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Review

Enhancing the Tribological Performance of Tool Steels for Wood-Processing Applications: A Comprehensive Review

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Abstract: The stochastic nature of tool wear during wood machining, owing to the dynamic properties of the biological material and its dependence on various factors, has raised significant industrial and research concerns in recent years. Explicitly, the tool wear is a product of the interaction between wood properties (such as hardness, density, and contamination level) and machining parameters (such as cutting speed, feed rate, and rake angle) alongside ambient conditions (such as temperature and humidity). The objective of this review paper is to provide an overview of recent advancements in the field of wood machining. To begin with, it highlights the important role of wood properties and ambient conditions influencing tool wear. Furthermore, the paper examines the various mechanisms involved in the wood-machining process and discusses their cost implications from an industrial perspective. It also covers technological advancements in the characterization of tool wear and explores the relationship between this parameter and other machining variables. It provides critical and analytical discussions on various methods for enhancing tool wear, including heat treatment, cryogenic treatment, thermochemical treatment, coating deposition, and hybrid treatments. Additionally, the paper incorporates statistical analysis to achieve two objectives. Firstly, it aims to identify the most significant wood property that affects tool wear and establish the correlation between this parameter and wood properties. Secondly, it investigates the effect of heat treatment parameters and carbide characteristics on tool wear as well as their correlation. Lastly, the review provides recommendations based on relevant literature for prospective researchers and industrial counterparts in the field. These recommendations aim to guide further exploration and practical applications in the subject matter.

Keywords: wood machining; tool steels; tool wear; wear resistance; correlation analysis

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1. Introduction

Over the past two decades, there has been a significant growth in the demand for wood and wood composites for various applications, which is driven by the increasing global population [1–3]. This can be attributed to their availability [4], high specific strength [5], insulation properties [6], aesthetic appeal [4], and relatively low environmental impact [7]. For instance, wood and its composites find application in building construction [8], energy [9], packaging [4,10], electronics [9], and furnishing [3,11]. The transformation of raw wood into finished products involves primary and secondary transformation processes [12,13]. Primary processes include cutting the tree and branches, debarking, chipping, and cantering [12,14], while milling [10], drilling [15], shaping, and planing operations [3] fall under the secondary transformation category.

The process of wood transformation is highly intricate, involving the interaction between a cutting tool with a sharp edge and the impact from either the tree trunk or a partially machined section, such as a precut slice. Additionally, the process involves the presence of other hard materials, such as silica contaminants, as well as organic acids like tree sap [5]. According to forest management inventory data published by Natural Resources Canada, in 2020, approximately 143,061,196 cubic meters of trees were harvested in Canada for both domestic and foreign consumption. This harvesting process results in the generation of approximately 1.75 million metric tonnes of wood waste and contributes to approximately 3.5 megatonnes of CO_2 emissions annually [16,17]. One significant factor that contributes to wood wastage is the use of low-quality cutting tools. To address this issue, there is a need for technologically advanced cutting tools that can consistently deliver high cutting performance throughout their lifespan. By utilizing such tools, optimal machining can be achieved, resulting in high-quality products and a reduction in wood waste generation and greenhouse gas emissions. This drives the continuous pursuit of high-performance cutting tools by wood processing companies. The cutting performance of a tool plays a crucial role in determining the competitiveness of a cutting tool manufacturing company within the industry. However, it is important to highlight that the property requirement of the cutting tool depends on the wood machining operation. For instance, operations such as debarking, cantering, or continuous sawing are perceived to have a more severe effect on the cutting tool than finishing operations such as planing. Consequently, the cutting tools for the former would necessitate a higher set of property requirements than the latter [18]. Key characteristics used to evaluate the cutting performance include the hardness, toughness, and wear resistance of the tool. However, the manufacturing of high-performance cutting tools that exhibit prolonged cutting ability with high sharpness, elevated resistance to impact and surface deformation, considering the influence of the aforementioned factors, is a highly challenging task [12,13].

Over time, wood transformation has been achieved using a variety of cutting tools, including tool steels [10], cemented carbides [19], cobalt-base alloys [20], and ultrahard tool materials [21]. Tool steels are iron–carbon alloys with carbon contents ranging from moderate (about 0.5%) to high amounts (about 2.25%) [12,13]. Cemented carbides are composed of a hard carbide material that is bonded together using a soft and ductile binder, such as tungsten, nickel, or cobalt [4,12]. On the other hand, cobalt-based alloys exhibit properties that lie between those of tool steels and cemented carbides. One popular cobalt-based cutting tool is Stellite [18,19,21]. Ultrahard tool materials, on the other hand, exhibit extremely high wear resistance and are primarily used for machining hard woods that cannot be easily transformed using the aforementioned cutting materials. Examples of ultrahard tool materials include Polycrystalline Diamond (PCD) and Polycrystalline Cubic Boron Nitride (PCBN) [12,22,23].

The selection of an appropriate cutting tool for wood machining often requires striking a balance between wear resistance, toughness, and cost considerations [12]. For example, while PCD and PCBN exhibit excellent wear resistance, they have lower toughness and higher cost. In contrast, tool steels offer excellent toughness and are more cost-effective, but their wear resistance is comparatively lower [4,20,23]. Additionally, achieving a balance between cutting speed and feed rate is crucial. Ultrahard materials can withstand high cutting speeds but can handle relatively lower feed rates, while tool steels exhibit the opposite behavior [22]. Therefore, the selection of cutting tool materials depends on various factors, including the type of wood being machined [24], desired performance in terms of wear resistance and toughness [22], and available resources [10]. Additionally, it is important to emphasize the significant role of the wood type on the cutting performance. For instance, a given cutting tool used for machining a very tough wood (e.g., oak wood) [25] or wood species containing a lot of defects (e.g., knotty pine) [26] or even high moisture content (e.g., sugar maple) [27] would likely display a relatively reduced cutting performance when compared to one used for machining one with lower toughness (e.g., black spruce) [28], or one with minimal defects (e.g., African mahogany) [29] or one with low moisture content (e.g., teak) [4,30]. Again, the machining of wood composites characterized by high abrasive properties, such as particle board [31], medium-density fiberboard (MDF) [32], and oriented strand board (OSB) [33] are also prone to higher tool wear than those used for machining natural wood [11].

In many cases, tool steel is the preferred choice for cutting tools due to several advantages. Firstly, tool steels are readily available and relatively affordable compared to other materials. Secondly, they offer a good balance of wear resistance and toughness, even at high temperatures. Thirdly, tool steels have a low wedge angle, which allows for efficient cutting [10]. Additionally, tool steels can be easily fabricated into various cutting tool shapes, including intricate designs [34–36]. Furthermore, tool steels can be modified and tailored to specific applications through heat treatment, providing further versatility and advantage over cobalt-base alloys [12]. Tool steels are commonly classified according to the American Iron and Steel Institute (AISI) and Society for Automotive Engineers (SAE) standards, with the AISI standard gaining wider acceptance in recent years [37]. Under the AISI classification, tool steels are categorized into various types, including water-hardening (W), shock-resisting (S), mold steels (M), high-speed (T and M), hot-work (H), and cold-work (O, A, and D) tool steels, among others [38]. However, when it comes to wood machining, high-speed and cold-work tool steels are the most commonly used types [1,5,12,39,40].

Unfortunately, even though tool steel remains prevalent in the wood-cutting industry, manufacturers of wood products frequently face the challenge of low tool life. Tool steels often fall short in sustaining the desired product quality, leading to increased production downtime for tool edge replacement or regeneration. This directly impacts production costs, as the frequent need for tool maintenance and replacement drives up expenses [41,42]. Consequently, scientists and industry professionals have initially focused on optimizing machining parameters in an attempt to address this issue [43,44]. Subsequently, attention turned toward technologically enhancing the surface properties of tool steels [12]. Various approaches were explored, including modifying the surface microstructure [45], altering surface chemistry [46], or applying surface coatings [39]. Bendikiene and Pupelis also proposed submerged arc surfacing with alloying as a cost-effective alternative to conventional surface engineering processes [3]. Additionally, the adoption of powder metallurgy as a method for manufacturing tool steels has been recommended by others, citing improvements in microstructure and mechanical properties [23]. As a result, significant advancements in tool life have been observed over the years [4,41]. These innovative approaches offer promising solutions to enhance the performance and durability of tool steels in wood machining applications.

A literature survey has revealed that studies on wood machining are relatively limited compared to metal machining. However, it should be noted that the technological advancements and innovations in metal machining cannot be wholly applied to wood machining. This is primarily due to the significant differences in the material properties and machining mechanisms between wood and metal [4]. Wood machining, in fact, is even more complex than metal machining. This is primarily due to the combination of high machining speed [19], intricate machining conditions [47], and the influence of multiple factors [48]. Furthermore, it is worth noting that the number of published review articles on wood machining remains limited, indicating a scarcity of comprehensive literature in this area. In the past three years, Nasir and Cool conducted an extensive analysis on wood sawing, covering various factors that impact the process and exploring methods for optimization [44]. Additionally, Al-Asadi and Al-Tameemi conducted a comprehensive review on different coatings applied to cutting tools, emphasizing the factors that influence their tribological performance [41]. Recently, Warcholinski and Gilewicz provided a comprehensive examination of cutting tools used in wood processing, focusing on enhancing cutting efficiency through coating deposition [4]. However, it is surprising that despite the progress made in research, there has been a lack of effort to quantify the correlation between wood properties and tool wear. This is equally applicable to the properties of the cutting tool and tool wear, particularly the microstructural composition such as the carbide characteristics of tool steels, which have a substantial impact on the tribological performance of the cutting tool. Establishing these relationships can enhance our current understanding of tool wear in wood machining and provide valuable tools for predicting and forecasting related parameters. Therefore, this article begins by addressing the challenges associated with wood machining using cutting tools and presents recent advancements in tool wear characterization. Subsequently, it examines the relationship between tool wear, wood properties, heat treatment parameters of tool steels, and carbide characteristics using correlation and regression analysis. Moreover, it provides critical analytical discussions on heat treatment, cryogenic treatment, and other surface engineering techniques aimed at enhancing tool life. The objective is to identify research gaps for future researchers and to serve as a valuable resource for industrial professionals in the field.

2. Wood Machining: Challenges, Temperature Effects, and Wear Mechanisms

2.1. Wood Machining

Wood machining involves sectioning the material to achieve a specific product with desired geometry and a high-quality surface finish. The chips generated during this process can be viewed as valuable wood products or waste, depending on the machining operation. Wood industries that carry out operations like milling, drilling, sawing, turning, and planing typically consider the chips as waste. Conversely, industries involved in flat slicing or peeling, such as veneer production, may view the chips differently. However, the majority of wood processing industries fall into the former category. Moreover, wood sawing constitutes the bulk of the wood processing operations, as it is widely used in primary and secondary transformation processes. Band sawing and circular sawing are the most common sawing operations in wood processing [44]. In wood cutting, the cutting tool section responsible for cutting through the wood is typically triangular in shape. Figure 1 shows a simplified model of the wood-cutting process [13].

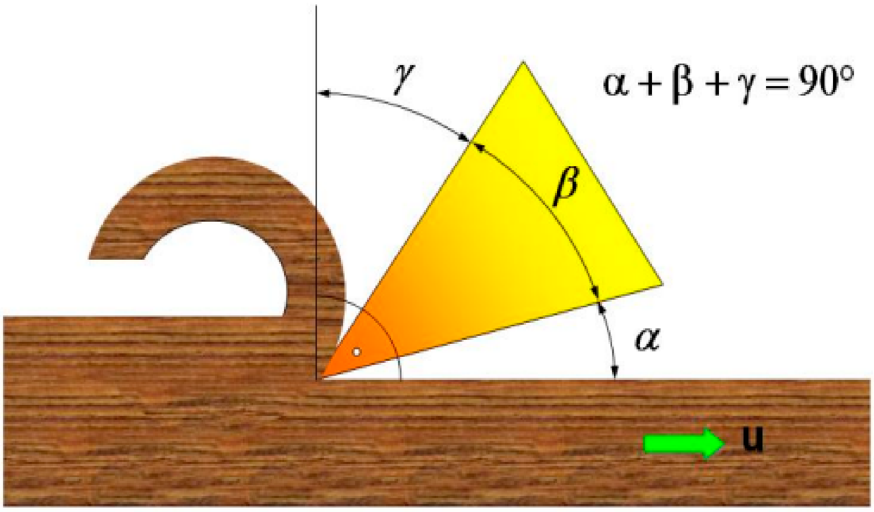


Figure 1. A simple model showing the wood-cutting process (γ—rake angle, β—wedge angle, α—clearance angle and u—cutting velocity) [13].

The edges of the cutting tool engaged during wood machining depend on the type of operation. For instance, in machining operations such as sawing, where the wood thickness is more than the length of the tool edge, both edges are usually engaged. Meanwhile, during wood planing, only one cutting edge is engaged, as the length of the cutting edge is usually more than the wood thickness. However, during wood milling, both of the aforementioned conditions are applicable [13]. Figure 2 shows some contemporary cutting tools for different wood machining operations.

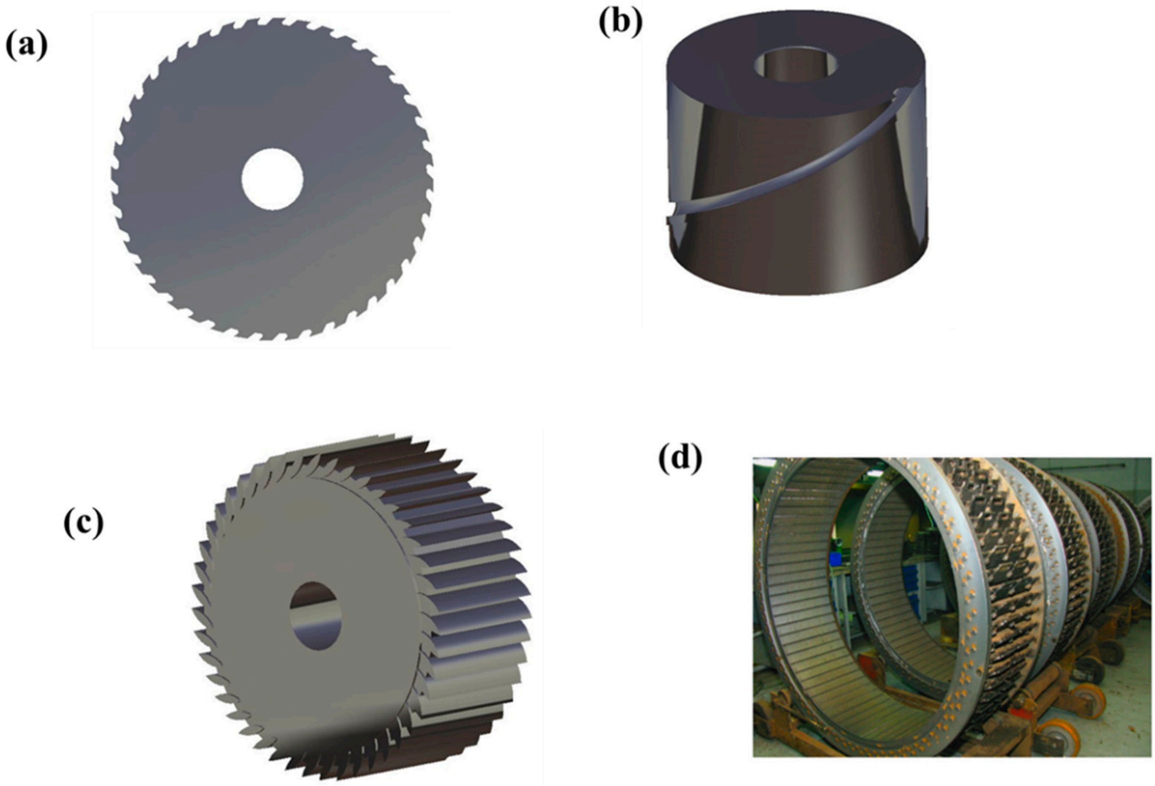


Figure 2. Wood machining tools: (**a**) Saw (for wood sawing); (**b**) Milling cutters (for wood milling); (**c**) Planer head (for wood planing); (**d**) Drum chipper (for chipping of wood composites) [6,49].

2.2. Challenges of Wood Machining: The Dynamic Properties of Wood

Since the inception of wood machining, the wood industry has been faced with the challenge of producing good quality wood products while simultaneously catering for the market demand. However, over time, although the wood machining industry has adopted automation of the machining process to cater for the ever-increasing demand for wood products, the industry is still confronted with the need to produce better-quality wood products, which requires high-performance cutting tools. Unfortunately, this objective is yet to be fully actualized, primarily owing to the insufficient tool life of the existing cutting tools [10,19]. This situation is further aggravated by the contrasting properties (physical, mechanical, and chemical) of the wood and the cutting tools [5,34].

On one hand, tool steel possesses a considerable combination of hardness and toughness, while wood, on the other hand, is a natural composite material whose property is significantly influenced by its composition [3]. Chemically, it contains cellulose, hemicellulose, lignin, extractives, organic acids, and mineral contaminants. Macroscopically, it contains piths, growth rings, sapwood, heartwood, rays, and resin canals [6,50,51]. Firstly, the biological nature of the material accounts for the variability in the properties even within a given specie. Secondly, its properties vary across cross-sections, radial, and transverse sections (anisotropy). Additionally, due to its hygroscopic nature, wood is in constant equilibrium with atmospheric water vapor, allowing it to absorb and release moisture from the surrounding environment. This implies a constantly changing wood moisture composition [6,7,52]. Therefore, the anisotropy and hygroscopicity of wood directly influence other properties such as strength, hardness, and workability. The dynamic properties of wood result in constantly changing machining parameters such as the cutting force and resistance [53]. Furthermore, the presence of knots and hard mineral contaminants of various sizes and colors also affect the wear of tool steels [5,54–56]. Moreover, organic acids such as acetic acid (e.g., in red oak) [57], formic acids (e.g., in pine) [58], oxalic acids (e.g., in walnut) [59], and tannic acids (e.g., in chestnut) [60] present in different concentrations also affect tool wear. Their effect is even more severe at higher concentrations as they contribute to tribochemical reactions during wood machining. But, unfortunately, the concentration of these acids also varies within a given wood species due to changes in climatic conditions [61]. Consequently, the dynamic properties of wood make wood machining very complex. For instance, a given cutting tool which had an excellent wear performance in the machining of a given wood species may perform poorly when used for machining another wood of a similar species [4,34,62]. Furthermore, fluctuations in climatic factors, especially temperature, further contribute to the dynamic nature of wood properties, affecting the machining process.

2.3. The Role of Temperature in Wood Machining

The temperature of the cutting tool and that of the surroundings play a pivotal role in the wood transformation process. Regrettably, despite the dynamic machinability of wood, lubricants or coolants are not used. This is due to the hygroscopic nature of the material. Already, the water and other organic acids contents of wood have a corrosive effect on the cutting tool. The addition of lubricants or coolants would result in unforeseen reactions, which might further increase the corrosivity or compromise the wood quality [10,19,52]. Hence, the inability to use lubricants or coolants creates the tendency for temperature rise during machining. The temperature rise varies from small increments (about 50 °C) to large amounts (about 800 °C) depending on the machining conditions [4,63]. During wood machining, the friction between the tool edges and the wood, alongside the continuous shear and plastic deformation during chip formation, leads to the generation of thermal energy resulting in the temperature rise. The energy is absorbed partly by the cutting tool and the wood, while the remainder is lost to the surroundings. The detrimental effect of the temperature rise is in two folds: on one hand, it compromises the desired accuracy and quality of the wood products. On the other hand, it degrades the cutting tool and affects the machining parameters. The tool steel degradation is characterized by a reduction in mechanical properties (hardness and toughness) and chemical stability, resulting in a reduced life span. Machining parameters such as cutting force [54], power consumption [10], depth of cut [5], and cutting speed [3] are also negatively affected. In this regard, a study was conducted by Zhu et al. on the relationship between cutting force, machining temperature, and tool wear during the milling of wood plastic composites using cemented carbide cutters. Their findings revealed that an increase in temperature of the cutting edge was accompanied by an increase in the cutting force of the cemented carbide cutters. This is an indication of increased power consumption. Additionally, the temperature rise was also correlated with increased tool wear [64]. In another study, Pei et al. reported a negative correlation between the machining temperature and the feed rate during the milling of wood plastic composite [65].

Furthermore, the ambient machining temperature affects the properties of the wood and also the quality of the machined products. For instance, the strength of wood varies with fluctuations in ambient temperature caused by seasonal changes [6,12]. Meanwhile, in a study conducted by Hernandez and Boulanger on the effect of ambient temperature on chip dimension for pulp industry application, it was observed that the sizes of the chips produced during summer were quite distinct from those produced in winter. Irrespective of the machining speed, the number of fines and pins produced in winter were twice those produced in summer, while fewer over-thicks were produced during summer than in winter. The fluctuation in the chip dimension was attributed to the changes in the wood properties with ambient temperature [66].

2.4. Wear and Its Mechanisms

Wear is the gradual material loss from the surface of a material due to mechanical or chemical factors during relative motion [41,54,67,68]. The surface properties of the participating materials, such as roughness and hardness, significantly influence the process [67]. For instance, the process has been observed to proceed faster with a lower hardness ratio (substrate/abradant) of the participating materials [69]. The product of the process (wear debris) either sticks with one of the materials or is released into the environment. Its aftermath includes loss of cutting ability [5], reduction in cutting speed [10,37], increase in power consumption [4], increase in downtime [41], and reduction in the quality of machined products [53]. Even after grinding (re-sharpening), the functional surface of the knives cannot be regained [53]. As a matter of fact, the wear of cutting tools is of great concern to the industrial counterpart due to its direct impact on the cost of production. Over time, researchers have recognized that the wear of tool steels progresses in three distinct stages. The first stage is usually characterized by a very fast rate of wear followed by a stable linear wear rate, as shown in Figure 3. The last stage represents tool failure where it is no longer usable [54,70,71].

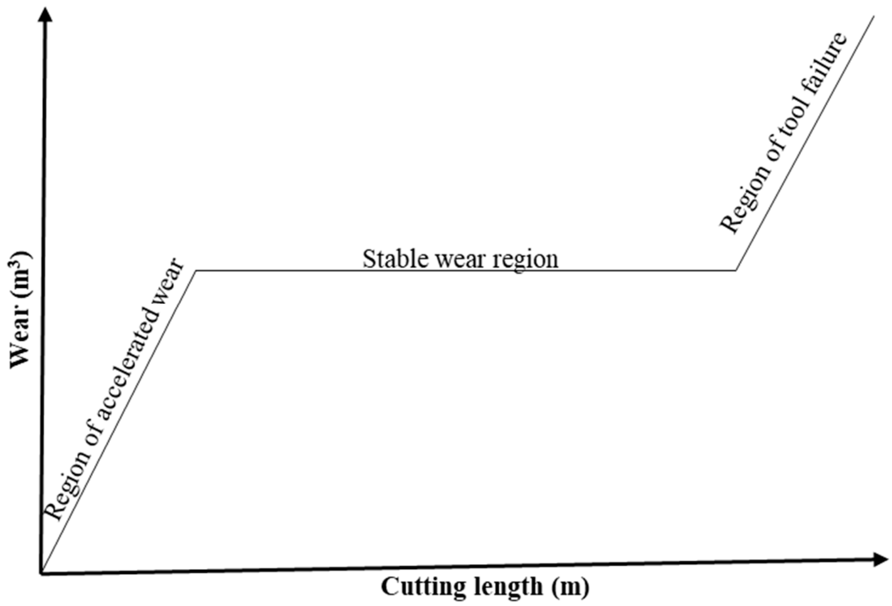


Figure 3. Stages of cutting tool wear during wood machining [72].

Tool wear during wood machining is a product of the interaction of the cutting tool with the wood, involving physical, mechanical, and chemical processes that lead to the transfer of materials and energy. The most prevalent wear mechanisms reported in the literature are abrasion, adhesion, surface fatigue, and tribochemical reaction [12]. Abrasion is characterized by material removal from a material surface as a result of scratching by an abrasive material. It mainly involves two or three bodies in contact. Microcutting, microploughing, and microcracking are associated with abrasive wear [12,68,73]. Meanwhile, in adhesive wear, adhesive bonds are disintegrated due to the surface interaction during relative motion [12,74]. Surface fatigue failures are either mechanically or thermally activated. It results from the repeated sliding in the presence of hard asperities and is characterized by cracking, flaking, work hardening and plastic deformation. Tribochemical reaction involves the intermittent removal of corrosion products facilitated by a combination of relative motion and a corrosive environment [12,75,76]. However, in service, tool wear involves a combination of the different wear mechanisms. Moreover, abrasive wear has been identified as the most prevalent wear mechanism and accounts for the bulk of the cost expended on wear maintenance, as shown in Figure 4.

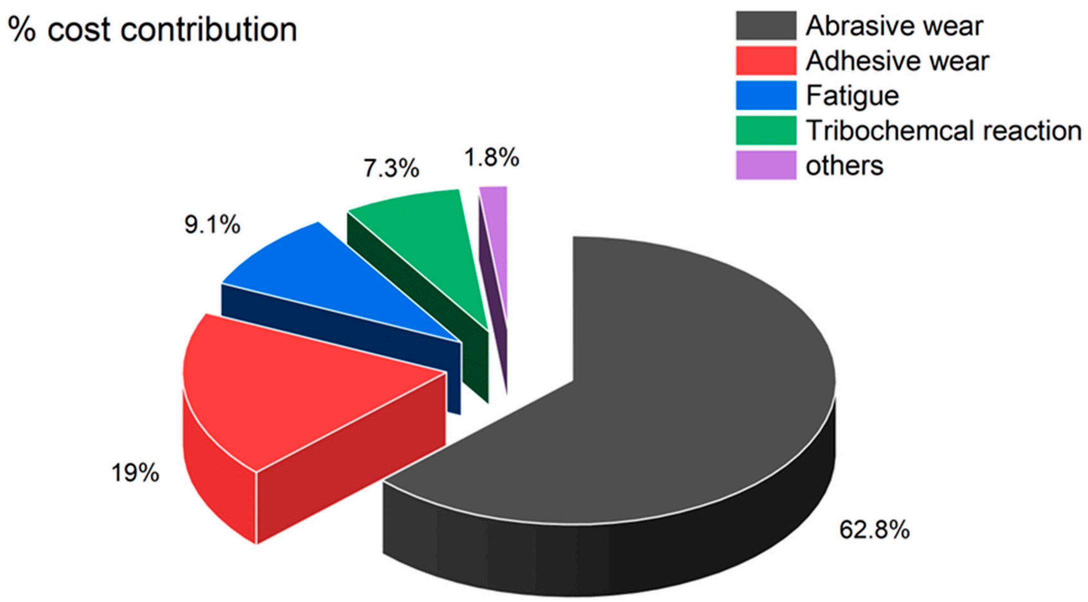


Figure 4. Cost of wear maintenance based on the results from an industrial survey conducted by Neale Consulting Engineers Limited in the UK [74].

Despite attempts by scientists to minimize the occurrence of these wear mechanisms, they are still prevalent in different tool steels, irrespective of the surface engineering treatment. Firstly, a study conducted by Heidari et al. [12] to understand the prevailing wear mechanisms in AISI A8 chipping and finishing knives for processing black spruce revealed the occurrence of microploughing, microcutting, cracking, and edge deformation of the cutting tool. The abrasive wear was characterized by uniform grooves whose depths were proportional to the machining force. The observation was attributed to wood contaminations culminating in a three-body abrasion. Meanwhile, the initiation and propagation of the cracks were ascribed to the high impact when the cutting tool comes into contact with defects such as knots during wood machining. Although this form of wear has received less concern, if not properly managed, it results in wood products with poor surface finish and also renders the cutting tools unusable. The consequence of the inability of the cutting tool to withstand further cutting force due to excessive wear was the deformation of the cutting edge [12].

These mechanisms are also not absent from tool steels with surface engineering treatments. In this regard, extensive cracking, protective layer delamination, and microcutting were observed in nitrocarburized Cr-Mo-V tool steels. The findings indicated that the alloy composition of the tool steels significantly affected the resulting hardness and wear resistance of the nitrocarburized tool steels. However, the tool steels displayed superior wear resistance compared to the ones without nitrocarburizing treatment due to the formation of a compound layer comprising ε-carbonitride and γ'-nitride. But with increased loading, the cracking extended beyond the compound layer toward the sub-surface [77]. In another study, Erdogan reported micro-scratching and micro-grooving in borided AISI H13 tool steel [46]. Nevertheless, the application of boriding treatment significantly minimized the micro-abrasive wear. This was due to increased hardness resulting from the formation of FeB-Fe_2B double phase boride layers. As previously observed by Psyllaki et al. [77], the authors also reported that the micro-abrasive wear accelerated with increased loading [46]. Furthermore, abrasive wear was also observed in shot-peened AISI D3 tool steel with a CrN/CrAlN nanolayer coating [40]. This occurrence can contribute to coating failure in the form of cracking and delamination [78]. Nonetheless, the hybrid treatment led to about a 47% increment in wear resistance compared to the untreated tool steel. This was attributed to the increased surface hardness, reduced surface roughness, and improved adhesion strength [40].

In summary, the wear of tool steels is one of the major constraints preventing the full exploitation of the production capacity of the wood-processing industries. The situation is further aggravated by the constantly changing wood properties coupled with the inability to use coolants or lubricants during wood processing. Consequently, the temperature rise is encountered during the machining process, which has a detrimental effect on the cutting tool and the quality of the machined products. Additionally, the ambient temperature also significantly influences tool wear and the quality of machined products. Although scientists have identified several wear mechanisms, most of the cost expended in industrial wear maintenance has been attributed to abrasive wear. More so, despite the success recorded in minimizing the occurrence of these mechanisms, they remain prevalent in the industrial daily production cycle.

3. Recent Advances in Tool Wear Improvement during Wood Machining

Before now, significant progress has been made in trying to curb the expenditure accrued to annual wear maintenance. Firstly, researchers developed techniques to characterize the mechanism so as to grasp a thorough understanding of the process. Thereafter, relationships were established between machining parameters, wood properties, and tool wear. Afterwards, several engineering treatments, including heat treatment, cryogenic treatment, thermochemical treatments, coating deposition, and hybrid treatments, were applied to the cutting tools. These subjects are discussed in the succeeding sections.

3.1. Wear Characterization

The direct impact of tool wear on production cost has attracted significant research concerns. One of the outcomes is wear characterization. Both direct and indirect methods have been developed [14,79]. The direct techniques are based on the measurement of dimensional changes in the cutting tool, particularly changes in the cutting edge region. Mass loss, volume loss, edge recession and changes in width track have been reported [5,80,81]. Szwajka and Trzepiecinski [11], Porankiewicz et al. [55] and Torkghashghaei et al. [82] characterized the edge recession of different tool steels using microscopy techniques. Szwajka and Trzepiecinski [11] in their study characterized the maximum edge recession in high-speed steel and cemented carbide cutting tools for the milling of particle board at different cutting speeds. It was observed that the edge recession increased with the cutting speed for both cutting tool types. Porankiewicz et al. [55] characterized the edge recession of high-speed cutting tools used for milling different wood species with varying density, silica contamination, and corrosivity. They reported that the recession of the cutting edge was more correlated with the corrosivity of the wood species than the density and silica contamination. Meanwhile, Torkghashghaei et al. [82] characterized the recession in the cutting edge of cemented carbide circular saws with different edge geometries (waterfall and up-sharp geometries) used in the sawing of spruce-jack pine-balsam fir. Their findings revealed that circular saws with waterfall geometry showed less recession than up-sharp geometry. Furthermore, Heidari et al. [12] characterized the effect of tempering temperature (500–540 °C) on the wear resistance of AISI A8 tool steels by measuring the volume loss. They noted that samples tempered at high temperatures displayed minimal volume reduction. Kumar et al. [83] characterized the wear resistance of high-silicon alloy steel with different surface engineering treatments using weight loss. They resolved that the minimum weight loss was recorded for samples with the highest hardness. The depth of wear track was adopted by Zeghni and Hashmi to characterize the effect of TiC coating and nitriding hybrid treatment on the wear resistance of AISI D3 and Vanadis 4 tool steels using stylus profilometry [81]. They reported that tool steels with hybrid treatment exhibited lower wear track depth than those with only TiC coating. Advances have also been made in measuring real-time tool wear using simulation techniques and microscopic analysis [5]. Accordingly, Lins et al. [84] successfully developed a cyber-physical system based on tool wear vision monitoring for the real-time measuring of tool wear. In another study, Qiao and co-workers [85] developed models based on deep learning and fog computing for real-time measurement and prediction of the wear of a twist drill. They reported a reasonable correlation between the predicted and actual tool wear.

Meanwhile, the indirect measurement involves the estimation of the tool wear using other machining parameters based on an already established relationship between the tool wear and the parameter [14]. Parameters such as power consumed, cutting torque, cutting force, acoustic emission, quality of machined product, and tool temperature have been used to indirectly estimate the wear of cutting tools during wood machining [54,86–90]. Like the direct techniques, the real-time assessment of tool wear has also been attempted for the indirect methods. In this regard, Aknouche et al. investigated the real-time tool wear during the machining of Aleppo pine wood with the cutting force as the parameter. Significant variations in cutting force were observed in some sections along the cutting length, which was attributed to the presence of knots with high density [54]. Cuppini et al. [86] indirectly measured the wear of cutting tools through cutting power measurement. Lemaster et al. conducted an indirect wear characterization of tungsten carbide inserts for machining medium-density particle board by measuring power consumption, machining noise, machine vibration and acoustic emission. They observed that measurement of the machine vibration and noise were more correlated to the tool wear than the other parameters [87,88]. Comparing both methods, the direct approach, although mostly characterized by intermittent measurements, is more reliable. On the other hand, the indirect method allows continuous measurement. However, Cuppini et al. [86] and De Lacalle et al. [52] opined that the efficiency of the measuring device strongly influences the reliability of the indirect method. Hence, they recommended setting a threshold for the parameter during real-time measurement to avert catastrophic failures [52,86]. Generally, for both methods, in order to ascertain the full extent of tool wear, it is better to use more than one parameter, such as cutting force and power consumption or machining noise and cutting force.

Studies have also been conducted to ascertain methods for correctly measuring the recession of the cutting tool edge. Tavodova et al. used three approaches. The first involved comparing the distance between the tip of a used cutting edge to that of an un-used one. The second approach calculated the difference in the radius of the circle inscribed on the cutting-edge profile of the used and un-used one, while the last approach focused on the alteration in wedge angle. They concluded that the second approach was more accurate as it showed the least variance [79].

Additionally, some experimental methods have also been developed to characterize tool wear mechanisms. Some of these techniques include the popular Pin On the Disk (POD) [91], Dry Sand Rubber Wheel (DSRW) test [92], and Taber abrasive wear test [93], among others. Wear characterization in these methods is based on weight loss after abrading the material for a period of time. The characteristic appearance of the abrasive wear mechanism is the presence of grooves, scratches, ploughed ridges (microcutting and microploughing) or even microcracks whose intensity correlates with the extent of wear. The rate of abrasive wear increases as the mechanism translates from microcutting through microploughing to cracking [68,73]. Figure 5a–c shows the characteristic appearance of abrasive wear. Adhesive wear, on the other hand, is typically characterized by inter-surface material transfer, consequently resulting in surface rupture, as shown in Figure 5d. Meanwhile, the effect of surface fatigue, due to impact from knots, sand, and rocks during wood machining, could manifest in the form of microcracks (Figure 5c) or even result in surface rupture (Figure 5d). Tool wear resulting from tribochemical reaction is less prevalent during wood machining [12].

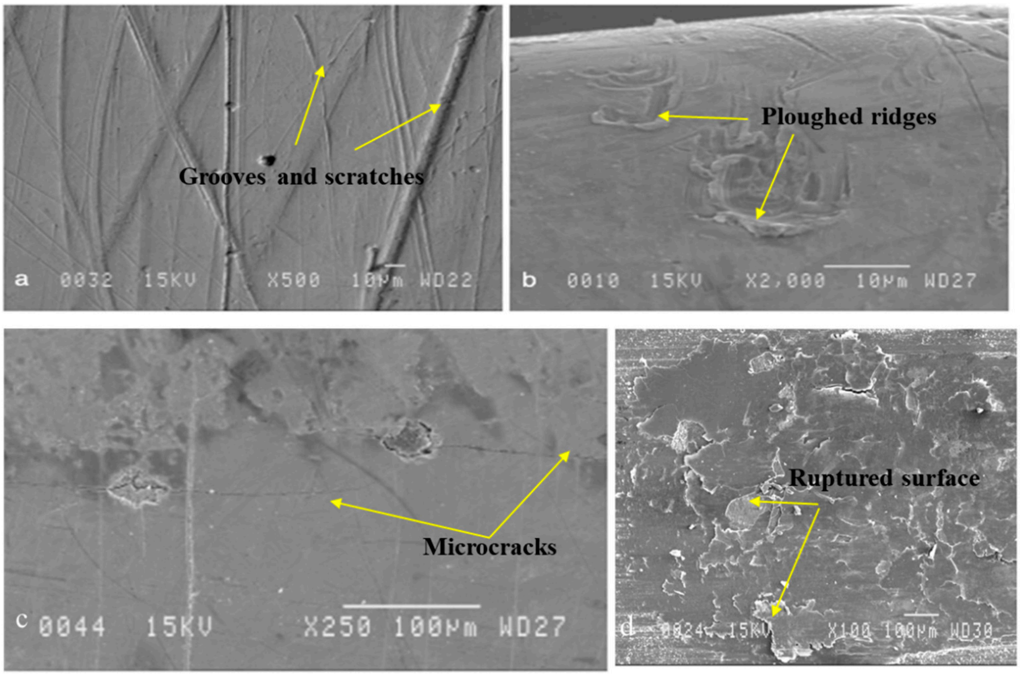


Figure 5. Wear mechanisms in AISI A8 chipper-canter knives: (**a**) microcutting; (**b**) microploughing; (**c**) microcracking; (**d**) surface rupture [12].

3.2. Effect of Machining Parameters and Wood Properties on Tool Wear

Wood machining parameters such as cutting speed, rake angle, cutting force, cutting length, machining time, and feed rate significantly affect tool wear [12,14,77,94]. Machining at high cutting speeds and cutting forces accelerate tool wear [11]. At high machining speeds, there is an increase in the amount of heat generated as a result of shearing, leading to tool degradation [52]. In most cases, wood machining within ranges that ensure a prolonged cutting tool life has been found to be inefficient and uneconomic. In this regard, Szwajka and Trzepiecinski reported that increasing the machining speed of high-speed tool steel and cemented carbide cutting tools above 18,000 rev/min (efficient speed range) during the machining of melamine-faced particle board resulted in reductions in tool life by 91% and 95%, respectively [11]. Meanwhile, investigations on the relationship between the cutting speed and the cutting forces during the machining of high density fiberboard was reported by Zhu et al. [95]. Interestingly, they observed that the cutting forces on the tool edge were negatively correlated with the cutting speed, as increasing the cutting speed (5000–10,000 rev/min) resulted in a reduction in the cutting forces on the edge of the cutting tool. This connotes an improvement in wood processing characterized by a reduction in energy consumption. The observation was attributed to the reduction in friction coefficient owing to the temperature rise associated with the increased cutting speed. However, it is important to highlight that the optimum machining parameters depend on the cutting tool material, wood type, and desired quality, among other factors. Nonetheless, in the light of these, wood product manufacturers try to achieve a compromise between tool life, cutting speed, and minimizing production cost.

As expected, the feed rate, machining time, and cutting length are positively correlated with the tool wear [10,14,19]. Bendikiene et al. [19] reported a positive correlation between the feed rate and cutting power during the machining of oak wood. Consequently, wood machining at relatively high feed rates and high machining length and time would increase the energy consumption, leading to tool life reduction as compared to lower values of the parameters. The increase in tool wear with increasing feed rate is connected with the increase in chip thickness, which is in accordance with the cutting theory [10]. Furthermore, analytical studies conducted by Ghosh et al. [14] revealed that the machining time had a more significant effect on tool wear than the type of knife (chipper or canter), irrespective of the point of measurement of tool wear along the cutting edge. Wood machining is usually carried out at low rake angles because of the desired surface finish. However, this results in increased tool wear [20]. Studies conducted by Zhu et al. [95] revealed a negative correlation between the rake angle and cutting forces, irrespective of the cutting speed. This is because increasing the rake angle implies a reduction in wedge angle (see Figure 1) and thus a sharper cutting tool. The authors concluded that for cost-effective wood machining and prolonged tool life, cutting tools with lower rake angles should be operated at higher speed and vice versa.

Further investigation using regression and correlation analysis was conducted to ascertain the effect of wood properties, including density, silica contamination, and its corrosive effect at elevated temperature (high temperature corrosivity) on tool wear using IBM® SPSS® Statistics version 26 [96–98]. Table 1 shows the density, silica contamination, high temperature corrosivity, and tool wear for different wood species. The wear of the cutting tools (μm) was obtained by measuring the recession of the cutting edge (clearance face) from the optical images of the respective cutting edge profile [99].

Table 1. Wood properties and tool wear for different wood species [99].

Wood Sample	**Origin**	**Density (kg/m^3)**	**Silica Contamination (mg/kg)**	**High-Temperature Corrosivity ($R^{W}{}_{mw}$)**	**Wear (μm)**
Nogal	Columbia	395	8.8	1.7	73
Passang	Japan	550	8.1	21.8	103
Red meranti	Indonesia	669	1.7	3.2	77
Teak	Indonesia	847	2573.8	1.0	77
Coconut	Indonesia	911	1540.6	2.1	69
Oil palm	Indonesia	482	5911.4	246.3	142

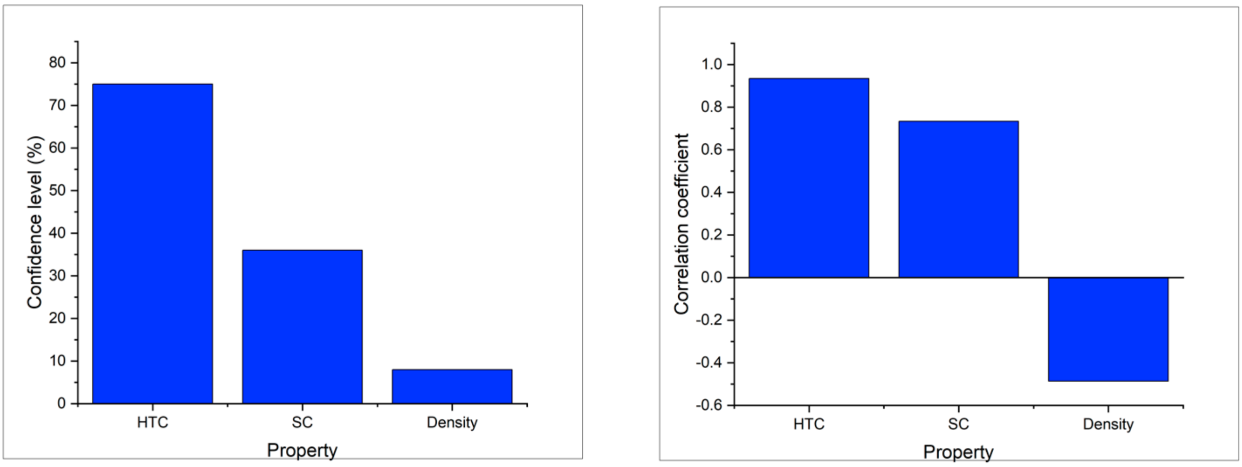
The effect of the wood properties on the tool wear can be evaluated using the significance levels of the t-values obtained from the regression analysis. Conventionally, parameters with significant values less than 5% are considered significant [11]. The result of the statistical analysis of the data in Table 1 is presented in Table 2 and Figure 6. Table 2 shows that the effect of the wood density, silica contamination, and high temperature corrosivity are statistically not considerable, as their respective significance values are greater than 5%.

Table 2. Significance values of the effect of wood density, silica contamination, and high temperature corrosivity on tool wear.

Parameter	**t-Values**	**Significant Values (%)**
Density (kg/m^3)	0.113	92.0
Silica contamination (mg/kg)	−0.557	63.4
High-temperature corrosivity ($R^{W}{}_{mw}$)	1.639	24.3

However, of all the three factors, a change in the high-temperature corrosivity is most likely to affect the wear of the tool steel at a confidence level of 75% compared to the 36% and 8% of the silica contamination and density, respectively, as shown in Figure 6a.

Figure 6b shows the correlation coefficient between tool wear and wood properties. The analysis revealed very high positive correlation coefficients of 0.935 and 0.734 for high temperature corrosivity and silica contamination, respectively. The observed positive correlations imply that there is a likelihood that an increase in these parameters will increase the tool wear, i.e., reduce tool life based on their respective confidence levels. Besides, the considerable oxygen content of these contaminants may also contribute to their corrosivity [99]. Nevertheless, the findings of Amos revealed that high silica contamination might not be the cause of tool wear is some wood species [100]. Meanwhile, a weak negative correlation was observed for the density. However, the likelihood of an increase in tool wear rate with lower wood density is only 8%. This is also coupled with the constantly changing wood density with environmental conditions. A similar finding was reported by Cristóvão et al. [101]. Moreover, the hardness of wood has been reported to increase with increasing density [53]. Hence, a denser wood is more likely to accelerate the tool wear process.



(**a**) (**b**)

Figure 6. (**a**) Confidence levels for the effect of wood properties on tool wear; (**b**) Correlation coefficient between wood properties and tool wear (HTC—high temperature corrosivity, SC—silica contamination).

From the foregoing, machining parameters such as cutting force, speed, power, feed rate, cutting length, and machining time have been reported to be positively correlated with tool wear. On the other hand, a reverse trend is observed for the wedge angle. Furthermore, wood with high temperature corrosivity and silica contaminants is more likely to accelerate the wear of tool steels during machining.

3.3. Tool Wear Enhancement via Application of Heat Treatment

The need to develop cutting tools with high wear resistance birthed the tremendous effort made by scientists to develop technologies capable of predicting material properties and phase compositions [102]. This was based on the underlying understanding that the service performance of materials is largely dependent on their phase composition and the resulting properties. Fortunately, five decades ago witnessed the arrival of CALculation of PHAse Diagrams (CALPHAD) technologies. The technology uses a computational approach involving thermodynamic and kinetic modeling to design materials with specific properties [103]. Some CALPHAD technologies reported in the literature include Thermo-Calc [104], MatCalc [105] and JMatPro [106]. These technologies create the possibility of determining the optimum heat treatment conditions which will provide optimum wear performance.

In order to enhance the wear performance of tool steels during wood machining, they are often used in a hardened condition. The process of hardening involves austenitization followed by quenching and tempering. The austenitization process of tool steels involves heating to the austenitic temperature range (usually between 850 and 1200 °C). The extent of austenitization is a function of the temperature [107,108]. On one hand, while austenitization at higher temperatures results in increased carbide dissolution, it is also accompanied by the tendency of having an increased level of retained austenite, delta ferrite, and coarse austenite grains, which impair the mechanical properties of the tool steels. On the other hand, low-temperature austenitization does not result in optimum wear properties due to inadequate carbide dissolution [107–109]. So most often, both high- and low-temperature austenitizations are applied to the tool steel to confer the benefits of both processes characterized by optimum combination of hardness and toughness required for increased tool life during wood machining [109,110]. Accordingly, Salunkhe et al. [110] recommended a double austenitization process: a high-temperature austenitization (to dissolve carbides) is followed by a low-temperature austenitization (to prevent grain coarsening and to reduce the retained austenite) to optimize the microstructure and final mechanical properties.

Upon quenching, martensite is formed alongside certain amounts of untransformed austenite (retained austenite) in some cases. The martensitic structure exits in lath, plate, or mixed morphologies depending on the carbon composition of the tool steel [39,111]. The strength and hardness of the phase are attributed to the different mechanisms hindering dislocation movement, including solid solution strengthening, grain refinement, and strain hardening. Unfortunately, the martensitic structure has limited applications owing to its insufficient toughness [112]. Hence, the tempering process is required.

The tempering of tool steels is usually in the temperature range of 200–550 °C [12,110]. During the process, there is a release of carbon from the saturated martensite matrix, which is followed by the transformation of retained austenite to martensite, leading to the release of residual stresses. The resulting tempered martensite has a slightly lower hardness but improved toughness suitable for wood machining applications. In some cases, when there are still high levels of un-tempered martensite or retained austenite, the need for another tempering process may arise [107,113]. For instance, Bochnowski et al. reported that three times tempering led to a 90% reduction in retained austenite in high-speed tool steel [114]. Additionally, due to the composition of most tool steels, secondary phases, predominantly carbides, also exist in the microstructure [111,115]. These carbides provide secondary hardening by further impeding dislocation movement, inhibiting grain growth, and reinforcing the matrix, thus enhancing the wear properties of the tool steels [107,116,117]. Therefore, the microstructure of most tool steels comprises predominantly tempered martensite and carbides alongside retained austenite in some cases [53,79,118,119]. Figure 7 shows a typical microstructure of AISI D6 tool steel austenitized at 1050 °C and 940 °C, oil-quenched, and tempered at 500 °C. It contains tempered martensite, carbides and retained austenite.

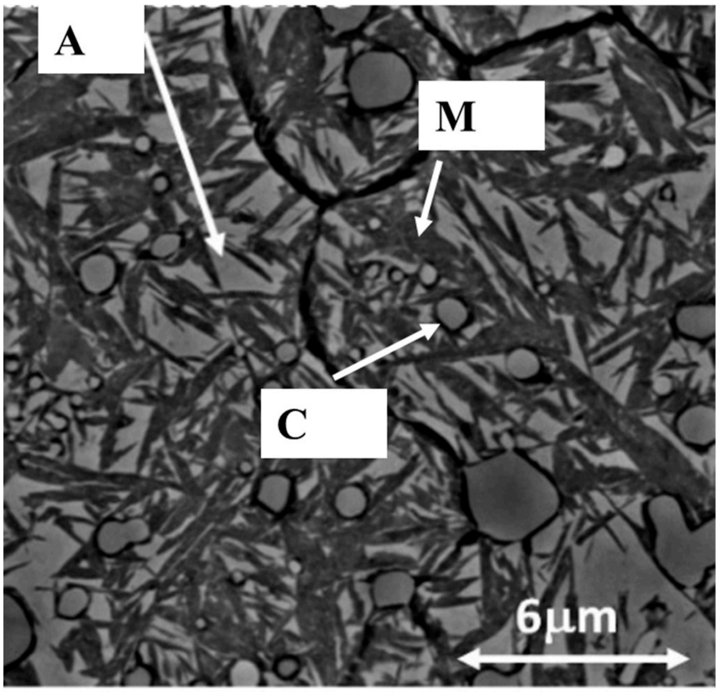


Figure 7. Micrograph showing carbides (C), martensite (M), and retained austenite (A) in AISI D6 cold work tool steel austenitized at 1050 °C and air quenched [120].

The level of retained austenite in the tool steel also affects the cutting tools' tribological performance during wood machining. The austenite phase having a relatively lower hardness than martensite has a negative effect on the overall hardness of the hardened tool steels [121]. Consequently, some reports have been documented on the detrimental effect of this phase on the tribological performance of tool steels. The study conducted by Colaco and Vilar revealed that as the level of retained austenite increased from 0 to 100% in AISI 420 steel, a 35% reduction was observed in the hardness. This resulted in a reduction in the wear resistance of the tool steel [122]. A similar investigation reported by Moradiani et al. revealed that as the level of retained austenite increased from 42 to 90% in AISI D2 tool steel, about an 8% reduction was observed in the hardness, which was accompanied by a reduction in wear resistance of the tool steels [123].

Unsurprisingly, the characteristics of the carbides, including carbide type, their distribution, volume fraction, and sizes, significantly affect the wear properties of the tool steels. Accordingly, extensive reports have been published on tool steels with similar hardness but completely different wear properties due to variation in the carbide characteristics [4,92,116]. In this regard, Bourithis et al. [92] studied the tribological performance of AISI O1 and D2 tool steels having the same hardness. Their findings revealed that the latter displayed superior wear resistance in both two-body and three-body abrasive wear tests. The observation was attributed to the presence of plate-like carbide morphology in the latter, which was absent in the former. In a study conducted by Bochnowski et al. on the effect of tempering on the carbide morphology of tool steel, it was observed that the presence of M_6C, MC, and M_2C primary carbides facilitated the formation of secondary carbides. Furthermore, increasing the tempering temperature beyond the optimum range resulted in a reduction in hardness due to the coarsening of the secondary carbides at higher temperatures. Interestingly, increased volume fraction and finer primary carbides hindered the transformation of residual stresses from tensile to compressive during the tempering process [114]. Meanwhile, Heidari et al. observed that increasing the volume fraction of fine carbides in AISI A8, H13, and S1 significantly improved their wear performance [12].

Expectedly, the austenitization and tempering parameters play significant roles in the wear behavior of tool steels. Attaullah reported that increasing the austenitization temperature in AISI D2 and H13 tool steels resulted in increased hardness owing to the increase in carbon concentration in the martensite matrix [37]. Similar observations have also been reported by other authors [116,124,125]. Meanwhile, poor wear properties were observed in AISI H11 tool steel with low austenitization temperature due to the reduced hardness. However, upon increasing the austenitization temperature, despite the increment in hardness, it was accompanied by a toughness reduction. This was attributed to the decrease in the volume fraction of carbides and the unrestricted austenite growth. Hence, optimum wear properties were obtained at intermediate austenitization temperature (between 1000 and 1200 °C) with the best combination of microstructural composition [116].

Studies have also been conducted on the effect of multiple austenitization on the hardness of tool steel. It was revealed that an increase in single and double austenitization temperatures increased the tool steel hardness. This was attributed to the inhibition of austenite grain growth and increased carbon composition in the martensite matrix following carbide dissolution. However, higher hardness was observed with double austenitization as compared to single austenitization because the former offered a greater dissolution of carbides and inhibition to grain growth than the latter [110].

Further statistical analysis was also conducted to ascertain the effect of carbide volume fraction, sizes, and tool steel hardness on the tool wear. Table 3 shows the wear of AISI A8 tool steel with single austenitization and tempering treatment temperatures alongside the hardness and carbide characteristics. The wear of the tool steels was characterized using the volume loss (mm^3) obtained from the DSRW test [12].

Table 3. Wear, hardness, and carbide characteristics of AISI A8 tool steel at different austenitizing and tempering temperatures [12].

Wear (mm^3) ± 0.2	Hardness (HRC) ± 0.5	Carbide Volume Fraction (%) ± 0.2	Average Carbide Size (µm) ± 0.01	Austenitizing Temperature (°C)	Tempering Temperature (°C)
88.9	53	20.15	1.25	980	500
85.3	53	21.3	1.28	980	520
78.0	51	24.79	1.33	980	540
95.5	54	17.3	1.22	1010	500
88.8	56	20.53	1.27	1010	520
83.7	52	24.77	1.30	1010	540
91.1	59	13.22	1.15	1040	500
90.8	58	14.42	1.21	1040	520
82.3	57	19.54	1.27	1040	540

Table 4 shows the significance values of the effect of heat treatment parameters, carbide characteristics, and hardness on the wear of AISI A8 tool steels based on the analysis of the results in Table 3.

Table 4. Significance values of the effect of heat treatment, hardness, and carbide characteristics on tool wear.

Parameter	t-Values	Significant Values (%)
Hardness (HRC)	−0.990	39.5
Carbide volume fraction (%)	−0.651	56.2
Average carbide size (µm)	1.322	27.8
Austenitizing temperature (°C)	2.081	12.9
Tempering temperature (°C)	−2.678	7.5

From Table 4, although the parameters have significant values greater than 5%, there is a likelihood that changes in the parameter would affect tool wear based on their respective confidence levels presented in Figure 8a. Accordingly, the tempering temperature is the most significant parameter influencing the tool wear, with the least significant parameter being the carbide volume fraction. The respective confidence levels for the tempering temperature, austenitizing temperature, average carbide size, hardness, and carbide volume fraction are 92.5%, 87.1%, 72.2%, 60.5%, and 43.8%. More so, the correlation analysis revealed that positive correlations were obtained for austenitization temperature (0.325) and hardness (0.479), while negative correlations were obtained for the tempering temperature (−0.854), average carbide size (−0.795) and volume fraction of carbides (−0.749), as shown in Figure 8b.

Based on the correlation results, increasing the tempering temperature would be likely accompanied by an improvement in tool wear resistance (reduction in wear amount) at the respective confidence level. This might be attributed to the increase in carbide volume fraction [12]. Also, the weak positive correlation obtained for the austenitizing temperature implies that increasing the austenitizing temperature is likely accompanied by an increase in tool wear at the respective confidence level. Despite the corresponding increment in hardness (positive correlation) and reduction in average carbide sizes (negative correlation) with increasing austenitization temperature, the increase in tool wear may be attributed to the reduction in the carbide volume fraction (negative correlation). A similar observation was reported by Heidari et al. [12].

In summary, austenitization and tempering processes can potentially improve tool wear resistance during wood machining. If single austenitization and tempering are to be carried out, the temperatures should be intermediate in order to achieve an optimum microstructural composition with improved wear performance. Meanwhile, double austenitization and multiple tempering operations confer properties with superior wear performance. Furthermore, the characteristics of the carbides influence the wear of tool steels. The resulting wear properties are a product of the interaction between the strengthening offered by tempered martensite, the volume fraction and sizes of the carbides, and the carbon concentration in the martensite matrix. Meanwhile, the statistical analysis in Figure 8 and Table 4 revealed that the effect of the heat treatment temperatures, carbide characteristics, and mechanical properties on tool wear was in the order of tempering temperature > austenitizing temperature > average carbide size > hardness > volume fraction of carbides.

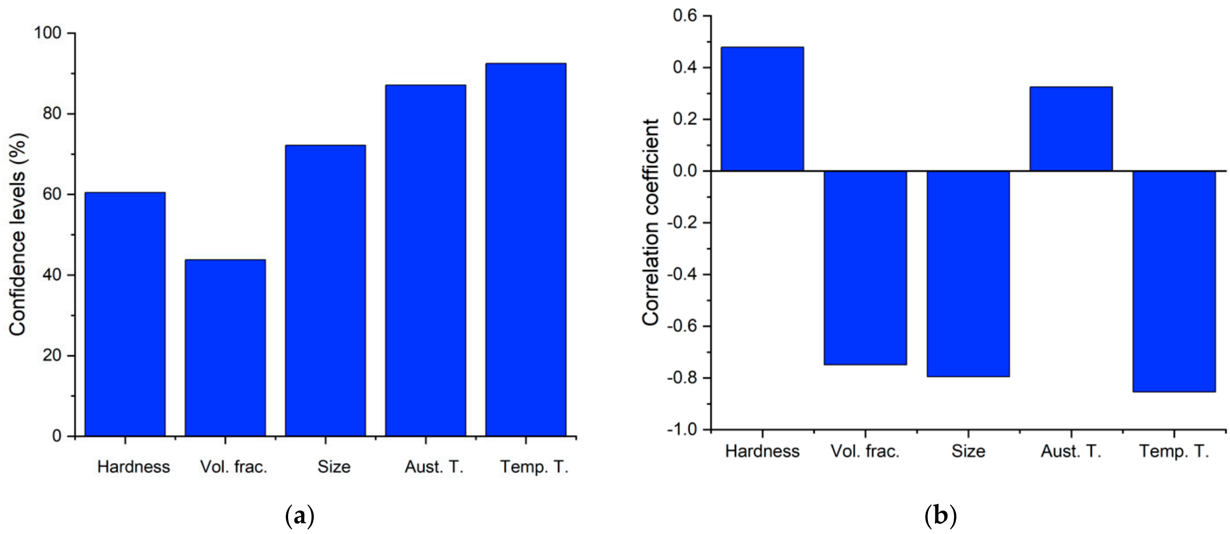


Figure 8. (**a**) Confidence levels for the effect of heat treatment, hardness, and carbide characteristics on tool wear; (**b**) Correlation coefficient between heat treatment, hardness and carbide characteristics and tool wear (Vol. frac.—carbide volume fraction, Size—average carbide size, Aust. T.—austenitizing temperature, Temp. T.—tempering temperature).

3.4. Tool Wear Enhancement via Cryogenic Treatment

The application of cryogenic treatment (low-temperature treatment) is another technique of improving the wear performance of tool steels for wood machining [111]. It is mostly carried out at temperatures in the range of dry ice temperature (about −80 °C, known as shallow treatment) or liquid nitrogen temperatures (about −196 °C, known as deep treatment) [126–128]. Like the conventional heat treatment, the process parameters such as the holding time and temperature influence the resulting properties [129]. Some reported effects of cryogenic treatment include an increase in hardness, wear resistance, corrosion resistance and reduction in residual stresses and toughness [130–133]. Consequently, this can lead to a reduction in the cost of production and production downtime of wood processing [134].

However, over time, some controversial arguments have evolved regarding the application of cryogenic treatment to tool steels. Firstly, while a majority of researchers have reported that the process improves wear resistance [126,135,136], some have reported otherwise [91]. Secondly, a group of researchers have opined that wear improvement during the process is due to the transformation of retained austenite to martensite [136,137], while others claim that the improvement is attributed to the precipitation of fine secondary carbides [127,138]. The precipitation of secondary carbides during cryogenic treatment has been attributed to the contraction of the martensite matrix leading to the segregation of the released carbon atoms near defects, which eventually transform into carbides [126]. As a matter of fact, some authors have reported a significant reduction in retained austenite composition in tool steel due to cryogenic treatment, which did not have any notable impact on their wear performance [91]. Another controversial issue is the position of the cryogenic treatment in the heat treatment cycle. Some researchers have reported that the cryogenic treatment should be applied prior to the tempering process [95,109], while others have applied it after the tempering process [134]. Nonetheless, improved wear resistance has been observed for both configurations.

A study was conducted by Molinari et al. [134] to ascertain the effect of the position of the cryogenic treatment in the heat treatment schedule and multiple tempering on the mechanical and wear properties of AISI M2 and H13 tool steels. Their findings revealed that both configurations resulted in improved wear resistance, but the samples with cryogenic treatment applied after tempering showed higher wear performance by about 30%. More so, double tempering after cryogenic treatment did not significantly improve the wear performance of the tool steels [134]. In another study conducted by Huang et al., it was observed that the low temperature treatment resulted in an increase in the volume fraction of carbides and produced a more homogeneous microstructure, which improved wear performance [127]. Researchers have also attempted multistage cryogenic treatment, highlighting its cost benefit. The process was observed to increase the volume fraction of carbides and produced a more homogeneous microstructure relative to the single-stage treatment [126]. Additionally, analytical studies conducted by Oppenkowski et al. revealed that the heat treatment parameters have a more significant effect on the mechanical and wear properties of AISI D2 tool steel compared to the cryogenic parameters [139].

3.5. Tool Wear Enhancement via Thermochemical Surface Treatment

Thermochemical treatment is often applied to tool steels for wood machining to improve wear behavior and load capacity [39]. It includes processes applied to modify the surface composition of the tool steels without major significant changes in the material dimension [12,140,141]. This is achieved by heating the tool steels to elevated temperatures in the presence of a medium comprising carbon, nitrogen, or boron, among others [12,140,142]. In this process, temperature, time, composition of the tool steels, and the composition of the medium are significant parameters that determine the resulting wear properties [143–145]. Wear improvement is achieved due to the increased surface hardness resulting from the formation of intermetallics, which is coupled with the generated strain field between the tool steel matrix and the intermetallics [146]. More so, the process does not result in a drastic hardness discontinuity between the bulk material and the surface compared to other surface engineering treatments like coatings [147]. Some thermochemical treatments reported in the literature are carburizing [117], nitriding [34], carbonitriding [47], boriding [118], and cyaniding [39].

Faga and Settineri presented a study on the effect of high (500 °C) and low (300 °C) temperature nitriding on the wear properties of HSS18 high-speed tool steel and 90MCV8 alloy steel. Their findings revealed that low-temperature nitriding did not significantly improve the wear behavior of both tool steels. In fact, a slight deterioration was reported for the alloy steel. However, upon increasing the nitriding temperature, a significant improvement was observed for both tool steels, which was characterized by a reduction in friction coefficient and wear track depth [5]. In another study conducted by Psyllaki et al. to ascertain the effect of microstructural composition and liquid nitrocarburizing on the wear of AISI H13, D6, and Cr-Mo-V tool steels, they reported that the AISI H13 showed superior wear performance due to the formation of finely dispersed carbides as compared to the elongated carbonitrides and lamellar precipitates found in the AISI D6 and Cr-Mo-V grades, respectively. Additionally, the state of the hardening medium has been reported to significantly impact the wear of tool steels. For instance, liquid carbonitrided tool steels have been observed to exhibit superior wear performance and toughness than those subjected to gas carbonitriding, owing to the formation of an ε-carbonitride compound in the former [77].

Researchers have also highlighted the benefits of plasma nitriding over the conventional nitriding process. These include a reduction in the environmental footprint, lower treatment temperature and greater versatility [147,148]. Accordingly, an investigation on the effect of plasma nitriding temperature (460–520 °C) and time (6–12 h) on the mechanical and corrosive properties of 90CrMoV8 tool steel for the machining of oak wood was conducted by Nouveau et al. They reported that optimum hardness was achieved at intermediate plasma nitriding parameters. However, the plasma nitriding process did not improve the resistance of the tool steel to corrosive wear in the wood electrolyte [147].

The effect of boriding temperature on the wear properties of AISI H13 tool steel was studied by Erdogan [46]. It was reported that increasing the temperature resulted in a corresponding increase in wear resistance. This was attributed to the reduction in surface roughness and the formation of double ferrite phases leading to an increased hardness. The hardness was observed to further increase with the thickness of the intermetallic layers. Other authors have reported that such double intermetallic phases are sites of crack initiation owing to the difference in properties between the phases and the matrix [149]. More so, the reduction in tool wear was partly attributed to the adherence of abrasive particles to the surface of the tool steels. A similar occurrence was reported by Krelling et al. [150]. The size of the abrasive particle also played a significant role in the wear process, as coarse-sized particles resulted in accelerated tool wear [46]. A similar study on the effect of boriding temperature and time on the mechanical properties of tool steel was reported by Sen and Sen [145]. They reported a positive correlation between the treatment parameters, hardness, and thickness of the intermetallic layers. However, this was accompanied by a reduction in toughness owing to the interaction between the different brittle intermetallic boride phases [151].

From the foregoing, it is evident that tool wear enhancement by thermochemical diffusion treatment is a function of the process parameters. While relatively low temperatures are likely to have an insignificant impact on tool wear performance, improved wear performance would be likely obtained at higher temperatures due to increased hardness resulting from the formation of the hard intermetallic layer. More so, the surface roughness and the composition of the tool steels play significant roles in the wear behavior. However, the presence of excessive intermetallic phases due to increased process parameters might have a detrimental effect on the toughness of the tool steels, resulting in premature failure in the form of cracking during wood machining.

3.6. Tool Wear Enhancement via Coating Application

Coating deposition is another promising method of improving the wear behavior of tool steels for wood machining applications. It has previously been adopted for metal machining purposes, but recently, it attracted the interest of the wood machining industry due to its cost-effectiveness compared to other wear enhancement techniques [41,52,53]. Tool wear enhancement is achieved through tool edge temperature reduction by heat dissipation, a reduction in frictional force and stresses at the cutting edge, and an increase in hardness alongside improvement in corrosion resistance to the corrosive effect of the wood fluids [53,152,153]. In coating selection, some of the properties sought after are hardness, toughness, adherence to the substrate, and chemical stability, especially at elevated temperatures [41,97,154–158]. Generally, the coating hardness is considered the most significant parameter affecting the wear resistance of tool steels [12,159]. It is a function of several factors, including the method of deposition, coating composition, and the size of the crystallites, among others [41,160,161]. For uncoated substrates, increased hardness correlates to improved wear resistance in most cases [41]. However, the same was believed for coated substrates until failures were observed in some hard coatings due to poor adhesion and reduced resistance to elastic and plastic deformation [2]. Hence, in addition to increased coating hardness, parameters such as resistance to elastic strain (H/E) and plastic deformation (H^3/E^2) are often used for the assessment of the quality of coatings [70,162–165]. Like the hardness, a positive correlation has been observed between H/E, H^3/E^2 and the wear resistance of tool steels [157,165].

Prior to coating deposition, adequate substrate preparation is necessary so as to make the substrate more receptive to the coating and ensure proper adhesion. The importance of surface preparation during coating deposition has not received due attention from researchers in the past years despite its significant role in the overall performance of the coatings [4,42,118,166]. Accordingly, a considerable amount of coating failure has been attributed to insufficient bond strength owing to inadequate surface preparation [165]. The process has been reported to account for at least 45% and up to 90% of the labor cost during the entire coating process. The surface preparation of tool steels involves the removal of surface contaminants followed by profiling [157]. While the effect of surface contaminants has been well documented, insufficient studies in the literature are available regarding the latter [41,167]. Again, another issue that is less discussed is the bond coating: an adhesive layer deposited on the substrate prior coating deposition. In addition to enhancing coating adhesion, it also protects cracks initiated at the coating from easily propagating to the substrate [118,165].

3.6.1. Method of Coating Deposition

The method of coating deposition and the deposition parameters significantly affect the wear properties of the tool steel [5,53]. Several coating deposition methods involving electrochemical treatments (electroplating and anodizing), chemical treatment (physical and chemical vapor deposition), and thermal spraying have been reported in the literature [12,41,141]. However, chemical deposition treatments have received a wider range of acceptance due to their large application spectrum, as little or no metallurgical compatibility between the substrate and coating is required. For this reason, their application has been extended to ceramic coating depositions [159].

Coating deposition by the physical vapor deposition (PVD) technique is achieved either by vaporization or atomization of the coating material from the target thermally or kinetically followed by deposition on the substrate. On the other hand, chemical vapor deposition is achieved by chemical reactions between the coating materials at much higher temperatures (800–1500 °C) [141,159,168]. Meanwhile, despite the high bond strength previously obtained from chemical vapor deposition coatings, the physical vapor techniques are preferred because of the lower temperature of deposition, increased hardness, reduced surface roughness, and finer crystallites [39,40]. The deposition temperature is of prime importance, as higher values have a detrimental effect on the hardened substrate [79]. Some physical vapor deposition techniques reported in the literature are cathodic arc evaporation, electron beam physical vapor deposition, magnetic sputtering deposition, and ion beam-assisted deposition, among others [41]. PVD techniques involving arc deposition are preferred to sputtering techniques because of the high deposition rate and the bond strength of the former [40]. The reduced bond strength in the latter is due to the high residual compressive stresses in the coated substrate resulting from its ionic bombardment during deposition [165,169].

3.6.2. Coating Types

Previously, coatings were classified according to their resistance to deformation (hard or soft coatings) and chemical bonds (metallic, covalent, or ionic coatings). However, the recent trend involves the development of coatings with composite compositions and structures having scales ranging from micro to nano [39,159,168]. In the past few years, different coating types, including nitride-based, carbide-based, and diamond-based coatings, have been deposited on tool steels, resulting in significant wear improvement [5,39]. Most significantly, advances have been made in developing coatings with multiple layers [170]. This offers benefits such as enhancing the corrosion resistance, the surface residual stress of the substrate, and resistance to plastic deformation due to the possibility of combining layers with different properties to suit the desired application [118,157,171]. In a recent study conducted by Naghashzadeh et al., the wear behavior of a ternary, binary TiN-based, and uncoated AISI D3 tool steel was investigated. It was observed that the improvement in wear performance was in the order of ternary multilayer > binary multilayer > uncoated substrate [157]. Similar findings were recently reported by Çelik et al. [172]. Although limited studies are available regarding the number of layers for optimized wear performance, the coating composition plays a more significant role in the tool wear performance compared to the number of layers.

A few authors have studied suitable coatings for optimum wear performance during wood machining. Firstly, Heidari et al. investigated the wear performance of CrN, CrAlN, TiAlN, TiAlCrN, TiAlCrN-CrC, and AlCrTiN coatings deposited on AISI A8, H13, and S1 tool steels. The AlCrTiN and TiAlCrN-CrC coating showed the optimum wear performance for the A8 and H13 tool steels, respectively, while TiAlCrN showed the least wear performance for both grades. Contrastingly, TiAlCrN and AlTiCrN exhibited the highest and lowest wear performance for the S1 tool steel. They attributed the observation primarily to the surface stiffness of the substrates and their residual stress support capacity [12]. In another study, Faga and Settineri investigated the wear performance of CrN and diamond-like carbon single and multilayer coatings deposited on HSS18 and 90CMV8 tool steels. Their investigations revealed that the multilayer coatings generally exhibited superior wear performance. This improvement was ascribed to the reduction in residual stresses on the surface of the substrate [5]. Kazlauskas et al. also investigated the wear performance of CrN, TiCN, TiAlN, AlTiN, and AlCrN coatings deposited on tungsten carbide for the machining of oak wood. The wear performance was in the order of CrN > AlCrN > TiCN > TiAlN > AlTiN [2]. One notable finding from their study is that the TiCN coating with the highest hardness did not exhibit the optimum wear performance. This might be attributed to the reduced resistance of the coatings to elastic strain and plastic deformation, which the authors did not take into consideration.

In another report, Liu et al. conducted a comparative study on the tribological performance of TiN, TiAlN, AlTiN, and CrAlN coatings deposited on cemented carbide cutting tools. Their results revealed that the tribological performance of the coatings was in the order TiAlN > TiN > CrAlN > AlTiN. The observed trend in tribological performance was attributed to the hardness and friction coefficient of the respective coatings. This study emphasized the detrimental role of high aluminum composition (in CrAlN and AlTiN), leading to their reduced mechanical and tribological properties. Property deterioration was attributed to the high chemical reactivity of the metal, resulting in the formation of interfacial bonds with the abrading surface leading to adhesive wear [173].

The thickness of the coatings also plays a significant role in the wear performance of tool steels. Many authors have reported a negative correlation between the coating thickness and the tool wear. However, a threshold of coating thickness was observed, above which the wear performance begins to deteriorate [4,39,41]. This is because an increase in the thickness of the coatings is accompanied by increased residual stress, which is detrimental to the growth of the coating films. When the stress exceeds the bond strength of the coatings, it results in the delamination of the coating from the substrate [39]. Meanwhile, as the thickness of the coating reduces, the effect of the substrate on the tribological properties increases [168]. However, irrespective of the thickness of the coating, the substrate should have sufficient strength to support the load applied to the coating. Otherwise, even with a high wear-resistant coating with the appropriate thickness, premature coating failure would likely occur [41,174].

3.6.3. Effect of Coating Doping

The doping of coatings is another attempt by researchers to further enhance the wear resistance of tool steels. Coatings doped with carbon, nickel, and silicon, among others, have been reported by different authors [41]. Some of the benefits of doping documented in the literature are an increase in hardness, resistance to plastic deformation, corrosion, and oxidation [165,175–177].

Studies were conducted by Kong et al. [70] on the effect of carbon doping on the wear performance of CrN coating deposited on AISI M2 tool steel. They reported that carbon doping improved the wear performance of the tool steel, which was characterized by the increment in hardness, resistance to elastic strain, and plastic deformation. The improvement was attributed to the formation of carbides. However, increasing the carbon composition above a certain threshold had a detrimental effect on the wear performance despite the increment in coating thickness. This was due to the presence of excess amorphous carbon, which led to the formation of a porous microstructure. Interestingly, the doped multilayer coating also showed a superior wear performance compared to the single layer coating [70]. Similar observations were reported for TiAlCrN coatings doped with carbon [71]. Recently, Akhter et al. investigated the effect of Ni doping on CrN coatings deposited on AISI M2 tool steel. They recorded optimum wear performance at lower compositions of the dopant. Wear enhancement was attributed to the increase in hardness resulting from grain reformation and solid solution hardening [165]. As observed by Kong et al. [70], they also reported a deterioration in tool wear performance at higher dopant compositions.

To add up, wood machining with an uncoated substrate is already complicated. The incorporation of the coating further complicates the process due to the increase in the factors upon which tool wear is dependent. However, from an economic standpoint, the achieved wear improvement correlates with the cost implication. Furthermore, in the decision-making for coating selection for wood machining, resistance to elastic strain and plastic deformation should also be considered coupled with the hardness. More so, the substrate should possess sufficient strength and toughness to support the load applied to the coatings. The difference in surface chemistry between the substrate and coating accounts for the difference in wear performance when a given coating is deposited on different substrates. Nonetheless, the properties of the coatings can be further enhanced by doping with optimum elemental compositions.

3.7. Wear Enhancement via Hybrid Treatment

In an attempt to further enhance the wear of tool steels, researchers have also explored the possibility of hybrid treatments. This involves a combination of two or more surface modification processes, such as nitriding and coating or shot peening and coating, among others [159,178,179].

A significant number of studies have been documented on the effect of combined nitriding and coating on the wear performance of different tool steels. The nitriding process prior to the coating deposition has been reported to improve the adhesion of the coating to the substrate [118,180]. Firstly, Zeghni et al. investigated the wear behavior of AISI D3 and Vanadis 4 tool steels, which were nitrided prior to the coating process. For most of the investigated coatings, the authors reported an improvement in wear performance accompanied by an increment in hardness and bond strength. Meanwhile, drastic reductions in wear resistance were recorded for other coated tool steels [81]. In another study, Faga and Settineri investigated the effect of nitriding temperature on diamond-like carbon and CrN coatings deposited on tool steels for the machining of black spruce. While the nitriding temperature had no significant effect on the tool wear with diamond-based coating, low-temperature nitriding improved the wear performance of the substrates with CrN-based monolayer coatings. However, inconsistent wear performances were recorded for tool steels with CrN-based multilayer coatings. Nonetheless, compared to the overall wear performances of the coated tool steel without nitriding, they exhibited inferior wear performances [5]. In a related study, Panjan observed that plasma nitriding at lower temperatures and shorter time improved the coating adhesion to the substrate due to the reduction in the formation of nitride layers. However, no significant improvement in tool wear was recorded [146]. Some authors have opined that the nitride layers have high compressive stresses and affect the growth of the coating films [5,146]. Others have attributed the observation to the reduction in toughness upon nitriding [181]. However, current reports by Çelik and co-workers revealed that the nitriding of Cr-Mo-V tool steel at 585 °C for 6 h, followed by the deposition of CrN, AlTiN, and CrN/AlTiN coatings, resulted in an improved tribological performance with the multilayer coating exhibiting the optimum performance. This was due to the increased hardness resulting from the combined effect of the hard ceramic coatings and the diffusion layer produced by nitriding [182].

Researchers have also explored hybrid treatments combining shot peening treatments and coating on tool steels [40,183]. Shot peening involves altering the surface microstructure by plastic deformation, resulting in the inducement of compressive residual stresses [140,184,185]. It confers benefits such as an increase in hardness and reduction in surface roughness [40]. Accordingly, a study conducted by Pak et al. on the hybrid coating and ultrasonic peening treatment revealed an improvement in wear performance by 47%. More so, the coating did not significantly influence the surface roughness but contributed substantially to the surface hardness, which accounted for the improved wear performance. However, high compressive stresses resulted in a reduced wear performance due to the reduction in bond strength [40].

Similarly, hybrid treatments involving burnishing, high-energy beam treatments, and the nitriding of tool steels have been reported [23,186,187]. In this regard, Ormanova et al. studied the effect of electron beam treatment and nitriding on the hardness of AISI W320 tool steel. They observed an increase in hardness with the hybrid treatment. But an additional electron beam treatment after nitriding resulted in hardness reduction primarily due to grain coarsening [187]. In another study, Tobola et al. investigated the effect of nitriding and burnishing on the wear performance of AISI D2 and Vanadis tool steels. Prominently, they found that nitriding and burnishing enhanced the wear of the tool steels owing to the increase in the compound layer accompanied by increased surface hardness. However, nitriding offered a more significant improvement in tool wear relative to the latter. Consequently, they recommended that the burnishing should precede the nitriding treatment for optimum wear performance [23].

In summary, hybrid treatment has the potential to provide tool wear enhancement if appropriately applied. In the case of the combination of nitriding and coating, despite exhibiting superior wear performance compared to the untreated substrate, based on the preponderance reports, it is not recommended if optimum wear performance is desired. This is because the coated substrate without nitriding exhibits far superior wear performance in most cases. However, if nitriding is supposed to be applied prior to the coating, in that case, it should be carried out at lower temperatures and shorter times in order to maximize the adhesive benefits of the nitride layers while minimizing the thickness due to their detrimental effect on the wear performance.

4. Summary and Research Gaps

4.1. Summary

Tool wear, characterized by various mechanisms, significantly limits the overall productivity of the wood machining industry by reducing the lifespan of cutting tools. This issue is further exacerbated by the dynamic properties of wood and dry machining conditions. To address this challenge, several techniques for characterizing tool wear have been developed alongside promising methods for enhancing tool lifespan. Multiple austenitization and tempering operations have demonstrated optimal tool wear performance, while cryogenic treatment has also shown improvements. Thermochemical treatments have shown positive outcomes when applied at intermediate process parameters. When it comes to coating selection for wood machining application, factors such as hardness, resistance to elastic strain (H/E), and plastic deformation (H^3/E^2) should be taken into consideration to make informed decisions. Furthermore, the utilization of hybrid treatments can ultimately result in significant enhancements in tool wear performance.

4.2. Research Gaps

In light of the review, the following recommendations are outlined for researchers and industrial practitioners involved in enhancing tool wear for wood processing applications:

- Researchers should explore the development of innovative wood machining lubricants or coolants, similar to those used in metal machining, that do not compromise wood quality or negatively affect cutting tools. If achievable, the use of hardened tool steel

without additional surface modification treatments could be considered, leading to potential cost savings in wood machining.
- In addition to the experimental tests reported in the existing literature, more field tests conducted under practical industrial scenarios with optimized machining parameters are needed. Subsequently, further studies should be undertaken to investigate any disparities in tool wear behavior.
- Given the absence of an all-inclusive coating, researchers should focus on developing coatings specifically tailored for particular wood species to achieve optimal wear performance. This approach can then be expanded gradually to cover a wider range of wood species.
- More studies should be conducted to understand the bonding mechanism and surface chemistry at the interface between the substrate and coating. This understanding could shed light on the variations in wear behavior exhibited by the same coating deposited on different substrates.
- Most coatings examined in the review employed Ti or Cr bond coatings/interlayers. Further studies should investigate the effect of bond coating/interlayer thickness and explore alternative options to enhance bond adhesion to the substrate.

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