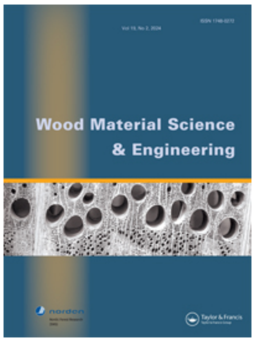

Wood Material Science & Engineering

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/swoo20

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To cite this article: Jozef Krilek, Iveta Čabalová, Eva Výbohová, Miroslava Mamoňová, Miroslava Ťavodová, Ján Melicherčík, Arkadiusz Gendek, Monika Aniszewska, Luigi Todaro & Valentina Lo Giudice (2024) Assessment of the chipping process of beech (*Fagus sylvatica* L.) wood: knives wear, chemical and microscopic analysis of wood, Wood Material Science & Engineering, 19:2, 473-484, DOI: 10.1080/17480272.2023.2259343

To link to this article: https://doi.org/10.1080/17480272.2023.2259343

Published online: 21 Sep 2023.

WOOD MATERIAL SCIENCE & ENGINEERING
2024, VOL. 19, NO. 2, 473–484
https://doi.org/10.1080/17480272.2023.2259343

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Assessment of the chipping process of beech (*Fagus sylvatica* L.) wood: knives wear, chemical and microscopic analysis of wood

Jozef Krilek [a], Iveta Čabalová [b], Eva Výbohová [b], Miroslava Mamoňová [c], Miroslava Ťavodová [d], Ján Melicherčík [a], Arkadiusz Gendek [e], Monika Aniszewska [e], Luigi Todaro [f] and Valentina Lo Giudice[f]

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ABSTRACT
The objective of this work was to investigate the rate of knife wear during the beech wood chipping process and to evaluate the changes in the chemical and microscopic structure of wood. A knife coated with AlCrN was selected for the study. This coating creates an abrasion resistant layer on the knife and has a higher resistance to abrasive wear and, therefore, a longer life. After chipping, the degree of knife wear was assessed using a gravimetric method and 3D scanning analysis. Microstructural and surface characterisation revealed that cracking and abrasive wear were the main causes of tool blunting. The maximum removal of material on the cutting edge was 240 µm, the average weight loss of 0.58 g. In relation to wear, wood fragments remained on the cutting knife. Infrared spectroscopy of wood fragments showed changes in the chemical composition due to the high temperatures in the blade of the knife, and elemental analysis, the higher content of Al, Cr, and N elements in the wood fragments, probably due to the presence of particles from the coating of the knives. Microscopic analysis of the chips revealed the presence of metal particles from the knives on the structural wood elements.

ARTICLE HISTORY
Received 29 March 2023
Accepted 11 September 2023

KEYWORDS
Coated knife; cutting edge; chemical structure; SEM analysis; BSE detector

Introduction

Wood chipping is an important process in forestry, wood processing, and primarily in pulp processing. As almost 35% from the overall number of trees harvested on all continents is used for pulp production (Aremu *et al.* 2015). For pulp production, it is important to use wood chips of a good quality, whereas there is a direct relationship with the effectiveness of the pulping process (Malkov *et al.* 2001, Ding *et al.* 2009, Freitas *et al.* 2018, Eugenio *et al.* 2019). Wood-chipping machines were designed to obtain chips from small and medium-diameter logs with very low production of sawdust in one operation (Kuljich *et al.* 2017). For good chip quality, one of the most important parameters is the condition of the knife edge during chipping (Heidari *et al.* 2013, Spinelli *et al.* 2014, Nadolny *et al.* 2020). Knowledge of local wood properties, including resistance to chipping, is significant for the improvement of structural components such as chipping tools (Pichler *et al.* 2018). Tool wear increases the cutting force, which leads to an increase in temperature, which results in lower cutting stability. The high temperature of the knife is also caused by the tension of the material and depends on the type of conditions and the cutting mode (Kara and Li 2011). Wear of the cutting tool has a significant effect on the quality of the machined part. Ramasamy and Ratnasingam (2010), as well as Okai *et al.* (2005), noted that mechanical, thermal, and chemical interactions between the cutting tool and wood are important factors for tool wear. According to several studies (Klamecki 1979, Porankiewicz *et al.* 2005, 2006), the chemical composition of wood may play a role in cutting tool wear rates. The presence of silica content and other abrasive agents in wood (Porankiewicz and Grönlund 1991, Cristóvaõ *et al.* 2011, Ekevad *et al.* 2012), as well as the wood extractives content (Cristóvaõ *et al.* 2011) influences knives wear rate. When the cutting tool wears, it is damaged (abrasion, chipping) at the micro level (Jeon *et al.* 2017). An effective method of reducing tool wear is its modification with a thin hard coating produced by PVD (Physical Vapour Deposition) or CVD (Chemical Vapour Deposition methods) (Schalk *et al.* 2022, Warcholinski and Gilewicz 2022). The coating of tools is used to reduce the wear of the cutting edges, which should ensure an increase in their service life. Priority is given to the coating of tools for chip machining or metal forming. Cho *et al.* (2015) and Kazlauskas *et al.* (2022) have confirmed the importance of using this

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surface treatment technology on tools. Also coating of tools also for wood chipping in secondary production (e.g. mills, drills, knives for veneer peeling) is becoming a common practice and brings many advantages. Such as increasing the life of the tool, as well as the quality of the resulting product, was observed by e.g. Kalincová *et al*. (2018), Nadolny *et al*. (2020) and Warcholinski and Gilewicz (2022). However, the tools for the primary processing of wood, the coating method is not so commonly used and is not sufficiently described in the literature.

The temperature of the cutting tool, as one of the most important factors affecting tool wear in wood processing, causes a change in its basic properties, such as hardness, toughness, and chemical stability (Ekevad *et al*. 2012). The temperature of the knife depends on several factors, including the cutting speed, the continuity of the cutting process, the depth of the cut, and the shape of the tool (Horman *et al*. 2014). During the processing of wood with knives, the source of heat is the friction work performed on the contact surfaces. The temperature is influenced by the properties of the cutting tool, its geometric properties, the thermal conductivity of the material and its specific heat. During friction, energy is consumed, and shear stress creates deformations in both contacting materials. Frictional heat is generated at the interface between the chip and the tool, while a smaller part of the heat flows into the chip and a larger part flow into the knife (Kumar and Jagath 2013). The temperature in some places of the cutting tool is more than 500°C (Horman *et al*. 2014). The effect of high temperatures on wood causes changes in its chemical structure and main constituens (cellulose, hemicelluloses, lignin, extractives) (Sandberg *et al*. 2013, Kamperidou 2019). These processes take place through various reactions such as oxidation, dehydration, hydrolysis, decarboxylation, while changes in lignin-saccharide structures can be characterised using infrared spectroscopy (FTIR) (Kubovský *et al*. 2020). Changes in the chemical structure can influence the quality of wood chips. Moreover, the result of the chip production process is that, in addition to the wear, the fragments of wood remained on the cutting knife. Due to the repeated exposure to the high temperatures of the cutting tool, the chemical composition of the wood fragments will be changed compared to the processed original material or the resulting product – wood chips.

In the primary processing of wood, cutting tools are used in their basic state (uncoated), which have their own service life. Changing knives is a time-consuming process, which is reflected in the lower performance of the machine itself. By increasing the service life of cutting tools, the costs of chip production will be reduced, energy requirements will be reduced, and the machine performance and the chip quality will be increased.

The aim of this paper is to assess the wear rate of knives wear during the beech wood chipping and to evaluate the changes in the microscopic and submicroscopic structure of wood.

In this paper, knives coated with CROSAL plus based on AlCrN (Aluminium Chromium Nitridate) were used for the experiment. They were selected based on resistance test and hardness measurement. This coating is mainly used to increase the life of cutting tools in the metalworking and woodworking industries, while it was only used for the primary processing of wood in this experiment.

Material and methods

Material

Beech wood trees (*Fagus sylvatica* L.) with a trunk diameter of 18 cm ± 1 cm and an age up to 50 years, harvested in the middle part of Slovakia (Zvolen region, Tŕnie forest district) in April 2022, were used for the chipping process. The moisture content (w) of the green beech wood was determined in a RADWAG moisture analyser, MAC series (INTERTEC, Banská Bystrica, Slovakia), and density (ρ) using the gravimetric method.

Chemical composition of raw beech wood

The beech wood was disintegrated into sawdust and fractions of 0.5 to 1.0 mm in size were used for chemical analyses. The extractives content (EXT) was determined on a Soxhlet apparatus with a mixture of absolute ethanol for analysis (Merck, Germany) and toluene for analysis (Merck, Germany) (2:1, v:v) according to the ASTM D1107-21 (2021). Lignin (LIG) was determined according to Sluiter *et al*. (2012), holocellulose (HOLO) according to the method of Wise *et al*. (1946), and cellulose content (CEL) according to the method of Seifert (1956). Hemicelluloses (HEMI) were calculated as the difference between the holocellulose and the cellulose content. Measurements were performed on four replicates per sample. The results (Table 1) are presented as percentages of oven-dry wood.

Methods

Selection of knife material

Before the beech wood chipping process, an abrasive wear resistance test and HRC (Hardness Rockwell C) measurement were performed, and a better quality knife material was selected for the experiment.

Two materials were used in the experiment: uncoated (Figure 1) and coated (Figure 2). The basis of both is steel X48CrMoV8-1-1 (2019) (WNr. 1.2360) (PILANA Group a.s., Hulín, Czechia) with a diameter of 248 mm × 115 mm × 13 mm; edge of 25°/35°; 3×groove, size of 14 mm (knife designed for the type of chipping machine of PEZZOLATO H 780/200). It was an alloy steel tool, designed for dies for forging presses, die inserts, extrusion tools, tools with good compressive strength and especially with high abrasion resistance. This type of material is usually used to sharpen strained knives. The chemical composition according to the material sheet (www.dashofer.cz) is shown in Table 2.

The strength limit of steel in the hardened and tempered state Rm is from 1270 to 2100 MPa. The achievable hardness is declared according to the selected tempering speed in the range of 40 ± 1.5 to 56 ± 0.4 HRC. This material was hardened at a temperature of 1032 °C and the tempered temperature was T = 542°C.

The coated tool (Figure 2) was coated with CROSAL plus. It is a new generation coating based on AlCrN (Aluminium Chromium Nitridate) (voestalpine High Performance Metals Division, s.r.o., Martin, Slovakia). This coating is an advanced development of the older, but practice proven, well-established CROSAL coating. This coating is characterised by high

Table 1. Characteristic of green beech wood material: moisture, density, extractive content (EXT), lignin content (LIG), holocellulose content (HOLO), cellulose content (CEL), hemicellulose content (HEMI).

Sample	Moisture *w* (%)	Density ρ^* (kg·m^{-3})	Chemical composition (%)				
			EXT	LIG	HOLO	CEL	HEMI
green beech wood	45.94 ± 0.47	1016 ± 24	3.60 ± 0.03	20.09 ± 0.08	81.25 ± 0.01	37.38 ± 0.13	43.87 ± 0.14

*Wood density at the moisture content of green beech wood.

resistance to oxidation and wear, excellent adhesion, and heat hardness. Its basic applications are for e.g. metalworking and forming tools, used for high-performance cutting. The basic properties are listed in Table 3. The coating on the base of AlCrN according to Souza *et al*. (2020) has a lower friction coefficient and wear rate than the TiAlN coating under distinct (mild and severe) sliding.

Abrasive wear resistance test and HRC hardness measurement

The test of abrasive wear resistance was performed according to the GOST 23.208-79 (1979) standard GOST 3647-80 (1982) method consists in comparing the weight loss of the tested material with that of the standard material under the same test conditions. Electrocorundum with a grain size of 100–250 µm is used as an abrasive material, with a maximum moisture content of 0.15%. Its hardness corresponds to the 9th degree according to the Mohs scale. When assessing wear resistance in specific wear conditions, it is allowed to use an abrasive material corresponding to the material that acts during operation, but with a grain size of no more than 1.0 mm (GOST 23.208-79 1979). The test was carried out in the laboratory of the Faculty of Technology of the Czech University of Life Sciences in Prague using Tester T-07 test equipment, ITC PIB Institution of Technology Radom, with the controller BT-16 (Institute for Sustainable Technologies, Radom, Poland). Each sample was prepared using abrasive water jet cutting technology, milled and ground on a magnetic plane grinder to dimensions of 30 mm × 30 mm × 10 mm with a surface roughness Ra of 0.4 µm. The test conditions were established as follows:

- length of the friction track in one cycle $R = 153.6$ m,
- rubber disc diameter $D = 48.9$ mm,
- pressing force $F = 15.48$ N,
- number of turns in one cycle $n = 1000$,
- abrasive – silica sand OTTAWA with a grain size of 0.1 mm and
- hardness of the abrasive material 54 HRC.

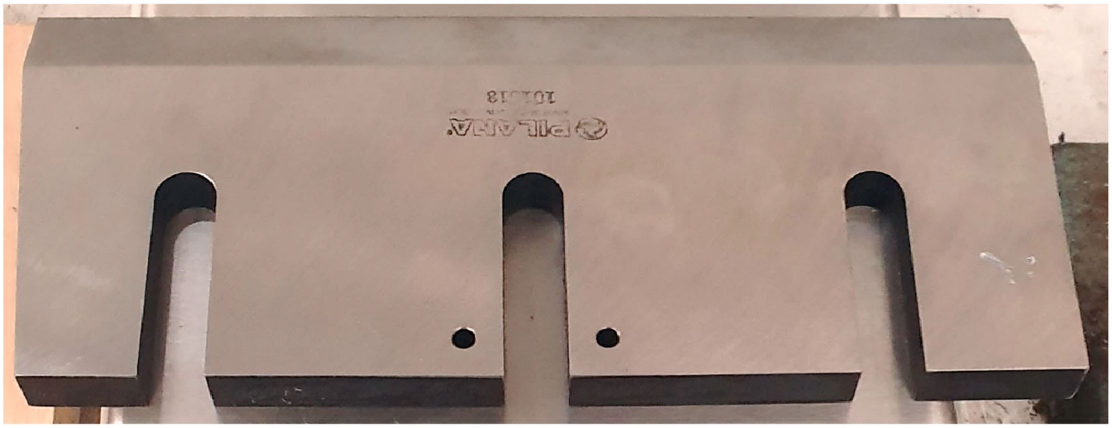

Figure 1. An uncoated cutting knife.

Figure 2. Cutting knife coated with AlCrN (Aluminium Chromium Nitridate).

Table 2. Chemical composition of steel X48CrMoV8-1-1.

Element	C	Si	Mn	P	S	Cr	Mo	V
Values (hm. %)	0.45–0.50	0.70–0.90	0.35–0.45	0.020	0.005	7.30–7.80	1.30–1.50	1.30–1.50

Table 3. Properties of the coating with CROSAL plus stated by the manufacturer.

Trait	Hardness	Friction coefficient	Coating thickness	Thermal threshold	Coating temperature	Colour
Value	3200 ± 300 HV0.05 61HRC	0.45	2–5 µm	1100°C	400°C	slate grey

Each test sample was weighed three times before the test and placed on the test device. Subsequently, the abrasive feed was started and the rubber disk was pressed against the test sample. After each cycle was completed, the sample was reweighed three times. From the results weights, the average weight loss w_h for each material was calculated.

Rockwell hardness was performed in accordance with ISO 6508-1:2016. A Rockwell hardness tester, type UH250 (Buehler Ltd., Lake Bluff, Illinois, USA) with a loading force F of 1471 N was used to determine the hardness. Measurements were performed on five replicates per sample as shown in Table 4 and Figure 3.

Relative resistance to abrasive wear Ψ_{abr} was calculated according to:

$$\Psi_{abr} = \frac{W_{hR}}{W_{hC}} \tag{1}$$

where w_{hR} is weight loss of the uncoated sample (g), w_{hC} is weight loss of the coated sample (g).

Coefficient of hardness K_T. Coefficient of hardness K_T of uncoated sample H_R – abrasive H_a

$$K_T = \frac{H_R}{H_a} \tag{2}$$

Table 4. Results of the resistance test to abrasive wear and HRC hardness measurement.

Trait/ Type of material	The total distance covered, R (m)	Average weight loss, w_h (g)	Hardness (HRC)
Uncoated	1650	0.0030	57
Coated	1650	0.0028	61

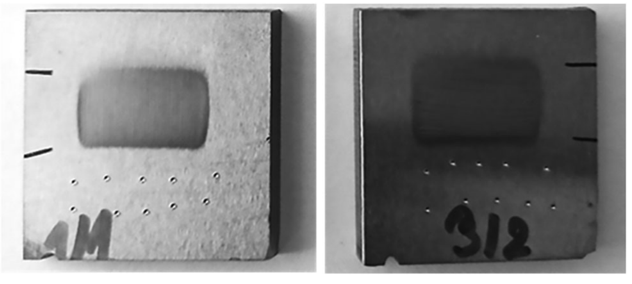

Figure 3. Samples of uncoated (left) and coated knives (right) after the test of resistance to abrasive wear and measurement of HRC hardness.

Coefficient of hardness K_T of coated sample H_c – abrasive H_a

$$K_T = \frac{H_C}{H_a} \tag{3}$$

where: HR – hardness of the uncoated sample (HRC), H_a is hardness of the abrasives (HRC), H_C is hardness of the coated sample (HRC).

Chipping process, gravimetric analysis, and 3D scanning of knives

The realisation of the experimental measurement consists of a control weight method for testing chipping knives, where the weight of each knife was recorded before the measurement. Weighing was carried out on a professional laboratory balance RADWAG PS3500R2 (Libra, Bratislava, Slovakia), 3500 g capacity, 0.01 g readability. Before performing the experimental measurements, a control measurement and 3D scanning of the geometrical parameters of the chipping knives were required by a non-contact method, using the Alicona Infinity Focus device (Bruker Alicona, Graz, Austria). The experimental measurement was carried out on a Pezzolato H780/200 cardan-mounted mower (Pezzolato S.P.A, Envie CN, Italy) at a constant speed of 540 rpm, driven by a Zetor Proxima wheeled tractor (ZETOR TRACTORS, a.s., Brno, Czechia). After processing of green beech wood, the coated chipping knives (three pieces) were disassembled and the final weighing and 3D scanning were carried out to evaluate the wear rate of the cutting edge. The volume of green beech processed was determined based on previous experiments with basic uncoated knives. The results of these experiments are the subject of other upcoming publications.

Chemical changes in the wood structure

After the chipping process, the wood fragments remained on the knives. The total weight of the wood fragments was 0.43 g (taken from the three knives). The wood fragments taken from the knives were analysed by ATR-FTIR spectroscopy and elemental analysis compared to green beech wood.

ATR-FTIR spectroscopy

Samples of beech wood and wood fragments of wood taken from knives were analysed using ATR-FTIR spectroscopy. The measurements were carried out using a Nicolet iS10 FTIR spectrometer equipped with Smart iTR attenuated total reflectance sampling accessory with diamond crystal (Thermo Fisher Scientific, Madison WI, USA). The spectra were recorded in the wavenumber range of 4000 to 650 cm^{-1}. The resolution was established at 4 cm^{-1} and 32 scans were recorded for each analysis. Four analyses were performed per both specimens. Spectra were evaluated using the OMNIC 8.0 software (Thermo Fisher Scientific, Madison WI, USA).

Elemental analysis

Elemental analysis of beech wood and the wood fragments of wood taken from the knives was carried out. The determination of carbon (C) was carried out according to the ISO 13878 (1998) standard, and nitrogen (N) according to the STN ISO 10694 (2001) standard using the EA-TCD elemental analysis by thermal-conductivity detection. Other elements: phosphorus (P), calcium (Ca), magnesium (Mg), potassium (K), sodium (Na), iron (Fe), manganese (Mn), zinc (Zn), aluminium (Al), boron (B), copper (Cu), silicon (Si), chrome (Cr) were determined in the mineral by microwave decomposition in the presence of HNO_3 and H_2O_2 according to the ISO 11885 (2007) standard using AES-ICP (atomic emission spectrometry with inductively coupled plasma).

SEM analysis of wood chips

SEM analysis was performed to detect the presence of metal particles in the wood chips originating from the chipping process. The evaluation of the metal particles was performed with an electron microscope detection system, using the back-scattered electrons (BSE) detector. The BSE signal originates from the interaction of the primary electron beam with the sample. Larger atoms scatter the electrons more than the light atoms do thereby, creating a higher signal for the BSE detector (Reimer 1998, Salh 2011). The number of backscattered electrons detected with the BSE detector is proportional to the atomic number of the investigated material. Phases with a higher atomic number (metal particles) will be displayed as brighter regions. This effect allows for the identification of different phases in the materials.

Wood chip mounting samples were attached to the aluminium stubs using conductive carbon adhesive tape, and the circumference was covered with conductive colloidal silver paint, sputter coated with gold in device K650X (Quorum Technologies Ltd., Laughton, UK), and examined with high-vacuum scanning electron microscopy using a Tescan Vega SEM (Tescan, Brno, Czech Republic) operating at 30.0 kV. The electron source was a tungsten filament. The operating conditions, including magnification and scale bar, were recorded on the data bar at the foot of the SEM image.

Results and discussion

Evaluation of knives abrasive wear resistance and HRC hardness

The quality of the chips is closely related to the quality of the knives used for the chipping process. Chipping knives made of steel without heat-chemical surface treatment are commonly used for the chipping process. Knives with surface treatment are mainly used in the woodworking and metalworking industries (Kazlauskas *et al*. 2022). In this work, an experiment was carried out, where knives with thermal-chemical surface treatment were used for the first time for the production of wood chips. Based on the chemical composition of the chipping knife material and the wood chipping process, a surface treatment was proposed. In order to confirm the better resistance of the knife with surface treatment (coated), a comparison of resistance to abrasive wear and HRC hardness with an uncoated knife was performed.

In laboratory conditions, it was verified that coating the knife with an AlCrN coating (CROSAL plus) mentioned properties were improved.

Relative resistance to abrasive wear Ψ_{abr} calculated according to the Eequation (1) was:

$$\Psi_{abr} = \frac{0.0030}{0.0028} = 1.07$$

Sample with the AlCrN coating reached relative resistance to abrasive wear Ψ_{abr} better by 7%.

Coefficient of hardness K_T calculated according to the Equation (2) of uncoated sample H_R – abrasive H_a:

$$K_T = \frac{57}{54} = 1.06$$

Coefficient of hardness K_T calculated according to the Equation (3) of coated sample H_c – abrasive $H_{a:}$

$$K_T = \frac{61}{54} = 1.13$$

The sample with the CROSAL plus coating reached HRC hardness better by 13%.

Based on the experiments, it was proven that coated knives have a better resistance to abrasive wear and HRC hardness compared to uncoated ones.

Gravimetric analysis and 3D scanning of cutting knives

When the cutting tools wear, their weight also decreases, and may lead to an unbalanced cutting mechanism and an increase in vibrations (Poje *et al*. 2018). The results of the gravimetric analysis of the knives with a coating based on AlCrN (Table 5) show that after wood chipping, the weight of the knives decreased (on average by 0.56 g) due to the knives wear. After the experiment, a certain amount of wood fragments remained (Figure 4) on the knives in the range from 0.11 g to 0.18 g.

The 3D scanning microscopic analysis of the cutting knife showed slight damage to the cutting edge, removal of material on the cutting edge by a maximum of 370 µm (Figure 5). In the picture it can be seen an overlay of the scans of the cutting edge before and after the chipping process. Green points displayed on the cutting edge (grey area) indicate positive or negative deformations. Surface treatment of the knife with a AlCrN coating did not prevent the formation of a wood

Table 5. Gravimetric analysis of knives and wood fragments taken from knives.

Weight (g)/ Knife No.	Knife before chipping	Loss of knife weight after chipping	Wood fragments taken from the knives
1.	2227.25	0.64	0.11
2.	2234.62	0.56	0.18
3.	2231.29	0.48	0.15

Figure 4. Coated knife after the beech wood chipping process, wood fragments in a white rectangle.

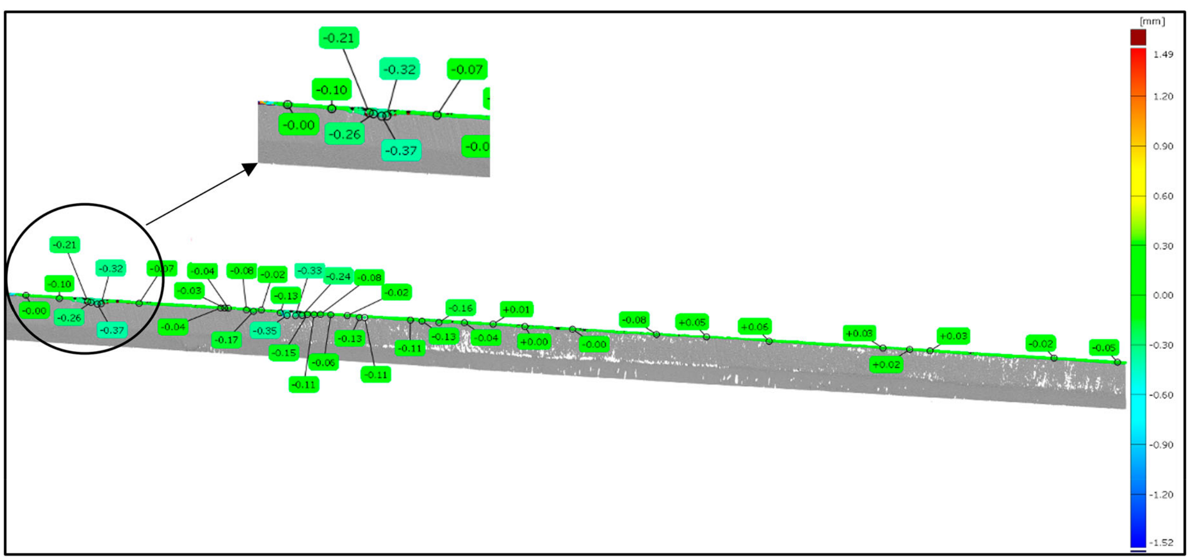

Figure 5. Evaluation of the primary surface of the knife, cutting edge (grey area), before and after chipping. Green points show positive (+) or negative (–) deformations.

particles on the knives. Nevertheless, the damage of the chipping knife cutting edge is minimal.

Varghese *et al*. (2022) modelled cutting edge degradation by chipping in micro-milling. The length of the chipped portions of the cutting edges was between 15.76 and 96 µm, whereas their width was between 7 and 29 µm, and they were found to have a positive correlation.

Krilek *et al*. (2021) performed a stress analysis FEM on a chipping knife in its basic condition (without surface treatment) material type EN 41 9802. The result of the stress analysis of a knife with a flat blade edge indicated a deformation greater than 14.44 µm. Stress analysis showed that this material is suitable to produce cutting knives for the processing of wood waste and dendromass. The comparison between the durability of uncoated and coated knives was evaluated by Kalincová *et al*. (2018). The use of the CrN/TiN coating on tools for woodworking technology lead to a significant increase in the resistance against the thermal influence and to a decrease in abrasive wear of the cutting edge, which is also in comparison with results by Warcholinski and Gilewicz (2011) and Jaroš and Fiala (2016). Wu *et al*. (2023a, 2023b) who investigated the abrasive wear of blade tip on the knives made from martensitic steels. The wear rate of steels has been determined to be 1.98×10^{-4} $mm^3/(Nm)$ for 5Cr15MoV and 1.5×10^{-4} $mm^3/(Nm)$ for 9Cr18MoV, respectively. According to authors, volume is proportional to the cutting cycles and actual applied load.

During the primary processing of the wood, in the interaction of the tool and the wood, the energy demand during the transverse cutting of the wood was monitored. The

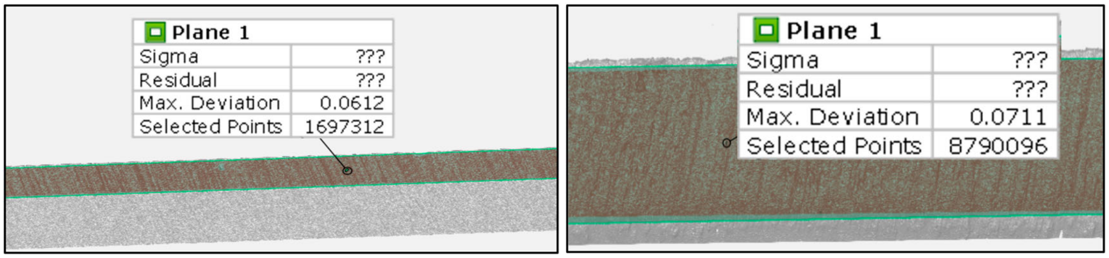

Figure 6. Results of evaluating the flatness of the primary surface of the chipping knife.

results show a reduction in the energy consumption of the entire wood splitting process when using a PVD coating based on AlTiN (Aluminium Titanium Nitride) on saw blades (Kováč *et al*. 2022).

The geometric deviation of flatness before the experiment was 61 µm, and after the experiment was 71 µm (Figure 6).

The surface roughness of the cutting edge of the knife (Rz) was 18 µm before the experiment. This value was averaged over the entire length of the cutting edge. The roughness of the cutting edge after experimental measurements was 8 µm, which represents a decrease of 56%. %. It can be stated that wood behaves as an abrasive material and affects roughness. On the one hand, this can be positive due to a decrease in roughness, which will be reflected in reduced energy requirements during wood processing. Also, the cutting edge the cutting edge of the knife material wears out, which leads to an increase in the radius of the cutting edge and its deformations, to a decrease in chips quality and productivity. Using material with lower wear resistance leads to the fast dulling and bending of materials (Kováč *et al*. 2014). According to Spinelli *et al*. (2014), knife wear determines a 20% decrease in chip productivity and a dramatic decline in chip quality. Facello *et al*. (2013) showed that knife wear caused a 50% reduction in productivity. Ťavodová *et al*. (2022) analysed harvester delimbing knives manufactured from special hardened and tempered Borarc alloy steel. Based on their results, the knives worn abrasively. The thickness of the knife was gradually decreased, the profile of the knife lost stability, and it was plastically deformed with the final phase of breaking the integrity.

Chemical changes in the wood structure

When high temperatures, such as those reached at the point of contact of the knife blade with the wooden material, the chemical structure of the wood changes. After our experiment, wood fragments with a changed chemical structure compared to green wood were found on the knives, which is confirmed by the results of the FTIR analysis (Figure 7).

The comparison of the spectrum of beech wood and the spectrum of wood fragments taken from the knives (Figure 7), shows considerable differences in several regions. When interpreting the differences in the spectra, considering the facts that during the cutting of chips, there is an increase in temperature at the point of contact of the knife's material with the wood, and therefore observed changes in the wood fragments taken from the knives related to the thermal degradation of the wood sample.

The absorption band in the range 3700–3000 cm^{-1} is in the spectrum of the wood fragments taken from knives is more intensive, and its maximum is shifted to a higher wavenumber (3357 cm^{-1} vs. 3345 cm^{-1} in the spectrum of beech wood). This band is associated with vibrations of the OH groups. The

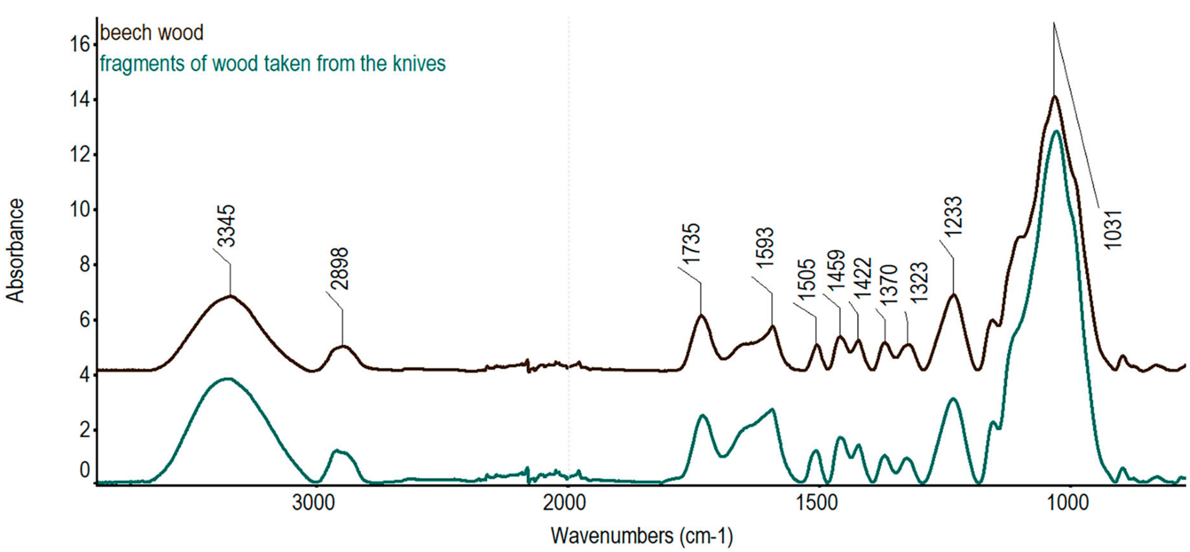

Figure 7. ATR-FTIR spectra of beech wood and wood fragments taken from knives.

differences mentioned above can be caused by an increase in the intensity of O-H from the phenolic groups in lignin. It is a well-known fact that the lignin percentage increases because of carbohydrate degradation due to increased temperature (Esteves *et al*. 2013, Výbohová *et al*. 2018, Hill *et al*. 2021, Čermák *et al*. 2022).

Another important region is the region of characteristic for stretching the vibrations of the C=O groups. In the spectrum of the wood fragments taken from the knives, we observe a higher intensity of the absorption band at 1732 cm^{-1} and its shift to lower wavenumbers compared to the spectrum of wood, where the maximum of this band is at 1735 cm^{-1}. These differences may be due to an increase in carbonyl or carboxyl groups in lignin by oxidation (Tjeerdsma and Militz 2005, Esteves *et al*. 2013).

It is very well-known fact that the thermal stability of lignin is higher compared to the other wood components and the increase in its percentage after the chipping process in the wood fragments taken from the knives is evident by an increase in the intensity of the absorption bands at 1593 and 1508 cm^{-1}. These bands correspond to aromatic ring stretching vibrations. Their observable broadening suggests that in the wood fragments taken from the knives there is a greater structural diversity around the benzene rings than in the wood (Esteves *et al*. 2013). The different position of the maximum of the second peak in compared spectra (1508 cm^{-1} in the spectrum of wood fragments taken from the knives vs. 1505 cm^{-1} in the spectrum of wood) indicates that lignin macromolecule in the wood fragments taken from the knives has lower methoxyl groups. It can be assumed that the higher temperature during chipping causes demethoxylation of lignin, respectively easier cleavage of syringyl units since these are less condensed by C–C bonds than guaiacyl units (Faix *et al*. 1990).

Also, the mentioned spectra differ in the shape of the peak in the region from 1350 to 1300 cm^{-1}. The peak maximum is found at 1323 cm^{-1} in the spectrum of the wood fragments taken from the knives, is shifted to a higher wavenumber, namely to 1327 cm^{-1}. Based on the peak assignments according to Bhagia *et al*. (2022) it can be assumed that this is caused by a decrease in the intensity of absorption bands originated from vibrations of thermally less stable polysaccharides, which are found at lower wavenumber. On the other hand, the band at 1327 cm^{-1}, which corresponds to more stable monomers of the lignin macromolecule, maintains its intensity.

It is difficult to interpret the differences between 1180–910 cm^{-1} because in this region more absorption bands are characterised for various groups and bonds in all wood components overlapped. The highest absorption band, with a maximum at 1030 cm^{-1}, corresponds to the C–O–C vibrations. When the differences in this region of spectra are compared, we can state that in the spectrum of the wood fragments taken from the knives the ratio of the intensity of absorption bands H_{1030}/H_{1370} considerably increased which means that the proportion of C–O–C bonds is higher in the sample of wood fragments taken from the knives compared to beech wood.

The wear of the knives was also confirmed by elementary analysis. Comparing the results between the wood fragments taken from the knives and green beech wood (Table 6) shows the lower amount of elements: P, Mg, Ca, Mn and Cu and the highest amount of N, C, K, Na, Fe, B, Si, Al and Cr in the wood fragments taken from the knives. The presence of a higher content of Al, Cr, and N elements in the wood fragments taken from the knives could be due to the wear of the surface part of the knife material, the coating of which is formed by the elements Al, Cr, and N. Cristóvaõ *et al*. (2011) and Porankiewicz *et al*. (2005) showed that the cutting-edge damage can be associated with the interaction between the tool and large silica particles in the early stage of the cutting-edge wear process. In beech wood samples were recorded a higher content of Si (688 mg/kg) compared to the results obtained by Anca-Couce *et al*. (2020), with Si content of 106 mg/kg.

According to Telmo *et al*. (2010), the typical values in hardwoods for minor elements contents in mg/kg are Cd (0.10), Cr (1.0), Cu (2.0), Ni (0.5) and Zn (10). Anca-Couce *et al*. (2020) performed an elemental analysis of beech wood and found the following concentrations of elements: 65 mg/g of Al; 3668 mg/g of Ca; 60 mg/g of Fe; 1490 mg/g of K; 654 mg/g of Mg; 65 mg/g of Na; 106 mg/g of Si and 2 mg/g of Zn. Our results show the highest content of carbon element of 451 g/kg. Compared with the results obtained by Anca-Couce *et al*. (2020), we found a higher content of all the elements determined. Mineral concentrations in trees depend on several factors, such as species, age, part of the tree and growth state, and especially the forest soil affects the uptake of minerals by trees through the root system (Szász-Len *et al*. 2016).

Scanning electron microscopy analysis

The quality of chips is very important for the needs of the pulp industry. When chipping wood, the knives wear out, which is manifested by the presence of metal particles in the chips.

The metal deposition in conjunction with organic xylem fragments is shown in Figure 8. Metal particles were captured in the lumens of both early and late vessels (Figure 8, B5). Knife wear was certainly caused by mechanical tissue (libriform fibres). Deposits of metal particles together with xylem fragments were located in the lumens of vessels, which are more porous compared to libriform fibres. Smaller metal particles were caught on the libriform fibres, which is probably due to

Table 6. The elemental analysis of green beech wood and the wood fragments taken from the knives.

Sample/Element	Green beech wood	Wood fragments taken from the knives
C (g/kg)	451	469
N (mg/g)	3380	3750
P (mg/g)	730	700
Ca (mg/g)	10,133	2482
Mg (mg/g)	895	827
K (mg/g)	2168	3018
Na (mg/g)	131	217
Fe (mg/g)	1659	2526
Mn (mg/g)	176	81
Zn (mg/g)	44	44
Al (mg/g)	385	1177
B (mg/g)	15	22
Cu (mg/g)	12	6
Si (mg/g)	688	809
Cr (mg/g)	5	160

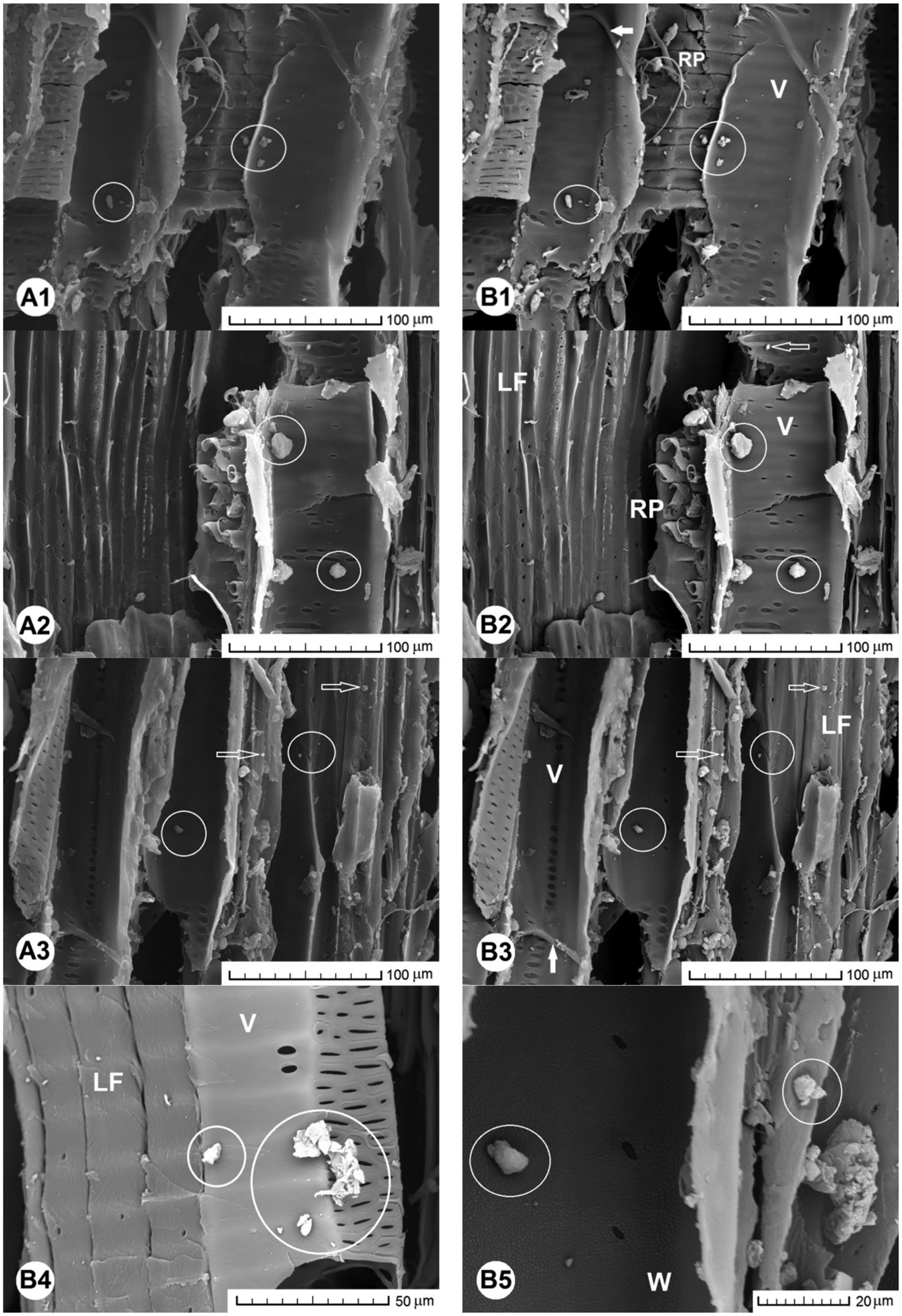

Figure 8. Presence of metal particles originating from the chipping process in the beech wood chips imaged by secondary (A1–A3) and BSE detectors (B1–B5). Scale bars = 100 µm (or 50 µm, exceptionally in exceptional cases B4, 20 µm in cases B5).

the higher density of their cell wall compared to early and late vessels (Figure 8, B3). It is assumed that in the processing of soft wood, e.g. poplar, willow, the metal particles would occur more evenly due to the wider lumens of libriform fibres. However, the question is whether the soft wood will cause wear at such level.

Abbreviations: V, vessel; LF, libriform fibres; RP, ray parenchyma cells; W, warty layer on the S3 wall of the latewood vessel;

white arrow – a simple perforation plate between vessels; white circles and arrow outlines – metal particles.

For the needs of the pulp production industries, the solution of cooking chemicals must completely penetrate the wood chips. The solution penetrates the wood chips by diffusing through the cellular elements of the wood. The increased temperature and effect of chemicals cause the delignification of the wood (removal of the majority of lignin) being inevitable for paper production. Incomplete penetration of chemicals into the wood chips is the major reason for inhomogeneous delignification during this process (Malkov *et al*. 2001). The presence of inorganic compounds could mean a problem for good penetration of the cooking chemicals into the entire volume of the chip. For this reason, it is necessary to use the best quality knives for the chipping process to achieve the best quality of the wood chip.

Conclusions

The production of high-quality wood chips requires the correct selection of the cutting tool, its setting, and careful maintenance. Using a high-quality knife in the chipper leads to an increase in productivity, a decrease in specific fuel consumption, the incidence of small chips, and fines decrease. In the present study, a knife coated with CROSAL plus based on AlCrN (Aluminium Chromium Nitridate) was selected for the chipping process based on its better abrasive wear resistance of 7% and HRC hardness of 13% compared to the uncoated, commonly used knife.

The wood chipping process causes:

- a loss of knife material on an average of 0.56 g,
- slight damage to the cutting edge and a maximum depth of material removal of 240 μm,
- an increase of the geometric deviation of the flatness by 16% and the decreas of roughness by 56%.

After removing the knives from the cutting disc, fragments of wood remained on the knives, in the range from 0.11 g to 0.18 g. Fourier transform infrared (FTIR) spectroscopy of the wood fragments in comparison to beech green wood shows:

- the changes in the wood structure as a result of the effect of high-temperature forming on the knives during the chipping process,
- an increase in carbonyl or carboxyl groups in lignin by oxidation reactions , and its demethoxylation.

Elemental analysis of the wood fragments taken from the knives pointed out the presence of a higher content of Al, Cr, and N elements which could be due to the wear of the surface part of the knife, from the coating.

Based on the results of microscopic analysis, the presence of inorganic components from chipping knives on the surface of the cellular structural elements was detected in the chips.

Based on the achieved results, it can be concluded that the coated knives are suitable not only for woodworking and metalworking, but also for the chipping process. We found only slight wear of the knives. The wear of the knives is also reflected in the wood, by the presence of elements from the knife in the wood chips as well as in the wood particles that remained on the knife after chipping.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by funding from the Slovak Scientific Grant Agency VEGA "Research of the cutting tools at the dendromass processing in agricultural and forestry production" [Contract no. VEGA 1/0609/20 (40%)]; and the Slovak Research and Development Agency [Contract no. APVV-21-0180 (40%) and no. APVV-22-0034 (20%)].

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