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The influence of the MCVA deposition parameters on the structure and tribological properties of DLC coatings on woodworking HSS tool substrates

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ABSTRACT

Purpose: The purpose of the present study was the influence of deposition parameters of diamond-like-carbon coatings (DLC), with the modified cathodic vacuum arc (MCVA) method deposited on tool substrates (high-speed steel HS6-5-2) for woodworking, on their structure and tribological properties.

Design/methodology/approach: DLC coating was deposited by MCVA method. Structure, adhesion, hardness, internal stresses and friction wear resistance of DLC coatings were tested. Tests of knives coated with DLC and uncoated ones was made by machining medium density fibreboard (MDF) using a industrial milling machine.

Findings: The hardness of DLC coatings was 22.7-57.1 GPa. The Raman spectrum of DLC coatings was analysed The high hardness and internal stresses of DLC coating is related to the amount of sp^3 bonds. DLC coatings display high adhesion: critical load in the scratch method (L_{C2} = 22-40 N), from Rockwell test (HF1). The influence of the structure, hardness and adhesion of coatings on wear resistance of coated tools is discussed.

Practical implications: The wide range of tribological properties of DLC coatings that are deposited with different parameters may indicate the possibility of their application for tools for wood-like materials in order to increase their durability.

Originality/value: Depending of the deposition parameters applied, it is possible to obtain DLC coatings in a wide range of hardness (22.7-57.1 GPa) and adhesion (L_{C2} = 22-40 N). The industrial tests of cutting wood-based materials indicate that the DLC coatings with different properties improve HSS tool performance. The DLC coatings show antiwear properties required in industry application. The DLC coatings might be apply on high-speed steel planer knives for woodworking industry.

Keywords: DLC coatings; Modified cathodic vacuum Arc; Coated woodworking tools

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PROPERTIES

1. Introduction

Properties of hydrogen free DLC coatings produced by PVD methods depend on the deposition parameters, mainly on the ion energy that can be influenced within wide limits by changing the substrate bias voltage and argon pressure [1-6]. The use of a metallic transition layer may cause a decrease of tension in the substrate - DLC coating system and improve the adhesion [3, 7-10]. DLC coatings, depending on the concentration of sp^3 bonds may have a high hardness, above 50 GPa [3,4,10-12], and high resistance to frictional wear [4,9,10,12,13,14]. They exhibit chemical inertness also giving high corrosion resistance in the aqueous environment [15,16]. They are thermally stable at high temperatures, often above 600°C [1,4,16]. When using PVD methods for the deposition of DLC coatings it is possible to obtain a low temperature process below 200 °C [3,4,6,10-13,17]. The DLC coatings exhibit characteristics indicating the possibility of their use for coating the cutting tools used also in the woodworking industry [2,3,7,8,17]. The DLC coatings, which testing is presented in this paper, with properties similar to those described in the literature [1-4,6,7,8,10,11,12,16], may be a mixture of a ta-C phase and an amorphous graphite-like phase (graphitic C).

For the processing of medium density fibreboards (MDF), there are commonly used tools made of sintered carbides or ceramic tools, uncoated or less commonly with anti-wear coatings, [7,18,19,20]. The coating of ceramic tools could have an effect on the growth in their durability just like while cutting the metallic materials [21]. Due to the fragility of sintered carbide and ceramic tools the option in application to the MDF processing can be tools made from high speed steel with hard coatings [20].

This paper presents the results of investigations on the effect of changed process parameters of the modified cathodic vacuum arc on the structure and the mechanical and tribological properties of DLC coatings deposited on substrates made of HS6-5-2 high speed steel. It also presents the results of semi-industrial testing and wear analysis of planer knives made of HS6-5-2 high speed steel without coating and with DLC coatings with different properties.

2. Experimental procedure

The DLC coating was deposited in a C55CT technological installation produced by INOVAP Dresden [22]. The vacuum chamber possesses two sources with graphite targets and one with chromium. The modified cathodic vacuum arc (MCVA) technique, described previously [10,20,23], was used. The coatings were deposited on planer knives (dimensions 40×30×3 mm), made of high speed steel HS6-5-2 after heat treatment (hardness 9.8 ±0.2 GPa) and grinding ($R_a < 0.1$ µm), and polished silicon plates: type n, orientation (100), dimensions 30×5×0.5 mm.

Prior to deposition, substrates have been cleaned in organic solvents and alkaline detergents and after them were placed in the chamber and cleaning with chromium ions in an argon atmosphere, described in authors' works [10,20].

On the planer knives intended for production tests 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.

The thickness of the DLC coatings was established on the silicon plates by means of the profilographometric method on a Hommel Waveline T8000 device and on the basis of an observation of the fractures of the coatings with a Scanning Electron Microscopy (SEM) JEOL 5500 LV.

Measurements of DLC coatings Raman spectra were carried out using the device Renishaw inVia, the Raman scattering spectrometer on 514nm and 785nm in the geometry of the reverse scattering. Raman spectra were stimulated by radiation of an argon-ion laser with the power 50 mW and energy equal to 2.41 eV (514 nm) focused on a sample in a spot with the diameter ca. 1 µm. The following combination was used for description of peaks G and D: the asymmetrical Breit-Wigner-Fano lineshape (BWF) for the peak G and Gaussian-Lorentzian for the peak D taking into account linear background [4,24].

The hardness (H) and the modulus of the elasticity (E) of the coatings were determined by means of the loading-unloading method with the use of a Berkovich indenter on a FISCHERSCOPE HM 2000 XYp microhardness tester with an indentation depth below 10% of the thickness of the coatings.

The adhesion of the DLC coatings to the substrates was characterized in a CSM Instruments S.A. Revetest® Scratch-Tester directly on coated planer knives. The C Rockwell indenter (radius 200 µm) type was used. Critical load L_c is the measure of adhesion which causes an adhesive damage of the coating. The following settings of the device were used when making the measurements: load changes in the range of 0÷100 N; normal loading rate 100 N/min; relative travelling speed of the table with the sample 10 mm/min; length of the scratch made 10 mm or 5 mm; distance between successive scratches ca. 1 mm. It is evident from the conducted microscopic optical analyses of the nature of damages to DLC coatings that they are subject to adhesion damage usually on three stages. With L_{C1} critical load there occur single small splinters or damages to the coating of a cohesive nature. With L_{c2} critical load, there occur distinct and regular damages to the coating; with L_{c3} critical load, there usually occurs a total delamination of the coating.

Adhesion and crack resistance of coatings was also described by means of Rockwell tests which consisted in driving in an C type indenter and a determination of the nature of damages to the coating that was expressed in HF1-HF6 degrees [25].

A internal stress (σ_s) occurring in the coating in relation to the Si (0.5 mm thick) substrate was determined using the Stoney's method equation [26]. The silicon radius of curvature before and after DLC coating deposition was measured using Hommel Waveline T8000 profilometer.

Tribological tests of the coatings were conducted on a T01M tester according to the ball-on-disk method. Al_2O_3 ceramic balls (ø10mm) were used as counterparts. For the purpose of a frictional contact of the DLC coating with an Al_2O_3 counterpart, the following test parameters were used: normal load L = 20 N; sliding speed v = 0.2 m/s; friction radius R = 10 mm. The tests were carried out in ambient air of relative humidity 50 ±5% and temperature 22 ±1°C. The coefficient of friction (µ) between DLC coatings and the and Al_2O_3 counterparts was recorded.

The volume of the worn coating was determined using profilometer. Further, the frictional wear rate of coatings (k_v) and Al_2O_3 counterparts wear rate (k_b) was determined from the Archard's equation according to the procedure which was described among others in the papers [9,13].

The DLC coated planer knives and for comparison without coating (HS6-5-2) 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. Wear area (S) of the cutting edge measure method was described in authors' work [23].

3. Results and discussion

3.1. DLC coatings characterization

The properties of DLC coatings produced in technological processes using various parameters were analyzed. Changes in substrate bias voltage and argon pressure allowed receiving coatings at different ion energy. The conditions for preparation of selected DLC coatings were chosen on the basis of the authors' previous test results [10,20]. The selected DLC coatings of composite properties were determined as follows:

- DLC(L) - coatings with high adhesion were determined by the scratch method (high values of critical load L_{C2}),
- DLC (S) - typically produced coatings (medium L_{C2} and hardness H),
- DLC (H) - coatings of high hardness (H) and a high (H/E) ratio.

The main process variables of the MCVA method and the selected properties of DLC coatings are presented in Table 1.

The SEM characteristic of architecture and microstructure of DLC coatings were presented in Fig. 1. Fractures of DLC coatings, deposited on Si samples, showed a glassy nature without delaminating, cracking and peeling (Fig. 1). The coatings had a total thickness of about 1.8 μm with the Cr sublayer of about 0.3 μm in thickness; it was deposited to improve adhesion of the DLC layer to steel substrates. On the coatings surface there was a characteristic droplet phase specific for the unfiltered arc technique [10,13,20,22,23,27], resulting in an increase of the surface roughness of coated knives (R_a parameter in the range of 0.13-0.16 μm).

Figure 2 illustrates Raman spectra of DLC coatings distributed using a Gaussian profile. Information on the position of bands and their intensity (I) was obtained. The position of G band for the coatings is in the range of 1555 cm^{-1} for DLC(L) coatings to 1566 cm^{-1} for DLC(H) coatings, and D band from 1384-1393 cm^{-1} respectively. The ratio ID/IG amounts to 0.92, 0.46 and 0.3 respectively. Comparing the obtained value with the data reported in Refs [2,4,11,12,22,23,24], it was estimated that the content of sp^3 bonds in DLC coatings being tested may vary in the range 30-60%. Recording of small values of a ratio ID/IG = 0.3, together with the position of the band G = 1566 cm^{-1}, much higher than 1550 cm^{-1} for visible excitation of Raman spectrum, may indicate the highest content of sp^3 bonds in DLC(H) coatings.

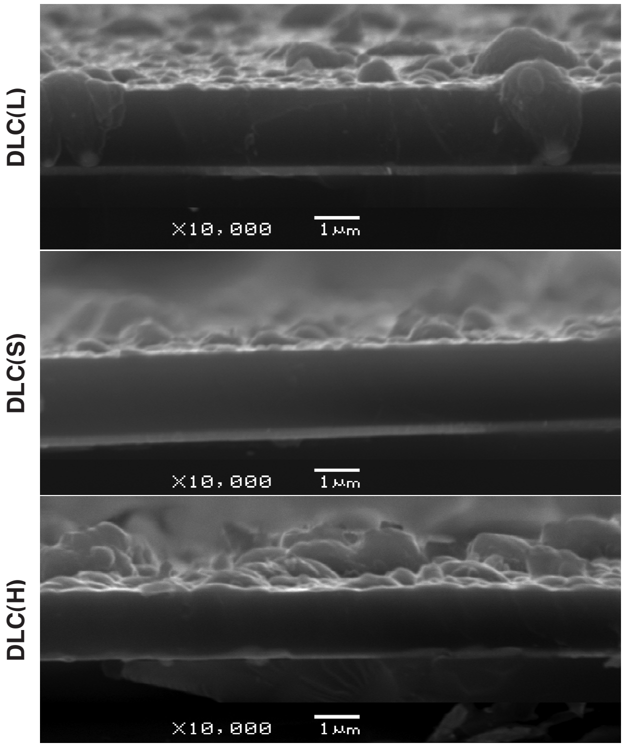


Fig. 1. SEM fracture images of DLC coatings with a Cr sublayer

The DLC coatings, deposited using various parameters exhibited a wide range 22.7-57.1 GPa of hardness (Table 1). The coatings with the highest hardness, produced at an argon pressure of 0.01 Pa and the substrate bias voltage -80 V, also revealed the highest compressive residual stress about -2.7 GPa.

The lowest average value of the critical load L_{C2} = 22 N, determined by the scratch method, showed the coatings obtained at an argon pressure of 0.01 Pa and substrate bias voltage of -80 V (Table 1). The highest adhesion (L_{C2} = 40 N) was marked by coatings obtained at an argon pressure of 0.25 Pa, and the floating potential of substrates (Table 1). Sample images of scratches after testing the DLC coatings, produced on planer knives made of HS6-5-2 steel, and the characteristic damages resulting from the critical loads (L_{C2} and L_{C3}) are illustrated in Fig. 3a.

The hardness of the coatings and the values of the critical load (L_{C2}) were consistent with the assumptions regarding the assumed properties of the deposited DLC coatings.

All the DLC coatings exhibited high adhesion (HF1) determined by Rockwell's test imprints (Fig. 3b). Around the imprints there were only minor radial fractures in coatings, visible only at higher magnification, without peeling and chipping.

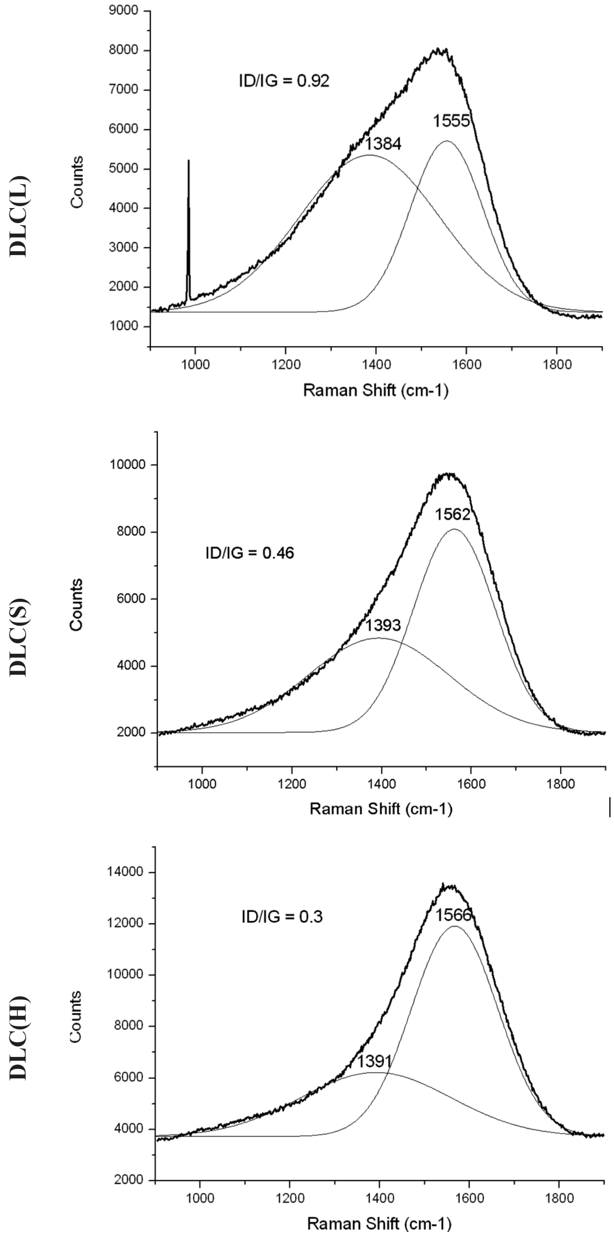


Fig. 2. Raman spectra of DLC coatings

During the tribological tests, using the ball-on-disk equipment, there were recorded significant fluctuations and differences in the mean values of the friction coefficient in the range of 0.11-0.17 for the tribo-couple: DLC coating - Al_2O_3 counterpart. During testing the coatings of more and more higher hardness and also showing higher and higher values of the H/E ratio in the range of 0.09-0.14 (Table 1), a noticeable decrease in abrasive wear (k_v) of DLC coatings with a simultaneous increase in wear of Al_2O_3 counterparts (k_b) were observed. The H/E ratio, in addition to information about the hardness, it can be a good parameter to enable prediction of the coating wear [2,23,28].

3.2. Wear and cutting properties of planer knives

The durability and abrasive wear of tools (without coating and coated planer knives) after production tests on double-side laminated MDF boards (16 mm in thickness) were subject to an analysis. The main processing parameters that were used during the production testing: the tool rotational speed 6000 min^{-1}, the cutting depth 1 mm, the cutterhead diameter 120 mm, the feed speed 6.3 m/min. Figure 4 shows the dependency of the average wear area (S) of uncoated (HS6-5-2) planer knives and knives coated with DLC coatings on the cutting length. Figure 5 presents the optical microscopic images of the cutting edge wear and for example chosen profiles, together with the determined average values of the uncoated knife blades radius (HS6-5-2) and with the DLC coatings, obtained after production tests carried out on the cutting length of 400 m.

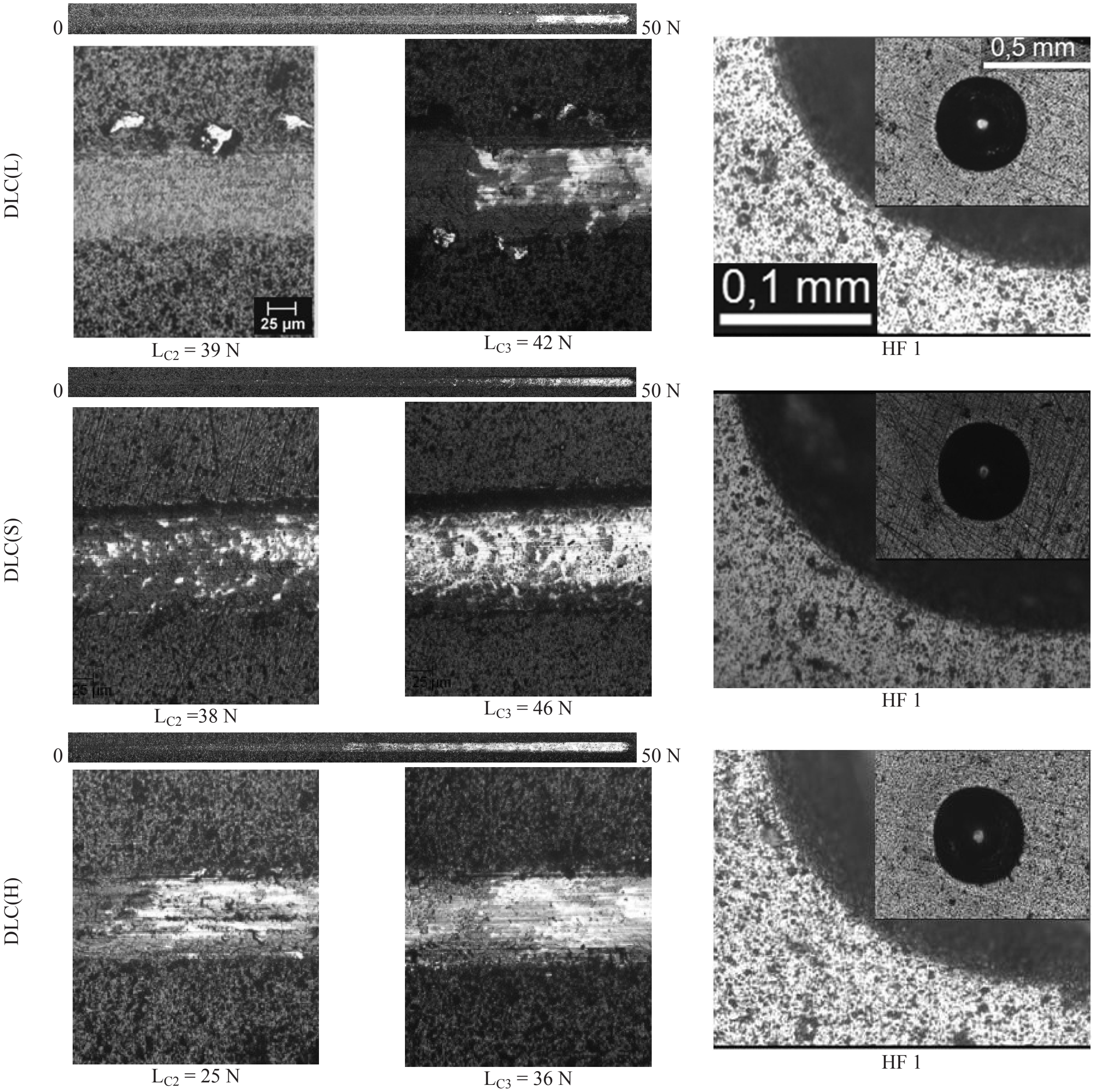
The planer knives of HS6-5-2 steel with DLC(S) coatings produced using the standard parameters were marked by the lowest wear area (S) of the blade, slightly lower than the wear of the uncoated tools (Fig. 4). The tools with DLC(L) and DLC(H) coatings showed the highest wear area (S), about 20% higher than in the case of uncoated tools. The high wear of the tools with DLC(H) coatings, despite the lowest values of the wear rate in tribological tests ($k_v = 2.96 \times 10^{-7}$ mm^3/Nm - Table 1), may result from a substantial embrittlement due to the high hardness (57.1 GPa) and the high compressive stress (-2.7 GPa) in the coating, and the low adhesion (L_{C2} = 22-25 N - Table 1 and Fig. 3), as specified in the scratch test. It was manifested by fragments of the coating chips at the edge of the blade and a significant rounding of the blade (blade radius of 34 mm - Fig. 5). The high hardness (57.1 GPa) and the high value of the H/E ratio (0.14), indicate the significant resistance of the DLC(H) coating to the plastic deformation, but do not indicate the capability of elastic deformation with simultaneous fracture toughness [2,23,28].

High wear of the tools with the DLC(L) coatings, despite they had the highest adhesion (L_{C2} = 40 N), as determined in the scratch test may result from their relatively low hardness (H = 22.7 GPa) and consequently the low resistance to frictional wear, expressed by the highest value of the coating wear rate $k_v = 6.15 \times 10^{-7}$ m^3/Nm. It could be confirmed by the abrasive nature of the cutting edge wear with the DLC(L) coating visible during microscopic observation of tools after production tests (Fig. 5).

Low adhesion of DLC coatings to steel substrates, despite the high hardness and high wear resistance in tribological tests, may be the main reason for their poor stability in production testing. The average values of critical load L_{C2} about 40 N for DLC(L) coatings and the maximum value of the critical load L_{C3} about 46 N (Fig. 3) for DLC (S), testify to the fact that it would improve the adhesion of DLC coatings to the high-steel substrates through the use of more complex sublayers, e.g. chromium-based [23], which could affect the result of increasing the wear resistance of coated tools for machining the wood based materials. From the Rockwell test (Fig. 3) it can be concluded that adhesion of the all DLC coatings is comparable. 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 DLC coated planer knife edge.

Table 1.
The main deposition parameters and selected DLC coatings properties

Coating denotation	Deposition parameters		Coating's properties							
	U_B [V]	p_{Ar} [Pa]	L_{C2} [N]	L_{C3} [N]	H [GPa]	H/E	σ_s [GPa]	μ	$k_v \times 10^{-7}$ [mm^3/Nm]	$k_b \times 10^{-7}$ [mm^3/Nm]
DLC(L)	floating	0.25	40	42	22.7	0.09	-1	0.12	6.15	0.88
DLC(S)	floating	0.01	38.5	45	40.8	0.12	-2	0.17	4.53	4.73
DLC(H)	-80	0.01	22	37.5	57.1	0.14	-2.7	0.11	2.96	12.3



a) Images of coating damage and corresponding critical loads

b) Images of Rockwell's test imprints

Fig. 3. Adhesion characteristic of DLC coatings

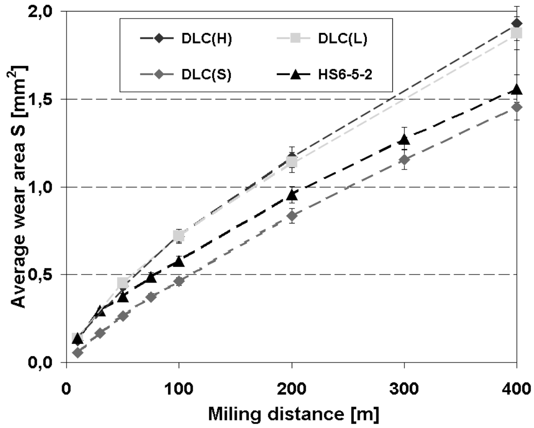


Fig. 4. Dependency of planer knives wear area S of the cutting edge in the function of the cutting length

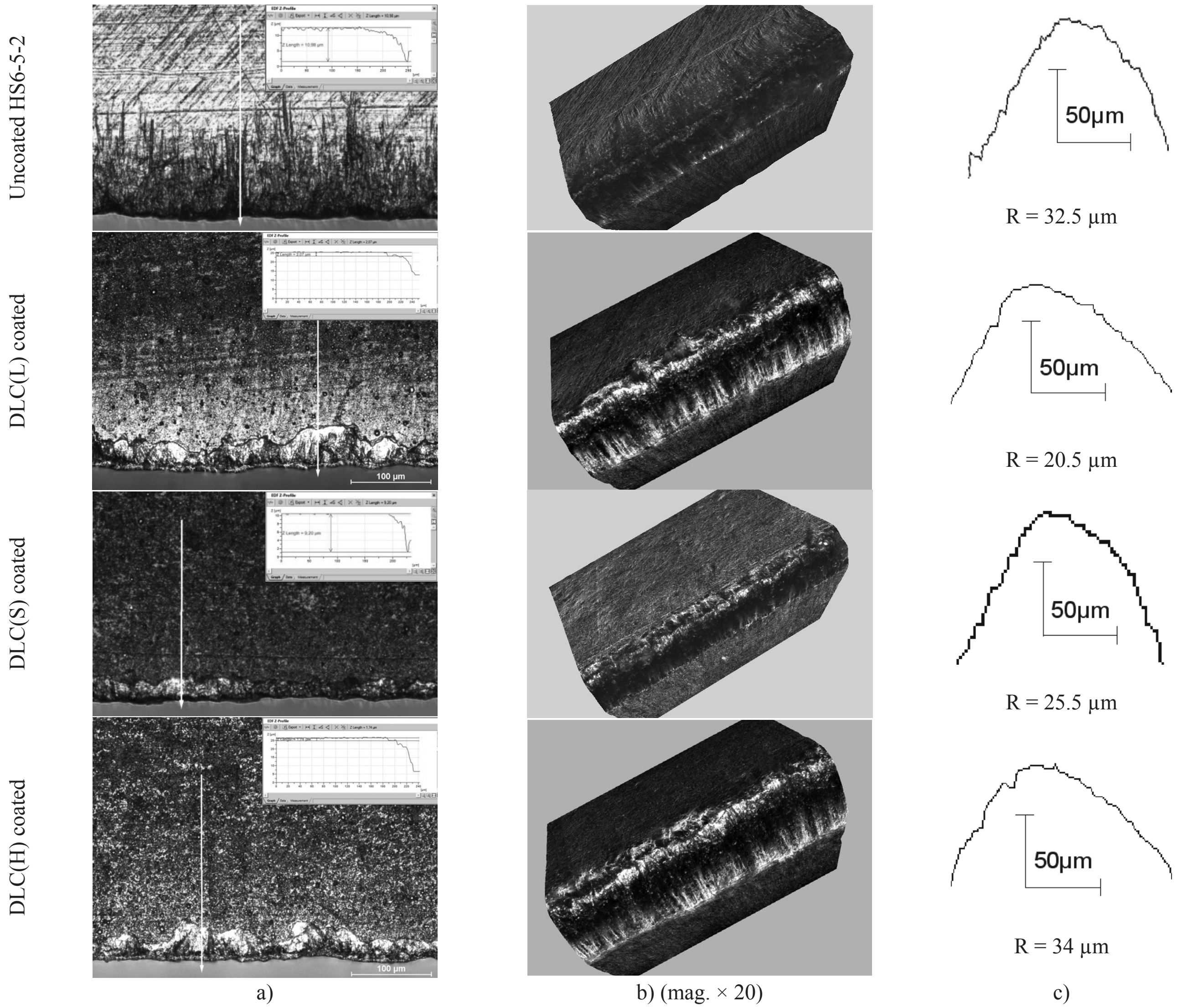


Fig. 5. Wear characteristic of DLC coated and uncoated planer knife after operational testing: images and profiles of rake face (a), 3D images of cutting edge (b), edge profiles and average value of blades radius R (c)

The nature of work of planer knife, in particular while working MDF board, causes its high mechanical and heat load [7,18-20]. Consequently elastic and plastic deformations occur of the knife material (high speed steel) which in the case of knife with a hard DLC coatings 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.

The use of appropriately selected of deposition parameters and properties of the carbon coating, such as DLC(S) with Cr sublayer, may effectively support the growth of stability of coated tools, relative to the HSS tools without the coating, when are applied to machining the wood-based material, that is laminated MDF. The DLC coatings on tools for machining the wood based materials should have high hardness, wear resistance and high adhesion; therefore investigations will be conducted on the coatings to achieve the high hardness at the surface, such as DLC(H), with gradient changing properties of the interlayer up to the steel substrate.

4. Conclusions

Variations of the argon pressure and the substrates bias voltage of while depositing by the MCVA technique made it possible to obtain the DLC coatings of significantly different properties. Fractures of the DLC coatings, deposited MCVA technique, during SEM observation revealed the glassy nature without delaminating, cracking and peeling. On the basis of the Raman spectral analysis it was estimated that the content of sp^3 bonds in DLC coatings being tested may vary in the range of 30-60%.

The hardness of the all DLC coatings was changed within 22.7-57.1 GPa, and the ratio H/E in the range of 0.09-0.14. The adhesion determined by the critical load L_{C2} in the scratch method was within the range of 22-40 N. All the DLC coatings in Rockwell test showed high adhesion and resistance to cracking determined by the highest (HF1) rate. Tribological testing, using ball-on-disk equipment revealed that all the coatings were marked by low abrasive wear, determined by the coating wear rate k_v of the order of 10^{-7} mm^3/Nm.

Suitably selected deposition parameters and properties of the obtained DLC(S) coatings, may drive an increase in durability of the coated planer knives compared to the steel tools (HS6-5-2) without coating, when applied to machining the wood-based material, such as laminated MDF boards. The highest values of the critical load L_{C3} more than 45 N and the intermediate values of the ratio H/E about 0.12 could be the cause of the highest durability of tools with DLC(S) coatings.

The relatively low adhesion of DLC coatings (critical load L_{C2} in the range of 22-40 N) to the steel substrates, despite the high hardness and wear resistance in tribological tests, may be the main reason for low durability of DLC coated HSS knives in production testing.

Further investigations will be performed to provide the high adhesion of DLC coatings, while maintaining their high hardness and wear resistance, e.g., by modification of the interlayer to the steel substrate.

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