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ENHANCING THE TRIBOLOGICAL PROPERTIES AND EXTENDING THE SERVICE LIFE OF CUTTING TOOLS AND INDUSTRIAL COMPONENTS USING HYBRID PVD AND PACVD (DLC) PROTECTIVE COATINGS^{***}

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Abstract

Hybrid physical vapor deposition (PVD) and plasma-assisted chemical vapor deposition (PACVD) technologies for depositing diamond-like carbon (DLC) coatings represent a modern, environmentally friendly and engineering-based approach to the surface protection of cutting tools and tribologically loaded industrial components. Unlike conventional thermal CVD processes, which require high temperatures (800–1000°C) and cause structural changes as well as tempering of previously hardened tool steels, hybrid PVD+PACVD systems operate in a low-temperature range (180–550°C; DLC deposition at ≤250–350°C). This regime fully preserves the microstructure, hardness and dimensional stability of the substrate.

This paper analyses eight different types of coatings (TiN, AlTiN, CrN, TiCN, CrAlSiN, DLC, Al-TiN+DLC and CrN+DLC) using TOPSIS multi-criteria analysis with five key engineering criteria: hardness, thermal stability, corrosion resistance, friction coefficient and substrate compatibility. The results show that hybrid multilayer architectures AlTiN+DLC and CrN+DLC achieve the highest closeness coefficients (0.91 and 0.88, respectively), indicating a pronounced non-linear synergistic effect that cannot be achieved by applying individual layers.

The paper defines a compatibility matrix, a decision tree and an algorithm for selecting the optimal coating architecture based on the dominant wear mechanisms in service. An analysis of contemporary industrial and literature data confirms that the application of hybrid PVD/PACVD systems enables a significant extension of the service life of cutting tools, sliding elements and machine components, while reducing friction, wear and energy losses. The technology is positioned within the concept of green tribology due to the complete absence of wastewater and harmful chemical effluents.

Keywords: PVD coatings, DLC, PACVD, hybrid coatings, TOPSIS, tribology, wear, green tribology

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1 INTRODUCTION

1.1 Research Significance

Wear of cutting tools and industrial components represents one of the key causes of reduced productivity, increased maintenance costs and energy losses in modern industry. Conventional materials, despite their high mechanical properties, are exposed to abrasive, adhesive, oxidative and fatigue wear during service. Therefore, increasing attention is being paid to surface engineering and the application of protective coatings, which enable a simultaneous increase in wear resistance, friction reduction and preservation of the fundamental properties of the substrate.

The aim of this paper is to evaluate the tribological and service characteristics of PVD, PACVD (DLC) and hybrid PVD/DLC coatings using TOPSIS multi-criteria analysis, with the goal of defining

optimal coating architectures for different industrial operating conditions. The scientific contribution of this paper lies in the quantitative ranking of the analysed systems, the identification of the synergistic effect of hybrid coatings and the consideration of their importance within the framework of green tribology and sustainable surface engineering.

2 MATERIALS AND METHODS

2.1 Analysed Types of Coatings

The study analysed eight types of protective layers. The input data and physico-mechanical characteristics were taken from the technical documentation of equipment manufacturers and relevant contemporary literature [1,2,3,4,5,6,15].

Table 1 Comparative specifications of the analysed PVD, PACVD (DLC) and hybrid coatings [1–7]

Coating type	Technology	Thickness (μm)	Hardness (GPa)	Friction coefficient (μ)	Max. working temperature (°C)	Oxidation resistance
TiN	PVD	2–5	20–25	0.45–0.60	500–600	Good
AlTiN	PVD	2–5	25–32	0.30–0.45	800–900	Very good
CrN	PVD	2–6	15–20	0.40–0.55	600–700	Very good (corrosion)
TiCN	PVD	2–4	28–35	0.30–0.45	400–500	Moderate
CrAlSiN	PVD	2–5	28–35	0.25–0.40	900–1000	Outstanding
DLC (a-C:H)	PACVD	1–3	15–40	0.05–0.15	250–350	Low to moderate
AlTiN+DLC	PVD+PACVD	3–6	System-dependent	0.05–0.15	up to approx. 800	Outstanding
CrN+DLC	PVD+PACVD	3–6	System-dependent	0.05–0.15	up to approx. 700	Excellent (corrosion)

2.2 Analysed Substrates and Industrial Applications

To ensure maximum adhesion, mechanical stability and coating functionality, four key groups of substrate materials were identified.

Table 2 Overview of substrates, temperature limitations and recommended coatings [3,4]

Substrate	Typical components	Max. deposition temperature	Recommended coatings
Tool steels (HSS)	Drills, milling cutters, knives and machining tools	Approx. 550°C	TiN, AlTiN, CrN, DLC
Cemented carbides (WC-Co)	Indexable inserts and tribologically loaded components	Above 800°C	AlTiN, TiCN, DLC, AlTiN+DLC
Alloyed structural steels	Gears, shafts, valves and sliding elements	Approx. 550°C	CrN, DLC, CrN+DLC
Hot-work tool steels	Moulds and tools for hot forming	Approx. 600°C	CrN, CrAlSiN, CrN+DLC

2.3 TOPSIS Multi-Criteria Analysis

For ranking the analysed coatings, the TOPSIS method (Technique for Order Preference by Similarity to Ideal Solution) was applied, one of the most frequently used multi-criteria decision-making methods. The method is based on the assumption that the optimal alternative has the smallest distance from the ideal solution and the largest distance from the anti-ideal solution [8].

The analysis included eight alternatives (A1 to A8), representing different types of PVD, PACVD and hybrid coatings. The evaluation was carried out based on five

criteria of importance for tribological performance and industrial application:

- C1 - Hardness ($w_1 = 0.30$)
- C2 - Thermal stability ($w_2 = 0.25$)
- C3 - Corrosion resistance ($w_3 = 0.15$)
- C4 - Friction coefficient ($w_4 = 0.20$)
- C5 - Substrate compatibility ($w_5 = 0.10$)

The weighting coefficients were determined based on the relative importance of individual properties for the service life and functionality of protective coatings under industrial conditions.

Table 3 Performance matrix for TOPSIS analysis

Coating	C1	C2	C3	C4	C5
TiN	6	5	4	3	8
AlTiN	8	9	6	5	7
CrN	5	6	9	6	8
TiCN	8	6	5	5	7
CrAlSiN	9	9	7	6	6
DLC	6	3	6	9	8
AlTiN+DLC	9	9	7	9	7
CrN+DLC	7	7	9	9	8

The TOPSIS procedure was carried out through five consecutive steps:

1. **Normalisation of the decision matrix** to eliminate the influence of different numerical ranges of criteria, formula (1):

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}} \quad (1)$$

2. **Formation of the weighted normalised matrix** by multiplying the normalised values by the corresponding weighting factors, formula (2):

$$v_{ij} = w_j r_{ij} \quad (2)$$

3. **Determination of the ideal (A+) and anti-ideal (A-) solutions**, where the ideal solution contains the best values of all criteria, and the anti-ideal solution contains the most unfavourable values.

4. **Calculation of the Euclidean distance** of each alternative from the ideal and anti-ideal solutions, formulas (3) and (4):

$$S_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^+)^2} \quad (3)$$

$$S_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - v_j^-)^2} \quad (4)$$

5. **Calculation of the closeness coefficient to the ideal solution**, formula (5):

$$C_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (5)$$

The value of the closeness coefficient (C_i) belongs to the interval from 0 to 1. Higher values indicate greater similarity to the ideal solution and, therefore, better overall performance of the analysed coating. Based on the obtained values, a final ranking of all analysed systems was made according to their expected tribological and service efficiency.

3 THEORETICAL FOUNDATIONS – PROTECTION MECHANISMS

3.1 Fundamental Principles of Coating Tribology

According to Holmberg and Matthews [1], the tribological behaviour of hard thin

films is determined by the ratio of hardness to elastic modulus (H/E and H^3/E^2), the critical load in the scratch test (L_c) and the surface topography (pp. 45–52). The H/E parameter defines the resistance of the coating to elastic deformation, while H^3/E^2 represents an indicator of resistance to plastic deformation and the occurrence of cracks.

3.2. Structure and Low-Friction Mechanisms of DLC Coatings

As extensively discussed by Donnet and Erdemir [2], DLC coatings are metastable amorphous carbon materials with a combination of sp^2 and sp^3 hybridised bonds (Chapter 2, pp. 25–40). The proportion of the sp^3 phase directly affects hardness, while the hydrogen content in a-C:H systems controls the friction coefficient [9]. The ultra-low friction coefficient of DLC layers ($\mu = 0.05$ – 0.15) results from:

1. **Tribo-induced graphitisation** – under the action of pressure and shearing in the contact zone, a local phase transformation of the surface layer into an sp^2 graphitic film occurs, which acts as a solid lubricant.
2. **Passivation of dangling bonds** – hydrogen atoms on the surface saturate the remaining free carbon bonds, thereby reducing surface energy and preventing the formation of adhesive bridges.

The thermal stability of monolithic DLC layers is limited to approximately 350°C , which is why DLC is used in modern systems as a final functional layer over thermally stable nitride bases [9,10].

3.3 Evolution of Hybrid PVD/PACVD Systems

According to Vetter [3], modern hybrid reactors integrate cathodic arc evaporation, magnetron sputtering and PACVD processes within a single vacuum cycle (pp. 215–

218). Such systems enable the synthesis of multilayer and gradient nanostructures with superior adhesion, controlled roughness and optimised tribological functionality [11,15].

3.4 Impact on Tool and Component Performance

According to Bobzin and colleagues [4], during high-speed machining of materials, AlTiN coatings extend the service life of tools due to the formation of a protective Al_2O_3 film at high temperatures (pp. 3–5). In contrast, DLC layers show superior performance under conditions of pronounced adhesive wear, particularly when machining aluminium and copper alloys [2,5,13].

4 MATERIAL COMPATIBILITY AND ENVIRONMENTAL ASPECTS OF THE PROCESS

4.1. Environmental Profile of the Technology (Green Tribology Concept)

According to Freschi and colleagues [11] and Ihara and colleagues [12], hybrid vacuum processes represent clean technologies that successfully replace conventional galvanic and high-temperature processes (pp. 3–5 in [11] and pp. 2–4 in [12]).

The environmental advantages include:

- Complete absence of wastewater – the entire material transformation takes place in a dry regime
- Absence of hazardous liquid chemicals – only inert gases (Ar, N_2 , CH_4 , C_2H_2) are used

- Minimal gas emissions – vacuum systems operate as closed loops
- Low energy consumption compared to high-temperature CVD processes
- Closed vacuum system without the release of harmful effluents

4.2 Preservation of Microstructure and Dimensional Stability of the Substrate

In conventional CVD processes, high temperatures (800–1000°C) cause tempering of the martensitic structure, a dramatic drop in core hardness and deformation of the tool, which often requires subsequent re-hardening.

In contrast, PVD and PACVD systems operate in a low-temperature range [3]:

- PVD nitride layers: 180–550°C
- PACVD (DLC) layers: ≤250–350°C

In this way, the hardness, toughness and dimensional stability of the substrate are fully preserved, with dimensional accuracy within $\pm 0.02 \mu\text{m}$ [4]. Similar effects on surface stability under thermal loads were identified by Wu and colleagues [14] in ultra-precision diamond machining.

5 RESULTS

5.1 Quantitative Results of TOPSIS Ranking

By applying the mathematical algorithm of the TOPSIS method [8], the closeness coefficients (C_i) relative to the ideal configuration were calculated.

Table 4 Final ranking of coatings according to TOPSIS analysis

Rank	Coating type	Closeness coefficient (C_i)
1	AlTiN + DLC	0.91
2	CrN + DLC	0.88
3	CrAlSiN	0.82
4	AlTiN	0.76
5	TiCN	0.69
6	CrN	0.66
7	DLC	0.62
8	TiN	0.58

5.2 Interpretation of Results and Synergistic Effect

The results show the dominant performance of hybrid multilayer systems AlTiN+DLC and CrN+DLC [4,6,7]. The combination of a hard nitride base and a DLC top layer enables a simultaneous increase in load-bearing capacity, wear resistance and friction reduction.

In the AlTiN+DLC system, the hard nitride sublayer (AlTiN, 25–32 GPa) provides mechanical stability and resistance to plastic deformation, while the DLC top layer ($\mu = 0.05\text{--}0.15$) reduces heat generation and

tangential stresses in the contact zone [2,4]. The closeness coefficient for AlTiN+DLC ($C_i = 0.91$) is significantly higher than the values for the individual layers AlTiN (0.76) and DLC (0.62), which confirms a **nonlinear synergistic effect**.

5.3 Quantitative Effects of Extending Component Service Life

Based on pilot projects and the literature [2,4,5,13]:

Table 5 Typical effects of applying PVD, PACVD and hybrid coatings

Component type	Coating	Service life extension	Mechanism
Cutting tools for steel machining	AlTiN	+50% to +150%	Formation of Al_2O_3 oxide film [4] p. 6
Tools for machining Al alloys	DLC	2 to 4 times	Elimination of adhesive galling [2]
Sliding tribological elements	CrN+DLC	2 to 3 times	Corrosion protection + low friction [6,7]
High-temperature tools	CrAlSiN	+80% to +200%	Oxidation stability up to 1000°C [6]
Mining picks (reconditioning)	AlTiN	+60% to +80%	Combined treatment [5] pp. 87–90

6 DISCUSSION

6.1 Decision Tree for Selecting the Optimal Coating Architecture

Based on the analysis of dominant wear mechanisms, the following engineering decision tree was defined [1–4,6,7]:

Start: Identification of the dominant wear mechanism

1. **High temperatures (above 600°C)**
 - Extreme (above 800°C) → CrAlSiN (or with DLC top layer)
 - Moderate ($600\text{--}800^\circ\text{C}$) → AlTiN
2. **Abrasive wear**
 - High pressure, dry cutting → TiCN or AlTiN
 - Standard conditions → AlTiN

3. Adhesive wear / Built-Up Edge (BUE)

- Aluminium, copper, brass → DLC top layer (mandatory)
- Steel, cast iron → AlTiN + DLC

4. Corrosive environment

- Corrosion + high friction → CrN + DLC
- Pure chemical exposure → CrN

5. Impact and interrupted loading

- Severe impacts → TiCN or TiN
- Moderate impacts + low friction → AlTiN + DLC

The Figure 1 shows a decision tree for selecting a coating depending on wear mechanisms during use.

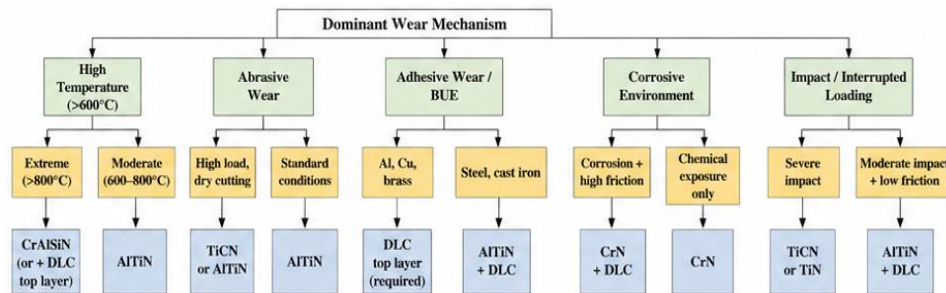


Figure 1 Decision tree for selection the optimal coating architecture

A typical layout of coating layers (AlTiN + DLC) is shown in Figure 2.

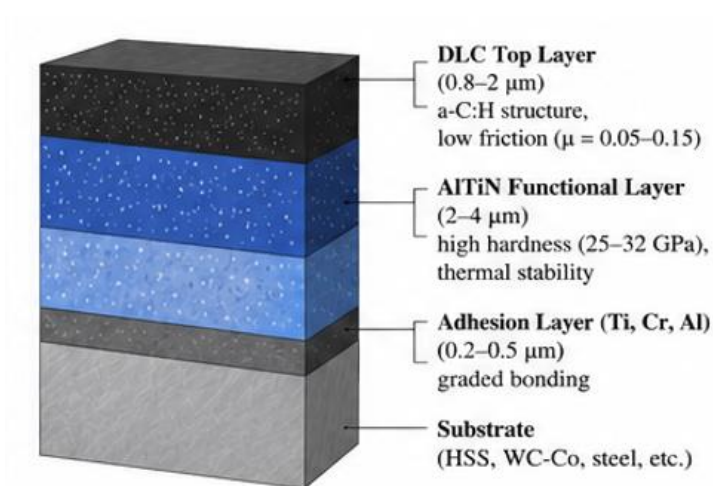


Figure 2 Typical hybrid multilayer architecture (AlTiN + DLC)

6.2 Positioning of Hybrid Coatings in the Tribological Space

Monolithic coatings show superiority along individual performance axes (CrAlSiN – thermal stability up to 1000°C; DLC – friction coefficient 0.05–0.15), while hybrid

systems (AlTiN+DLC and CrN+DLC) integrate high hardness, thermal stability and low friction coefficient, thereby occupying the **Pareto-optimal zone** of the tribological space [7,10].

6.3 Comparative Techno-Ecological Profile of Processes

Table 6 Comparative analysis of PVD, PACVD and CVD processes [3,11,12]

Parameter	PVD	PACVD (DLC)	Conventional CVD
Temperature	180–550°C	≤350°C	800–1000°C
Impact on substrate	Minimal	Minimal	Significant (tempering)
Layer thickness	2–6 μm	0.8–3 μm	5–15 μm
Wastewater	None	None	Present
Emissions	Low	Low	High (toxic precursors)

6.4 Limitations of DLC Coatings

DLC layers show limited thermal stability above 350°C due to graphitisation and relaxation of internal stresses [9]. Therefore, in demanding service conditions (cutting edge temperatures above 400°C), DLC is used exclusively as a top layer over thermally stable nitride bases (AlTiN, CrAlSiN) [10,14,15].

7 CONCLUSION

1. Hybrid PVD and PACVD (DLC) technologies represent a modern, environmentally friendly and technologically superior alternative to conventional surface protection methods. The low-temperature deposition regime (180–550°C for PVD, ≤250–350°C for DLC) enables the preservation of the microstructure and dimensional stability of the substrate, with the complete absence of wastewater and harmful chemical effluents, positioning them within the concept of green tribology [11,12].
2. The TOPSIS multi-criteria analysis showed a clear superiority of hybrid multilayer systems, with AlTiN+DLC achieving the highest closeness coefficient ($C_i = 0.91$) and CrN+DLC taking second place ($C_i = 0.88$).
3. A pronounced nonlinear synergistic effect was identified in combined PVD/PACVD systems, where the hard nitride base (AlTiN, 25–32 GPa) provides load-bearing capacity and resistance to deformation, while the DLC top layer ($\mu = 0.05$ – 0.15) enables an ultra-low friction coefficient and reduction of adhesive wear [2,4].
4. The developed decision tree enables a systematic selection of the optimal coating architecture based on five dominant wear mechanisms: thermal, abrasive, adhesive, corrosive and impact.
5. Contemporary industrial and literature data confirm that the application of advanced PVD, PACVD and hybrid multilayer coatings enables a significant extension of the service life of cutting tools (50–150%), tribological systems (2–4 times) and machine components, with reduction of wear, friction and energy losses [2,4,5,13].

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