coated tool, in order to lower its overall surface roughness and minimize the potential for material transfer [62]. Another method proposed to deal with cracks is shown in the paper presented by Faksa et al. [63], where the authors study the effect of shot peening on residual stresses and crack closure in CVD-coated hard metal cutting inserts. Due to the stresses seen on the deposition process of the CVD coating on hard metal, the surface layer of the coating exhibits cracks. The authors conclude that well placed and calculated shots can close these cracks and prevent crack nucleation and growth in CVD coatings. These residual stresses also have an influence on PVD films, as shown by Skordaris et al. [64], who studied the effects of PVD films' residual stresses on their mechanical properties, brittleness, adhesion and cutting performance. The coatings used are PVD TiAlN, and different coatings were used, these having different levels of residual stress, obtained by heat treatment. The authors concluded that there is a significant contribution of the film's compressive stresses to increasing the mechanical properties of the coating and adhesion, consequently improving tool life.

The wear mechanisms of a MTCVD–TiCN–Al<sub>2</sub>O<sub>3</sub>-coated cemented tool was also analyzed in another study [65], where wear patterns were observed after 142 min of turning 300 M steel, at a cutting speed of 300 m/min. Crater spalling could be observed, as well as evidence of molten metal particles, which means that the cutting temperature was very high. Signs of adhesion, matrix exposure and build up layer (BUL) were also observed. These wear patterns can be observed in Figure 16.



**Figure 16.** Different wear patterns on the MTCVD coating after 142 min of turning 300 M steel. The rake face (a) was analyzed in two regions A (depicted in (b) presenting signs of cooling molten metal), and region B (depicted in subfigure (c), where signs of BUL and micro-cracks can be noticed). In subfigure (d) the flank face is displayed, and zones C and D are analyzed. Zone C is displayed in subfigure (e), where adhesion damage can be noted, and some grooves. Lastly, zone D is displayed in (f), where adhesion damage is the predominant type of wear mechanism. Reproduced from [65], with permission from Elsevier, 2017.

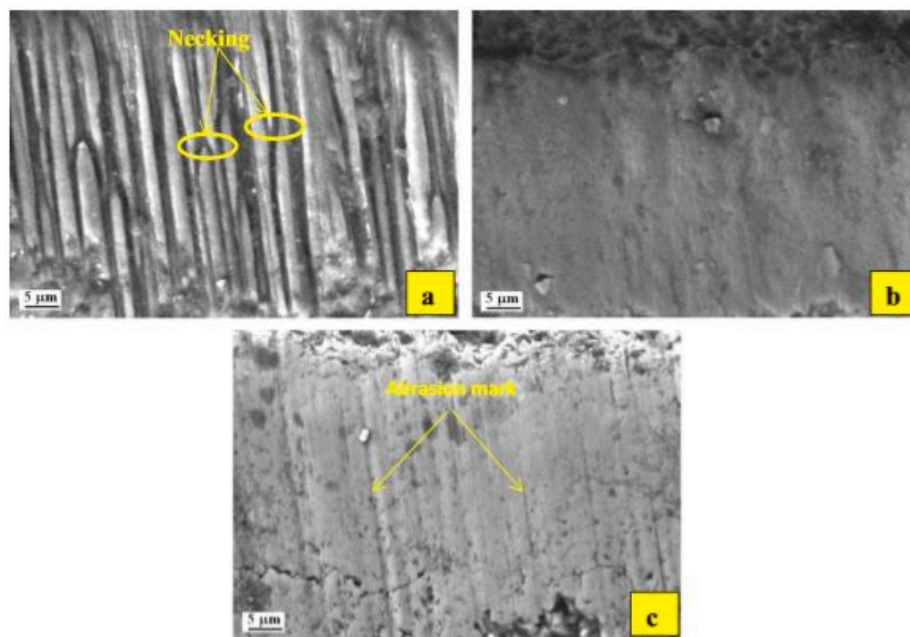


An analogous study [66] using similar conditions (maintaining the same coating and machined material) was conducted in order to analyze the main wear mechanisms of the coated tool. The wear patterns are like those observed in the previous study [65]: adhesive wear, build-up layer (BUL), molten material and crack wear patterns were detected in the coated tool. The authors conclude that the main wear mechanisms are adhesive wear, abrasive wear, oxidation wear and diffusion wear. During the tests, cutting parameters were varied, such as cutting speed and feed rate. Cutting forces were also analyzed, because this is an important step when optimizing a process.

In another work [67], the wear mechanism of PVD-, CrAlN- and TiAlN-coated  $\text{Si}_3\text{N}_4$  ceramic cutting tools was studied. The conducted tests consisted of the turning of GT250 gray cast iron using these coated tools and characterizing the wear mechanisms. It was found that the adhesive strength of the TiAlN was stronger than the CrAlN coating; during the turning of the material, the CrAlN coating suffered spalling at a cutting speed of 400 m/min, due to low adhesive strength. During the dry turning of the material, abrasive wear and minor adhesive wear were found to be the main wear mechanisms. It was possible to observe that coated tools suffered more adhesive wear than the uncoated inserts. Still regarding the coated  $\text{Si}_3\text{N}_4$  ceramic cutting tools, studies made on the wear mechanism of these tools coated with diamond were conducted [68,69], the authors observed the machining performance of coated and uncoated tools; it was found that the cutting force was higher during machining with diamond-coated tools, due to the surface roughness of the rake face. Additionally, the parameter that influenced these cutting forces the most was the feed rate, contributing more to the increase in cutting force than cutting speed. Regarding wear mechanisms, it was observed that the high machining temperature promoted the graphitization of the diamond coating, which resulted in its removal from the tool; however, there was no delamination observed in the coating after machining.

As previously stated, a recent shift to dry turning as an alternative to some machining methods has been observed, due to economic and environmental reasons. Naskar et al. [70] in their investigation, compared the flank wear mechanism of CVD and PVD hard coatings in the high-speed dry turning of low- and high-carbon steel. The steels in question are C20 and C80, and they were turned at a cutting speed of 300 m/min and 600 m/min with CVD  $\text{Al}_2\text{O}_3$  (top layer)/TiC (bottom layer), TiCN (top layer)/TiC (bottom layer) bilayer-coated, and PVD TiAlN single-layer-coated, inserts. The authors found that the main wear mechanisms were abrasive wear, however, plastic deformation-induced necking and dissolution-diffusion were also contributing to the acceleration of tool wear. They concluded that when designing a coating material for high speed machining, the solubility of coating materials has to be taken into account.

Figure 17, taken from the paper presented by Naskar et al. [70], exhibits the wear of coated tools (coatings presented in the above paragraph), in the machining of C80 steel.



**Figure 17.** Wear patterns for necking (caused by plastic deformation) (a) and abrasion marks (c). In image (b) the coating's surface is smooth after wear, with no evident abrasion marks or plastic deformation induced defects. Reproduced from [70], with permission from Elsevier, 2018.

Studies like these are very important to understanding and finding ways to improve tool life, by understanding how the wear patterns are displayed. Moreover, machining parameters can be found/calculated in order to optimize the process and improve tool life. Additionally, by observing these wear patterns, new ways of fabricating novel coatings can be achieved. The development of nanostructured composite coatings is still quite novel, and studies such as these help to gain a better understanding of how they behave in certain conditions, such as, for example, in the study carried out by Vereschaka et al. [71], in which the behavior of a nanostructure multilayered composite coating is tested under the high speed turning of steel. It was found that there was adhesive wear from the steel that was being turned. As a result of the turning process, a top layer was “destroyed”, no longer exhibiting a nanostructure.

## 5. Tool Life

Improving tool life has been a strong focus of the machining industry, as having cutting tools last longer and not underperform is quite appealing. Because of this, many studies have been conducted to increase understanding how to improve cutting tool life. As seen in the previous chapter, the knowledge of the cutting tool wear mechanisms is crucial when wanting to improve tool life [70]. There are many factors that directly influence tool life, such as the coating's properties, i.e., mechanical properties, coating architecture and microstructure, and chemical composition. These factors influence the coated tool's wear patterns, thus influencing tool life. Machining parameters also influence the tool's life, such as cutting speed, feed rate and even tool geometry, as there are some papers that study the influence of the micro-textures of cutting tools, relating their surface geometry with tool life [72]. Regarding the influence of machining parameters on cutting tool life, the study carried out by Asha et al. [73], analyzes the effect of these parameters on cutting temperature and tool life while turning EN24 and HCHCr Grade alloy steel. The authors carried out tests where the cutting speed and feed rate were varied, and the depth of the cut was kept constant. The coatings used in the carbide inserts were an M15 grade multilayer coating and an M20 grade. It was determined from the results of the turning tests, that the cutting temperature was higher when machining the HCHCr grade alloy steel, when compared to the EN24; the cutting speed increase applied during tests caused tool life to decrease,

however, feed rate did not have a high impact on the tool life. It was also found that the tool life was lower when machining the HCHCr alloy steel; this was possibly due to the presence of high alloying elements in the steel and the hardness of the HCHCr steel.

In this chapter, some studies focused on improving tool life are presented, and the various methods for determining tool life for different tools are also mentioned.

In the study carried out by Boing et al. [74], the tool life of PVD- and CVD-coated tools is evaluated when turning AISI 4340-, 52-, 100- and D2-hardened steels. The authors found that the TiAlN PVD-coated tool promoted better results when turning AISI 4340 steel. Otherwise, the MTCVD TiCN/Al<sub>2</sub>O<sub>3</sub>//TiN proved to be better at turning the other steels. The authors also found that the hardness and microstructure of these steels were the limiting factor, meaning that the carbide fraction that is present in the steel microstructure limits tool life, due to the impact on the cutting edge, similar to the study presented in the beginning of the chapter by Asha et al. [73].

Another paper presented by Vereschaka et al. [75] relates the coating thickness of a composite nanostructured coating Ti-TiN-(Ti,Al,Cr)N to its tool life, similar to the results from another work [56]. The coating with thinner layers presents overall better mechanical properties and wear resistance properties, having a longer tool life than its thicker competitor.

Another method to improve tool life involves ANOVA analysis, determining the best machining parameters in order to obtain the desired effects, from a better surface finish to a longer tool life. This method is presented in the work by Ranjan Das et al. [76], in which a process that involves the hard turning of AISI 4340 using a CVD TiN/TiCN/Al<sub>2</sub>O<sub>3</sub>//TiN coating is optimized.

There are some methods proposed to predict tool life based on certain parameters, such as the study that proposes a new model for the prediction of a time-varying heat partition coefficient at the coated tool–chip interface in continuous turning [77]. The heat partition coefficient at the tool-chip interface is important, as it helps to accurately estimate the distribution of heat flux and temperature while machining, therefore this is important, as it gives insight on what influences the heat distribution on the tool-chip; as, for example, coating thickness and substrate material influence the heat partition coefficient, the type of coating and cutting parameters also influences this coefficient, for example, increased cutting speed resulted in higher temperatures, and all of this has an influence on tool life. With this proposed method, there is a new way to design better and more optimized coated tools, and even help the selection of these tools for machining applications.

The study by Zhang et al. [78], proposes the prediction of tool wear, using a 2D Fractal analysis of the cutting force and surface profile, in the turning of an Iron-based super-alloy. Coated carbide tools and cermet tools were used to turn the material, and a dynamometer was used to measure the cutting force. MATLAB (MathWorks, Natick, MA, USA.) was used to calculate the fractal dimension. The results from these tests showed that the cutting force curve and the machined surface profile had fractal characteristics; the authors determined that by using this method, tool wear and machined surface finish quality could be predicted. This study yielded additional results, such as the coated carbide tools having a higher tool life than the cermet tools, and demonstrated that by increasing cutting speed the surface finish quality would also increase, however, with the increase in tool wear the surface quality would deteriorate. Having a prediction method such as this for tool life is very appealing for the industry.

There are also some studies on tool life that focus on the substrate. For example, in the study carried out by Uhlmann et al. [79], the substitution of commercially coated tungsten carbide tools in the dry cylindrical turning process with HiPIMS-coated niobium carbide cutting inserts is proposed. These niobium coatings have shown potential in the machining of iron-based materials. The authors found that, although the cutting performance of the HiPIMS-coated niobium inserts was higher than that of the uncoated inserts, when compared to the commercially coated tungsten carbide tool performance was not improved noticeably. However, it was found that the adhesion of this coating to the substrate was good, providing an alternative to regular coated tungsten carbide tools. Research like this is

important in finding new ways to optimize the machining of certain materials, as these new coatings may be a reliable option when wanting to improve cutting tool life.

## 6. Tool Coatings Under Advanced Cutting and Lubrication Conditions

Since using coated cutting tools for turning has its limitations, especially regarding the lubrication method, there have been some studies on employing some alternative lubrication methods in order to achieve better results in the finished product, and even optimizing the process, making it cheaper by improving tool life or even reducing power usage and, additionally, making the overall process safer for the environment.

In this chapter, recent studies regarding alternative lubrication methods are presented, drawing attention to the minimum quantity lubricant (MQL) method and cryogenic lubrication methods, paying attention to the overall process efficiency and tool behavior while turning. For example, in some cases MQL regimens can have a good impact on surface finish quality when compared, for example, to dry turning. Additionally, the dry turning of some alloys may cause a high temperature in the cutting area, provoking more work hardening when compared to MQL regimen [80]. As mentioned in Chapter One, there are papers that study the influence of extreme pressure anti-wear additives (EP/AW), in the MQL regimen, obtaining good results when compared to other MQL (without additives) regimen and dry turning. These types of lubrication method not only affect the overall finished quality of the product and tool life/performance, but they affect the microstructure as well. Studies show that MQL is quite advantageous when the best surface finish is one of the goals [81,82].

In the work presented by Marques et al. [83], the turning of Inconel 718, applying a vegetable-base cutting fluid mixed with solid lubricants by MQL, is proposed. The authors studied the turning process of this super-alloy under dry machining conditions and under MQL while using graphite solid lubricant. The authors found that under MQL conditions the tool life was improved, because the addition of solid lubricants reduced the cutting forces during the process, making it a good option when intending to extend tool life when turning Inconel 718.

Regarding the use of vegetable-based coolants in the turning process, in the study carried out by Elmunafi et al. [84] the tool life of a tool coated with TiAlN is analyzed under MQL using castor oil. The authors achieve satisfactory results by reducing the overall cutting temperature and cutting forces, suggesting that MQL method would prove to be useful in the turning of hard stainless steels. It was also found that the tool life is inversely proportional to both cutting speed and feed, with the effect of the first being more significant. Additionally, the use of castor oil is more environmentally friendly when compared to other coolants.

In the work presented by Chetan et al. [85], the wear behavior of PVD TiN-coated carbide inserts during the machining of Nimonic 90 and Ti6Al4V super-alloys under dry and MQL conditions is studied. The authors determined that the main mechanism for the wear of the coating during the machining of Nimonic 90 alloy was the abrasive wear and nose fracture, which caused the catastrophic failure of the tool. However, due to the wettability of Ti6Al4V under MQL mode, this provided less intense flank wear at high cutting speeds. Studies such as these help to understand when to apply certain lubrication regimens, depending not only on tool but the workpiece material as well.

There have been some recent studies on cryogenic pre-treated coated tool performance, such as the study performed by Kumar and Senthil [86]. In this work, PVD-coated TiN/AlTiN tungsten carbide inserts were used in the dry turning of a Ti6Al4V titanium alloy. The authors concluded that this treatment increased the hardness of the inserts. Additionally, the cutting forces obtained were lower when using cryogenic treated tools; overall better surface finish was reported, as well as less significant tool wear on the cryogenically treated tools.

Cryogenic cooling methods are a recent focus of attention as well, concerning coated tool behavior. In the study carried out by Dhananchezian et al. [87], the effects of cryogenic cooling on the turning of 2205 duplex stainless steel, using a PVD-coated nano multilayered TiAlN cutting tool, were analyzed and compared to dry turning. From this study, it was found that cryogenic cooling reduced cutting

temperature by more than 50% when compared to dry turning and decreased cutting forces by up to 40%. An improvement on roughness was also registered, of about 20%. These results contribute to finding better alternatives, especially when machining hard materials such as duplex steel. Regarding machining under cryogenic conditions, the Taguchi Method can also be used to optimize the machining parameters for these conditions, as shown in the study by Khare et al. [88]. The optimal parameters were chosen when machining AISI 4340. These parameters were: cutting speed, depth of cut and feed rate, while under cryogenic conditions. By optimizing a process such as cryogenic turning, it makes the process more viable, from a financial standpoint, making it more likely to be used in the industry. A similar method, the Taguchi incorporated Gray relational analysis (TGRA), is shown to be implemented with success in another study, this one regarding the cryogenic machining of 17-4 PH stainless steel. As in the previous study, the optimal parameters were predicted, these parameters being the cutting speed, feed rate and depth of cut [89].

There are some additives that can be used in lubricants to improve machining performance, reduce tool wear and even improve tool life. In this study, performed by Gutnichenko et al. [90], a study of the influence of adding graphite nanoplatelets (GnP) to vegetable oil on the MQL-assisted turning of Alloy 718 was performed. From the turning tests, the additives impact the machining performance in a positive manner; by adding the GnP to the vegetable oil, an increase in terms of tool life, surface finish and overall process stability was noted. In addition, adding GnP particles to the oil results in a significant reduction in friction in the cutting area. It was also noted that these particles influence the chip formation process, whereas a pure oil lubrication would act as a coolant. The authors also reported that using the vegetable oil without the nanoparticles would improve the machining process, however, these nanoparticles would contribute heavily to overall process stability.

## 7. Concluding Remarks

As the machining industry grows, the interest in making it more profitable grows as well. The turning segment still has an important presence in the machining industry and, because of this, is an important focus of research in order to optimize the process to achieve more and more satisfactory results. Tool behavior knowledge is necessary to understand the process, with a vast amount of literature existing in this field. In this paper, the recent studies on and advances in coated tool technology were presented.

Regarding the development of new coatings, the focus seems to be the development of nanolayered and nanocomposite coatings, however, there are many studies on the behavior of the most common CVD and PVD coatings. Many of these studies focus on the comparison of PVD- and CVD-coated tool performance, evaluating the influence of these coatings on the machining of certain materials. The coating's chemical composition, architecture and deposition method are all factors that contribute to the cutting performance of coated tools. Researches show that CVD- and PVD-obtained coatings are used for different types of operations, for example, thin PVD coatings provide a suitable option when the finishing quality is the most desired parameter, and, in turn, CVD coatings prove to be useful in most materials for roughing operations. Of course, this depends heavily on the material that is being machined and the coating properties.

Wear mechanisms were also analyzed, showing how different wear patterns present themselves on the coated cutting tool. There are many comparative studies as well in this field, as understanding how different coatings develop their wear mechanisms and how they develop is key when wanting to improve tool life. These wear patterns usually occur due to abrasion failure, adhesive wear or coating destruction. Properties, such as coating hardness, residual stress and chemical composition, directly influence these wear patterns.

One focus that remains the same is wanting to improve tool life. If a tool can function normally for longer, the machining process would be cheaper, as cutting tools wear out considerably quickly and are quite expensive. Attempts to lower these costs comprises a field with a large amount of research. In addition to tool life improvement, the recent trend is to increase eco-friendliness, with studies that



employ alternative lubrication methods in order to reduce the amount used in some current turning processes. This, coupled with the fact that some of these methods reduce the cutting forces of the process, means that the overall power usage will also be lower, lowering the price of the process, albeit slightly, thus making it more environmentally friendly.

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