Development and applications of protective dlc-based coatings in tooling industry

WIT GRZESIK
JOANNA MAŁECKA *

DOI: https://doi.org/10.17814/mechanik.2026.4.6

This article presents the state-of-the-art of the classification and fabrication methods of multilayer DLC-based coatings, as well as methods for tailoring specific physico -chemical, mechanical and tribological properties, e.g. through modification of their chemical composition and doping. The main techniques for deposition of DLC layers are discussed, with particular emphasis on the effect of process parameters on the composition, structure (sp^2/sp^3 bonding ratio), and internal stresses within the coatings. The paper presents extensive research results on the mechanical, tribological, and functional properties of DLC coatings under various operating conditions. Current and potential applications in various sectors of tooling industries, such as machining, metal forming, and pressure die-casting, are discussed. A substantial portion of the article is devoted to the use of multilayer, e.g. TiAlN /DLC coated cutting tools in the machining of different work materials. The article highlights the main technological limitations and the resulting directions for further development.

KEYWORDS: stereometric structure of the surface, grinding, contact joints

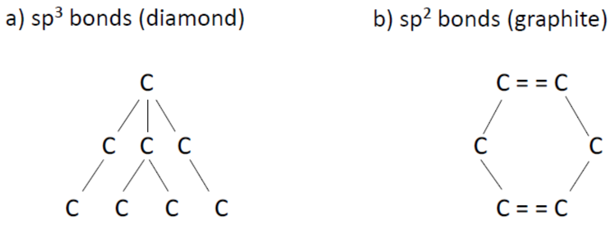
1. Introduction

1.1. Diamond-like layer (DLC) coatings

DLC (Diamond-Like Carbon) coatings belong to a group of amorphous carbon coatings with properties similar to diamond. Their structure comprises a mixture of sp^2 and sp^3 carbon bonds, which allows for tailoring a wide range of physical and mechanical properties. These coatings are characterized by high hardness, a very low coefficient of friction (0.12-0.15), and high resistance to abrasive and adhesive wear [1,2]. Consequently, they are widely used in the manufacturing industry, particularly to increase the machinability of cutting tools, the durability of internal combustion engine components, gears, and in tribological systems operating under difficult load and temperature conditions [1-3]. In many cases, these coatings are used in multilayer systems, including cutting tools, in which the DLC layer constitutes a low-friction outer nanolayer .

The development of DLC coatings has progressed from simple amorphous coatings to advanced multilayer and nanocomposite coatings [3], leading to the creation of numerous varieties differing in chemical composition, structure and functional properties [4].

The basic component of DLC coatings is carbon, which occurs in two main hybridization forms: sp^2 and sp^3 (fig. 1). Their proportion determines the mechanical and tribological properties of the coating. Sp^3 bonds are characteristic of the diamond structure and are responsible for the high hardness of the coating, while sp^2 bonds are responsible for graphite-like properties, such as higher electrical conductivity and the ability to reduce friction [4-6]. Vickers microhardness measurements show that the microhardness of TiAl -doped DLC coatings depends on the intensity ratio (peak heights in the D and G frequency bands in the Raman spectrum), i.e., I_D/I_G and sp^3/sp^2, with the higher the sp^3/sp^2 ratio or the lower the I_D/I_G ratio , the higher the hardness [8]. The optimal DLC structure is usually a compromise between these properties (Fig. 1).


a) sp^3 bonds (diamond)

b) sp^2 bonds (graphite)

Fig. 1. Scheme of atomic structure of DLC coatings including sp^2 (a) and sp^3 (b) bonds [according to Refs 4-6].

The quantitative ratio of these two phases to each other and the concentration of hydrogen atoms is the basic criterion for their classification [3]:

- ta-C (tetrahedral amorphous carbon) – characterized by a very high proportion of sp^3 bonds and a simultaneous absence of hydrogen in the structure. Coatings of this type typically have a smooth and stable structure and the highest hardness of all DLC coating varieties,
- ta-C:H - a coating variant containing about 70% of sp^3 bonds and hydrogen in the amount of about 25-35%, which influences the modification of the mechanical and tribological properties of the material,
- aC (amorphous carbon) - coatings with a relatively small share of sp^3 bonds, usually not exceeding about 30%, with a simultaneous lack of hydrogen in the structure,
- aC:H (hydrogenated amorphous carbon) - a variety of DLC coatings containing hydrogen in the amount of approximately 20-40%, which affects the structure and tribological properties of the coating.

Figure 2 shows the types of amorphous carbon depending on the concentration of hydrogen (H) and the share of covalent bonds expressed as the percentage ratio of C(sp^3) and C(sp^2) bonds.

---

* Prof. dr hab. inż. Wit Grzesik, em. prof. Politechniki Opolskiej – wit.grzesik@gmail.com, https://orcid.org/0000-0003-3898-5119
Dr hab. inż. Joanna Małecka – j.malecka@po.edu.pl, – Wydział Inżynierii Mechanicznej, Katedra Technologii Maszyn i Materiałoznawstwa, Politechnika Opolska, Opole, Polska

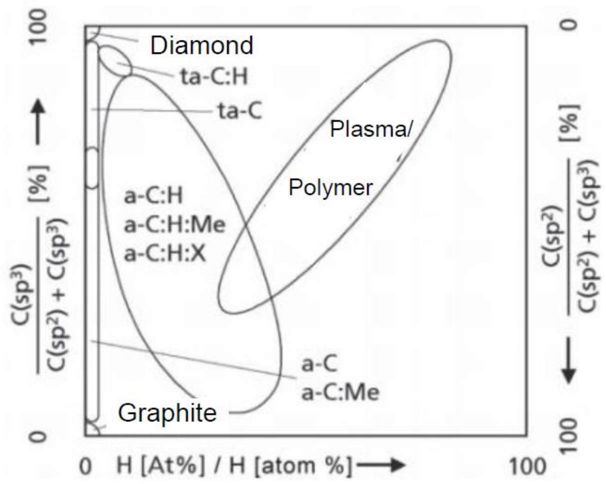


Fig. 2 Types of amorphous carbon in terms of hydrogen content and combination sp ^{3} and sp ^{2} bonds [1, 7]

1.2. DLC coating techniques

DLC coatings can be produced using various vapour deposition technologies [6,11,12]. The most commonly used methods are those belonging to the PVD (Physical Vapour Deposition) group:

- Magnetron Cathodic Sputtering (MCS),
- Ion Beam Deposition (IBD),
- Cathodic Arc Evaporation (CAE),
- High-Power Impulse Magnetron Sputtering (HiPIMS), and CVD (Chemical Vapor Deposition):
- Plasma Enhanced CVP - PECVD.

In modern coating systems, multilayer systems are increasingly used, in which the DLC coating constitutes the top layer on a substrate previously covered with nitride coatings, such as TiAlN or CrN [9]. This solution (as in Fig. 3b) allows for combining the high hardness of nitride layers with the low coefficient of friction of carbon coatings.

One of the most important technological challenges associated with DLC coatings is ensuring adequate adhesion of the coating to the substrate material. This is primarily due to the high residual stresses generated during coating deposition [4-5], which are related to the high proportion of sp³ bonds in the DLC structure and the energy of ions reaching the substrate during layer deposition. Effective adhesion of DLC coatings requires a comprehensive approach, including substrate preparation, the use of intermediate or gradient layers, and optimization of the deposition process parameters. Only then is it possible to obtain durable coatings with high wear resistance, widely used in modern manufacturing technologies [4, 6, 9-10].

The most commonly used method for improving adhesion is the use of intermediate layers, which act as a mechanical buffer between the substrate and the DLC coating, reducing differences in mechanical properties and limiting stress concentration. Typical materials for intermediate layers include Cr, Ti, Si, and transition metal nitrides (TiN, CrN). The intermediate layer reduces differences in elastic moduli and residual stresses between the coating and the substrate [4,5], thus reducing the risk of cracking, flaking, and delamination of the coating during tool operation.

Modern DLC coatings increasingly adopt a gradient structure, in which the chemical composition and mechanical properties change gradually from the substrate to the top layer [9]. Such solutions minimize stress concentration, improve layer adhesion, and increase resistance to shear and impact loads.

Equally important are the parameters of the DLC coating deposition process, i.e. substrate temperature, bias voltage, ion energy, working gas pressure and plasma source power [4,5,9]. Appropriate control of these parameters allows for limiting residual stresses and controlling the coating density and microstructure, which directly translates into improved adhesion to the substrate.

1.3. Development of DLC coatings

One of the important directions of development of DLC coatings is their modification by adding dopants of metallic or non-metallic elements [4, 9]. Doped coatings often adopt a nanocomposite structure**,** in which nanocrystalline metallic or carbide phases are dispersed in an amorphous carbon matrix.

The most commonly used admixtures include:

- metals: Ti, W, Cr,
- semiconductor elements: Si,
- non-metallic elements: N, F.

Doping with metals such as titanium (Ti), chromium (Cr) or silver (Ag) is intended to improve the adhesion of the coating layer to the substrate, increase wear resistance, and achieve functional effects, such as electrical conductivity. For example, Ti-DLC-doped coatings demonstrate significant improvement in tribological resistance under liquid or dry lubrication conditions, as well as improved thermal stability [5, 9]. Fig. 3 presents the structures of a monolithic Ti-DLC coating and a multilayer coating containing alternating DLC and Ti-DLC nanolayers .

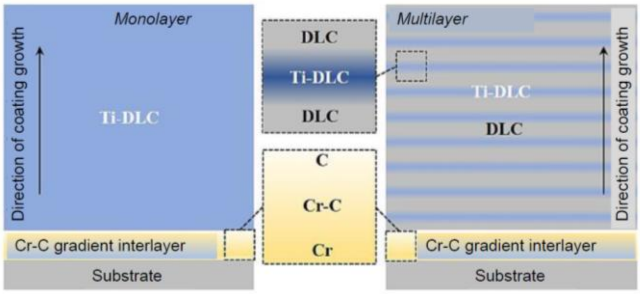


Fig. 3. Schematic structures of deposited doped monolayered mTi - DLC (left) and multilayered *M* Ti -DLC/DLC (right) coatings [13].

The thicknesses of the Cr–C gradient interlayer and the DLC-based coatings are similar for all applications , with average values of approximately 0.33 and 1.55 µm , respectively. All tested coatings demonstrated good adhesion, but the monolithic coating has comparatively higher adhesion, which is explained by the presence of internal stresses. In contrast, the multilayer coatings demonstrated improved mechanical properties (up to 33% increase in hardness and up to 25% increase in elastic modulus) compared to equivalent single-layer coatings.

The additional introduction of silver (Ag) into DLC coatings allows for increased electrical conductivity [10]. Doping with non-metals, such as silicon (Si), nitrogen (N), or fluorine (F), reduces residual stresses**,** increases the chemical stability of the coatings, and lowers the friction coefficient. For example, Si-DLC coatings exhibit greater resistance to oxidation and corrosion, which is important in chemically aggressive environments [6]. Furthermore, the introduction of nitrogen can improve the mechanical properties of coatings by strengthening the carbon-carbon and carbon-nitrogen bond networks [4-8].

2. Examples of applications of diamond-like coatings in various sectors of the tool industry

2.1. Machining

Deposition of diamond-like coatings on turning inserts, milling cutters and drills has contributed to the improvement of the machinability of many difficult-to-cut non-ferrous materials, such as wrought aluminum alloy for metal forming, die-casting aluminum alloy Al-Si (silumin), carbon fiber reinforced composites, graphite as a material for EDM electrodes, and sintered zirconia (ZrO_2) and silicon (Si_3N_4) ceramics [11,12]. CVD coated tools which are mainly used for cutting operations of such materials as carbon fiber reinforced plastics – CFRPs, metal matrix composites – MMCs, materials used for printed circuit boards – PCBs) are double, triple and quadruple including CrN, TiAlN. TiAlSN nitride coatings with an additional DLC top layer. Wear tests were conducted under orthogonal cutting conditions on an aluminum alloy of grade Al6061 (EN AW-6061) and a quenched steel of grade AISI 4340 (DIN 36CrNiMo4). The results of the analysis are presented in Fig. 4.

Fig. 4 shows that the lowest wear on both coated cutting edges was achieved with the TiAlN /DLC double coating (and also with the CrN /DLC coating for the aluminum alloy). This reduced cutting edge wear resulted in significantly lower surface roughness (Ra ≈1.24 μm and 1.45 μm for aluminum and alloyed steel, respectively). The coatings were deposited using the HiPIMS technique. Orthogonal machining under dry conditions with constant cutting parameters (speed of 240 rpm, depth of cut of 2 mm and feed rate of 0.15 mm/rev) was performed on soft, ductile (aluminum) and hard, brittle (quenched and tempered steel) materials. The coated tools resulted in approximately 20–30% reduction in contact temperature, workpiece roughness, and chip upsetting/thickness. DLC top coatings improved tool life for machining both ductile and brittle materials, as demonstrated by corresponding Raman analysis. Among the DLC coatings, the DLC/TiAlN coating demonstrated the highest wear resistance and longer tool life, as confirmed by SEM-EDS analysis.

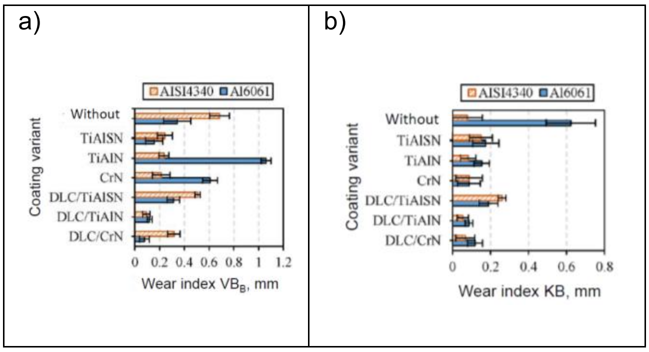


Fig. 4. Comparison of wear indexes for flank (a) and rake (b) faces of the cutting tools coated with single and double layers with additional DLC outer layer [12, 14].

An example of the effective combination of low friction and improved lubrication characteristic of DLC coatings with excellent oxidation resistance and higher machining speeds, which are characteristic of TiAlN coatings, is the use of a two-layer TiAlN /DLC coating for milling and finishing a wrought copper-beryllium alloy with the commercial grade AMPCOLOY® 83 [15]. SEM studies confirmed that the coating deposited by the PECVD method consists of two layers separated by a gradient transition. The coating had a hardness of 5.6 GPa and a Young's modulus of 93.2 GPa. It was found that after milling the wrought AMPCOLOY® 83 alloy, tools coated with the additional DLC layer showed improved performance compared to uncoated tools and reduced tool wear by approximately half. The main wear mechanisms were abrasion and loss of adhesion/ delamination of the coating material. In drilling operations of zirconia-based ceramics performed with ceramic (Si_3N_4) drill coated with a two-layer micro-/nanocrystalline diamond (MCD/NCD) provides good performance [16]. In turn, multilayer diamond coatings with a nanostructured NCD top coat (MNMN-CD) perform best in milling operations. The multilayer coating with mono- and nano - layers (MNMN-CD) is characterized by excellent machining efficiency and its service life is 3–7.5 times longer compared to single-layer diamond coatings.

Multilayer coatings TiAlN/TiN with TiAl dopants (see Fig. 3b), which combine the excellent lubricating properties of diamond-like carbon (DLC) with hard, thermally stable TiAlN / TiN layers, create excellent cutting tools with exceptionally low friction (as low as about 0.15), high wear resistance, and high oxidation resistance, especially in high-speed machining of hard materials. They effectively bridge the gap between hard nitride coatings (such as the popular titanium aluminum nitride coating - TiAlN) and low-friction solid lubricants, increasing tool life without the need for liquid coolants [17].

2.2. Micromachining

In this case, DLC coatings are an effective way to reduce numerous technological problems, such as the formation of built-up edge (BUE), which deteriorates surface quality, and limited strength and tool life [12]. In particular, micromachining of hard materials results in extremely low tool life. A major problem for catastrophic tool wear is BUE. In particular, tool life can be increased by optimizing cutting conditions [12]. It has been shown, among others, in [18] that coated micro- cutting tools significantly helps to increase their durability [13]. Literature studies indicate that AlCrN , TiAlN + AlCrN , AlCrN, TiAlN , and diamond coatings are preferred due to their high wear resistance. In [18], the results of investigations focused on the effect of coating materials (AlTiN, TiAlN + AlCrN, AlCrN, TiAlN + WC/C and DLC) in micro-milling of the superalloy Inconel 718 were presented. DLC and TiAlN + WC/C coated tools showed better performance due to reduced BUE formation. The performance studies of microcrystalline diamond, nanocrystalline diamond, DLC and TiAlN coatings in micro-drilling of graphite showed that the microcrystalline diamond coating showed better durability than the other three coatings [18]. Similar observations were noted during micro-milling of the face of Al6061-T6 aluminum alloy with DLC coated tools. It was observed that the DLC coated tool had good performance and provided longer tool life.

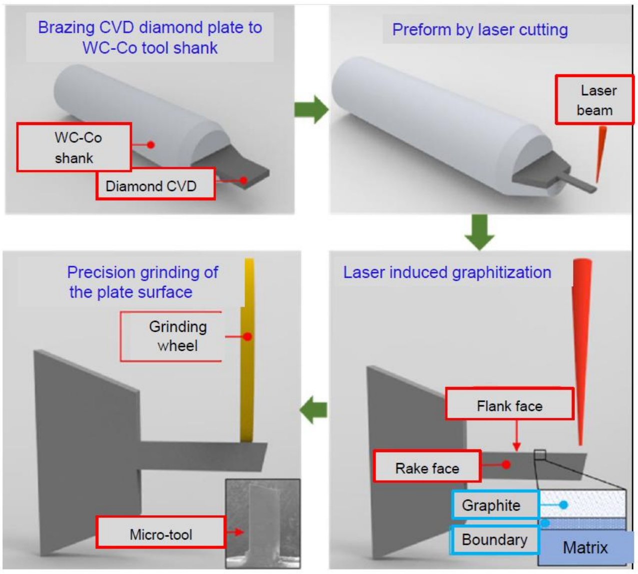


Fig. 5. Fabrication process of CVD CD coated micro-milling tools [19].

[19] presents the manufacturing technologies for micromilling tools used for machining oxygen-free copper, which is widely used in high-energy physics detectors and optical components due to its low background radiation and high thermal conductivity [19]. For this purpose, a combined process of laser-induced diamond graphitization followed by precision grinding was proposed to fabricate a diamond CVD micro-milling tool, as shown in Fig. 5. A nanosecond pulsed laser was used as a heat source to induce the diamond-graphite phase transformation. The graphite layer and the heat-affected layer were removed by precision grinding using a ceramic grinding wheel. The graphite layer was very easy to remove, resulting in high production efficiency. As a result, diamond CVD micro-milling tools with a sharp cutting edge and good tool surface quality were fabricated. The cutting forces, machined surface quality, burr formation, and tool wear were investigated. The experimental results in this work provided practical data on micro-milling using CVD diamond tools.

The results indicated [19] that the CVD diamond-coated tool was characterized by lower resultant forces, less burr formation, and minimal surface roughness (arithmetic mean surface roughness Ra=53 nm). The failure of the CVD diamond-coated tool was caused by flaking and flank/rake wear, while the failure of the cemented carbide tool was associated with extensive flaking, coating micro-chipping, and flank wear. Experimental studies demonstrated superior performance of the CVD diamond-coated tool compared to commercially available coated cemented carbide tools.

2.3. Tools for metal forming and die casting

Diamond-like coated tools have a significant impact on the manufacturing processes of metal forming tools, i.e., moulds and dies for stamping, extrusion, and forging. Due to the widespread use of HSM machining [12], the machining accuracy and durability of high-speed milling tools have in such cases a significant impact on the surface roughness and dimensional accuracy of these products. For instance, [20] presents the development of DLC-coated milling cutters for machining graphite hot-bending molds used in the production of three-dimensional, bent glass, such as protective screens and back covers of 3C electronic products [20]. For this purpose, microcrystalline diamond (MCD), submicro-crystalline diamond (SMCD), nanocrystalline diamond (NCD), and micro/nanocrystalline diamond composite (MCD/NCD) coatings were deposited on commercial corner radius end mills using a hot fiber chemical vapor deposition (HFCVD) deposition technique.

The results indicate that MCD/NCD coated end mills exhibit superior machining performance compared to other tools, thanks to comprehensive properties such as improved surface smoothness and higher adhesion to WC-Co substrates. Furthermore, the machining dimensional accuracy and surface roughness during high-speed milling of graphite hot-bending molds using MCD/NCD coated end mills can meet the stringent requirements for 3C electronic products, even without or with less need for subsequent lapping and polishing. This approach is consistent with the general concept of sustainable manufacturing [12, 21].

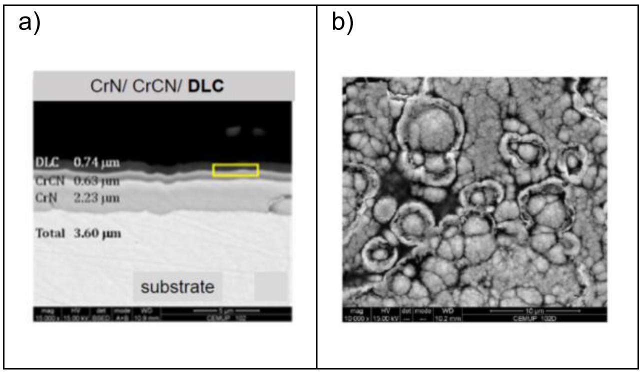


Fig. 6. SME image of cross-section of multilayer CrN / CrCN /DLC coating (a) and view of the die-casting mold surface after 135,000 injection cycles (b) [22]

In [22], laboratory and experimental wear tests of a multilayer coating with a CrN/CrCN/DLC structure deposited by the PVD method with unbalanced magnetron sputtering (UBMS) on the surface of injection molds are presented. The coating (Fig. 6a) consists of three different layers, including CrN at the bottom, CrCN as an intermediate layer, and DLC (diamond-like carbon) on top. It should be noted that depositing layers using the UBMS method increases their adhesion to the substrate, which corresponds well to the goal of depositing hard, abrasion-resistant coatings (e.g., TiN , CrN , TiAIN) on complex surfaces in the tool industry.

The coating shown in Fig. 6a was deposited on P20 steel injection mold cavities used in injection molding machines for the production of automotive parts from polypropylene reinforced with 30% (wt) glass fibers. This composite material exhibits a high abrasive action during injection molding, which poses significant challenges in terms of wear resistance of the mould surface. Tests showed that after 135,000 injection cycles, the multilayer coating significantly improved process performance compared to the results previously obtained for uncoated samples (see Fig. 6b). Fig. 6b shows still some remaining DLC top layer despite long-term use under extreme tribological conditions. The good performance achieved by this CrN / CrCN /DLC multilayer coating can be partially attributed to the properties of the DLC top layer due to its low coefficient of friction [22]. In the case of cold forging moulds increasing their durability by applying a coating allows for a 10% reduction in manufacturing costs [23].

An interesting example is the use of an additional outer DLC layer to cover the cutting surfaces of wood cutting knives. In this case, the best properties were demonstrated by two-layer TiN /DLC coatings (approx. 2.5 µm TiN plus 190 nm DLC) [24].

Conclusions

Based on the literature review conducted on the subject of manufacturing and application of diamond-like coatings in the improvement of technological tools, it can be authoritatively stated that:
- the use of cutting tools coated with diamond-like layers (DLC) is an effective means of increasing their life, which translates positively into increased efficiency and quality of processing.
- in turn, covering the wear-critical surfaces of metal forming and pressure casting moulds with DLC layers ensures an increase in their durability and the quality of parts manufactured from highly abrasive materials.
- DLC-coated tools contribute to the development of machining operations of many types of difficult-to-cut non-ferrous materials, such as wrought aluminum, die-cast Al-Si alloy, carbon fiber-reinforced composites, graphite as a material for EDM electrodes, and sintered zirconium (ZrO_2) and silicon (Si_3N_4) ceramics.
- the basic direction of development of multi-layer and multiple coatings includes primarily doping technologies and more efficient layer deposition techniques.

REFERENCES

[1] Ozimina D., Madej M., Kowalczyk J., Suchanek J., Taticek F., Kolariikova M., Zużycie powłok diamentopodobnych w zależności od rodzaju kompozycji powłokowej i materiałów pary trącej, Tribologia: tarcie, zużycie, smarowanie 3 (2012) 127–136

[2] Luo J., Liu M., Ma L., Origin of friction and the new frictionless technology-Superlubricity, Nano Energy 86/2 (2021) 10692

[3] Robertson J., Diamond-like amorphous carbon, Materials Science and Engineering R 37/4–6 (2002) 127–281

[4] Donnet C., Erdemir A., Tribology of Diamond-Like Carbon Films, Springer (2008)

[5] Feng X., Xia Y., Tribological properties of Ti-doped DLC coatings under ionic liquids lubricated conditions, Applied Surface Science 258 (2012) 2433–2438

[6] Musil J., Hard nanocomposite coatings: Thermal stability, oxidation resistance and toughness, Surface and Coatings Technology 207 (2012) 50–65

[7] J.C. Sánchez-López, A. Fernández, Doping and alloying effects on DLC coatings (Chapter), Tribology of Diamond-Like Carbon Films, Fundamentals and Applications, Springer (2008), https://link.springer.com/book/10.1007/978-0-387-49891-1

[8] Chi-Lung Chang, Jui-Yun Jao, Tang-Chun Chang, Wei-Yu Ho, Structural characterization of TiAl-doped DLC Coatings by Raman spectroscopy and X-ray photoelectron spectroscopy, Ming Dao Journal 1(1) 115–124(2005), Ming Dao University

[9] Shtansky D.V., Kiryukhantsev-Korneev Ph.V., Bashkova I.A., Sheveiko A.N., Levashov E.A., Multicomponent nanostructured films for tribological applications, International Journal of Refractory Metals and Hard Materials 28/1 (2010) 32–39

[10] Chen J., Yanqiu X., Yichao H., Bu H., Tribological performance of Ag coating under boundary lubrication, Tribology International 110 (2017) 161–172

[11] Grzesik W., Advanced protective coatings for manufacturing and engineering, Hanser Gardner Publications (2003), Cincinnati

[12] Grzesik W., Podstawy skrawania materiałów konstrukcyjnych, PWN (2018), Warszawa

[13] Haneef M., Evaristo M., Morina A., Yang L., Trindade B., New nanoscale multilayer magnetron sputtered Ti-DLC/DLC coatings with improved mechanical properties, Surface & Coatings Technology 480 (2024) 130595, https://doi.org/10.1016/j.surfcoat.2024.130595

[14] Ibrahim M.S., Sulaiman M.H., Samin R., Yaakob Y., Kamiz S.L., Ridzuan M.J.M., Pauzi A.A., Sukindar N.A., Bienk K., Tool wear of DLC coating as top layer to CrN, TiAlSN, TiAlN coatings in machining of steel and aluminium alloys, Wear, 558–559 (2024), 205574, https://doi,org/10.1016/j.wear.2024.205574

[15] Sebbe N., Freitas F., Silva F., Casais R., Martinho R., Magalhães L., Alexandre R., Sales-Contini R., Characterization and wear behaviour of TiAlN/DLC coating deposited on cutting tools for milling AMPCOLOY® 83, November 2025, The International Journal of Advanced Manufacturing Technology, DOI: 10.1007/s00170-025-16955-0

[16] Wang Ch., WangX., Sun F., Tribological behavior and cutting performance of monolayer, bilayer and multilayer diamond coated milling tools in machining of zirconia ceramics, Surface and Coatings Technology, Volume 353, 15 November 2018 49–57, https://doi.org/10.1016/j.surfcoat.2018.08.074

[17] Chang Ch.L., Jao J.Y., Ho W.Y., Wang D.Y., Characteristics of TiAl-Doped DLC/TiAlN/TiN Multilayered Coatings Synthesized by Cathodic Arc Evaporation, Solid State Phenomena, Vol. 118 247–256, https://doi.org/10.4028/www.scientific.net/SSP.118.247

[18] Ucun I., Aslantas K., Bedir F., The performance of DLC-coated and uncoated ultra-fine carbide tools in micromilling of Inconel 718, Precision Engineering, Volume 41, July 2015 135–144, https://doi.org/10.1016/j.precisioneng.2015.01.002Get rights and content

[19] Zhao G., Li Z., Hu M., Li L., He N., Jamil M., Fabrication and performance of CVD diamond cutting tool in micro milling of oxygen-free copper, Diamond and Related Materials, Vol. 100, December 2019, 107589, https://doi.org/10.1016/j.diamond.2019.107589

[20] Wang H., Yang J., Sun F., Cutting performances of MCD, SMCD, NCD and MCD/NCD coated tools in high-speed milling of hot bending graphite molds, Journal of Materials Processing Technology, Vol. 276, February 2020, 116401, https://doi.org/10.1016/j.jmatprotec.2019.116401

[21] Grzesik W., Wizje i strategie wytwarzania. Cz. I, Mechanik, 2010, nr 3 145–148

[22] Silva F.J.G., Martinho R.P., Baptista A.P.M., Characterization of laboratory and industrial CrN/CrCN/diamond-like carbon coatings, Thin Solid Films, Vol. 550, 1 January 2014 278–284, https://doi.org/10.1016/j.tsf.2013.11.042

[24] Dubar M., Dubois M., Dubar L., Wear analysis of tools in cold forging: PVD versus CVD coatings, Wear 259 (2005) 1109–1116

[24] Chayeuski V., Zhylinski V., Kazachenko V., Tarasevich A., Taleb A., Structural and Mechanical Properties of DLC/TiN Coatings on Carbide for Wood-Cutting Applications, MDPI, Coatings 2023, 13, 1192, https://doi.org/10.3390/coatings13071192