applied sciences

MDPI

Review

Surface Engineering of Woodworking Tools, a Review

Bogdan Warcholinski * and Adam Gilewicz

Faculty of Mechanical Engineering, Koszalin University of Technology, 75-453 Koszalin, Poland
* Correspondence: bogdan.warcholinski@tu.koszalin.pl

Abstract: The wide range of applications of wood are due to its strength properties. The mechanical properties of wood in various parts or directions are different. The complex structure of wood and its hygroscopicity prevent the use of coolants and lubricants, resulting in rapid tool wear disproportionate to the hardness of the processed material. This significantly affects machining efficiency and the quality of the processed surface. It seems that an effective method of reducing tool wear is its modification with a thin hard coating produced by the Physical Vapor Deposition or Chemical Vapor Deposition methods. The article presents tool materials used for woodworking, areas for improving the efficiency of their work, and the impact of thin hard coatings on the increase in tool durability, including binary coatings and also doping with various elements and multilayer coatings. Scientific centers dealing with the above-mentioned subject are also mentioned. A brief review of the effects of surface modifications of woodworking tools in the context of their durability is presented. It was found that the most promising coatings on tools for woodworking were multilayer coatings, especially based on chromium. Higher wear resistance was demonstrated by coatings with a lower coefficient of friction. This value was more important than hardness in predicting the service life of the coated tool.

Keywords: tool modification; woodworking tool; lifetime of the tool

check for updates

Citation: Warcholinski, B.; Gilewicz, A. Surface Engineering of Woodworking Tools, a Review. *Appl. Sci.* **2022**, *12*, 10389. https://doi.org/10.3390/app122010389

Academic Editors: Alena Očkajová, Martin Kučerka and Richard Kminiak

Received: 15 September 2022
Accepted: 13 October 2022
Published: 15 October 2022

1. Introduction

About 29% of the Earth's surface and over 44% of Europe is covered by forests. European forests represent about 25% of the world's forest resources. Forested areas have still been increasing, for the past 20 years by about 0.8 million ha per year.

Wood is an important raw material in construction, furniture, heating, the packaging industry, etc. The huge popularity of wood as a raw material results from its special properties and aesthetic qualities. It is an excellent, healthy, and renewable material with a complex structure consisting of many types of cells and substances present in different amounts, depending on the species of wood and its parts. In order to reduce unit manufacturing costs, woodworking plants and furniture companies strive to increase production of manufactured goods. Investments in modern tools, but also modern systems for processing wood and wood-based materials, devices for assessing wood quality, and processing technologies make it possible to meet growing environmental requirements and reduce production costs.

The key factor influencing the effectiveness of wood and wood-based product processing is the life of tools. This is directly related to tool wear and indirectly affects power consumption and the surface quality of the workpieces. The use of advanced high-performance cutting tools allows reduction in operating costs, which is directly responsible for increasing the productivity of the technology used. One of the factors is the selection of the tool material and the condition of machines. Processing hardwood species (oak, ash, hornbeam, ebony, pink lapacho) may require tools made of different materials than for soft wood (spruce, pine, larch) processing. The structure and chemical composition of wood species, including the amounts of minerals and resin, significantly affect this choice. For example, according to Kadur company [1], stellite planer knives are suitable for working with hard and semi-hard wood, and HSS planer knives of alloyed tungsten (6–18%) are suitable for semi-hard and soft woods.

In the wood industry, tungsten carbide tools are widely used for processing fiberboards, chipboards, and solid wood, as the successor to high-speed steel tools. However, they also show a relatively high degree of wear in some applications. Although they prove superior to high speed steel tools in many applications, the use of tungsten carbide tools in some particle board and fiberboard applications is limited due to the relatively high degree of wear. Therefore, there is an urgent need to search for new materials and technologies for their production that would improve the wear resistance of tools.

The analysis of the literature shows that, after the initial failure to improve the effectiveness of tools by applying a protective coating, current data indicate a significant improvement in abrasion resistance with a properly prepared substrate for the coating. One of the most commonly used methods to increase tool life is to apply thin, hard coatings to the cutting tool using physical vapor deposition (PVD) or chemical vapor deposition (CVD).

There are many reputable journals covering wood materials and wood-based products, the biology and physics of wood, wood processing technologies, and the application of these materials. These are, i.a., *Bioresources, European Journal of Wood and Wood Products, Journal of Wood Chemistry and Technology, Wood Material Science & Engineering, Wood Science and Technology*, and others. In many journals, there are special issues devoted to this subject; for example, in *Applied Sciences* there is *Application of Wood Composites, Advances in Wood processing Technology* [2–9].

The article presents a brief outline of the use of selected surface modifications of tools for processing wood and wood-like materials. The aim of the article is the chronological documentation of research conducted in this area, taking into account the type of wood processing and the tool used for it, and not the performance of a comprehensive analysis of the literature on wood processing. Due to the large differences in the structures of metal and wood (cellular nature, anisotropy, and multi-scale level organization), the test results of metalworking tools with a modified (hard thin coating) working surface cannot be directly applied to woodworking tools.

2. Tool materials

Due to machining conditions, cutting tools should be characterized by high resistance to mechanical loads and high temperatures. In the case of metal processing, frictional heat can increase the temperature in the cutting zone to 700 °C [10], but during wood processing and especially the processing of wood-like materials, the temperature exceeds 800 °C, which results from high friction forces in the machining zone [11]. Such temperature occurs both on the rake surface and the clearance surface, and has a significant impact on the wear rate of the cutting tool. The main parameters which ought to be taken into account are: chemical inertness and stable physical properties, including hardness at high temperatures, low wear ratio for different wear mechanisms, and sufficient toughness to avoid material fracture [12].

The history of the development of tool materials used for wood (wood-like materials) and metal processing is similar. Tool steels were applied as the first materials; they were relatively soon replaced by high-speed steels. The increased interest in wood-based material processing and related problems resulted in the introduction of composite tools based on hard, fine WC particles sintered with cobalt. Co is responsible for the elastic bounding of hard WC particles. By selecting the size of hard particles and the amount of bonding phase, the mechanical properties of sintered tools can be changed. Another group of tool materials is stellites, characterized by high hardness depending on the chemical composition (36–52 HRC), and high resistance to abrasion and high temperatures (up to 950 °C).

In the early 1980s, one of the most modern tools was sintered carbide. After the dramatic question "Is there life after tungsten carbide?" [13], the answer was almost immediate, with "PCD replacing carbide in woodworking applications" [14]. At this time, there was an abrupt increase in interest in modified woodworking tools. The polycrystalline diamond (PCD) displaced traditional steel and cemented carbide tools in woodworking [15–18]. The significantly better strength and tribological properties of PCD, such as hardness (about 40–50 GPa, compared to 10–22 GPa for carbides) and low coefficient of friction, meant it could enable an increase in durability and minimize the machine downtime of tools. This meant that PCD tools offered considerable potential for cost savings in the machining of wood and wood-like materials. Boyle indicated [15] that the life ratio of PCD tools compared to carbide cutters was about 17:1. Only its price forced the search for new solutions. These were the thin hard coatings deposited on tools' working surfaces.

The application of tools with modified hard coatings for metalworking resulted in an abrupt increase in production capabilities and product quality. Knowledge of the research and exploitation of the coatings for metalworking tools cannot be fully adopted in woodworking. This is related to the differences in their structures and properties, including mechanical properties, coefficients of thermal conductivity, roughness, and absorption of various substances. This results in the need to design new coatings that meet market expectations.

Due to the hygroscopicity of wood and wood-like materials, an application of cooling and lubricating agents is excluded. It seems that the best perspective to adopt is the improvement of tool durability by surface modification. Klamecki [19], in one of the first literature reviews of wood cutting tool wear, indicated the problems with the measurement of edge dulling. He stated that tool wear deals primarily with the tool material, with the work material, and with tool–work interactions, and the chemical nature of wood may play a large part in cutting tool wear. Thibault et al. [20] summarized wood machining over the last 50 years in France. They found that tool wear depends on the cutting process parameters, and kind and quality of timber. Coating technologies may improve tool life. Based on the literature, they indicated steel tool nitriding [21–23], and thin coating with a hard material (Cr_xN_y type) using physical vapor deposition gave promising results [24].

3. The Areas for Improving the Efficiency of Work Tools

The current requirements of users are mainly related to higher durability and reliability of tools and productivity. They expect an increase in the speed of machining, the ability of tools to work in automatic machining centers, and the processing of new, often difficult to process materials. Therefore, investigations are needed to design, manufacture, test on a laboratory scale, and implement such tools with the above requirements. These expectations can be met through three groups of activities:

- Introduction of new materials for their production or modification of the properties of the materials used, and selection of the geometry of the working parts of the tools [13,20,25–37];
- Application of appropriate cooling and lubricating agents;
- Selection of the proper surface-coating system, and shaping of the surface properties in terms of increasing the durability of the tools [14,24,38–41].

In recent years, there has been a growing interest in the subject of woodworking tools. Figure 1 shows the number of publications on woodworking and woodworking tools as well as tools with working surfaces modified by thin hard coatings.

In the last few years, a systematic increase in the number of publications has been noticeable. The number of articles on uncoated tools is approximately four times that of articles on coated tools. These articles discuss the results of new coatings formed on a wide range of tools, and the processing of various materials under carefully selected conditions. The aim of many works is to correlate the type of coating with the processed material and processing conditions.

The analysis was made on the basis of the SCOPUS database, a scientific database maintained by the Elsevier publishing house, containing information about published scientific papers. The data presented in the Figure present the database resources, taking into account the terms "woodworking", "woodworking tool" and "woodworking tool + coating " searched within all fields in the database.

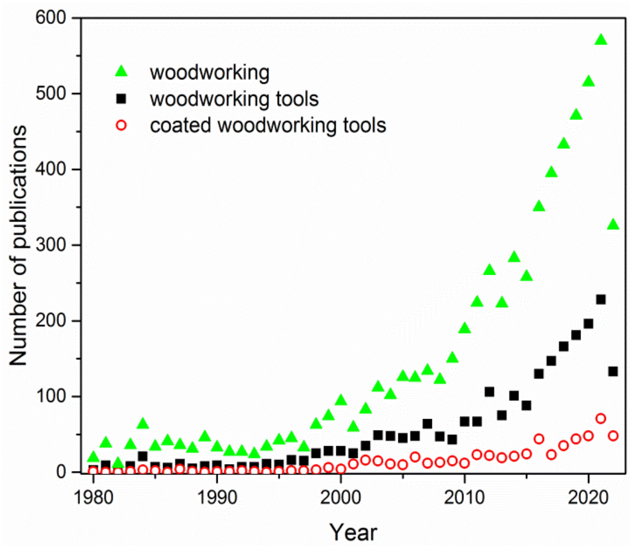

Figure 1. The subject of woodworking and woodworking tools in scientific articles, 1980–2022.

4. Surface Technologies

The development of tool materials looks to combine high hardness with high toughness, to improve their mechanical, tribological and thermophysical properties, leading to an improvement in the durability of cutting tools. One of the most important properties of the coating is good adhesion to the substrate and between the substrate layers. Other important properties are chemical stability and high wear resistance in working conditions. One can specify two groups of technologies that improve the wear resistance of tools.

The first one includes methods for improving the mechanical properties of the material tools (such as heat or thermo-chemical treatment). Heat treatment is to give them the desired mechanical properties by changing their structure, while the thermo-chemical treatment is to enrich the surface layer of the alloy in a certain element, such as C, N, Al, Cr, Si, or group of elements, e.g., C and N, N and S, N and O. The aim of these treatments is to give the surface layer specific physical properties—mainly resistance to abrasion, or chemicals—usually by resistance to oxidation at high temperatures. The quality of the tool is improved by applying heat treatment that allows it to obtain the desired hardness of the blade, and the appropriate fine-grained structure of steel and toughness.

Thermo-chemical treatment, especially nitriding, has a beneficial effect on the performance characteristics of tools. Many scientists indicate an increase in the wear resistance of nitrided tools for woodworking. Dependent on the type of technology used, this increase is as high as 100% [14,23,39].

The second group of technologies includes working surface modification techniques for tools by applying coatings with special properties. Among these, CVD (chemical vapor deposition) [42] and PVD (physical vapor deposition) [43] methods and surfacing using a submerged arc welding (SAW) technique and a mixture of alloying elements spread on the surface under industrial flux [44] can be listed.

The properties of the coatings can be modified by the type and roughness of the substrate, the deposition temperature, the composition and pressure of the gaseous atmosphere in the vacuum chamber, substrate bias voltage, and arc current or magnetron power, dependent on the deposition method. The above parameters influence the chemical and phase composition of the coatings, crystallite size, density of the coating, and surface quality (roughness). As an effect of properties such as hardness, elastic modulus, and also adhesion, toughness and wear resistance can be improved. The findings of Valleti et al. [45]

indicate that increase in substrate hardness results in higher adhesion of the coatings, but increase in substrate roughness results in lower adhesion of the coating investigated.

5. Coatings Used for Woodworking Tools

5.1. Binary Coatings

The first coatings applied were two-element systems. There are three main elements to synthesize protective coatings deposited on tools for woodworking: titanium [29,46–49], chromium [14,24,39,50–54] and carbon [39,49,53,55–57]. The transition metal nitrides were the most promising solution and they did not disappoint. One of the first tests in wood machining by TiN coating was sawing the following materials: hardboard, polyvinylchloride coated particleboard, waste paper-based paperboard, plywood, and spruce. The coatings were deposited by reactive triode ion plating on tungsten carbide with the thickness varied from 0.7 to 1.0 μm. The results indicated various effects on tool wear. On the one hand, when sawing hardboard and spruce, the coating reduced the wear on the rake face about 50% and 20%, respectively, compared with the uncoated tools. On the other hand, during sawing of particleboard, paperboard, and plywood, there was no increase in the durability of tools with a TiN coating [46]. This was one of the first signals that there is no universal coating. A proper coating should be selected for each treatment and type of workpiece. Additionally, other studies indicate that tool coatings can significantly improve wear resistance, especially when proper substrate preparation and proper tool geometry and cutting conditions are selected [29].

The advantages associated with the application of coatings to cutting tools are mainly high surface hardness, improved abrasion resistance, chemical inertness, and a relatively low coefficient of friction. After TiN coatings improving the durability of tools and machine parts, but also limiting applications and environment, attention was paid to chromium nitride coatings. These coatings, compared to coatings of other transition metal nitrides, are characterized by high resistance to corrosion and oxidation. Other features include high hardness and wear resistance, good adhesion of the coating to the steel substrate, high operating temperature, and a relatively low coefficient of friction [58–62]. A thin coating with a thickness of 2–3 μm may constitute a thermal barrier limiting heat transfer to the substrate. The results of investigations conducted by Kusiak et al. [50] indicated a significant reduction in the heat flux passing through the CrN coating, compared to the TiN coating. This was due to the nearly three times higher thermal conductivity of titanium nitride compared to chromium nitride. Single-layer CrN coatings are widely described in the literature both in the field of basic research and in applications, including woodworking. The higher resistance of the coatings to oxidation, and higher operating temperature are characterized by multi-component coatings in which one of the components is aluminum, e.g., TiAlN, forming thermally stable oxide coatings. In the cutting area, as a result of the forces acting on the blade, the oxide coating is removed and immediately, under the influence of high temperature, it is rebuilt.

It would seem that the thicker the coating on the tool, the longer it will last. Unfortunately, this is not true. Research carried out by Wiklund et al. [63] on a group of coating-substrate systems used in mechanical applications showed that thinner coatings are less susceptible to damage due to residual stresses as a result of adapting the geometric conditions at the interface. They also found that there is a critical coating thickness at which the stresses generated in it can cause the coatings to delaminate.

Durability tests of WC-Co inserts with CrN and Cr_2N coatings (thickness up to about 6 μm) synthesized by magnetron sputtering have shown that knives with coatings 1–2 μm thick have the best anti-wear properties. The service life of such tools was about four times higher than that of uncoated tools [24]. The thicker coatings showed signs of wear much earlier, probably due to the higher stresses in the coatings, confirmed by investigations conducted by Djouadi et al. [26].

The investigations conducted by Beer et al. [53] showed that CrN coatings on the 60SMD8 steel substrate are characterized by a smaller (about 52%) reduction of the knife edge compared to steel knives. W-C:H (DLC with WC precipitations) coatings show worse anti-wear properties. During the test, they showed delamination, and until the test was stopped, they showed only about 40% improvement in knife edge reduction. It should also be noted that the results varied significantly depending on the conditions of coating deposition and the preparation of the tool for the test. Also, during the test, decreasing power consumption and vibrations were observed for tools with CrN coatings, and the cutting process was stable [53]. Similar results are presented in [26]. Such good results for CrN coatings may have resulted from better adhesion of the coatings and a lower coefficient of friction, which also reduced the cutting forces and made the cutting process more stable in terms of vibration and veneer thickness [26].

5.2. Binary Coatings Doped with Various Elements

New requirements for tools, related to the increase in machining parameters or type of machining and the processing of new materials, led to the design and manufacture of new coatings. Two directions of change in coatings for woodworking tools were observed: formation of three- and more-component coatings, and forming of multilayer coatings. The influence of such elements as C, Si, Al, B, W, and Zr on the properties of coatings based on titanium [26,29,41,64,65] and chromium [38,41,66,67] was investigated. The next group, multilayer coatings, was also intensively studied [39,41,68–73]. Investigations of multilayered structures with chromium nitride as one of the layers indicated that it was possible to further improve hardness and toughness [14,74,75]. Some information about the applied coatings, the effects of their use, and the materials machined are summarized in Tables A1–A3. The coatings deposited on the tools are manufactured generally using PVD and CVD methods. Here, the results of PVD coatings are analyzed and summarized in Table A1 (magnetron sputtering) and Table A2 (cathodic arc evaporation). In Table A3, are gathered coatings formed and described by authors as Physical Vapor Deposition (PVD).

It should be noted that the first works including the assessment of the durability of the coating-modified tools did not reveal positive test results [76,77]. Titanium nitride (TiN), titanium carbide (TiC), and titanium aluminum oxynitride (TiAlON) were formed by plasma-assisted chemical vapor deposition on tungsten carbide tools applied to milling laminated particleboard. It was found that the tools with TiC provided only a slight improvement, and the tools with TiN and TiAlON did not provide any improvement in wear resistance compared to the uncoated carbide tools [77]. The analysis of the results of tests of TiN, TiAlN and TiN/TiCN coatings deposited by the PVD method on K grade tungsten carbide tools used for continuous milling of particleboards showed that wear resistance depends on the quality of the substrate, with the grain size and binder (cobalt) content being the decisive factors in the tool. For tools with a low cobalt content and small grains, there was a slight improvement in wear resistance, while coatings deposited on tools with a higher cobalt content and larger grains reduced the wear resistance. The authors observed the chipping of the coatings on the tool rake face, which was related with poor adhesion of the coating to the substrate (tool), and indicated this as the primary cause of poor wear resistance. [78]. Also, Darmawan et al. [68] indicated the poor adhesion of the coatings as the reason for its low wear resistance. For all tested systems: tool TiN, CrN, CrC, TiCN, and TiAlN, coating at both low and high cutting speeds of the wood-chip cement board, delamination occurred, as well as oxidation of the coating accelerated by the increase in cutting temperature. The above studies show the importance of adhesion to their wear resistance.

The research indicates that the most important factors determining the improvement of the performance of woodworking tools, but also of other types of processing, are good adhesion of the coating to the substrate (tool), low friction coefficient, and good abrasion resistance [26]. Many research centers have been involved in the optimization of these factors, and the results of their work can be found in many reputable journals. The final results of these works, with reference to specific applications for woodworking tools, are also included in this study. Benlatreche et al. [38] investigated CrN-based coatings with the addition of Al or Si, because such three-component coatings have modified structural, mechanical and tribological properties, including higher resistance to oxidation, higher hardness, and lower friction coefficient. Medium density fiberboard was subjected to routing tests. It has been found that the CrN coating improves the life of the cemented carbide tool by about 25 to 40%, depending on the coating deposition parameters and the deposition system used. The CrAlN coating had larger nose widths than the CrN coating, but with the increase in aluminum concentration in the coating, the difference in nose width between the coated and uncoated tool decreased. Depending on the type of MDF material being processed, the reduction in nose width was from about 25% (MDF fireproof) to about 40% (MDF standard). CrSiN coatings are characterized by slightly longer durability than CrN coatings. The nose width is reduced by approximately 35% compared to the uncoated tool and approximately 25% for the CrN coating. As for the aluminum coating, an increase in silicon concentration causes a decrease in its wear resistance. Above results are comparable with Ref. [69].

An important problem already at the early stage of tool testing was the monitoring and evaluation of the machining efficiency of woodworking tools [3,79,80].

5.3. Multilayer Coatings

Multilayer coatings generally have better wear resistance compared to single-layer coatings. This takes into account many factors such as: total thickness of the coating and individual layers, type of layer, functions performed in the coating (adhesive, abrasive, sliding, etc.). Greater wear resistance is connected with reduction in crack propagation at grain boundaries and layers. The coated carbide tools provide better wear resistance, surface roughness, and lower noise level compared to uncoated tungsten carbide tools in the cutting of asbestos, WPC, LVL, and OSB. Among the coated carbide tools, the multilayer TiAlN/TiBON coated carbide tool is the highest in wear resistance and is proposed for cutting wood composites. The abrasives contained in the wood composite are important in the wearing of the tungsten carbide tools. The structures of the wood composites are important in determining the roughness of the machined surfaces. The noise level and roughness increase due to an increase in wear and should be a good indication for determining the wear of the coated and uncoated tungsten carbide tools [81]. This is probably related to the high hardness of the coating, low coefficient of friction, and the reported lubrication effect at high temperatures in cutting.

Ti-W-N/Ti-W and Cr-W-N/Cr-W multilayer coatings with different periods, as well as comparison of single-layer coatings Ti-W-N and Cr-W-N with a thickness from 0.5 to 2.0 μm, deposited on WC-Co substrates, were the subject of research conducted by Pinheiro et al. [41]. The results showed that both 1 μm thick single-layer coatings, tested when cutting OSB, increased wear resistance approximately 2.5 times compared to uncoated cutting tools. Using the same cutting parameters (as those used in industry), they showed that the best result was achieved by applying the Cr–W–N/Cr–W multilayer coatings (three layers). This coating increases the cutting ability of wood-based products by 500% compared to the uncoated cemented carbide tool.

Kong et al. [54] conducted a comparative study of the wear resistance of HSS and cemented carbide knives with a single-layer CrN and CrN/CrCN multi-layer coatings during rounding of wood. They showed that the service life of CrN/CrCN-coated tools increased by 170% (HSS) and 110% (cemented carbide) compared to uncoated tools and by approximately 33% and 7%, respectively, compared to CrN-coated tools. Two important conclusions can be drawn from this work: a harder substrate contributes to an increase in durability more than a lower hardness substrate when covered with the same coating, and a multi-layer coating gives a greater increase in durability compared to a single-layer coating. A similar result was obtained for the same multilayer coating on HSS knives [71].

Figure 2 shows the parts of two planer knives, without a coating (top) and with a CrN/CrN coating (bottom) [82]. The left side shows the knife wear after a distance of 77 km of machining pinewood at feed speed—90 m/min, cutting speed—36 m/s and cutting depth 2 mm. The right side shows a fragment of the knife after sharpening, without wood machining. The tests were performed using Weinig Hydromat 22A.

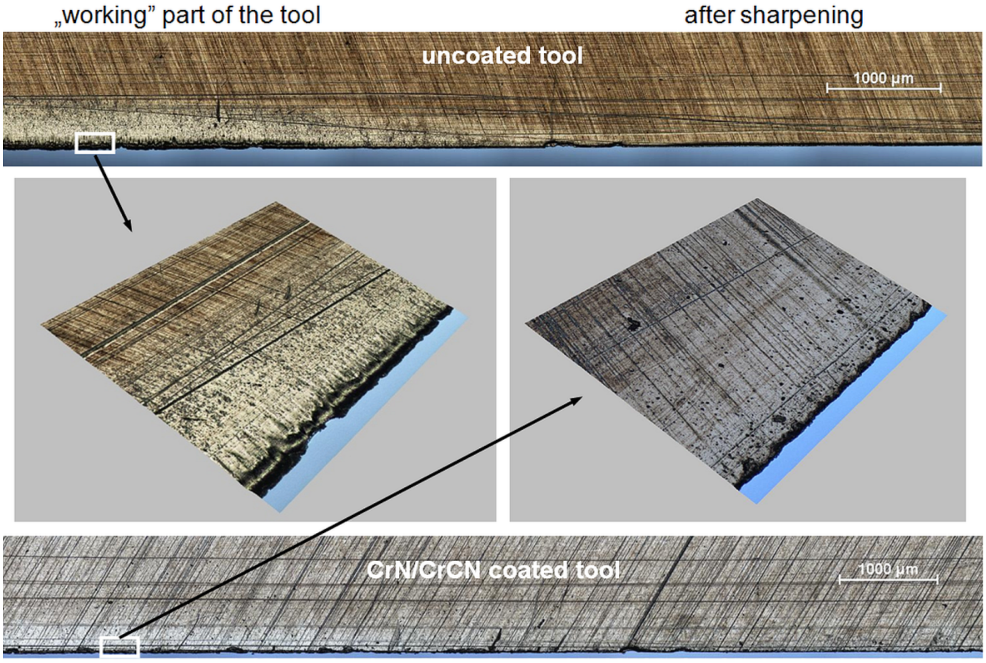

Figure 2. Fragments of uncoated HS6-5-2 steel knives (**top**) and CrN/CrCN (**bottom**). The left part after processing pine wood; the right part, after sharpening, did not process the wood [82].

Plastic deformation caused by high temperatures during cutting is visible on the edge of the uncoated tool. The blade was heavily worn after the machining test. On the edge of the CrN/CrCN-coated tool, slight wear is observed compared to the uncoated tool. In the middle part of Figure 2 is an enlargement of the edges of both knives. In the case of a tool with a CrN/CrCN coating, wear and delamination of the coating on the edge are hardly visible.

The test conditions favored an increase in temperature on the cutting edge and on the rake face. This leads to accelerated wear of the tools, resulting in, e.g., an increase in power consumption by the milling machine, and on the other hand, a deterioration in the quality of the processed material. Dependent on the type of processed wood, the wear rate and its symptoms may vary.

Tool wear is observed in the rounding of the edge of the blade and the abrasion of the rake face of the knife. Figure 3 shows a 3D view of the knife blade without a coating ready to work (Figure 3a), as well as the knife blade without coating (Figure 3b) and the knife blade with a CrN/CrCN multilayer coating (Figure 3c) after planing dry beech wood. The cutting path in this case was 6000 m. After sharpening, the uncoated knives had a blade radius of about 7 µm, while the coated knives had a slightly larger blade radius of about 10 µm. After cutting beech wood along a path of 6000 m, the radius of the knife blade without the coating increased more than three times and amounted to 24 µm. Under the same cutting conditions, the tip radius of the coated knife was approximately two times greater, at 20 µm.

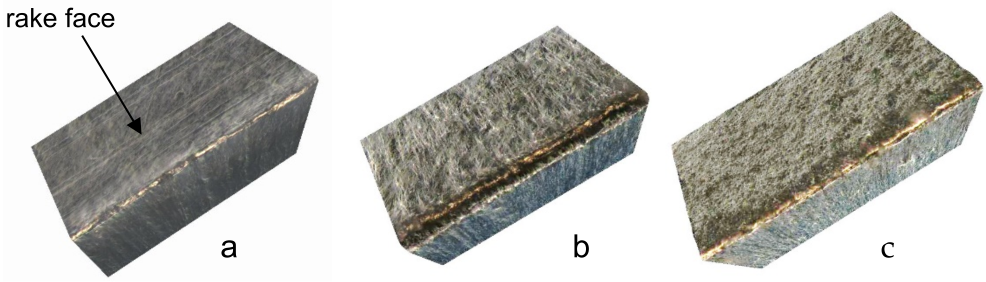

Figure 3. 3D image of cutting edge of planer knife without the coating after sharpening (**a**), the cutting edge of planer knife without the coating (**b**), and with CrCN/CrN multilayer coating (**c**) after 6000 m of dry beech wood cutting [83].

The rake face (Figure 3a) shows a different surface morphology in the blade working zone, caused by the temperature increased by machining, higher than the tempering temperature of the HS6-5-2 steel, i.e., above 550 °C (see Figure 2). This is represented by an image of the rake face profile perpendicular to the edge of the blade. There is visible wear of the knife rake face without the coating as a result of abrasion of the knife material. The coated knife does not show this type of wear (Figure 4). This indicates the good anti-wear properties of the coatings. The coatings also restrict the heat flow to the tool [50], which can reduce or eliminate the tempering effect of the tool material. High temperature causes plastic deformation of the material in the area of the blade edge, which promotes edge rounding and accelerates tool wear, and also deteriorates the quality of the machined wood surface. When sharpening the tool, restoring its original cutting properties, the material with mechanical properties changed by temperature should be removed. In the case of the tested knives made of HS6-5-2 steel, it is even 0.3 mm. This requires both an increase in the tool regeneration time and a reduction in the number of such processes, resulting in an increase in machining costs. In the case of knives with coatings, no negative influence of temperature and no reduction in the hardness of the tool material was observed.

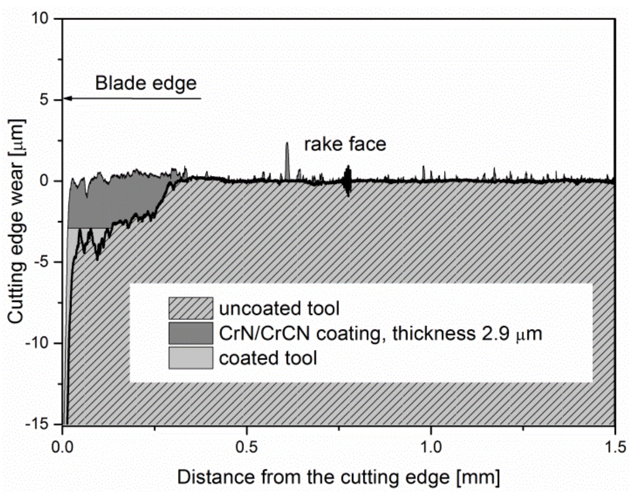

Figure 4. The cutting edge profile of planer knife with CrN/CrCN multilayer coating after 6000 m of dry beech wood cutting [83].

The greater efficiency of tools with a CrN/CrCN multilayer coating is manifested in the lower surface area of the blade wear in relation to the uncoated knife. For such selected tool-machined material systems and cutting process parameters, the surface area of the blade wear for the coated knife is approximately 25% lower, which translates into approximately three times longer cutting distance.

The analysis of the data presented in Tables A1–A3 shows that they are very diverse. The substrate, coatings, material treatments, and the material itself are different, as well as the presentation and evaluation of the results.

The records in the above Tables are arranged according to the sequential year of publication. It is not possible to unambiguously observe an increase in durability due to the variety of coatings, types of material being processed, and probably different machining parameters. One can also notice the important role of the deposition method and the tool material used as a substrate for the coating. The above data confirm that there is no universal coating that will be equally effective in the machining of various materials. The coating design process should take into account the type of material being processed, the machining parameters, and the type of tool to be used.

Nevertheless, based on the results presented in Tables A1–A3, it can be noted that:

- A comparison of various coatings operating in the same conditions shows the advantage of CrN both in the treatment of beech wood [53] and OSB [24,71];
- Worse performance properties of Cr_2N coatings compared to CrN [24,84] were confirmed, which may be caused by their greater brittleness and worse adhesion to the substrate;
- A comparison of the wear resistance of single-layer coatings was presented by Kazlauskas et al. [85]. Binary CrN and ternary AlCrN and TiCN coatings deposited on WC-Co tools (substrates) during the milling of oak wood showed improved wear resistance of cutters by factors of 3.0, 1.9, and 1.7, respectively. They also found that CrN was characterized by the best adhesion among the tested coatings and a low and stable coefficient of friction. They stated that low-friction coatings exhibited better wear resistance;
- Ti-based coatings have inferior wear resistance compared to Cr-based coatings. This applies to both magnetron- and arc-formed coatings. The Ti-W-N/Ti-W coating is characterized by twice the tool wear area compared to the Cr-W-N/Cr-W coating in the milling of OSB and particle board [41]. The wear of the tool covered by TiCN and CrN coating is smaller by 1.6 and 2.0, respectively [57,65]. The above conclusions are confirmed by Kazlauskas et al. [85];
- Multilayer coatings have better properties compared to single-layer coatings. CrN and CrN/CrCN coatings were deposited on a substrate made of M2 steel and cemented carbide and the timber boles were rounded [54]. Two significant effects were observed:
    (a) The multilayer coating was characterized by a greater wear resistance of about 170%, while in the case of CrN coatings the increase was about 100%. These results relate to the tests carried out on the M2 steel tool coating system. Cemented carbide tools with coatings were characterized by a slightly lower durability of approx. 110% (CrN/CrCN) and 100% (CrN). It should be noted, however, that uncoated tools made of M2 steel rounded 15 boles, and cemented carbide tools 188 boles;
    (b) The comparison of these coatings shows that in M2 steel tools with CrN/CrCN coatings the service time is about 33% higher compared to the CrN coating, and in the case of a cemented carbide tool the increase is about 7% [54]. This confirms the reports of many authors about the importance of the substrate;
- A comparison of the edge recession of tungsten carbide tools with TiAlN monolayer coating and TiAlN/TiSiN and TiAlN/TiBON multilayer coatings in milling different wood composites indicates a greater edge recession of the TiAlN and TiAlN/TiSiN coatings [81]. Among the tested coatings, the smallest edge recession was demonstrated by the TiAlN/TiBON multilayer coating, despite the fact that its hardness was the lowest among the tested coatings, 2700 HV. The TiAlN/TiSiN coating, with a hardness of 3600 HV and the highest coefficient of friction (0.9), showed greater edge recession than the TiAlN single-layer coating. The results of these tests confirm that a lower coefficient of friction is more important than hardness.

5.4. Substrates Used for Testing the Properties of the Coatings

There are basically two types of substrates in Table A1, 60SMD8 alloy steel with a hardness of 57–59 HRC [26,53], commonly used for cutting tools for peeling lathes, and 90MCV8 steel, hardness of 63–65 HRC, suitable for cutting and punching tools, etc., and cemented carbide with a hardness of about 17 GPa.

The substrate has a major influence on the performance of the coating. Chekour et al. considered the effect of the nitriding conditions of the 32CrMoV13 steel substrate as a tool for the peeling of beech [23]. It was found that in most cases the nitrided layer is about 200 nm thick and the surface hardness is about 1000 HV, twice that of unnitrided steel. Tool tests during peeling of the beech showed that the nitrided tool in a mixture with a small concentration of nitrogen performs like an unnitrided tool. Duplex-treated tools (nitriding and CrN coating) performed better than nitrided tools and allowed almost twice as much processing as untreated tools. Duplex processing (nitriding and CrN coating) of low-alloy steel, commonly used in the production of knives for the wood industry, allowed over 70% reduction of knives' edges [37].

5.5. Scientific Centers

One can indicate the scientific centers dealing with the production, implementation and testing of tools modified with coatings for processing of wood. Based on SCOPUS and Web of Science databases, one can indicate the dominant position of France [14,20–24,26,41,48,50–53,66–68,84,86] in this challenge but Germany [49,76], Japan [40,48,68,87], USA [71,87,88], UAE [28,29,71,87] and Poland [21,53,55–57,69–74,89–92] also deal with this subject extensively. Also, scientists from such countries as: Belarus [93–96], China [54,75], Finland [46], Indonesia [40,48,68,81], Italy [39], Lithuania [44,65,85,97–99], Portugal [41–100], Slovakia [94], and Switzerland [33] have significant achievements in research and dissemination of knowledge about modified protective coatings for woodworking tools.

6. Conclusions

The history of thin hard coatings goes back to the 1970s. The possibilities of new tool modification techniques were verified in laboratories and in industry, initially for metalworking, and somewhat later also for woodworking. Wood is a specific material; it is characterized by strong fluctuating local anisotropy, porosity, and a hygroscopic nature. Hence, the demands placed on woodworking tools are particularly high. Thanks to the progress in surface treatment, it is possible to obtain tools that meet the requirements of customers to a greater extent than before. Knowledge about the applied modifications of tools is becoming more and more available, as evidenced by the growing number of scientific publications, as well as the multinational composition of research teams. The main difficulty in analyzing the results is:

- Many articles are related to the processing of fiberboard or very dense homogeneous wood, the most homogeneous and isotropic materials. The processing of other materials, softwood and wood-based materials, does not give unequivocal results in the durability of the tools. It seems that the most important factors in modifying a wood knife are low friction value, good abrasion resistance, good coating adhesion, and thermal resistance. Most of the tested coatings belong to the simplest, two- or three-element systems. Only in some cases have more complex coatings, such as quaternary systems or multi-layer coatings with different structures, been investigated. The test results indicate that the latter have better wear resistance, but standardized tests should be performed to confirm this.

The analysis of the test results for the properties of coatings and the durability of woodworking tools covered with these coatings allows for the presentation of several conclusions:

- A comparison of various coatings operating in the same conditions shows the advantage of CrN both in the treatment of beech wood and OSB. This is probably due to the

lower brittleness of the CrN coatings, relatively low coefficient of friction, and very good adhesion to the substrate;
- Chromium-based coatings have better wear resistance compared to titanium-based coatings;
- Multilayer coatings are characterized by better wear resistance compared to single-layer coatings. This may be related to the reduction of crack propagation at the phase and grain boundaries. As in the case of a single-layer coating, higher wear resistance is found in coatings that exhibit a lower friction coefficient and are less brittle. The results of the tests confirm that a lower coefficient of friction is more important than hardness;
- The type of tool material used, and its possible thermochemical treatment, have a great influence on tool life. Increasing the hardness of the tool increases its productivity, although not always its durability.

Future Directions

The field of wood-cutting tools still requires further research. It seems that future research should focus on selecting one method of coating formation on a clearly defined substrate (tool). The choice of the tested multilayer coating (coatings) showing the best anti-wear properties is much more complex. It should be characterized by high hardness, good adhesion to the substrate, stability at elevated temperatures, relatively low coefficient of friction, and chemical inertness. Processing tests of the selected type of wood (wood-based) material should be limited to one specific species and the same series of processing parameters. It is also important to present the research results so that they can be compared with the references.

Author Contributions: Conceptualization, B.W. and A.G.; methodology, B.W. and A.G.; software, B.W.; validation, B.W.; formal analysis, A.G.; investigation, B.W. and A.G.; resources, B.W. and A.G.; data curation, B.W. and A.G.; writing—original draft preparation, B.W.; writing—review and editing, A.G.; visualization, B.W..; supervision, A.G.; project administration, A.G.; funding acquisition, A.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was part-financed by the NATIONAL CENTER FOR SCIENCE AND DEVELOPMENT of Poland within the 3rd strategic competition of the "Environment. Agriculture and Forestry" Program—BIOSTRATEG. No. BIOSTRATEG3/344303/14/NCBR/2018.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

MDF	medium density fiberboard
OSB	Oriented Strand Board
ta-C	tetragonal carbon
WPC	wood plastic composite
LVL	laminated veneer lumber
GRC	Glass-reinforced concrete

Appendix A

Table A1. Magnetron sputtering. Protective coatings applied to woodworking tools, synthetic information on the coatings used, the materials processed, the type of substrate and the effect of its modification.

Coating/ Structure	Substrate	Type of Machining	Machining Material	Results	Year	Reference
W-C:H (DLC with WC precipitations) CrN	60SMD8	peeling	beech wood	reduction of the knives' edges by 38% (W-C:H) and 52% (CrN)	1999	[53]
CrN W–C:H(DLC)	60SMD8	peeling	beech wood	cutting edge reduction up to: DLC—60%, CrN—130%.	1999	[26]
CrN Cr_2N	Carbide	cutting	OSB	reduction of the knives' edges 52% (CrN) and 40% (Cr_2N)	2000	[84]
CrN Cr_2N	Carbide	cutting	OSB	service life four times higher (CrN), about 1.8 times higher (Cr_2N)	2001	[24]
CrN	32CrMoV13 Nitrided	peeling	beech wood	increase the service of the tool by a factor of 1.3	2003	[23]
CrN	Carbide	routing	OSB	decrease in nose width about 64%	2003	[51]
CrN	90MCV8	peeling	MDF	reduction in the wear of the edge by about 50%	2005	[14]
CrN	different carbidess	milling	OSB	dependent on type of substrates	2005	[52]
CrAlN	Carbide	routing	MDF	increase up to 2.5 times more than unmodified ones	2007	[66]
CrAlN	90CrMoV8	peeling	beech wood	reduction in the wear of the edge by about 50%	2009	[37]
AlCrN	WC-2% Co	routing	MDF, (M) standard, and (E) fireproof	max decrease in nose width about 25%—MDF(M), 40% MDF(E) and 44% MDF	2009	[83]
CrSiN	WC-2% Co	routing	MDF	max decrease in nose width about 33%	2009	[38]

Table A1. *Cont.*

Coating/ Structure	Substrate	Type of Machining	Machining Material	Results	Year	Reference
Ti-W-N/Ti-W Cr-W-N/Cr-W	WC+4%Co	milling	OSB	reduction in average wear area: Ti based coatings—to 54%, Cr—to 100%,	2009	[41]
Ti-W-N/Ti-W Cr-W-N/Cr-W	WC+4%Co	milling	particle board	reduction in average wear area: Ti based coatings—to 215%, Cr—to 460%	2009	[41]
TiAlN TiAlN/aCN	Carbide	cutting	chipboard	max. increase by 23% (TiAlN/aCN)	2020	[89]
TiN/AlTiN TiAlN/a-C:N	Different carbides	cutting	chipboard	max. increase by 56% (TiN/TiAlN)	2021	[90]

Table A2. Cathodic arc evaporation. Protective coatings applied to woodworking tools, synthetic information on the coatings used, the materials processed, the type of substrate and the effect of its modification.

Coating/ Structure	Substrate	Type of Machining	Machining Material	Results	Year	Reference
TiN (Ti,Zr)N	60SMD8 90WDCV	peeling	beech wood	cutting edge reduction up to: Ti based coatings 17%,	1999	[26]
CrN/CrCN	HS6-5-2	planing	pine wood	reduction in average wear area to 170%	2011	[71]
Cr_2N/CrN	HS6-5-2	cutting	pine wood	reduction in average wear area of 60%	2011	[69]
TiCN CrN DLC	K01–K20	milling	wood panel oaken scantlings glued by polyvinyl acetate	wear compared to the uncoated cutters. TiCN—smaller by 1.6 × DLC—smaller by 1.9 × CrN—smaller twice	2015	[65]
ZrN MoN	WC + Co	milling	particle board	reduction in volume wear to 150% (MoN) and 110% (ZrN)	2016	[93]
TiAlN	K10	cutting	mersawa wood fiberboard, particleboard, GRC	edge recession reduction by factor: 0.27 0.60 0.33 0.38	2016	[40]
TiAlN/TiSiN	K10	cutting	mersawa wood fiberboard particleboard GRC	edge recession reduction by factor: 0.38 0.78 0.43 0.54	2016	[40]

Table A2. *Cont.*

Coating/ Structure	Substrate	Type of Machining	Machining Material	Results	Year	Reference
TiAlN/TiBON	K10	cutting	mersawa wood fiberboard particleboard GRC	edge recession reduction by factor: 0.62 1.13 0.83 1.10	2016	[40]
CrN CrN/CrCN	M2 steel	cutting	timber	improvement in the tool durability of 170% (CrN/CrCN), 100% (CrN)	2018	[54]
CrN CrN/CrCN	cemented carbide	rounding	timber	improvement in the tool durability of 110% (CrN/CrCN), 100% (CrN)	2018	[54]
TiAlN	K10 tungsten carbide tool	milling	asbestos WPC LVL OSB	edge recession reduction by factor: 2.12 1.09 1.5 1.54	2019	[81]
TiAlN/TiSiN	K10 tungsten carbide tool	milling	asbestos WPC LVL OSB	edge recession reduction by factor: 1.08 0.84 1.35 1.33	2019	[81]
TiAlN/TiBON	K10 tungsten carbide tool	milling	asbestos WPC LVL OSB	edge recession reduction by factor: 2.33 3.18 4.0 3.67	2019	[81]
CrN/CrCN	HS6-5-2	planing	pine wood	improvement in the tool durability of 142%	2020	[91]
AlCrBN	HS6-5-2	planing	pine wood	improvement in the life service by 205%	2021	[92]

Table A3. Physical vapor deposition (PVD). Protective coatings applied to woodworking tools, synthetic information on the coatings used, the materials processed, the type of substrate and the effect of its modification.

Coating/ Structure	Substrate	Type of Machining	Machining Material	Results	Year	Reference
ta-C	cemented tungsten carbide	milling	melamine laminated particle board	2.5-fold lifetime increase	1999	[49]
TiN	SKH 51	sawing	oil palm afina sugi	tool wear 10% decrease 25% increase 64% increase	2006	[47]

Table A3. *Cont.*

Coating/Structure	Substrate	Type of Machining	Machining Material	Results	Year	Reference
TiN	P30	cutting	hardboard, cement board	life time increase 30–45%	2008	[48]
TiAlN/TiBN, TiAlN/TiSiN, TiAlN/CrAlN TiAlN	K10	milling	particle board	multilayer-coated tools experienced a smaller amount of delamination wear than the monolayer-coated tool. The best multilayer coating was TiAlN/CrAlN	2010	[68]
CrN, AlTiN, TiAlN, TiCN, and CrN	WC-Co	milling	oak wood	improvement in wear resistance by factors of: 3.0 (CrN), 1.9 (AlCrN), 1.7 (TiCN)	2022	[85]

References

1. Available online: www.Kadur.com (accessed on 31 August 2022).
2. Dembiński, C.; Potok, Z.; Kučerka, M.; Kminiak, R.; Očkajová, A.; Rogoziński, T. The Flow Resistance of the Filter Bags in the Dust Collector Operating in the Line of Wood-Based Furniture Panels Edge Banding. *Appl. Sci.* **2022**, *12*, 5580. [CrossRef]
3. Dong, W.; Xiong, X.; Ma, Y.; Yue, X. Woodworking Tool Wear Condition Monitoring during Milling Based on Power Signals and a Particle Swarm Optimization-Back Propagation Neural Network. *Appl. Sci.* **2021**, *11*, 9026. [CrossRef]
4. Mračková, E.; Schmidtová, J.; Marková, I.; Jad'ud'ová, J.; Tureková, I.; Hitka, M. Fire Parameters of Spruce (*Picea abies Karst.* (L.)) Dust Layer from Different Wood Technologies Slovak Case Study. *Appl. Sci.* **2022**, *12*, 548. [CrossRef]
5. Orlowski, K.A.; Dudek, P.; Chuchala, D.; Blacharski, W.; Przybylinski, T. The Design Development of the Sliding Table Saw Towards Improving Its Dynamic Properties. *Appl. Sci.* **2020**, *10*, 7386. [CrossRef]
6. Pędzik, M.; Rogoziński, T.; Majka, J.; Stuper-Szablewska, K.; Antov, P.; Kristak, L.; Kminiak, R.; Kučerka, M. Fine Dust Creation during Hardwood Machine Sanding. *Appl. Sci.* **2021**, *11*, 6602. [CrossRef]
7. Sporek, M.; Sporek, K.; Stebila, J.; Kučerka, M.; Kminiak, R.; Lubis, M.A.R. Assessment of the Mass and Surface Area of the Scots Pine (*Pinus sylvestris* L.) Needles. *Appl. Sci.* **2022**, *12*, 8204. [CrossRef]
8. Sydor, M.; Mirski, R.; Stuper-Szablewska, K.; Rogoziński, T. Efficiency of Machine Sanding of Wood. *Appl. Sci.* **2021**, *11*, 2860. [CrossRef]
9. Sydor, M.; Pinkowski, G.; Kučerka, M.; Kminiak, R.; Antov, P.; Rogoziński, T. Indentation Hardness and Elastic Recovery of Some Hardwood Species. *Appl. Sci.* **2022**, *12*, 5049. [CrossRef]
10. Norrby, N.; Johansson, M.P.; M'Saoubi, R.; Odén, M. Pressure and temperature effects on the decomposition of arc evaporated $Ti_{0.6}Al_{0.4}N$ coatings in continuous turning. *Surf. Coat. Technol.* **2012**, *209*, 203–207. [CrossRef]
11. Grobelny, T. Thermo-Mechanical Condition of the Tool Blade in the Process of Milling Wood and Wood Materials. Ph.D. Thesis, SGGW, Warsaw, Poland, 1999.
12. Lopez De Lacalle, L.N.; Lamikiz, A.; De Larrinova, J.F.; Azkona, I. Advanced Cutting Tools. In *Machining of Hard Materials*; Davim, J.P., Ed.; Springer-Verlag: London, UK, 2011; pp. 33–85.
13. Yates, J.M. Is there life after tungsten carbide? *Wood Wood Prod.* **1987**, *92*, 77–87.
14. Boyle, G.R. PCD replacing carbide in woodworking applications. *Cut. Tool Eng.* **1983**, *35*, 60–61.
15. Aytacoglu, M.E. PCD cutting tools gaining momentum. *Cut. Tool Eng.* **1983**, *35*, 49–50.
16. Heimbrand, E. Machining wood products with PCD. *Ind. Diam. Rev.* **1985**, *45*, 187–190.
17. Herbert, S. Wood products latch on to PCD. *Ind. Diam. Rev.* **1984**, *44*, 159–162.
18. Klamecki, B.E. A review of wood cutting tool wear literature. *Holz Als Roh-Und Werkst.* **1979**, *37*, 265–276. [CrossRef]
19. Thibaut, B.; Denaud, L.; Collet, R.; Marchal, R.; Beauchene, J.; Mothe, F.; Méausoone, P.J.; Martin, P.; Larricq, P.; Eyma, F. Wood machining with a focus on French research in the last 50 years. *Ann. For. Sci.* **2016**, *73*, 163–184. [CrossRef]
20. Rudnicki, J.; Beer, P.; Sokołowska, A.; Marchal, R. Low-temperature ion nitriding used for improving the durability of the steel knives in the wood rotary peeling. *Surf. Coat. Technol.* **1998**, *107*, 20–23. [CrossRef]
21. Nouveau, C.; Steyer, P.; Mohan Rao, K.R.; Lagadrillere, D. Plasma nitriding of 90CrMoV8 tool steel for the enhancement of hardness and corrosion resistance. *Surf. Coat. Technol.* **2011**, *205*, 4514–4520. [CrossRef]
22. Chekour, L.; Nouveau, C.; Chala, A.; Djouadi, M.A. Duplex treatment of 32CrMoV13 steel by ionic nitriding and triode sputtering: Application to wood machining. *Wear* **2003**, *255*, 1438–1443. [CrossRef]

23. Nouveau, C.; Djouadi, M.A.; Decès-Petit, C.; Beer, P.; Lambertin, M. Influence of Cr_xN_y coatings deposited by magnetron sputtering on tool service life in wood processing. *Surf. Coat. Technol.* **2001**, *142–144*, 94–101. [CrossRef]
24. Labidi, C.; Collet, R.; Nouveau, C.; Beer, P.; Nicosia, S.; Djouadi, M.A. Surface treatments of tools used in industrial wood machining. *Surf. Coat. Technol.* **2005**, *200*, 118–122. [CrossRef]
25. Anon, J.C.R. Modern cutting tools adapt to changing woodworking needs. *Wood Wood Prod.* **1984**, *89*, 201–203.
26. Djouadi, M.A.; Beer, P.; Marchal, R.; Sokolowska, A.; Lambertin, M.; Precht, W.; Nouveau, C. Antiabrasive coatings: Application for wood processing. *Surf. Coat. Technol.* **1999**, *116–119*, 508–516. [CrossRef]
27. Naylor, A.; Hackney, P. A Review of Wood Machining Literature with a Special Focus on Sawing. *BioResources* **2013**, *8*, 3122–3135. [CrossRef]
28. Sheikh-Ahmad, J.Y. Effect of Cutting Edge Geometry on Thermal Stresses and Failure of Diamond Coated Tools. *Procedia Manuf.* **2015**, *1*, 663–674. [CrossRef]
29. Sheikh-Ahmad, J.Y.; Morita, T. Tool coatings for wood machining: Problems and prospects. *For. Prod. J.* **2002**, *52*, 43–51.
30. Gogolewski, P.; Klimke, J.; Krell, A.; Beer, P. Al_2O_3 tools towards effective machining of wood-based materials. *J. Mater. Process. Technol.* **2009**, *209*, 2231–2236. [CrossRef]
31. Guo, X.L.; Cao, P.X.; Liu, H.N.; Teng, Y.; Guo, Y.; Wang, H. Tribological Properties of Ceramics Tool Materials in Contact with Wood-Based Materials. *Adv. Mat. Res.* **2013**, *764*, 65–69. [CrossRef]
32. Zhu, Z.; Guo, X.; Na, B.; Liang, X.; Ekevad, M.; Ji, F. Research on cutting performance of ceramic cutting tools in milling high density fiberboard. *Wood Res.* **2017**, *62*, 125–138.
33. Eblagon, F.; Ehrle, B.; Graule, T.; Kuebler, J. Development of silicon nitride/silicon carbide composites for wood-cutting tools. *J. Eur. Ceram. Soc.* **2007**, *27*, 419–428. [CrossRef]
34. Ugulino, B.; Hernandez, R.E. Assessment of surface properties and solvent-borne coating performance of red oak wood produced by peripheral planing. *Eur. J. Woo Prod.* **2017**, *75*, 581–593. [CrossRef]
35. Blugan, G.; Strehler, V.; Vetterli, M.; Ehrle, B.; Duttlinger, R.; Blösch, P.; Kuebler, J. Performance of lightweight coated oxide ceramic composites for industrial high speed wood cutting tools: A step closer to market. *Ceram. Int.* **2017**, *43*, 8735–8742. [CrossRef]
36. Beer, P.; Gogolewski, P.; Klimke, J.; Krell, A. Tribological Behaviour of Sub-micron Cutting-ceramics in Contact with Wood-based Materials. *Tribol. Lett.* **2007**, *27*, 155–158. [CrossRef]
37. Beer, P.; Rudnicki, J.; Ciupinski, L.; Djouadi, M.A.; Nouveau, C. Modification by composite coatings of knives made of low alloy steel for wood machining purposes. *Surf. Coat. Technol.* **2003**, *174–175*, 434–439. [CrossRef]
38. Benlatreche, Y.; Nouveau, C.; Aknouche, H.; Imhoff, L.; Martin, N.; Gavoille, J.; Rousselot, C.; Rauch, J.Y.; Pilloud, D. Physical and Mechanical Properties of CrAlN and CrSiN Ternary Systems for Wood Machining Applications. *Plasma Process. Polym.* **2009**, *6*, S113–S117. [CrossRef]
39. Faga, M.G.; Settineri, L. Innovative anti-wear coatings on cutting tools for wood machining. *Surf. Coat. Technol.* **2006**, *201*, 3002–3007. [CrossRef]
40. Fahrussiam, F.; Praja, I.A.; Darmawan, W.; Wahyudi, I.; Nandika, D.; Usuki, H.; Koseki, S. Wear characteristics of multilayer-coated cutting tools in milling wood and wood-based composites. *Tribol. Ind.* **2016**, *38*, 66–73.
41. Pinheiro, D.; Vieira, M.T.; Djouadi, M.A. Advantages of depositing multilayer coatings for cutting wood-based products. *Surf. Coat. Technol.* **2009**, *203*, 3197–3205. [CrossRef]
42. Vahlas, C. Chemical vapor deposition of metals: From unary systems to complex metallic alloys. In *Surface Properties and Engineering of Complex Metallic Alloys*; Belin-Ferre, E., Ed.; World Scientific Publishing Company Co., Pte. Ltd.: Singapore, 2010; Volume 3, pp. 49–82.
43. Gulbiński, W. Physical vapor deposition of thin film coatings. In *Surface Properties and Engineering of Complex Metallic Alloys*; Belin-Ferre, E., Ed.; World Scientific Publishing Company Co., Pte. Ltd.: Singapore, 2010; Volume 3, pp. 83–92.
44. Bendikiene, R.; Keturakis, G.; Pilkaite, T.; Pupelis, E. Wear Behaviour and Cutting Performance of Surfaced Inserts for Wood Machining. *Stroj.Vestn.-J. Mech. E.* **2015**, *61*, 459–464. [CrossRef]
45. Valleti, K.; Rejin, C.; Joshi, S.V. Factors influencing properties of CrN thin films grown by cylindrical cathodic arc physical vapor deposition on HSS substrates. *Mater. Sci. Eng. A* **2012**, *545*, 155–161. [CrossRef]
46. Osenius, S.; Korhonen, A.S.; Sulonen, M.S. Performance of TiN-coated tools in wood cutting. *Surf. Coat. Technol.* **1987**, *33*, 141–151. [CrossRef]
47. Okai, R.; Tanaka, C.; Iwasaki, Y. Influence of mechanical properties and mineral salts in wood species on tool wear of high-speed steels and stellite-tipped tools—Consideration of tool wear of the newly developed tip-inserted band saw. *Holz Als Roh-Und Werkst.* **2006**, *64*, 45–52. [CrossRef]
48. Darmawan, W.; Usuki, H.; Quesada, J.; Marchal, R. Clearance wear and normal force of TiN-coated P30 in cutting hardboards and wood-chip cement boards. *Holz Als Roh-Und Werkst.* **2008**, *66*, 89–97. [CrossRef]
49. Endler, I.; Bartsch, K.; Leonhardt, A.; Scheibe, H.J.; Ziegele, H.; Fuchs, I.; Raatz, C. Preparation and wear behaviour of woodworking tools coated with superhard layers. *Diam. Relat. Mater.* **1999**, *8*, 834–839. [CrossRef]
50. Kusiak, A.; Battaglia, J.L.; Marchal, R. Influence of CrN coating in wood machining from heat flux estimation in the tool. *Int. J. Thermal Sci.* **2005**, *44*, 289–301. [CrossRef]
51. Nouveau, C.; Djouadi, M.A.; Decès-Petit, C. The influence of deposition parameters on the wear resistance of Cr_xN_y magnetron sputtering coatings in routing of oriented strand board. *Surf. Coat. Technol.* **2003**, *174–175*, 455–460. [CrossRef]

52. Nouveau, C.; Jorand, E.; Decès-Petit, C.; Labidi, C.; Djouadi, M.A. Influence of carbide substrates on tribological properties of chromium nitride coatings: Application to wood machining. *Wear* **2005**, *258*, 157–165. [CrossRef]
53. Beer, P.; Djouadi, M.A.; Marchal, R.; Sokolowska, A.; Lambertin, M.; Czyzniewski, A.; Precht, W. Antiabrasive coatings in a new application—Wood rotary peeling process. *Vacuum* **1999**, *53*, 363–366. [CrossRef]
54. Kong, Y.; Tian, X.; Gong, C. Enhancement of toughness and wear resistance by CrN/CrCN multilayered coatings for wood processing. *Surf. Coat. Technol.* **2018**, *344*, 204–213. [CrossRef]
55. Niedzielski, P.; Miklaszewski, S.; Beer, P.; Sokolowska, A. Tribological properties of NCD coated cemented carbides in contact with wood. *Diam. Rel. Mater.* **2001**, *10*, 1–6. [CrossRef]
56. Pancielejko, M.; Czyzniewski, A.; Gilewicz, A.; Zavaleyev, V.; Szymański, W. The cutting properties and wear of the knives with DLC and W-DLC coatings. deposited by PVD methods. applied for wood and wood-based materials machining. *Arch. Mater. Sci. Eng.* **2012**, *58*, 235–244.
57. Kaczorowski, W.; Batory, D.; Szamanski, W.; Niedzielski, P. Carbon-based layers for mechanical machining of wood-based materials. *Wood Sci. Technol.* **2012**, *46*, 1085–1096. [CrossRef]
58. Olaya, J.J.; Wei, G.; Rodil, S.E.; Muhl, S.; Bhushan, B. Influence of the ion–atom flux ratio on the mechanical properties of chromium nitride thin films. *Vacuum* **2007**, *81*, 610–618. [CrossRef]
59. Odén, M.; Ericsson, C.; Håkansson, G.; Ljungcrantz, H. Microstructure and mechanical behavior of arc-evaporated Cr–N coatings. *Surf. Coat. Technol.* **1999**, *114*, 39–51. [CrossRef]
60. Oden, M.; Almer, J.; Hakansson, G.; Olsson, M. Microstructure property relationships in arc-evaporated CrN coatings. *Thin Solid Films* **2000**, *377–378*, 407–412. [CrossRef]
61. Navinsek, B.; Panjan, P.; Milosev, I. Industrial applications of CrN (PVD) coatings. deposited at high and low temperatures. *Surf. Coat. Technol.* **1997**, *97*, 182–191. [CrossRef]
62. Rebholz, C.; Ziegele, H.; Leyland, A.; Matthew, A. Structure, mechanical and tribological properties of nitrogen-containing chromium coatings prepared by reactive magnetron sputtering. *Surf. Coat. Technol.* **1999**, *115*, 222–229. [CrossRef]
63. Wiklund, U.; Gunnars, J.; Hogmark, S. Influence of residual stresses on fracture and delamination of thin hard coatings. *Wear* **1999**, *232*, 262–269. [CrossRef]
64. Castanho, J.M.; Vieira, M.T. Effect of ductile layers in mechanical behaviour of TiAlN thin coatings. *J. Mater. Proc. Technol.* **2003**, *143–144*, 352–357. [CrossRef]
65. Kazlauskas, D.; Keturakis, G. Wear of TiCN, CrN and DLC coated tungsten carbide router cutters during oak wood milling. In Proceedings of the 20th International Scientific Conference: Mechanika 2015, Kaunas University of Technology, Kaunas, Lithuania, 23–24 April 2015.
66. Nouveau, C.; Labidi, C.; Ferreira Martin, J.P.; Collet, R.; Djouadi, M.A. Application of CrAlN coatings on carbide substrates in routing of MDF. *Wear* **2007**, *263*, 1291–1299. [CrossRef]
67. Nouveau, C.; Labidi, C.; Collet, R.; Benlatreche, Y.; Djouadi, M.A. Effect of surface finishing such as sand-blasting and CrAlN hard coatings on the cutting edge's pelling tools' wear resistance. *Wear* **2009**, *267*, 1062–1067. [CrossRef]
68. Darmawan, W.; Usuki, H.; Rahayu, I.S.; Gottlöber, C.; Marchal, R. Wear Characteristics of Multilayer-Coated Cutting Tools when Milling Particleboard. *For. Prod. J.* **2010**, *60*, 615–621. [CrossRef]
69. Warcholinski, B.; Gilewicz, A.; Ratajski, J. Cr_2N/CrN multilayer coatings for wood machining tools. *Tribol. Int.* **2011**, *244*, 1076–1082. [CrossRef]
70. Warcholinski, B.; Gilewicz, A.; Kuklinski, Z.; Myslinski, P. Hard CrCN/CrN multilayer coatings for tribological applications. *Surf. Coat. Technol.* **2010**, *204*, 2289–2293. [CrossRef]
71. Gilewicz, A.; Warcholinski, B.; Myslinski, P.; Szymanski, W. Anti-wear multilayer coatings based on chromium nitride for wood machining tools. *Wear* **2010**, *210*, 32–38. [CrossRef]
72. Warcholinski, B.; Gilewicz, A. Multilayer coatings on tools for woodworking. *Wear* **2011**, *271*, 2812–2820. [CrossRef]
73. Gilewicz, A.; Warcholinski, B.; Szymanski, W.; Grimm, W. CrCN/CrN + ta-C multilayer coating for applications in wood processing. *Tribol. Int.* **2013**, *57*, 1–7. [CrossRef]
74. Kot, M.; Rakowski, W.A.; Major, Ł.; Major, R.; Morgiel, J. Effect of bilayer period on properties of Cr/CrN multilayer coatings produced by laser ablation. *Surf. Coat. Technol.* **2008**, *202*, 3501–3506. [CrossRef]
75. Chang, Y.Y.; Yang, S.J.; Wang, D.Y. Structural and mechanical properties of TiAlN/CrN coatings synthesized by a cathodic-arc deposition process. *Surf. Coat. Technol.* **2006**, *201*, 4209–4214. [CrossRef]
76. Salje, E.W.; Stuehmeier, W. Milling particleboard with high hard cutting materials. In Proceedings of the Ninth International Wood Machining Seminar, Richmond, VA, USA, 10–12 October 1988; pp. 211–228.
77. Fuch, I.; Raatz, C. Study of wear behavior of specially coated (CVD.PACVD) cemented carbide tools while milling of wood-based materials. In Proceedings of the 13th International Wood Machining Seminar, Vancouver, BC, Canada, 17–19 June 1997; pp. 709–715.
78. Sheikh-Ahmad, J.Y.; Stewart, J.S. Performance of different PVD coated tungsten carbide tools in the continuous machining of particleboard. In Proceedings of the 12th International Wood Machining Seminar, Kyoto, Japan, 2–4 October 1995; pp. 282–291.
79. Li, Y.; Liu, Y.H.; Tian, Y.B.; Wang, Y.; Wang, J.L. Application of improved fireworks algorithm in grinding surface roughness online monitoring. *J. Manuf. Process.* **2022**, *74*, 400–412. [CrossRef]

80. Li, Y.; Liu, Y.H.; Wang, J.L.; Wang, Y.; Tian, Y.B. Real-time monitoring of silica ceramic composites grinding surface roughness based on signal spectrum analysis. *Ceram. Int.* **2022**, *48*, 7204–7217. [CrossRef]
81. Pangestu, K.P.T.; Darmawan, W.; Nandika, D.; Usuki, H. Cutting performance of multilayer coated tungsten carbide in milling of wood composites. *Int. Wood Prod. J.* **2019**, *10*, 78–85. [CrossRef]
82. Warcholinski, B.; Gilewicz, A. Coating for better endurance. In *FMD ASIA Solid Wood Panel Technology*; 2012; pp. 26–29.
83. Warcholiński, B.; Gilewicz, A.; Szymański, W.; Pinkowski, G. Improvment of durability of engineering tools for wood. *Surf. Eng.* **2011**, *2*, 73–80. (In Polish)
84. Djouadi, M.A.; Nouveau, C.; Beer, P.; Lambertin, M. Cr_xN_y hard coatings deposited with PVD method on tools for wood machining. *Surf. Coat. Technol.* **2000**, *133–134*, 478–483. [CrossRef]
85. Kazlauskas, D.; Jankauskas, V.; Kreivaitis, R.; Tuckute, S. Wear behaviour of PVD coating strengthened WC-Co cutters during milling of oak-wood. *Wear* **2022**, *498–499*, 204336. [CrossRef]
86. Benlatreche, Y.; Nouveau, C.; Marchal, R.; Ferreira Martins, J.P.; Aknouche, H. Applications of CrAlN ternary system in wood machining of medium density fibreboard (MDF). *Wear* **2009**, *267*, 1056–1061. [CrossRef]
87. Kato, C.; Bailey, J.A. Wear Characteristics of a Woodworking Knife with a Vanadium Carbide Coating only on the Clearance Surface (Back Surface). *Key Eng. Mater.* **1998**, *138–140*, 479–520. [CrossRef]
88. Makala, R.S.; Yoganand, S.N.; Jagannadham, K.; Lemaster, R.L.; Bailey, J. Diamond Coated WC Tools for Machining Wood and Particle Board. *MRS Online Proc. Libr.* **2001**, *697*, 819. [CrossRef]
89. Czarniak, P.; Szymanowski, K.; Kucharska, B.; Krawczyńska, A.; Sobiecki, J.R.; Kubacki, J.; Panjan, P. Modification of tools for wood based materials machining with TiAlN/a-CN coating. *J. Mater. Sci. Eng. B* **2020**, *257*, 114540. [CrossRef]
90. Kucharska, B.; Sobiecki, J.R.; Czarniak, P.; Szymanowski, K.; Cymerman, K.; Moszczyńska, D.; Panjan, P. Influence of Different Types of Cemented Carbide Blades and Coating Thickness on Structure and Properties of TiN/AlTiN and TiAlN/a-C:N Coatings Deposited by PVD Techniques for Machining of Wood-Based Materials. *Materials* **2021**, *14*, 2740. [CrossRef]
91. Nadolny, K.; Kapłonek, W.; Sutowska, M.; Sutowski, P.; Myśliński, P.; Gilewicz, A. Experimental Studies on Durability of PVD-Based CrCN/CrN-Coated Cutting Blade of Planer Knives Used in the Pine Wood Planing Process. *Materials* **2020**, *13*, 2398. [CrossRef] [PubMed]
92. Nadolny, K.; Kapłonek, W.; Sutowska, M.; Sutowski, P.; Myśliński, P.; Gilewicz, A.; Warcholiński, B. Moving towards sustainable manufacturing by extending the tool life of the pine wood planing process using the AlCrBN coating. *SM&T* **2021**, *28*, e00259.
93. Chayeuski, V.; Zhylinski, V.; Grishkevich, A.; Rudak, P.; Barcik, S. Influence of high energy treatment on wear of edges knives of wood-cutting tool. *MM Sci. J.* **2016**, *6*, 1519–1523. [CrossRef]
94. Latushkina, S.D.; Rudak, P.V.; Kuis, D.V.; Rudak, O.G.; Posylkina, O.I.; Piskunova, O.Y.; Kováč, J.; Krilek, J.; Barcík, S. Protective Woodcutting Tool Coatings. *Acta Univ. Agric. Silvic. Mendel. Brun.* **2016**, *64*, 835–839. [CrossRef]
95. Chayeuski, V.; Zhylinski, V.; Cernashejus, O.; Visniakov, N.; Mikalauskas, G. Structural and Mechanical Properties of the ZrC/Ni-Nanodiamond Coating Synthesized by the PVD and Electroplating Processes for the Cutting Knifes. *J. Mater. Eng. Perform.* **2019**, *28*, 1278–1285. [CrossRef]
96. Kuleshov, A.K.; Uglov, V.V.; Rusalsky, D.P.; Grishkevich, A.A.; Chayeuski, V.V.; Haranin, V.N. Effect of ZrN and Mo-N coatings and sulfacyyanization on wear of wood-cutting knives. *J. Frict. Wear.* **2014**, *35*, 201–209. [CrossRef]
97. Kazlauskas, D.; Jankauskas, V.; Tuckute, S. Research on tribological characteristics of hard metal WC-Co tools with TiAlN and CrN PVD coatings for processing solid oak wood. *Coating* **2020**, *10*, 632. [CrossRef]
98. Kazlauskas, D.; Jankauskas, V. Woodworking tools: Tribological problems and directions of solutions. In Proceedings of the 9th International Conference BALTTRIB'2017, Kaunas, Lithuania, 16–17 November 2017.
99. Kazlauskas, D.; Keturakis, G.; Jankauskas, V.; Andriušis, A. Investigation of TiCrN-Coated High Speed Steel Tools Wear during Medium Density Fiberboard Milling. *J. Frict. Wear* **2021**, *42*, 124–129. [CrossRef]
100. Castanho, J.M.; Pinheiro, D.; Vieira, M.T. New Multilayer Coatings for Secondary Wood Products Cutting. *Mater. Sci. Forum.* **2004**, *455–456*, 619–622. [CrossRef]