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The cutting properties and wear of the knives with DLC and W-DLC coatings, deposited by PVD methods, applied for wood and wood-based materials machining

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ABSTRACT

Purpose: Performance of DLC and W-DLC coated woodworking knives was investigated. The results of testing DLC and W-DLC coating properties as well as the results of life-time tests in the form of wear of HSS and HM knives with these coatings is presents.

Design/methodology/approach: DLC coating was deposited by MCVA method, and W-DLC coating was deposited by pulsed RMS. Tests of knives coated with DLC and W-DLC as uncoated ones was made by machining: MDF board, pinewood slats and floorboard - using a typical industrial milling machine.

Findings: DLC coating is significantly harder (33-40 GPa) than W-DLC coating (19 GPa). From Rockwell test it can be concluded that both coatings display high adhesion (HF1), whereas in the scratch methods, significantly lower adhesion of DLC coating can be observed (L_{C2} = 17-21 N) in comparison to W-DLC coating (L_{C2} = 54 N). Influence of the hardness and adhesion of coatings on wear resistance of coated tools is discussed.

Practical implications: Wear resistance of planer knives coated with DLC is by approx. 20%, and W-DLC by approx. 30% higher in comparison with uncoated knives during MDF milling. Wear of planer knives with W-DLC coating is approx. by 10%, and DLC by approx. 25% lower in comparison to uncoated HSS knives during pinewood milling. Lifetime of HM shape tools coated DLC and W-DLC is considerably higher (200-300 %) during floorboard milling.

Originality/value: The industrial tests of cutting wood and wood-based materials indicate that the carbon coatings deposited on the tool generally improve its performance and all wear indexes for the tools are lower than for uncoated. The DLC and W-DLC coatings show good antiwear properties required in industry application.

Keywords: Wear resistance; DLC and W-DLC voatings; Coated woodworking tools

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Currently, tools for working wood and wood-based materials are made of low alloy tool steel, high speed steel (HSS), sintered carbides (hardmetal - HM) and polycrystalline diamond (PCD). In the recent years, increase in the cutting properties of tools made of tool steel and high speed steel dedicated to solid wood working has been achieved owing to the use of hard coatings, in particular based on CrN and CrCN [1-6]. Few studies show that increase in the sintered carbides tools wear resistance was achieved using carbon based coatings, type ta-C [7] and TiC/a-C [8].

The ta-C coatings, depending on concentration of sp^3 bounds, demonstrate high hardness, from 40 GPa to nearly 100 GPa [9-12] and high wear resistance [9,12]. The tests presented in the study, of amorphous carbon coatings, specified as DLC, constitute a mixture of ta-C phase and graphitic C phase, and they are classified by many authors as DLC coatings [10,13,14].

Properties of X-DLC coatings, where DLC - Diamond-Like Carbon, and X - W, Ti, etc., mainly depend on relative concentration of carbide phase (XC) and amorphous carbide matrix DLC (a-C:H or a-C). Coatings with excess carbon in relation to stoichiometric composition demonstrate nanocomposite construction of aggregate composite structure, i.e. composed of nanocrystalline carbide phase scattered in amorphous matrix type a-C or a-C:H [15-22]. If the volume-based content of amorphous carbon phase is 15-20%, X-DLC coatings may demonstrate significantly higher hardness than stoichiometric nanocrystalline coatings, especially if nanocrystalline phase comprises titanium carbides [18,19]. With increase in amorphous carbon phase, hardness of X-DLC coatings decreases, but their ductility increases significantly. From the perspective of application of coatings on woodworking tools, favourable properties are present in W-DLC coatings, containing 40-60 % DLC phase due to high hardness (over 20 GPa) and at the same time with a high fracture resistance [20,23]. Results of tests of high speed tools coated with W-C:H [24] demonstrate the potential possibility of using such coatings.

For working wood and wood-based materials, e.g. MDF (Medium Density Fibreboard), typically sintered carbide tools are used. Recently, satisfying results while tooling MDF have been achieved using sintered carbide tools coated with CrAlN [25]. Nevertheless, sintered carbides tools are significantly more expensive than high speed tools and are often subject to damage (chipping, fractures), which reduce or eliminate their re-use after regrinding.

The purpose of this study was to assess the possibilities of using high speed steel (type HS6-5-2) planer knives and sintered carbides (HM) shape knives with DLC and W-DLC coatings for working laminated MDF boards, wood and wood-based materials.

2. Experimental procedure

The tested coatings were deposited on three kinds of tools (Table 1):

- TEST 1 - planer knives, dia. 40 × 30 × 3 mm, made of high speed steel (HS6-5-2, hardness 9.8 ±0.2 GPa, $R_a < 0.06$ mm),
- TEST 2 - planer knives, dia. 100 × 30 × 3 mm, made of high speed steel (HS6-5-2, hardness 9.8 ±0.2 GPa, $R_a < 0.06$ mm),
- TEST 3 - shape tools (two types to forming tongue-and-groove joint in floor boards), universal sintered carbides (HM) with increased hardness and strength (KCR 08 type, hardness 22 ±0.5 GPa, $R_a < 0.03$ mm).

Prior to deposition, knives have been ultrasonically cleaned in organic solvents and alkaline detergents. The final operation was cleaning in organic solvent vapour and drying with compressed nitrogen.

DLC coating was deposited in a C55CT technological installation produced by INOVAP Dresden. The vacuum chamber possesses three arc sources (targets of 72 mm in diameter and thickness of 10 mm), two with graphite targets with the purity of 99.99% and one with chromium target with the purity of 99.9%. The modified cathodic vacuum arc method (MCVA) [9,26] was used, which consists in applying on the direct current of 50 A a pulsed current of 1400-1600 A. The frequency of the pulse repetition was 100 Hz, and its duration was ca. 0.3 ms. The technique used results in a substantial increase of the plasma ionization degree and may have an influence on an improved adhesion of carbon coatings with a relatively low deposition temperature. Once the substrates were placed in the chamber and the pressure of residual gases reached ca. 10^{-4} Pa, cleaning was applied with chromium ions in an argon atmosphere.

On the tools in the TEST 1 next thin chromium under-layer (0.3 μm) was deposited to improve the adhesion of DLC coating. In the next step DLC coating was deposited to the thickness of about 1.2 μm, called DLC-1. On the tools in the TEST 2 and TEST 3 next Cr/CrN/Cr under-layer (1.2 μm) was deposited to improve the adhesion of DLC coating. In the next step DLC coating was deposited to the thickness of about 0.8 μm, called DLC-2.

W-DLC coating has been deposited by pulsed reactive magnetron sputtering in coating system described earlier [27] on the all tools in the TESTS 1-3. The vacuum chamber possesses two sources operating in magnetron or arc mode and equipped with chromium (99.8%) and tungsten (99.99%) targets of 100 mm in diameter. The vacuum chamber has been pumped down to the ultimate pressure of 2×10^{-3} Pa. Substrates were heated using a radiation heater up to the temperature of approximately 200°C. To improve adhesion and crack resistance of W-DLC coatings, Cr under-layer followed by Cr/W transition interlayer was deposited. Chromium was deposited by a combination of vacuum arc evaporation and pulsed magnetron sputtering techniques, to achieve Cr interlayer with high adhesion to steel substrate [28]. In the next step acetylene flow rate was gradually increased up to required value and deposition of W-DLC coating was continued to the thickness of about 3 μm.

Chemical composition of coatings was checked by Energy Dispersive X-ray Spectroscopy (EDS - INCA x-ray microanalysis). Their microstructure was examined by Scanning Electron Microscopy (JEOL 5500 LV) and also by High Resolution Transmission Electron Microscopy (HR-TEM - TECNAI G^2 operating at 300 kV). Hardness and elastic modulus were evaluated by nanoindentation technique using Fischerscope 2000. A Berkovich diamond tip was used at a maximum indentation depth of 100-200 nm. Adhesion and crack resistance of the coatings were investigated by scratch method with Revetest® CSM (normal load increase rate 100 N/min, sliding speed 10mm/min) and Rockwell C (HRC) test directly on HSS and HM coated knives.

In the TEST 1 (Table 1) planer knives with DLC and W-DLC coating and for comparison without coating (HSS) were tested for machining the laminated MDF board 16 mm in thickness (forms about dimensions 250 × 2070 mm) using typical industrial bottom milling machine. The constant feed speed and feeding was realized by the mechanical device. Knives wear measurements were performed after each 100 m of milling. Knives were dismantled from the cutterhead and washed in organic solvents and alkaline solutions.

In the TEST 2 (Table 1) planer knives with coatings and for comparison without coating (HSS) were tested for machining the lamella (solid pinewood and glued, with dimensions of 70 × 19 mm), using typical industrial bottom milling machine. No proper surface finish the processed material they attested to the considerable wear of tool and stopped operational tests. Knives wear measurements were performed after milling. Knives were dismantled from the cutterhead and washed in organic solvents and alkaline solutions. Wear assessment was performed by geometric measurements and observation of the cutting edge of the knife by profilometer and optical microscope with software for 3D analysis, respectively. Wear area of the cutting edge were determined from profiles recorded with profilometer along the cutting edge [5].

In the TEST 3 (Table 1) shape knives with coatings and for comparison without coating (HM) were tested for machining the floorboard (plywood - oak or beech, with dimensions 15 × 126 × 1000 mm) using industrial milling machine. Cutterheads diameter 240 mm and 220 mm, with 6 knives to shape tongue and groove floorboard joint. Floorboards are subject to periodic review (after every 150 m^2) of the quality of their performance. Improper fitting of the tongue-and-groove floorboard joint or the presence of burns the material and no proper surface finish (cracks, breaks and defects of the processed material) they attested to the considerable wear of tool and stopped operational tests.

3. Results and discussion

3.1. Characterization of coatings

The architecture and microstructure of W-DLC and DLC coatings were presented in Fig. 1. W-DLC coating (Fig. 1 a, Fig. 2) with overall thickness of about 2.8 μm consist of a chromium adhesive sublayer with total thickness of 0.6 μm followed by W/W-DLC interlayer (bright layer) and W-DLC layer with glass-like structure. Fig. 2 illustrates the nanocomposite structure of the W-DLC coating consisting of nanocrystalline tungsten carbide precipitates (in white circle) with sizes below 3 nm dispersed in the amorphous DLC matrix of a-C:H type.

DLC coatings (DLC-1 and DLC-2 type) were of the total thickness of app. 1.5 μm and 1.9 μm (Fig. 1 b,c). In order to improve DLC coatings adhesion, approx. 0.3 μm thick, Cr (DLC-1 - Fig. 1b) and approx. 1.2 μm Cr/CrN/Cr (DLC-2 - Fig. 1c) sublayer was used. DLC coatings demonstrates amorphous, glassy and dense structure, without fractures and delaminations. Droplets phase on the coating surface is present (Fig. 1 a,b), typical of unfiltered arc method [9,26].

The nanocomposite structure of W-DLC coating is due to the fact that the deposition of coatings in the presence of carbon-containing reactive gas (for example acetylene) is a hybrid process, i.e. exhibiting the characteristics of both the methods of physical vapour deposition (PVD) and chemical vapour deposition (CVD). As a result, the coating growth is due to the sputtering of tungsten and reaction products (carbide and hydrogenated carbon) occurring on the target, and also as a result of decomposition of acetylene and deposition of hydrogenated carbon, mainly in the form of CH radicals, directly from the magnetron discharge plasma. Chemical composition and mechanical properties of coatings are presented in Table 2. As it could be expected, DLC coatings contained mainly carbon, app. 92-93 at.% (Table 2) as they were created by vacuum arc of graphite target. They contained app. 7-8 at.% additives coming from desorbed oxygen and argon from the technological vacuum chamber. Analysis of the chemical composition (Table 2) and previous investigations [20] show that W-DLC nanocomposite coating is made of nanocrystalline tungsten carbide (WC_{1-x} type) precipitates in an amount of about 40% and the amorphous a-C:H matrix in an amount of about 60%.

Table 1.
Operational tests parameters

Parameters	Test denotation		
	TEST 1	TEST 2	TEST 3
Tool	Planer knife	Planer knife	Shape knives
Sharpness angle	50°	41°	55°
Tool material	HS6-5-2 steel	HS6-5-2 steel	Sintered carbides HM
Tool hardness	9.8 ±0.2 GPa	9.8 ±0.2 GPa	22 ±0.5 GPa
Tool length	40 mm	100 mm	25 mm
Tool thick	3 mm	3 mm	2 mm
Cutterhead diameter	120 mm	260 mm	220 and 240 mm
Number of knives in cutterhead	3	8	6
Cutting speed	36 m/s	50 m/s	78 m/s
Cutting depth	1 mm	1 mm	~ 0-8 mm
Feed speed	6.3 m/min	70 m/min	16 m/min
Processed material	MDF laminated board	Pinewood slats	Floorboard (plywood - oak or beech)
Moisture	6%	8%	6-8%

Table 2.
Chemical composition and mechanical properties of W-DLC and DLC coatings

Coating denotation	Chemical composition (at. %)			Total thickness (µm)	Hardness (GPa)	Young modulus (GPa)	R_a (µm)	R_z (µm)
	W	C	O+Ar					
W-DLC	23.6 ± 1	72.9 ± 1	3.5 ± 1	2.8 ± 0.1	18.6 ± 1	178 ± 5	0.03	0.43
DLC-1	-	93 ± 3	7.0 ± 3	1.5 ± 0.1	40.8 ± 3	331 ± 10	0.16	1.98
DLC-2	-	92 ± 3	8.0 ± 3	1.9 ± 0.1	33.4 ± 3	284 ± 10	0.19	2.07

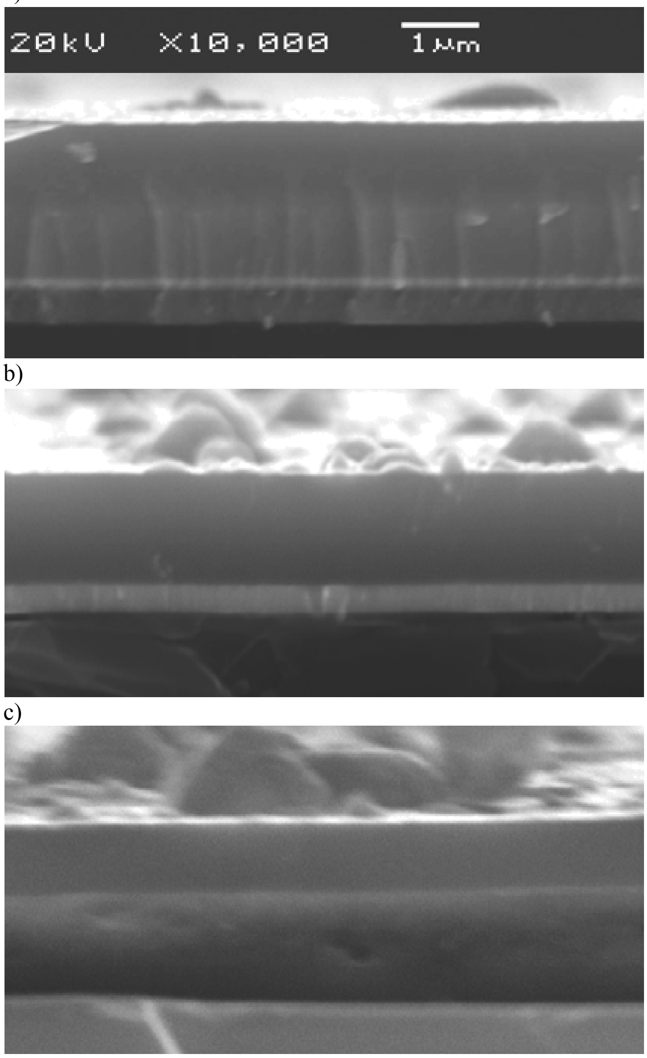
a)
b)
c)


Fig. 1. SEM images of W-DLC (a) and DLC: DLC-1 (b), DLC-2 (c) coating fracture

DLC coatings shows significantly higher hardness (33.4 and 40.8 GPa - Table 2) than W-DLC coatings (18.6 GPa). DLC coatings, due to the method of depositing (MCVA) and the resulting presence of micro-droplets demonstrates significantly higher roughness (R_a = 0.16-0.19 µm) than W-DLC coating (R_a = 0.03 µm).

In Rockwell C tests, both of the coatings display similar good adhesion and resistance to fracture (HF1, Fig. 3), whereas radial fractures along the imprints on W-DLC (Fig. 3a) are more distinctive and slightly longer than for DLC coatings (Fig. 3 b,c). They are particularly visible on enlarged fragments of the imprints (Fig. 3 b,c).

However, in the scratch method, W-DLC coating (Fig. 4a) demonstrates significantly higher values of critical loads than DLC coating (Fig. 4 b,c,d). The first fractures of DLC coatings (cohesion damages) occur at critical load L_{C1} equal to 16-21 N (Fig. 4 b,c,d) and 21 N for W-DLC coatings (Fig. 4a). A significant difference occurs for critical load L_{C2}, respectively 17-38 N and 54 N, for which the first adhesive damages (delamination) of the coating are observed (Fig. 4).

Differentiation of results of adhesion tests may arise from significantly higher hardness of DLC coating in relation to W-DLC coating (Table 1), and at the same time their higher brittleness, which leads to proneness to fractures of DLC coating in scratch method (Fig. 4). A significant difference in the total thickness of coatings, especially the thickness of used Cr sublayer, may have influence on significantly higher adhesion of W-DLC coatings. Using Cr/CrN/Cr sublayer significantly improves the adhesion of the DLC coatings (Fig. 4 c,d) to the high-speed steel and sintered carbides blades.

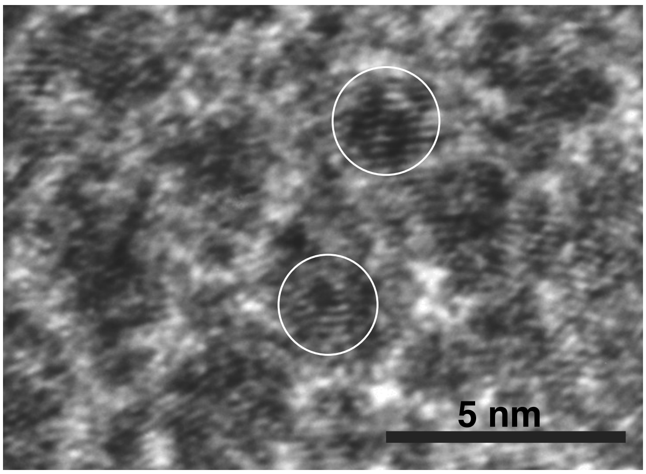


Fig. 2. HR-TEM image of the nanocomposite structure of W-DLC coating

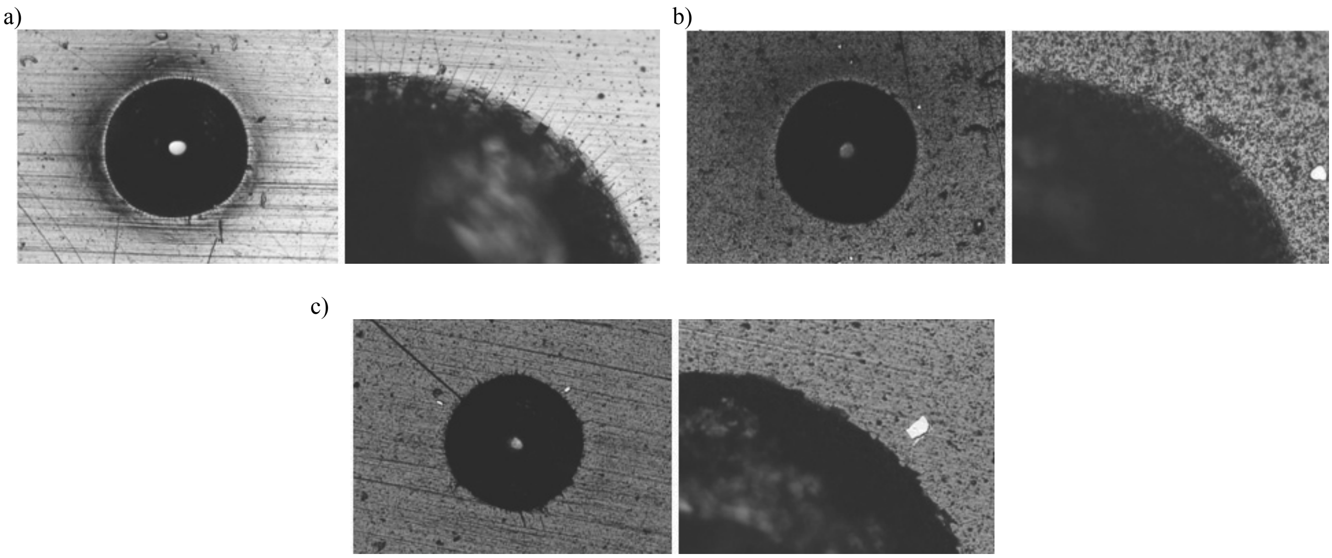


Fig. 3. Characteristics of the adhesion of W-DLC and DLC coatings that were deposited on an HS6-5-2 steel substrates, determined in Rockwell C tests: a) W-DLC, b) DLC-1, c) DLC-2

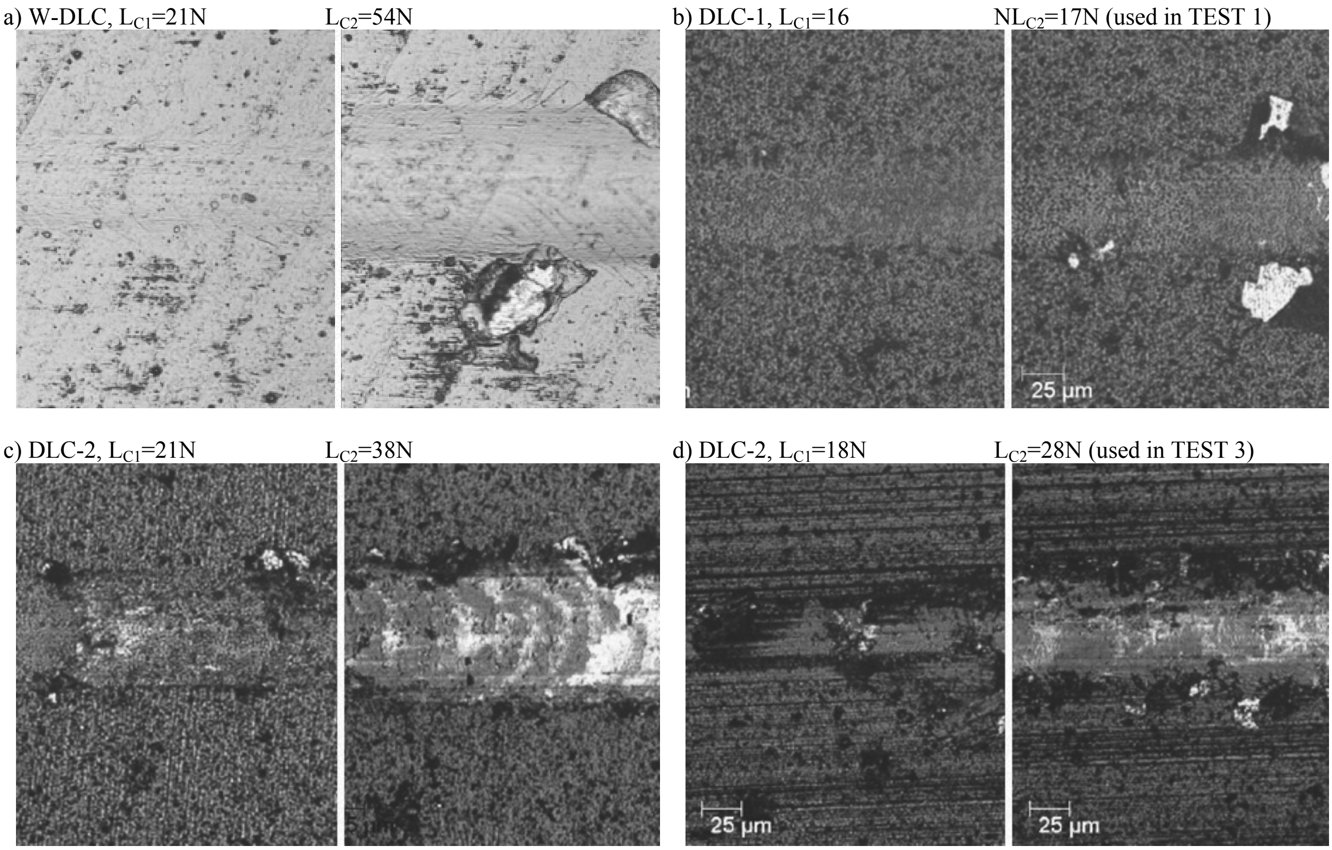


Fig. 4. Test results of adhesion of W-DLC used in operational TEST 1-3 (a) and DLC: DLC-1 used in operational TEST 1 (b), DLC-2 used in TEST 2 (c), DLC-2 used in TEST 3 (d) coatings determined by the scratch method

3.2. Cutting properties of the HSS and HM knives

- Operational TEST 1

Dependency of the average wear area of uncoated HSS planer knives and knives coated with W-DLC and DLC (DLC-1) on the cutting length is presented in Fig. 5.

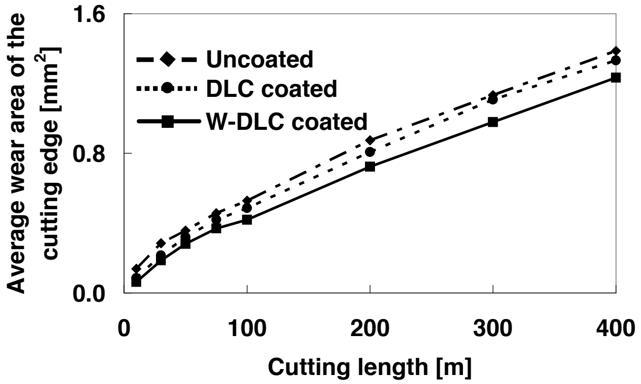


Fig. 5. Dependency of HSS planer knives wear area S of the cutting edge on the cutting length

Analysis of dependencies (Fig. 5) shows that life-time of planer knives with DLC coating is app. by 20%, and W-DLC coating by app. 30% higher in comparison to uncoated knives (HS6-5-2). The form of wear of rake face and cutting edge of the planer knives uncoated and coated with DLC (DLC-1) and W-DLC after operational wear testing (cutting length 400 m) are presented in Fig. 6. On the rake face of uncoated planer knife (Fig. 6a) typical signs of wear can be observed, in the form of wide wear area caused mainly by abrasive wear. This can be distinctly seen on the wear profile of this surface presented in the top right corner of Fig. 6a and on 3D image of cutting edge (Fig. 6b). The nature of wear of the rake face of the knife with W-DLC coating (Fig. 6c) is similar to the uncoated knife (Fig. 6a), whereas the width of wear area of this surface is significantly smaller (Fig. 5). This is also visible on the wear profile of rake face presented in Fig. 6c and on 3D image of the cutting edge presented on Fig. 6d. This results mainly from higher hardness of W-DLC coating (18.6 GPa) in comparison to high speed steel HS6-5-2 (9.8 GPa) and as a result its higher resistance to abrasive wear. On the rake face, no chipping failure of W-DLC coating can be observed, which results from its high adhesion (Fig. 4). Rake face wear of the knife with DLC coating is of a different nature (Fig. 6e). Its main form of wear are chipping failure of the coating in the area close of cutting edge caused probably by its too low adhesion (Fig. 4). Also significant is high hardness of DLC coating (app. 40 GPa) and as a result its brittleness. Due to high hardness of DLC coating, practically no abrasive wear of rake face can be observed, which is also confirmed by its profile shown in Fig. 6e as well as 3D imaged of cutting edge (Fig. 6f). The nature of work of planer knife, in particular while working MDF board, causes its high mechanical and heat load [5]. Consequently elastic and plastic deformations occur of the knife material (high speed steel) which in the case of knife with a hard coating may cause its fractures and as a result chipping failure in particular if the coating adhesion is low. This effect is aggregated by chips flowing along the rake face, which while catching the coating edges in non-ductile sites causes that its fragments are torn, the more intensively, the lower coating adhesion. From the Rockwell test (Fig. 3) it can be concluded that adhesion of DLC coating is comparable to adhesion of W-DLC coating, and from the scratch method (Fig. 4) it can be seen that a significantly higher is the adhesion of W-DLC coating. While analysing the nature of stresses and deformations affecting the coating during Rockwell and scratch method it seems that during the scratch method is appears that it is closer to real stresses and deformations present in particular on the rake face of the coated planer knife edge. As a result, despite significantly higher hardness and resistance to abrasive wear of DLC in comparison to W-DLC coating, lower adhesion of DLC, as it can be concluded from the scratch method, is probably one of the main reasons for lower life-time of planer knives coated with DLC in comparison to W-DLC coating. Taking into consideration high temperature of the cutting edge in particular while working MDF board, and the aforesaid nature of wear of knives with W-DLC coating, it seems that W-DLC coating, apart from abrasive wear may be subject to gradual wear by graphitization and oxidation of amorphous carbon matrix (a-C:H) and oxidation of isolations of tungsten carbides (WC) [27].

The result is the creation in the contact zone of the coated knife with worked material, graphite related substances and tungsten oxides demonstrating low shear resistance [27] and meeting the role of solid lubricant. This results in reduction of abrasive wear of rake face, reduction of edge temperature and as a result limiting the wear of cutting edge. In the case of DLC coating, whose properties are similar to ta-C coating, demonstrating high resistance to graphitization even at 600-700 C [10,29], the aforesaid mechanism is probably non-existent. This may also be a reason of the observed lower life-time of planer knives coated with DLC in comparison to W-DLC.

- Operational TEST 2

Average cutting edge wear area (S) of uncoated HSS planer knives and knives coated with W-DLC and DLC (DLC-2) on miling distance 1000 m is presented in Fig. 7. Wear of planer knives, characterized by wear area S, with W-DLC coating is app. by 10%, and DLC coating by app. 25% lower in comparison to uncoated HS6-5-2 knives. The form of wear of rake face and cutting edge of the planer knives uncoated and coated with W-DLC and DLC (DLC-2) and after operational wear testing are presented in Fig. 8.

- Operational TEST 3

Lifetime of DLC (DLC-2) and W-DLC coated and uncoated HM knives is presented in Fig. 9. Forms of wearing the uncoatedand coated with W-DLC and DLC (DLC-2) HM blades (knife forming groove and forming tongue)) after operational tests in the Figs. 10 and 11 were shown. The blades of HM knives with W-DLC coating were shown after ca. 8500 m cutting distance (Fig.10a, Fig. 11a), with DLC-2 coating after 15000 m cutting distance (Fig. 10b, Fig. 11b) and uncoated HM after ca. 4500 m cutting distance (Fig. 10c, Fig. 11c).

From analysis of images of the machining edge of uncoated HM knives and W-DLC and DLC-2 coated it results that the wear had frictional character. They were also found in areas of the tool the excessive loaded of wide removing the coating from the rake face (Fig. 10 a,b – zone 2 and Fig. 11 a,b - zone 1) but narrower than that of uncoated tools ((Fig. 10 c - zone 2 and Fig. 11 c - zone 1). Operational testing are pointing, that applying carbon coatings (particularly multilayer DLC-2) on HM shape knives to cutting of containing glue wood-like materials (plywood) he influences on lower adherence cutting products and a significant increase in tool lifetime. Using ceramic tools with hard coatings could increase the permanence at processing of wood-like materials [30].

a) b)

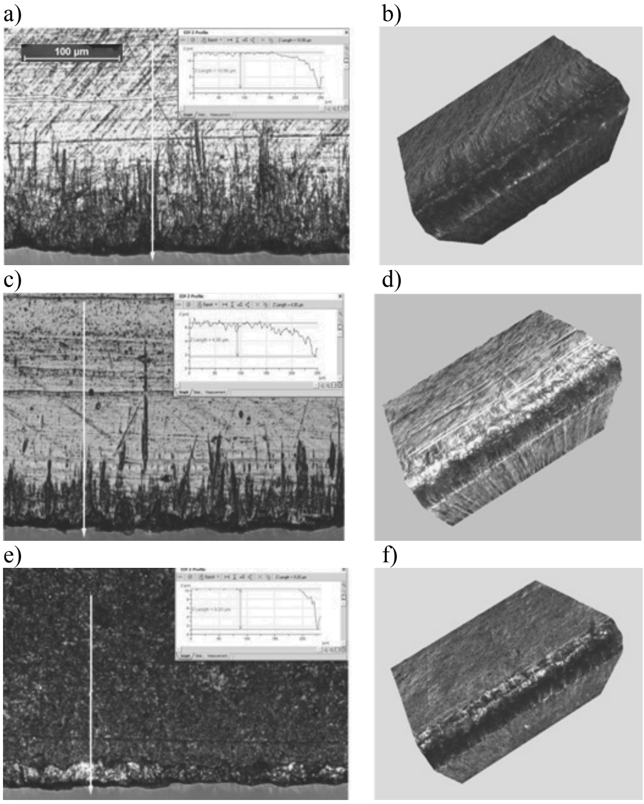


Fig. 6. Images and profiles of rake face as well as 3D image of uncoated planer knife (a and b) as well as respectively coated with W-DLC (c and d) and coated with DLC (e and f) after operational wear testing (mag. ×20)

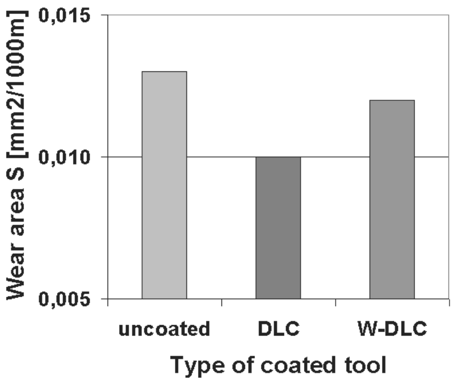


Fig. 7. Average cutting edge wear area S (on miling distance 1000 m) for uncoated and W-DLC and DLC-2 coated tools

a) Rake face, mag. ×50 b) Cutting edge 3D image, mag. x10

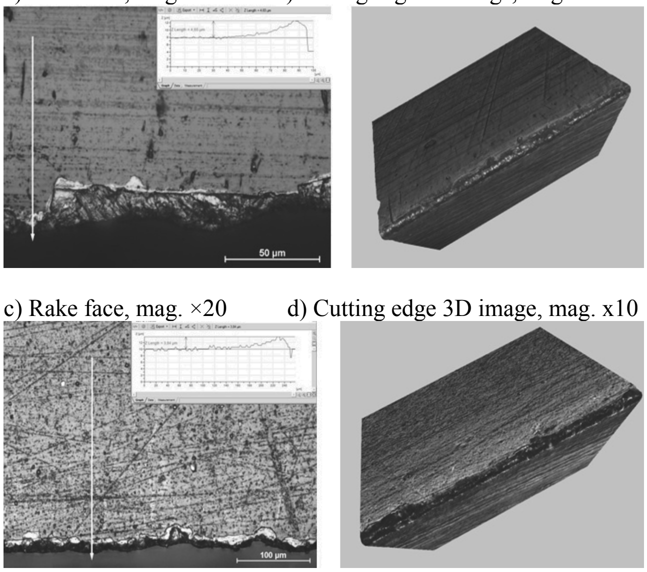


Fig. 8. Images and profiles of rake face and 3D cutting edge images of HSS planer knives coated with W-DLC (a,b) and DLC (DLC-2) coatings (c,d) after operational wear testing

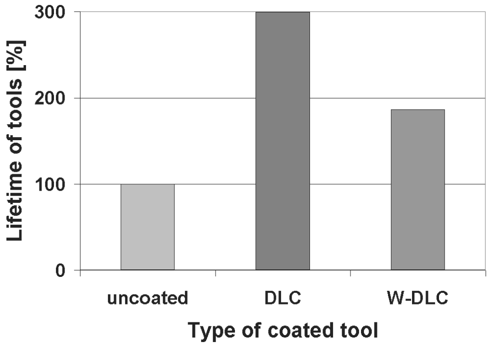


Fig. 9. Lifetime of DLC (DLC-2) and W-DLC coated and uncoated HM shape knives

4. Conclusions

DLC coating was deposited by modified vacuum arc method, and W-DLC coating was deposited by pulsed reactive magnetron sputtering. DLC coating demonstrates significantly higher hardness (33.4 and 40.8 GPa) than W-DLC coating (18.6 GPa). From Rockwell C test it can be concluded that both coatings display high adhesion (HF1-HF2), but in testing using the scratch method a significantly lower adhesion of DLC (L_{C2} = 17-21 N) can be seen in comparison to W-DLC (L_{C2} = 54 N).

Tests of HSS planer knives with DLC and W-DLC coatings and uncoated knives showed that life-time of DLC coated knives is app. by 20%, and W-DLC by app. 30% higher in comparison to uncoated knives. The reason for relatively low increase in the life-time of knives coated with DLC is probably too low adhesion of the coating whereas in the case of W-DLC coating, the reason is too low hardness and abrasive wear nature. Despite a significantly higher hardness and resistance to abrasive wear, DLC coatings in comparison to W-DLC coating, lower adhesion of DLC, as it results from the scratch method, is probably one of the main reasons of lower life-time of knives coated with DLC in comparison to the ones coated with W-DLC. It should be concluded that increasing the adhesion of DLC coatings for high speed steel, which is currently the subject of authors' studies, will allow increasing the life-time of knives with such a coating, to the level allowing its commercial application for woodworking and wood-based materials (MDF).

Use of W-DLC and DLC coatings may influence the reduction of wear of high speed steel knives and it indicates the possibility of using them for working MDF board and replacing sintered carbide knives used so far. Wear mechanism of coated tools in dry wood machining is mainly abrasive.

Lifetime of HM tools coated with DLC and W-DLC is considerably higher (200-300%). Wear of HM coated tools is considerably lower. The industrial tests of cutting floorboard (plywood) indicate that the coating deposited on the tool generally improve its performance. All wear indexes for the tool with the coating are lower than for tool without the coating.

The purpose of the study was to evaluate the possibility to use knives made of high speed steel HS6-5-2 and hardmetal (HM) coated with DLC and W-DLC for working wood and wood-based materials. The DLC and W-DLC coatings show very good antiwear properties required in industry application.

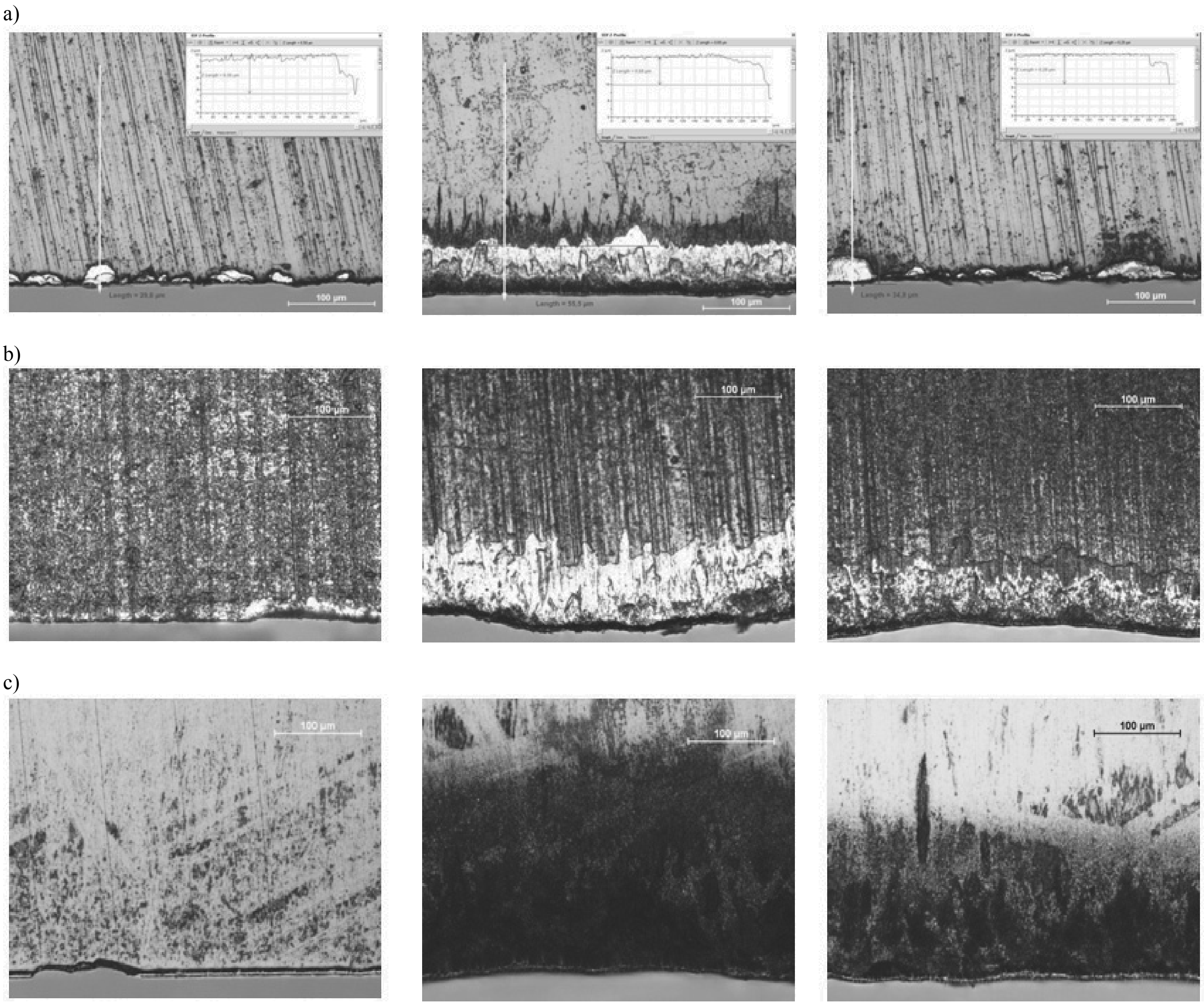


Fig. 10. Images of rake face of HM blades (knife forming groove) coated with W-DLC (a) and DLC-2 (b) coatings and uncoated (c) after operational wear testing

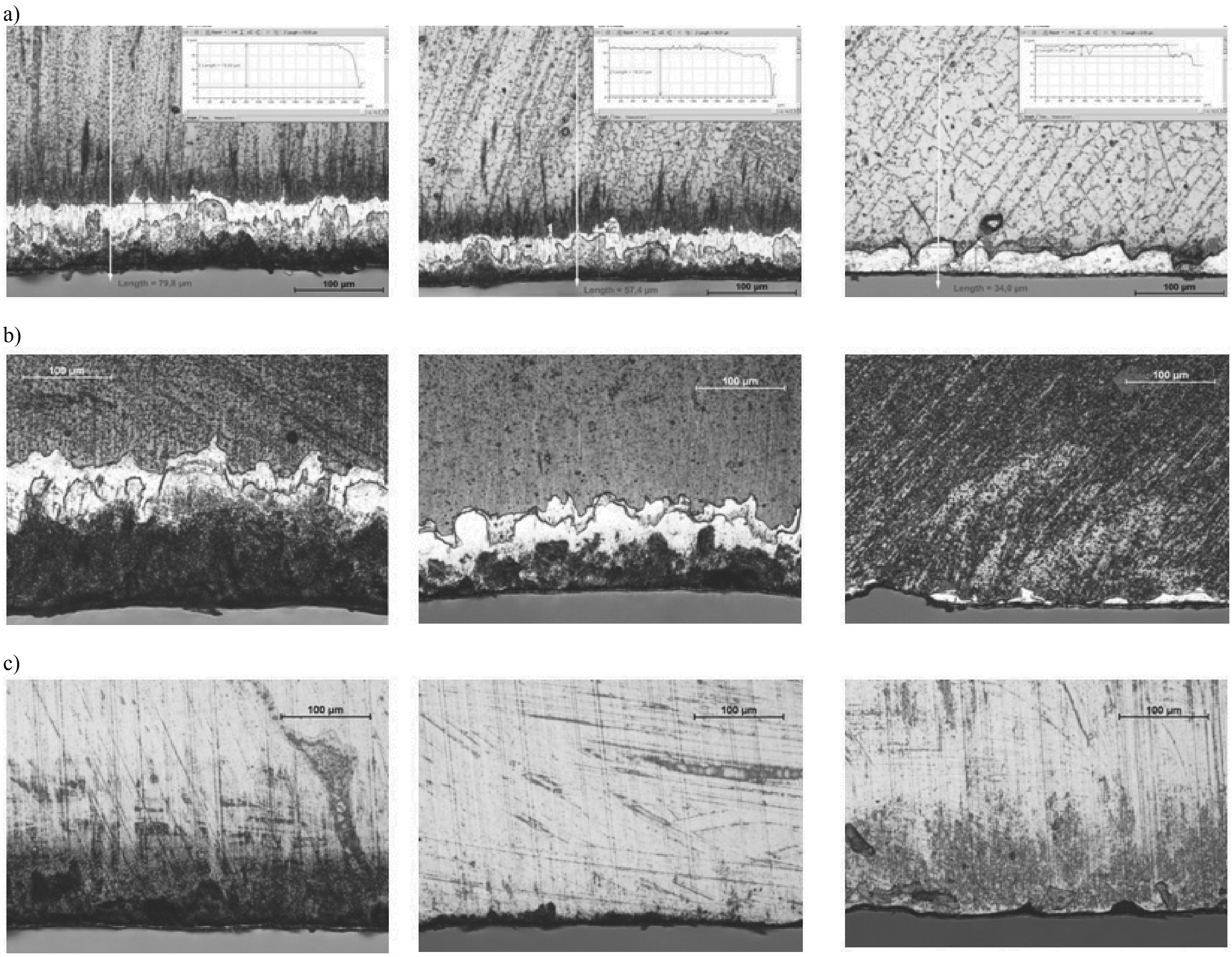


Fig. 11. Images of rake face of HM blades (knife forming tongue) coated with W-DLC (a) and DLC-2 (b) coatings and uncoated (c) after operational wear testing

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