

Tribological Behavior of Various Surface-treated X48CrMoV8-1-1 Tool Steel for Application on Chipping Knives in Wood-Chipping Machines

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The aim of this work was to assess the suitability of selected methods of surface treatment on X48CrMoV8-1-1 tool steel for application on chipping knives in wood-chipping machines. Three material surface conditions of X48CrMoV8-1-1 tool steel were evaluated for their tribological scratching behavior. The first surface condition was related to the conventionally machined chipping knife from the manufacturer without surface treatment. The second condition involved plasma nitriding treatment, and the third was a PVD-coated surface with “CROSAL ® Plus” (AlCrN based) coating. Several complementary analyses were carried out, namely microstructural observations, nano-indentation measurements, and tribological scratch tests. From the scratch tests, friction coefficients depending on applied load were determined. The best nano-indentation results were obtained for the PVD-coated surface, namely 23.7 ± 1.6 GPa for nanohardness and 270.3 ± 19.0 GPa for elasticity modulus. The best results of tribological and scratching behavior were obtained for the plasma-nitrided surface, namely 0.34 ± 0.21 for coefficient of friction and 1.88×10^{-6} mm³/N.m for specific wear rate. Based on the obtained results of laboratory tests, it can be concluded that the plasma-nitrided surface of X48CrMoV8-1-1 tool steel can ensure its better tribological performance compared to other investigated material conditions.

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INTRODUCTION

Currently, there is great research emphasis on renewable resources. Among these is biomass, which is a source of renewable raw materials and energy. Biomass can be used for many purposes in specialty industrial, technical, and energy sectors (Kühmaier and Erber 2018). Biomass utilization currently accounts for 14% of global energy consumption (Latushkina *et al.* 2016). The importance of the woodworking industry is still high, and wood chipping is an important step in most forest-industrial processes (Krilek *et al.* 2024). Chippers are devices that split wood into chips. The chipping knives achieve the cutting of

fibers and at the same time dividing the material into the required thickness. Wood chipping machines have been designed to obtain chips from small and medium-diameter logs with low production of sawdust in one operation (Aremu *et al.* 2015; Kuljich *et al.* 2017). The quality of wood chips depends on the processed raw material. In addition, the type of wood and part of the wood (residues or logs) have a significant influence on the size distribution of the chips (Patterson *et al.* 2011; Spinelli *et al.* 2011; Kupte and Hartmann 2015). The requirements for high fuel quality are best met by wood chips made from logs, as they contain a smaller proportion of oversized particles and a higher proportion of impurities. Conversely, wood chips from forest residues can be considered more suitable for medium or larger combined heat and power plants because they do not require high quality chips (Kupte and Hartmann 2015). Wood chips are a frequent primary raw material to produce pellets as fuel for both the industrial and private sectors. Tool wear during wood cutting is characterized by the phenomenon that the cutting edge of the tool is not suitable for further use due to extensive deformation and/or breakage of the cutting edge. The wear of the cutting tool has a significant impact on the quality of the machined surfaces and directly affects the quality of the finished product (Nati *et al.* 2010; Spinelli *et al.* 2011; Warcholinski and Gilewicz 2022) as well as other machining parameters, such as noise (Lemaster *et al.* 1985), increased energy consumption (Ratnasingam and Perkins 1998; Nati *et al.* 2014; Krilek *et al.* 2024), and vibration (Haddadi *et al.* 2008). Tool wear increases the cutting force, which leads to an increase in temperature, resulting in lower cutting stability. The increased temperature of the knife is also caused by the tension of the material and depends on the type of conditions and cutting mode (Kara and Li 2011). The temperature of the cutting tool, as one of the important factors affecting tool wear during wood processing, causes a change in its basic properties, such as hardness, toughness, and chemical stability. Mechanical, thermal, and chemical interactions between the cutting tool and wood are important factors in tool wear (Okai *et al.* 2005; Ramasamy and Ratnasingam 2010). Hardened steels, high-speed steels, stellites, sintered carbides, and polycrystalline diamond (PCD) are still successfully used for woodworking. Sintered carbides have good wear resistance and at the same time a lower price compared to PCD. Tools made of these materials can also resist wear due to their structure (Schindlerová and Šajdlerová 2017; Wu *et al.* 2023). Chipping knives are affected by several factors that enter the chipping process and have a negative effect on tool wear. For good chip quality, one of the most important parameters is the condition of the knife edge during chipping (Heidari *et al.* 2013). One of the possibilities of increasing wear resistance, surface hardness, and fatigue resistance of the material due to the formation of a hard layer is plasma nitriding (ion nitriding). It is a plasma-assisted thermochemical nitridation of steel (Joska *et al.* 2020; Dobrocky *et al.* 2022; Šramhauser *et al.* 2022). An effective method of reducing tool wear is its modification with a thin hard coating, produced by the physical vapor deposition (PVD) or chemical vapor deposition (CVD) methods. For a long time, coated tools have been successfully used for chip machining or metal forming (Souza *et al.* 2020; Mitterer *et al.* 2023; Brezinová *et al.* 2024). The coating on the tools enables, among other benefits, a reduction in the wear of the cutting edges, which should ensure an increase in their service life (Schalk *et al.* 2022). The main reason for coating tools is to increase resistance to abrasive wear. A further goal is to minimize the risk of adhesion and sticking of the processed material to the tool. This leads to the desired results in practice, which is higher productivity in the process and higher quality of products. Many authors, *e.g.*, Warcholinski and Gilewicz (2011), Cho *et al.* (2015), Rudak *et al.* (2015), and Kazlauskas *et al.* (2022), reported their application to wood-working tools, usage, and advantages.

Their use has been a common way of improving the cutting properties of tools for several years. A properly chosen coating significantly increases tool performance, resistance to abrasive and adhesive wear, and at the same time reduces the coefficient of friction. Coating concepts based on CrCN/CrN, TiN/AlTiN, TiN, and AlCrN have proven to be suitable in practice, which was confirmed by several authors (Czarniak *et al.* 2020; Kucharska *et al.* 2022; Nadolny *et al.* 2020). In the study by Jeyapandiarajan *et al.* (2021), the wear performance of the coated cubic boron nitride (cBN) over the uncoated inserts was evaluated. It was found that the AlCrN-coated cBN inserts can produce 10 to 12% drop in the cutting force, 15% reduction in the flank wear, and 10% reduction in the surface roughness. The results obtained in Lacki *et al.* (2020) show that the examined tool without coating, made of steel 1.2344, was intensively worn, which increases the risk associated with the continued use of the tool and indicates a low tool life. The use of AlCrN coating led to an increase in tool life. The results by Warcholinski *et al.* (2020) and Wang *et al.* (2022), show that the surface of the CrN/AlCrN coating can be smooth and dense without obvious defects, with high hardness, low roughness, and good bonding strength, thereby presenting excellent mechanical properties. The coating showed better tribological performance and a lower friction coefficient under low load than that under high load, and the wear types included adhesive wear and a small amount of oxidation wear.

The coating should form a natural barrier to prevent heat from entering the tool and thus reduce deformation and wear of its cutting parts (Ratajski *et al.* 2009; Krilek *et al.* 2023; Krilek *et al.* 2024). Coating of tools in secondary production, *e.g.*, milling cutters, saws, drills, knives for peeling, cutting veneers, or processing composite wood materials, *etc.*, is becoming a common practice and brings many advantages. The advantages of this modification for increasing the service life of the tool, as well as the quality of the final product, have been published in many works (Sheikh-Ahmed *et al.* 2003; Faga and Settineri 2006; Kowaluk *et al.* 2009; Ratajski *et al.* 2009; Csanády and Magoss 2013; Krilek *et al.* 2023; Krilek *et al.* 2024). However, for tools in primary wood processing (*e.g.*, splitting, chipping), this method of surface treatment is not so common (Kalinová *et al.* 2018; Warcholinski and Gilewicz 2022; Ťavodová *et al.* 2024). Compared to metals, wood does not have homogeneous structural properties (Čunderlík 2009). Its structure contains elements that, during its processing, act to accelerate the wear of the cutting parts of the tool. The wood has good machinability, but contains a small amount of H₂O, which causes corrosion on the cutting tool. It also contains minerals from the soil of varying hardness, dissolved in water. These, in turn, can damage the tool through abrasion or adhesion, or otherwise contaminate the wood and thus negatively affect the surface of the tool (Österås 2004; Okai *et al.* 2005; Čunderlík 2009; Iacoban *et al.* 2019). Wood can also contain various surface defects, which can cause blunting of the cutting tool. Therefore, materials with low toughness are not used (Latushkina *et al.* 2016; Nadolny *et al.* 2020; Warcholinski and Gilewicz 2022). Applications of surface treatments on tools for primary wood processing (chipping, splitting) remain more or less at the level of primary heat treatment, which is suitable and proven for alloyed tool steels. These tools then have the expected properties and, to a certain extent, are able to resist wear, deformation, abrasive or adhesive wear, in interaction with different types of processed wood. The development of the application of other surface treatments in this area is still not as fast as for woodworking in secondary production, and certainly not as fast as the trends in increasing the service life and cutting edge of tools for metal processing. The goal of this work is to enlarge knowledge in the applications of plasma nitriding and the AlCrN-based “CROSAL® Plus” PVD coating on X48CrMoV8-1-1 tool steel for application on chipping knives in wood-

chipping machines. The obtained results about tribological performance of selected surface treatments are discussed in correlation with their microstructural and tribological track fractographic characteristics.

EXPERIMENTAL

Materials

The experimental material was a tool steel X48CrMoV8-1-1, suitable for cold and hot work, intended for tools with good compressive strength and high abrasion resistance. The strength limit of the steel in the hardened and tempered state is $R_m = 1270$ to 2100 MPa. The achievable hardness is declared, according to the selected tempering temperature in the range of 40 ± 1.5 to 56 ± 0.4 HRC. In the present investigation, the material was hardened from a temperature $T_h = 1032$ °C and tempered at a temperature $T_t = 542$ °C. The hardness of the steel declared by the manufacturer is 57 ± 1 HRC. This represents approximately a hardness value of 727 HV. The chemical composition of the experimental material is listed in Table 1.

Table 1. Nominal Chemical Composition (wt%) of Steel X48CrMoV8-1-1

C	Si	Mn	Cr	Mo	P	S	V	Fe
0.45 to 0.5	0.70 to 0.90	0.35 to 0.45	7.30 to 7.80	1.30 to 1.50	max 0.020	max 0.005	1.30 to 1.50	Rest

Three surface conditions of X48CrMoV8-1-1 steel were investigated on real chipping knives:

- “Condition 1” – unmodified surface of the knife in the condition delivered by the manufacturer, *i.e.*, hardened and tempered (1032 °C/542 °C) and conventionally machined surface (Fig. 1a);
- “Condition 2” – plasma-nitrided surface of the knife after the plasma nitriding in a protective nitrogen atmosphere, with a regime of 480 °C/20 h, to a final hardness value of 1120 HV1. Nitriding took place in a RÜBIG Pulse Plasma Nitriding Furnace (PN DUO100/180; RÜBIG GmbH & Co KG, Wels, Austria), see Fig. 1b;
- “Condition 3” – PVD-coated surface of the knife after the deposition of AlCrN-based “CROSAL ® Plus” coating (Fig. 1c). The coating was deposited at a temperature of 400 °C reaching the manufacturer’s expected thicknesses of 2 to 5 µm.



Fig. 1. Experimental chipping knives: knife in “Condition 1” - unmodified (a), knife in “Condition 2” - plasma nitrided (b), knife in “Condition 3” – PVD-coated with CROSAL ® Plus (c)

From each experimental knife, the testing specimens were cut for conducting of individual laboratory investigations. The studied materials related to individual surface conditions were subjected to following material analyses and tests.

The nanoindentation measurements for determination of nanohardness and elastic moduli were performed using the nanoindenter Agilent G200 (Agilent Technologies, Inc., Chandler, AZ, USA). Nanohardness measurements were performed according to the ISO 14577–1 standard using a diamond Berkovich tip. A load-controlled indentation method was used. The maximal loads were 100 mN for “Condition 1” and “Condition 2”. Due to the thin PVD coating (“Condition 3”), the measurement of its nanohardness was taken at a very low load (25 mN) to avoid undesired penetration of the indenter through the PVD layer into the steel substrate.

Tribological tests were performed according to the ASTM G133 – 05 standard by using an automatic tribometer Bruker UMT 3 (Bruker Nano GmbH, Berlin, Germany) in translational dry sliding conditions, using ball on disc geometry, at ambient temperature and pressure. An SiC ceramic ball with 6 mm diameter was used as a tribological partner. All tests were conducted under 20 N normal load, 0.1 m/s sliding velocity and 5 mm track radius. The total sliding distance was 250 m. The coefficient of friction (COF) was calculated by taking the ratio of the tangential and normal forces, and it was reported *versus* the sliding distance. The volume removed was measured using a confocal microscope PLu neox 3D Optical Profiler (Sensofar, Barcelona, Spain), where a hundred layers along the depth of the track were recorded. The wear rate (W) was determined in terms of the volume loss (V) per distance (L) and applied load (F) according to the following Eq. 1:

$$W = \frac{V}{L \cdot F} \quad (1)$$

Tribological scratch tests were performed according to the ASTM C1624 – 22 standard by using the universal tribometer and scratch tester Bruker Mod. UMT 2M (Bruker-Nano Surfaces TMT Unit, Campbell, CA, USA) with Vickers diamond indenter and acoustic emission (AE) detector model AE-5. The scratch tests were performed within the load range from 1 to 30 N.

Microstructural and fractographic analyses of profile metallographic cross-sections and tribological scratching tracks were performed using light-optical microscope (LOM) Olympus GX71 (Olympus Corporation, Tokyo, Japan) and scanning electron microscope (SEM) Tescan Vega-3 LMU (Tescan Brno, s.r.o., Brno, Czech Republic) with an energy dispersive X-ray (EDX) spectrometer Bruker XFlashDetector 410 m (Bruker Nano GmbH, Berlin, Germany).

RESULTS AND DISCUSSION

Microstructure Characterization

The microstructure related to “Condition 1” (hardened and tempered without chemical-thermal surface treatment) was visualized using 15% HCl solution (Fig. 2). It is formed of tempered martensite (sorbite) with carbide precipitates in sorbitic blocks and along the boundaries of the blocks (Fig. 2).

The microstructure related to “Condition 2” (plasma-nitriding surface treatment) is shown in Fig. 3. It shows a nitrided solid layer. Underneath, there is a layer that was created by affecting the base material after the application of the nitrided layer.



Fig. 2. Microstructure of X48CrMoV8-1-1 tool steel in “Condition 1”, *i.e.*, hardened and tempered material state without chemical-thermal surface treatment

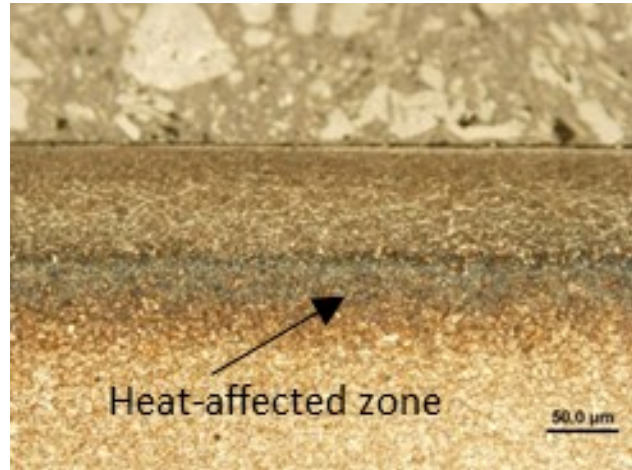


Fig. 3. Microstructure of X48CrMoV8-1-1 tool steel in “Condition 2”, *i.e.*, nitrided layer with heat-affected zone

The microstructure related to “Condition 3” (PVD-coated surface) is shown in Fig. 4. It shows a compact layer of AlCrN coating. Beneath, there is a slightly affected layer, which was created in the base material after the coating was applied. By comparison of Figs. 3 and 4 it can be stated that there were significant differences in thickness of heat-affected layers related to individual material states, *i.e.*, around 45 μm and 10 μm for Conditions 1 and 2, respectively. The observed differences are likely related to applied conditions of individual surface treatments differing in both the processing temperature and time.

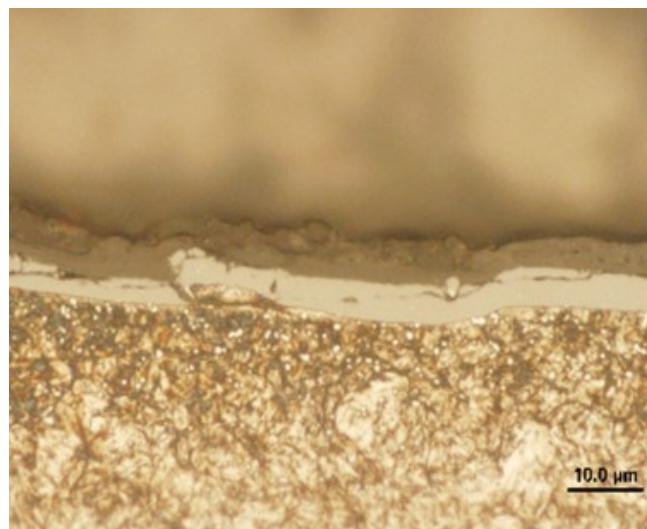


Fig. 4. Part of the PVD-coated layer with a slight indication of decohesion failure

Nano-indentation Measurements

Nano-indentation experiments were conducted for individual surface conditions of studied X48CrMoV8-1-1 tool steel to determine two criteria having, in general, crucial effects on the material wear resistance, namely the hardness and modulus of elasticity.

Table 2. The Results of Nano-indentation Measurements for Individual Material Conditions

Surface Treatment	Nanohardness (GPa)	Elasticity Modulus (GPa)
“Condition 1”	8.04 ± 0.6	213.8 ± 8.6
“Condition 2”	11.8 ± 2.3	232.8 ± 23.2
“Condition 3”	23.7 ± 1.6	270.3 ± 19.0

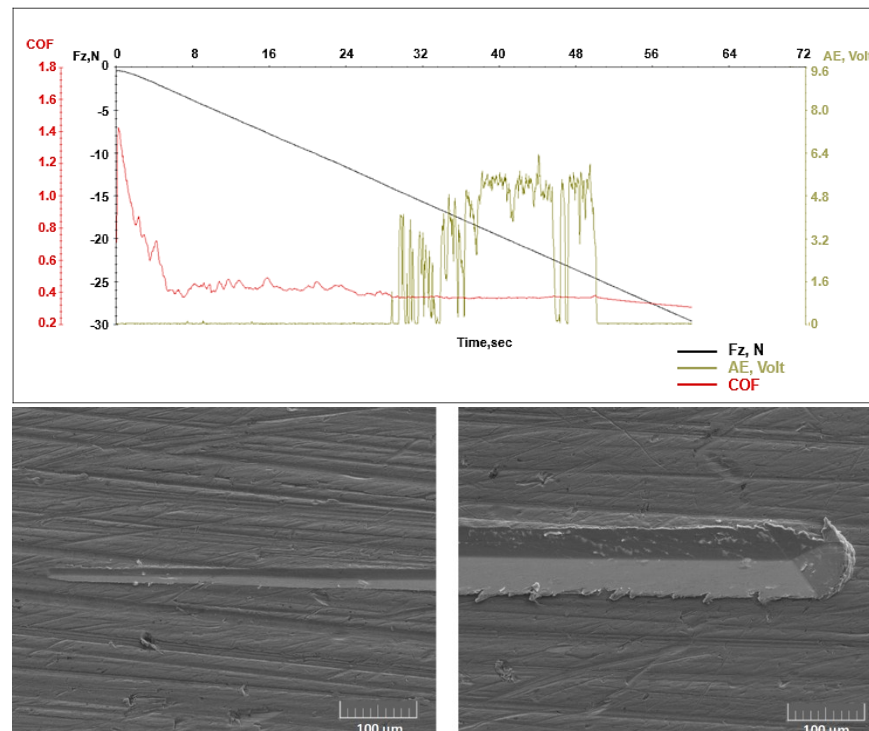
Tribological and Scratching Behavior

The results of tribological tests performed for individual surface conditions of studied X48CrMoV8-1-1 tool steel are summarized in Table 3.

Table 3. Tribological Tests Results for Individual Material Conditions

Surface Treatment	Coefficient of Friction COF (-)	Specific Wear Rate ($\text{mm}^3/\text{N.m}$)
“Condition 1”	0.51 ± 0.14	2.38×10^{-6}
“Condition 2”	0.34 ± 0.21	1.88×10^{-6}
“Condition 3”	0.35 ± 0.17	3.91×10^{-6}

By comparison of the obtained results in Tables 2 and 3, it can be stated that the wear resistance did not necessarily increase with increasing the nanohardness and modulus of elasticity. It can be assumed that the wear resistance of a coated material will strongly depend on adhesiveness of the surface layer. The bonding strength between the coating and the substrate can be estimated by tribological scratch tests. Figures 5 to 7 show the results of performed scratch tests in loading range from 1 to 30 N for individual surface treatment conditions of the investigated X48CrMoV8-1-1 tool steel.

**Fig. 5.** Scratch test results and corresponding surface morphology for “Condition 1”

The typical main transitions on the studied materials during the scratch tests are the following: the 1st stage – onset of plastic deformation, the 2nd stage – peak accompanied by change in the surface morphology of the scratch track, and 3rd stage – chipping observed at the edges of the track. The acoustic emission (AE) record for “Condition 1” in upper portion of Fig. 5 shows a sudden amplitude increase in the 28th second, indicating the first cracking in the substrate surface occurred at 14 N. The red curve representing the COF indicates onset of the smooth friction track with lowest COF. The SEM micrographs in the lower portion of Fig. 5 show that the surface for “Condition 1” was not very smooth, with a surface roughness value of 0.4 μm . The behavior of plasma-nitrided surface, *i.e.*, “Condition 2” is shown in Fig. 6.

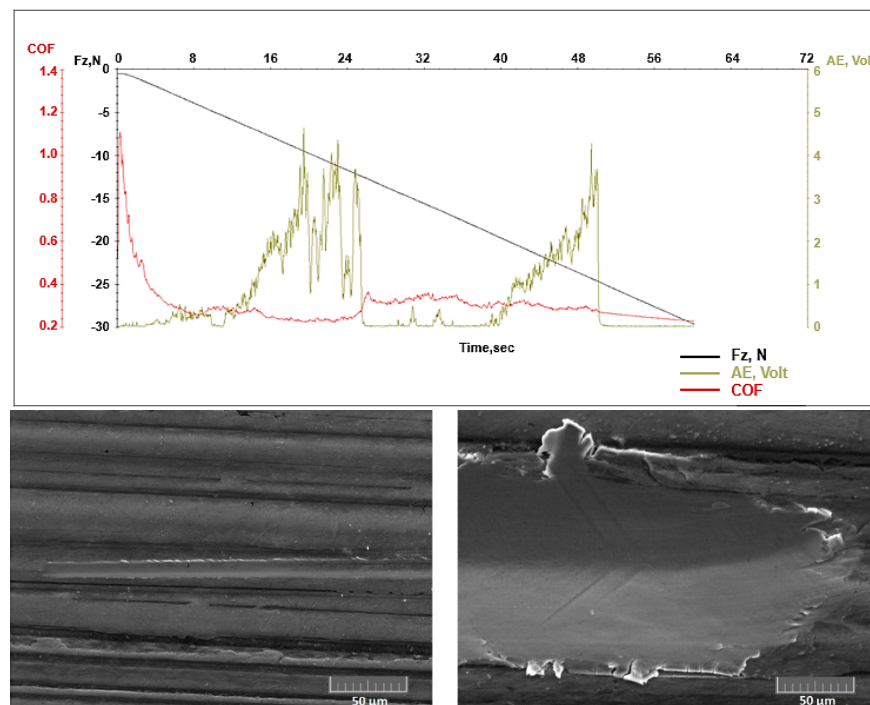


Fig. 6. Scratch test results and corresponding surface morphology for “Condition 2”

The scratch test results for “Condition 2” are visualized in Fig. 6. In the upper portion of Fig. 6, a strong influence of normal load on the scratching behavior can be seen. The main transitions on the plasma nitride substrate were the following: the 1st stage - onset of non-elastic deformation at 6 N load, the 2nd stage - pop-in observed by the decrease of COF to a minimum value of 0.25 with increasing AE signal to 4.5 mV, followed by the 3rd stage related to chipping observed at the edges of the track (see lower portions of Fig. 6). The scratch test results for “Condition 3” are visualized in Fig. 7

For “Condition 3”, the elastic-plastic deformation dominated in the initial stage (up to 3 N load). The plastic deformation and wear (chipping) of PVD layer were dominant processes in the next stage (Fig. 7). The COF for AlCrN PVD layer within the all load range of 1 to 30 N shows cyclic shape with the values oscillating between 0.25 to 0.5, which was probably caused by high surface roughness (see upper portion of Fig. 7). Despite the strong influence of the substrate observed on the SEM micrographs, the observed wear behavior gives rise to the assumption for suitable application of used surface treatments in

wood cutting tools. The observed behavior indicates that the PVD layer was not fully delaminated from the tool steel substrate (see lower portion of Fig. 7).

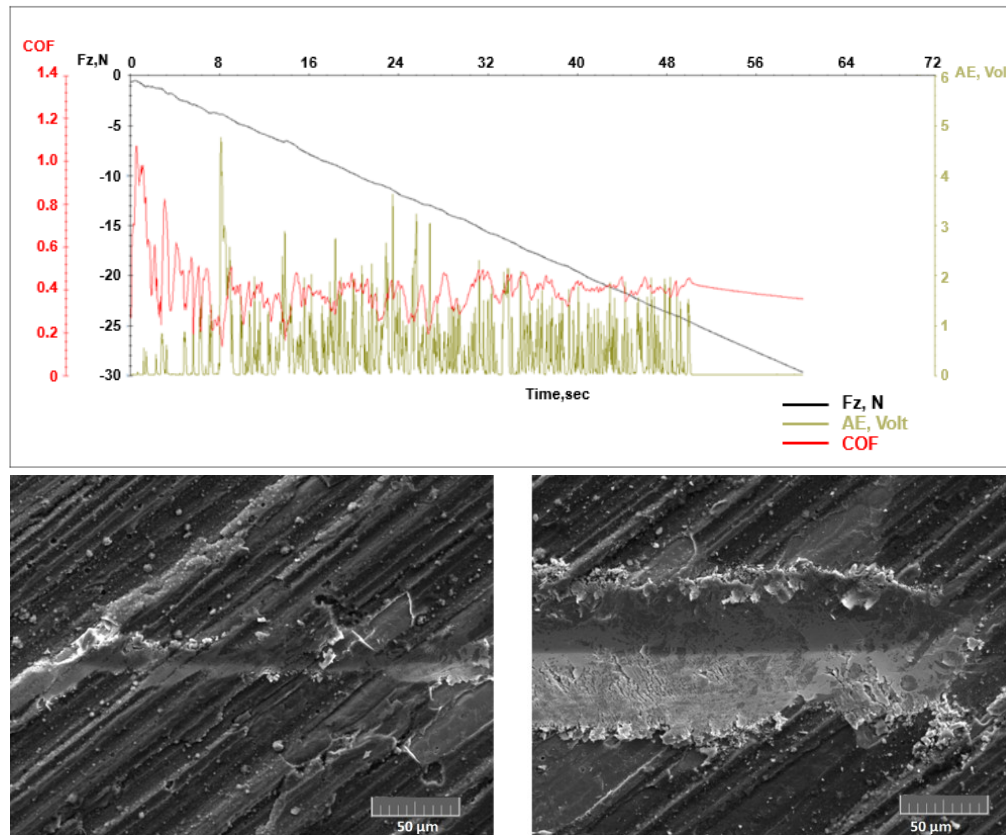


Fig. 7. Scratch test results and corresponding surface morphology for “Condition 3”

The aim of performed analyses and measurements was to characterize tribological (friction and wear) behavior of variously surface-treated chipping knives made of X48CrMoV8-1-1 tool steel and to indicate their suitability for use in wood chipping applications. It has been clearly shown that neither hardness nor elasticity modulus may always necessarily represent a governing criterion for satisfactory tribological performance, although the results by Warcholinski *et al.* (2020) and Wang *et al.* (2022), show that the surface of the CrN/AlCrN coating is has high hardness, low roughness, and good bonding strength, presenting excellent mechanical properties. According to the mentioned authors, the use of AlCrN coating led to an increase in tool life. In presented article, the adhesiveness between the surface layer and steel substrate was found to have a decisive effect on resulting wear resistance. This fact is also confirmed by the studies of Warcholinski *et al.* (2020) and Wang *et al.* (2022). A properly chosen coating significantly increases tool performance, resistance to abrasive and adhesive wear, and at the same time reduces the coefficient of friction. Coating concept based on AlCrN has proven to be suitable in practice, which was confirmed by several authors (Czarniak *et al.* 2020; Kucharska *et al.* 2022; Nadolny *et al.* 2020).

The authors' next research will be focused on conducting operational experiments of real wood chipping processes with the aim of searching suitable quantities enabling correlations with performed laboratory experiments.

CONCLUSIONS

This work focused on investigating the effect of surface treatments - plasma nitriding and physical vapor deposition (PVD) coating “CROSAL® Plus” (AlCrN) on the nano-indentation characteristics, tribological and scratching behavior of X48CrMoV8-1-1 tool steel for application on chipping knives in wood-chipping machines. The results of the laboratory tests and analyses are summarized in the following conclusions:

1. The results of nano-indentation measurements indicated that the highest nanohardness and modulus of elasticity were associated with the “CROSAL® Plus” PVD coating, namely 23.7 ± 1.6 GPa for nanohardness and 270.3 ± 19.0 GPa for elasticity modulus. However, the tribological performance of the PVD coated material was worse compared to the material subjected to plasma nitriding. The results showed similar values in coefficient of friction and worse value of specific wear rate, namely 3.91×10^{-6} mm³/N.m.
2. The plasma-nitrided surface condition of the studied tool steel exhibited medium nanohardness and modulus of elasticity compared to the original unmodified surface of the hardened and tempered tool steel and the PVD-coated material, namely 11.8 ± 2.3 GPa for nanohardness and 232.8 ± 23.2 GPa for elasticity modulus. However, it exhibited the lowest values of the coefficient of friction and specific wear rate, compared to other investigated material conditions, namely 0.34 ± 0.21 for coefficient of friction and 1.88×10^{-6} mm³/N.m for specific wear rate.
3. The scratch tests revealed the reasons for the best tribological performance of plasma-nitrided material surface among the studied material surface conditions. The higher thickness of plasma-nitrided layer and its better adhesiveness with the steel substrate assured better resistance against abrasive wear. Thus, the plasma-nitrided surface was more resistant against peeling compared to thin PVD coating with lower bonding strength with the steel matrix.

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