



## Deposition Methods of Multilayer Hard Coatings for Improving Tribological Performance: A Mini-Review

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<p>Received: January 20, 2026 Peer-reviewed: January 27, 2026 Accepted: January 29, 2026</p>	<p><b>ABSTRACT</b> Multilayer hard coatings remain among the most effective engineering solutions for reducing friction and wear and for extending the service life of components operating under high contact loads. However, their practical performance is governed not by multilayering per se, but by the extent to which the selected deposition technology enables reproducible control over three key parameters: layer density and defectiveness, adhesion to the substrate and/or interlayers, and architectural tunability through interface quality. This mini-review systematizes deposition approaches relevant to tribological applications and proposes a generalized classification comprising chemical processes (sol–gel, chemical vapor deposition (CVD), atomic layer deposition (ALD), hydrothermal synthesis, electrodeposition, anodization, and electroless coatings), physical vacuum techniques of the PVD family (magnetron sputtering, cathodic arc deposition, hollow cathode discharge (HCD) ion plating, ion beam assisted deposition (IBAD), among others), as well as hybrid and functional solutions (PVD+CVD, composite, self-lubricating, and nanocomposite systems). It is demonstrated that the selection of a deposition process for multilayer architectures must be based on technological constraints that directly affect interface stability and coating durability, including the deposition temperature window and conformality, interfacial diffusion-induced boundary blurring, residual stresses, and critical defects such as porosity, macroparticles, and growth-related imperfections. Practical guidelines are formulated for correlating “architecture–deposition regime–microstructure–tribological behavior,” and key directions for future research are identified, including interface and defect engineering, targeted hybridization of deposition processes to compensate for intrinsic limitations (conformality, density, adhesion, and interface stability), and the use of predictive modeling validated by comparable tribological testing.</p>
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## Introduction

In mechanical systems, friction and wear inevitably arise at interfaces where components move relative to one another under direct contact, leading to significant energy losses and premature equipment failure [[1],[2]]. To address these challenges, researchers have developed a wide range of innovative approaches aimed at reducing friction and mitigating wear [[3],[4]]. Among them, the application of protective coatings remains one of the most reproducible and technologically mature engineering solutions, as coating properties can be purposefully tailored through the selection of material composition and architectural design.

Multilayer hard coatings have moved to the foreground as deposition technologies and surface-engineering strategies mature. Their performance is now dictated not only by chemical composition, but by the layer architecture itself and the way it is manufactured [[5],[6]]. In tribological service, two variables dominate: the quality of interfaces and the characteristic architectural length scales. Interfaces control barrier behavior, redistribute stresses, and impede crack propagation. Shrinking the multilayer period, in turn, is typically coupled with structural hardening and a shift in the prevailing damage mechanisms. A third factor cannot be treated as secondary: protective tribofilm formation at the sliding contact often sets the boundary conditions for friction and wear, and therefore directly shapes the measured tribological response [[7], [8], [9]].

At the same time, “multilayering” is not a performance guarantee. In practice, the ceiling is frequently imposed by structure-formation parameters of the chosen process rather than by the concept of layering itself. Deposition temperature and conformality, diffusion-driven interfacial smearing, defect population, and residual-stress state repeatedly emerge as the controlling limitations [10]. For that reason, we treat the deposition route as part of coating-architecture engineering, not as an afterthought. The selected process must deliver sharp interfaces, reproducible layer thickness, and a controllable defect spectrum for the specific substrate and component geometry under consideration.

In this mini-review, we systematize deposition technologies for multilayer coatings (MLCs) aimed at friction and wear reduction and compare them through a single set of capability–limitation criteria. Chemical routes are examined first (sol–gel, chemical vapor deposition (CVD), atomic layer deposition (ALD), hydrothermal synthesis,

electrodeposition, anodization, and electroless coatings). We then analyze physical vacuum approaches from the PVD family, including magnetron sputtering, cathodic arc deposition, hollow cathode discharge (HCD) ion plating, ion beam assisted deposition (IBAD), and related variants. Finally, hybrid and functional solutions are discussed – PVD+CVD combinations, composite architectures, self-lubricating systems, and nanocomposites. On this basis, we formulate practical guidelines for selecting deposition technologies to match the target architecture and service conditions, and we delineate research priorities centered on interface engineering, process hybridization, and predictive modeling of tribological response.

## Market Overview of Multilayer Coating Deposition Technologies

Demand for hard protective coatings is shaped by engineering use-cases rather than by academic curiosity. Industry asks for measurable outcomes: higher wear resistance, lower friction coefficient, longer fatigue life, and stronger corrosion tolerance in parts that see high contact stresses and/or elevated temperatures. In this context, multilayer architectures function as a design lever. By tuning interface density and layer periodicity, engineers adjust the residual-stress state, raise crack tolerance, and steer the tribochemical response of the coating through controlled interfacial phenomena.

Specialized market reports place the global hard-coatings market at roughly USD 1.72–1.73 billion in 2025, forecast it to reach USD 1.84–1.85 billion in 2026, and project USD 2.98–3.01 billion by 2033; these trajectories correspond to a CAGR of about 7.0–7.2% [[11], [12], [13]]. These numbers should be read for what they are: outputs of market-research models rather than experimentally validated scientific measurements. We cite them here for one purpose only – to justify the technological relevance of those market segments where multilayer coatings (MLCs) are deployed.

## Segmentation by End-Use Applications

Figure 1 summarizes how hard protective coatings are allocated across industrial sectors (2025 baseline with forecast estimates for 2026). The demand profile is skewed toward applications in which the coating operates as a functional reliability layer rather than a purely decorative finish. The

strongest pull comes from heavily loaded transportation and aerospace components, followed by medical devices and electronic systems, where service integrity is tightly coupled to surface performance.

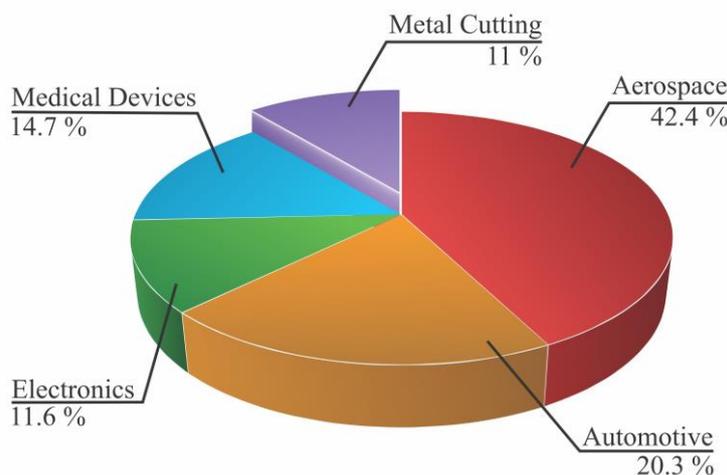
For multilayer coatings, the commercial value therefore extends beyond hardness metrics. It is set by manufacturing discipline: whether interfaces can be reproduced with minimal drift, whether friction and wear remain stable over long service intervals, and whether the defect population can be held within controlled bounds from batch to batch at production scale.

Figure 1 maps hard-coating demand across industrial sectors. The largest portion is tied to heavily loaded engineering domains, where coatings must satisfy concurrent constraints: high wear resistance, thermal stability, and a tribological response that remains predictable over prolonged service intervals.

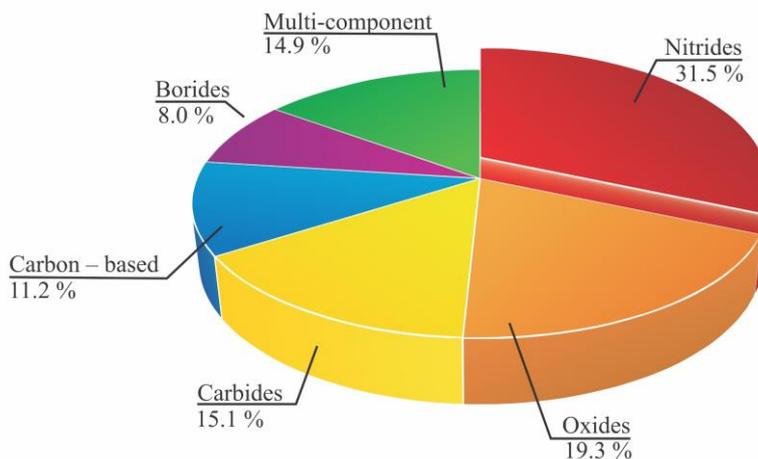
### Segmentation by Coating Material Type

Figure 2 compiles the material-type breakdown of hard coatings using aggregated statistics for 2023–2025. In this dataset, nitride-based coatings form the largest group (31.5%). Oxides follow at 19.3%, then carbides at 15.1%. Carbon-based coatings account for 11.2%, borides for 8.0%, and multicomponent systems for 14.9%.

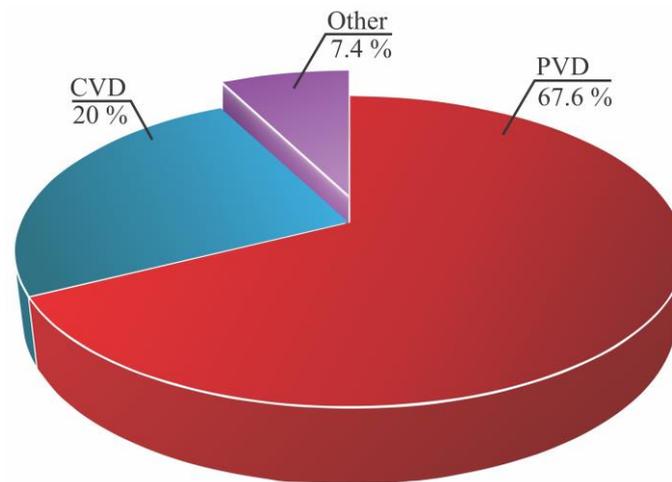
The ranking aligns with the engineering rationale of multilayer design. Nitrides are routinely selected as load-bearing and/or diffusion-barrier layers. Carbides and carbon-containing phases are introduced when the architecture must deliver lower friction and/or higher chemical resistance. Multicomponent compositions, by contrast, offer a practical route to stack several functions—hardness, oxidation resistance, and friction control—while preserving adhesion and maintaining thermal stability.



**Figure 1** - Distribution of end-use application sectors for hard protective coatings (2025 estimates with forecast values for 2026; aggregated from marketing review data) [11]



**Figure 2** - Material-type distribution of hard coatings (aggregated data for 2023–2025) [11]



**Figure 3** - Distribution of hard coating deposition technologies (2025 data; aggregated from marketing review sources) [11]

As summarized in Figure 2, nitride-based systems occupy the largest share of the dataset. This prevalence is consistent with their processing flexibility in PVD routes and with their practical role in multilayer periodic architectures, where stable growth conditions enable tight control over interface formation.

### Segmentation by Deposition Technology.

Figure 3 compares deposition routes used for hard coatings. The dataset is clearly PVD-weighted: physical vapor deposition accounts for  $\approx 67.5\%$  of reported technologies, CVD contributes roughly 20%, and the balance is distributed among other methods. This dominance matters for multilayer systems. PVD routes typically allow tighter metrology-level control over individual layer thickness and preserve interface sharpness – two parameters that govern whether interface-mediated strengthening and crack-arrest mechanisms can be reliably activated in service.

CVD retains a distinct niche. When the application prioritizes high thermal stability and/or strong conformality, CVD often provides the required film continuity on complex geometries. That advantage has a cost: the thermal budget intrinsic to CVD narrows the set of compatible substrates and constrains which multilayer architectures can be implemented without substrate degradation or interfacial smearing.

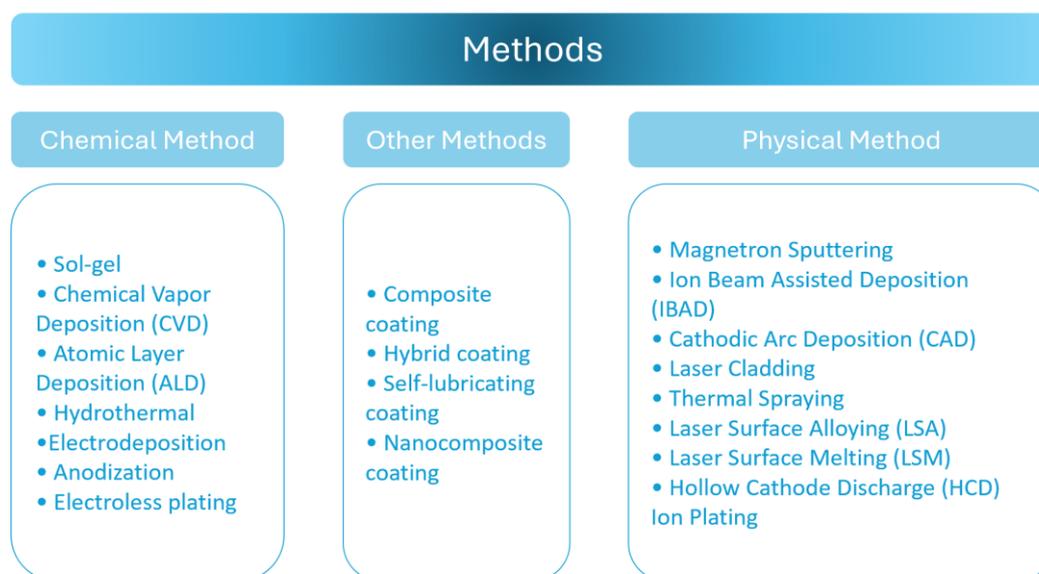
Figure 3 makes the market's technological base unambiguous: hard coatings are produced predominantly by PVD routes, and this positioning effectively turns PVD into the main industrial

platform for multilayer coatings (MLCs). CVD still occupies a sizeable fraction, yet its wider deployment is curtailed by the admissible deposition-temperature window and by substrate compatibility constraints.

The same segmentation points to a pragmatic selection criterion. Industry favors technologies that scale without losing reproducibility, i.e., routes that can hold layer periodicity, interface integrity, and defect population within controlled bounds while staying within an acceptable cost envelope. As a result, the deposition method is not chosen solely based on peak coating performance. Process robustness, the breadth of the workable parameter space, and batch-to-batch tolerances for property scatter carry comparable weight in decision-making.

### Classification of Multilayer Coating Deposition Methods

Deposition routes for multilayer coatings (MLCs) are best treated as an engineering toolbox: each process expands certain capabilities while simultaneously setting hard constraints on the properties that can be realized. In tribological practice, three control targets repeatedly determine success. The first is layer compactness together with the defect landscape (porosity, droplets/particles, columnar boundaries). The second is adhesion – both to the substrate and, where relevant, across interlayers. The third is functional response, which in multilayer systems is inseparable from the ability to reproduce the intended architecture (period, thickness ratios, and interface integrity).



**Figure 4** - Classification of multilayer coating deposition methods

With these requirements in view, we organize the deposition methods discussed in this review into three generalized groups. This classification provides a practical basis for selecting deposition routes intended to optimize coating performance, rather than treating deposition as a secondary processing step.

As illustrated in Figure 4, the methods are classified into three blocks: chemical methods, in which coating formation is governed by reactive transformations in the gas and/or liquid phase; hybrid and functional approaches that combine elements of chemical and physical processes to produce multifunctional layers; and physical methods, predominantly of the vacuum-based class, which enable controlled microstructure development and precise engineering of interlayer interfaces.

Chemical methods comprise processes in which coating growth is governed by reaction-controlled transformations and mass transport in the gas and/or liquid phase. This group includes sol-gel processing, chemical vapor deposition (CVD), atomic layer deposition (ALD), hydrothermal synthesis, electrodeposition, anodization, and electroless plating. From an engineering perspective, these approaches are typically regarded as effective routes for producing uniform and conformal layers on a wide range of substrates at moderate process temperatures, making them particularly suitable for forming individual functional layers and/or process stages where coating continuity is critical. At the same time, when applied to multilayer architectures, a specific limitation emerges:

diffusion – and reaction-driven phenomena at interfaces may lead to interlayer boundary blurring and, consequently, to reduced reproducibility of the intended architectural effects.

Hybrid and functional approaches are considered as a separate category, as they represent not a single deposition technique but rather a class of solutions in which the targeted tribological functionality is achieved through the combination of multiple processes and/or materials. As shown in Figure 4, this group includes composite, hybrid, self-lubricating, and nanocomposite coatings. From a practical standpoint, such solutions are employed to integrate properties that are difficult to achieve within a single process or material system—for example, low friction while maintaining load-bearing capacity and resistance to degradation. Accordingly, the key issue for this category is not the enumeration of composite variants, but rather reproducibility criteria, including controllability of phase/component distribution and interface stability within multilayer systems during scale-up.

Physical routes include vacuum evaporation and sputtering, along with allied processes in which coating outcome is set primarily by plasma/particle flux characteristics and by growth kinetics during film formation. In the scheme summarized in Figure 4, this class covers physical vapor deposition (PVD), magnetron sputtering, ion beam assisted deposition (IBAD), cathodic arc deposition (CAD), laser cladding, thermal spraying, laser surface alloying (LSA), laser surface melting (LSM), and hollow cathode discharge (HCD) ion plating. For multilayer coatings, these methods offer a practical advantage: they give

the operator comparatively direct leverage over microstructure and interface integrity. Layer thickness can be metered with high precision, and interface sharpness can be preserved – both are prerequisites for activating architecture-driven mechanisms that raise wear resistance.

This category, however, is not uniform. It spans fundamentally different process families and distinct engineering purposes. At one end sit vacuum thin-film techniques that enable nanometer-scale control of periodicity; at the other, localized deposition or surface-modification routes intended for thick coatings and repair scenarios. Such breadth forces a different comparison logic: we cannot rank technologies by name alone. Instead, we evaluate the constraints each process places on component geometry, defect generation, adhesion, and – crucially – the reproducibility of multilayer architectures.

Figure 4 therefore, functions as the organizing scaffold for the present mini-review. It allows us to compare deposition methods against three operational criteria – layer density/defectiveness, adhesion, and functional performance coupled with architectural controllability – and to select deposition routes that match specific tribological requirements.

### Chemical methods

Chemical methods for the formation of multilayer coatings (MLCs) are based on reaction-controlled layer growth in the gas and/or liquid phase and are applied where conformality, uniformity, and/or the formation of functional barrier or interlayers within the architecture are required. Chemical approaches include sol–gel processing, chemical vapor deposition (CVD), atomic layer deposition (ALD), hydrothermal synthesis, electrodeposition, anodization, and electroless plating.

For tribological applications, chemical methods can be rationally viewed as tools for addressing two practical tasks: (1) the fabrication of a continuous functional layer with a predefined chemical nature; and (2) the integration of this layer into a hybrid architecture with vacuum-based methods, where compatibility in terms of adhesion and interface stability is required.

CVD enables the deposition of dense coatings (reported to exceed 95% of the theoretical density) with high adhesion strength ( $\sigma_{adh} > 50$  MPa), including coatings on internal surfaces. However, its applicability to multilayer architectures is

constrained by the process window, notably high deposition temperatures ( $T \approx 1173$  K), precursor toxicity, and the risk of diffusion-induced interfacial blurring.

ALD is described as a self-limiting process with atomic-scale growth control and is particularly relevant for nanolaminates and thin functional interlayers, where reproducibility and nanometer-level thickness control are critical.

Sol–gel processing is characterized by low-temperature synthesis (293–423 K) and the capability to conformally coat complex geometries. Nevertheless, for tribological applications, key limitations summarized in Table 1 must be considered, including shrinkage during thermal treatment (up to 30%), porosity (>10%), and hydration. Consequently, sol–gel approaches are well-suited for forming oxide-based functional layers (e.g.,  $\text{SiO}_2$ ,  $\text{TiO}_2$ ); however, when designing wear-resistant multilayer systems, the effects of porosity and shrinkage on mechanical integrity and interface stability must be carefully accounted for.

Hydrothermal and solution-based processes are employed to form specific functional layers. Hydrothermal synthesis is conducted in aqueous solutions under elevated pressure and is described as an approach that promotes crystallization of oxide structures without the use of organic solvents. Electrodeposition and electroless plating enable the formation of metallic layers at near-room temperature, but require strict control of pH and electrolyte composition due to the risk of hydrogen embrittlement. Anodization produces porous oxide films and is inherently limited to valve metals.

A critical limitation of chemical methods in multilayer coatings is interfacial diffusion, which can lead to boundary blurring and reduced mechanical integrity of the multilayer system. To mitigate these effects, post-treatments aimed at improving interface quality are often required. Consequently, in tribological multilayer coatings, chemical methods typically function as part of a broader technological route—often at early stages of graded structure formation—and/or as elements of hybrid schemes, where their combination with physical methods is considered a means to enhance resistance to tribological degradation.

Comparative characteristics of chemical methods, including temperature windows, risks of porosity and shrinkage, interfacial blurring, and typical application domains, are summarized in Table 1.

**Table 1** - Chemical methods

Method	Advantages	Limitations	Scientific Applications	References
<b>Sol-gel</b>	Low-temperature synthesis (293–423 K); molecular homogeneity; conformal coating of complex topologies	Shrinkage during heat treatment (up to 30%); porosity (>10%); hydration	Formation of amorphous oxide matrices (SiO <sub>2</sub> , TiO <sub>2</sub> ) for biocompatible implants and optical coatings	[[14], [15]]
<b>Chemical Vapor Deposition (CVD)</b>	High density (>95% of theoretical); excellent adhesion ( $\sigma_{adh} > 50$ MPa); capability to coat internal surfaces	High thermal load (T > 1173 K); diffusion-induced interface blurring ( $D > 10^{-18}$ m <sup>2</sup> /s <sup>-1</sup> ); toxic precursors	Thermal barrier coatings (YSZ); monolithic carbide layers on WC-Co	[[16],[17], [18]]
<b>Atomic Layer Deposition (ALD)</b>	Self-limiting growth (0.1–0.3 Å/cycle <sup>-1</sup> ); conformality >99%; atomic-scale thickness control	Low deposition rate (1–5 nm/min); high precursor cost (TiCl <sub>4</sub> , TMA); vacuum requirements	Nanolaminates (Al <sub>2</sub> O <sub>3</sub> /TiN); barrier layers in microelectronics; polymer protection	[[19],[20]]
<b>Hydrothermal synthesis</b>	Crystallization at moderate temperatures (373–573 K); environmentally benign; solvent-free organic chemistry	Restricted to aqueous systems; low kinetics (hours–days)	Nanostructured oxide synthesis (ZnO, TiO <sub>2</sub> ) for photocatalysis and sensors	[[21], [22]]
<b>Electrodeposition</b>	Room-temperature processing; scalability; low cost	Limited to conductive substrates; hydrogen embrittlement risk	Electrochemical deposition of Ni–P, Cu for corrosion protection	[[23], [24]]
<b>Anodization</b>	Local strengthening; formation of porous oxides (pore diameter 20–200 nm)	Restricted to valve metals (Ti, Al, Ta); thickness <50 μm	Anodized Ti <sub>6</sub> Al <sub>4</sub> V for osteointegration and biomedical implants	[[25], [26], [27]]
<b>Electroless plating</b>	Deposition on dielectrics; high thickness uniformity (±5%)	Bath instability; phosphorus-induced embrittlement	Ni–P coatings on polymers and printed circuit boards	[[28], [29]]

Table 1 indicates that chemical methods can be rationally regarded as tools for forming functional layers with high uniformity, albeit with fundamentally different technological trade-offs. Sol-gel processing offers advantages in terms of temperature window and cost, but is limited by shrinkage and porosity; CVD provides high density and strong adhesion, yet requires elevated temperatures and toxic precursors; ALD delivers the highest level of thickness control at the nanometer-scale, but is primarily suited for thin layers and localized architectural tuning; solution-based methods (hydrothermal synthesis, electrodeposition, electroless plating, and anodization) are advantageous under low thermal loads, while imposing constraints related to process chemistry, risks of hydrogen embrittlement, and/or substrate material compatibility.

### Other / Hybrid Methods

In this work, the group of Other Methods is treated as a separate category, as it does not represent an additional deposition technique per se, but rather a set of engineering solutions aimed at multifunctionality, in which the desired tribological response is achieved through combinations of phases and structures and/or through the integration of multiple technological routes. The main variants within this group include composite, hybrid (PVD+CVD), self-lubricating, and nanocomposite coatings; their comparative characteristics are summarized in Table 2.

Composite coatings exploit dispersed functional phases to couple two targets that often compete: high hardness and low friction. Table 2 lists representative performance benchmarks ( $H > 40$

GPa,  $\mu < 0.2$ ) and provides example formulations used in cutting-tool service, including nc-TiN/a-Si<sub>3</sub>N<sub>4</sub> architectures with MoS<sub>2</sub> additives. The approach remains sensitive to microstructural stability. Phase segregation and the practical difficulty of metering dispersion quality and spatial distribution limit repeatability; in multilayer systems, that variability translates directly into scatter of measured properties.

Hybrid PVD+CVD schemes address a different constraint set and are typically adopted as a process-level compromise. Here, PVD supplies nanostructuring capability, whereas CVD is used to achieve high layer density. Table 2 illustrates this route with TiCN/TiN coatings deposited on cemented carbide inserts. Two obstacles recur in industrial deployment: high capital cost and the emergence of thermal gradients. Both factors complicate scale-up and can erode architectural stability when the process is pushed to production throughput.

Self-lubricating coatings pursue friction reduction through the in situ generation and/or controlled release of lubricious species. Table 2 highlights a MoS<sub>2</sub>-based system that undergoes transformation to MoO<sub>3</sub> and reports friction coefficients as low as  $\mu < 0.1$  under vacuum – conditions characteristic of dry-friction assemblies, including space mechanisms. Their weakness is equally clear. Oxidative degradation limits operation at elevated temperature (Table 2 indicates constraints above  $T > 673$  K), and service life is finite, which must be accounted for when defining operating windows and when selecting multilayer architectures.

Nanocomposite coatings exploit nanoscale phase dispersion to achieve a combination of superhardness and fracture toughness. Table 2 reports representative benchmarks ( $H > 40$  GPa,  $K_{(IC)} > 5$  MPa·m<sup>1/2</sup>) and example systems (nc-TiC/a-C, nc-WC/DLC) intended for extreme loading conditions. The primary technological risk is nanoparticle agglomeration and the complexity of synthesis and dispersion control, which can lead to property scatter and reduced coating strength.

Across all Other Methods, a common bottleneck is the controllability of phase dispersion and the stability of interphase and interlayer boundaries. The manuscript explicitly notes that difficulties in dispersion control promote nanoparticle agglomeration and, in multilayer systems, phase segregation; compared to physical methods, these approaches often exhibit inferior density unless additional post-treatment is applied. Consequently, their use in tribological multilayer coatings is primarily justified in applications where adaptability (self-lubrication and multifunctionality) is required and where increased process complexity is acceptable, including hybridization with vacuum-based methods to improve interface quality.

Table 2 indicates that Other Methods provide enhanced functionality—such as friction reduction, adaptive lubricating phases, and the combination of high hardness with fracture toughness—but require substantially stricter structural control. The key risks are associated with phase segregation and agglomeration, thermal stability limitations (particularly for self-lubricating systems at  $T > 673$  K), and the technological complexity inherent to hybrid PVD+CVD routes.

**Table 2** - Other/Hybrid Methods

Method	Advantages	Limitations	Scientific Applications	References
<b>Composite coatings</b>	Synergistic strengthening ( $H > 40$ GPa) with reduced friction ( $\mu < 0.2$ ); adaptive response	Phase segregation; difficulty in dispersion control	nc-TiN/a-Si <sub>3</sub> N <sub>4</sub> + MoS <sub>2</sub> for cutting tools	[[30], [31]]
<b>Hybrid coatings (PVD + CVD)</b>	Combined microstructure: PVD-induced nanostructuring and CVD-derived high density	High capital cost; thermal gradients complicating scale-up	TiCN/TiN coatings on cemented carbide inserts	[32]
<b>Self-lubricating coatings</b>	In situ formation of lubricious phases (MoS <sub>2</sub> → MoO <sub>3</sub> ); $\mu < 0.1$ in vacuum	Oxidative degradation at $T > 673$ K; limited lifetime	Space mechanisms; dry-friction systems	[[33], [34]]
<b>Nanocomposite coatings</b>	Superhardness ( $H > 40$ GPa); high fracture toughness ( $K_{(IC)} > 5$ MPa·m <sup>1/2</sup> )	Nanophase agglomeration; synthesis complexity	nc-TiC/a-C, nc-WC/DLC for extreme loading conditions	[[35], [36], [37]]

## Physical PVD Methods

Physical deposition methods for multilayer coatings (MLCs), primarily those belonging to the PVD family, remain the core technology for tribological systems, as they offer high adhesion, microstructural control, and architectural reproducibility under vacuum conditions and at moderate process temperatures. As summarized in Table 3, the key processes in this class—magnetron sputtering, HCD ion plating, IBAD, CAD, as well as laser cladding, thermal spraying, and LSA/LSM – differ mainly in terms of achievable density and defect levels, adhesion strength, controllability of layer thickness, and technological constraints (vacuum requirements, deposition rate, and growth-related defects).

Relative to chemical routes, physical processes preserve interface sharpness more reliably and allow tighter defect management through plasma tuning and/or ion bombardment. That capability matters for MLCs subjected to abrasive wear and contact-fatigue loading, where interfacial integrity and defect population often set the failure threshold. The same vacuum-based PVD family carries a structural drawback: most techniques are intrinsically line-of-sight. Uniform coverage on complex geometries therefore degrades unless the process is supported by compensatory технологические решения (fixturing, motion strategies, plasma configuration, and related measures).

For multilayer tribological coatings, magnetron sputtering remains the workhorse for building periodic stacks and functionally graded designs under controlled plasma conditions. Reported characteristics include a high ionization degree (up to 70%), dense columnar growth ( $\rho > 98\%$  of the theoretical value), and high adhesion strength ( $\sigma_{\text{adh}} > 80$  MPa) when substrate ion bombardment is applied. The method also enables nanoscale metering of layer thickness (0.1–5 nm per layer) with an indicated accuracy of  $\pm 2\%$ . The limitations are largely technological: stringent vacuum requirements are cited (ultra-high vacuum,  $P < 10^{-4}$  Pa), and the geometry dependence typical of PVD persists due to the line-of-sight nature of the flux.

HCD ion plating is characterized by an even higher ionization fraction ( $>90\%$ ) and strong adhesion ( $>60$  MPa), combined with a highly dense columnar microstructure ( $\rho > 99\%$ ). The constraints

here are practical rather than conceptual. A more complex plasma source and higher ion energies demand tighter control of substrate bias and of interlayer boundary formation; if these variables drift, defect generation and residual-stress buildup become increasingly likely.

IBAD and CAD can both be positioned as routes for interface strengthening and/or throughput gains, but they reach that goal through different compromises. IBAD delivers ion-induced interfacial reinforcement ( $E > 10$  keV) and is associated with reduced residual stresses. Deposition rate, however, is extremely low ( $<1$  nm·s<sup>-1</sup>), which limits industrial use for thick coatings and large production batches. CAD moves in the opposite direction: deposition rates can reach 100 nm·s<sup>-1</sup>, and adhesion remains high, yet macroparticles ( $d > 1$  μm) represent a critical defect class. If filtration and defect control are insufficient, these inclusions become failure initiation sites and can partially erode the advantages expected from multilayer architectures.

A separate class comprises technologies intended for thick coatings and localized repair or modification. Laser cladding enables localized deposition and alloying with thicknesses exceeding 1 mm and allows the formation of graded properties; however, it is constrained by the risk of thermal cracking and porosity ( $>5\%$ ), which imposes strict requirements on thermal cycling and surface preparation. Thermal spraying provides high productivity (coating thicknesses of 50–500 μm), but is characterized by significant porosity (5–15%) and relatively low adhesion; consequently, it is more commonly applied as a thick protective solution under abrasive wear conditions rather than as a method for precise interface engineering. LSA and LSM are surface modification techniques affecting the near-surface layer (up to 1 mm) and promoting microstructural homogenization; nevertheless, the risk of martensitic transformation—i.e., undesirable structural changes in the substrate and heat-affected zone—must be considered, as it can be critical for component service life.

Overall, most physical methods share two systemic limitations: (1) geometric directionality (line-of-sight), which reduces coating uniformity on complex three-dimensional components; and (2) the need for separate optimization of adhesion and defect populations, including issues related to macroparticles in arc-based processes and porosity in thick-coating technologies.

**Table 3** - Physical Methods (PVD-Based)

Method	Advantages	Limitations	Scientific Applications	References
<b>Magnetron sputtering</b>	High plasma ionization (up to 70%); dense columnar structures ( $\rho > 98\%$ ); excellent adhesion ( $\sigma_{\text{adh}} > 80$ MPa); nanometer-scale thickness control (0.1–5 nm/layer <sup>-1</sup> , $\pm 2\%$ ); absence of macroparticles (CFUBMS); suitability for complex 3D geometries	Line-of-sight limitation; requirement for ultra-high vacuum ( $P < 10^{-4}$ Pa)	Functionally graded TiN/TiCN/TiC multilayers for cutting tools and biomedical implants	[[38], [39], [40]]
<b>HCD ion plating</b>	Ionization degree $>90\%$ ; dense columns ( $\rho > 99\%$ ); high adhesion ( $>60$ MPa)	Complex plasma source; high ion energy requiring strict process control	TiC/TiCo <sub>0.5</sub> No <sub>0.5</sub> /TiN multilayers on high-speed steel	[41]
<b>IBAD</b>	Interface strengthening via ion bombardment ( $E > 10$ keV); reduced residual stresses	Very low deposition rate ( $<1$ nm/s <sup>-1</sup> )	Functionally graded interlayers	[42]
<b>Cathodic Arc Deposition (CAD)</b>	Very high deposition rate (up to 100 nm/s <sup>-1</sup> ); excellent adhesion	Macroparticles ( $d > 1$ $\mu\text{m}$ ); requires filtration	TiN, CrN coatings on cutting edges	[[43], [44]]
<b>Laser cladding</b>	Local alloying; thickness $>1$ mm; gradient properties	Thermal cracking; porosity ( $>5\%$ )	Turbine blade repair	[45]
<b>Thermal spraying</b>	High productivity; thick coatings (50–500 $\mu\text{m}$ )	Porosity (5–15%); relatively low adhesion	Protection against abrasive wear	[46]
<b>LSA / LSM</b>	Near-surface modification (up to 1 mm); microstructural homogenization	Risk of martensitic transformation	Surface strengthening of high-speed steels	[[47], [48], [49], [50], [51], [52], [53], [54], [55], [56], [57], [58]]

Table 3 captures a key practical insight: physical processes—primarily those of the PVD family—provide the highest level of control over multilayer architectures at the nanometer scale, including bilayer thickness, interface sharpness, coating density, and adhesion; however, the selection of a specific process is governed by characteristic trade-offs. Magnetron sputtering represents the baseline option for dense, functionally graded multilayer systems under stringent vacuum requirements; HCD ion plating is preferred where high ionization and strong adhesion are critical; IBAD is employed for interface engineering under constraints on deposition rate; CAD is selected for high productivity, provided that macroparticle suppression is ensured; and laser cladding, thermal spraying, and LSA–LSM are suitable for thick coatings and localized strengthening or repair, albeit with typical risks of porosity and thermally induced defects.

Physical routes are generally favored for multilayer coatings (MLCs) because they offer the

highest reproducibility in defining interlayer boundaries and bilayer thickness, while keeping interdiffusion within a limited range. This consideration motivates a shift from the broad классификационного обзора to process-specific discussion. We therefore narrow the scope in the following section and examine PVD methods in detail, treating them as the baseline industrial platform for fabricating thin-film multilayer systems. PVD processes are inherently designed for controlled sputtering/evaporation under vacuum conditions and for precise tuning of particle flux and plasma parameters, which directly determine coating density, growth-related defect populations, and interface quality.

Within the PVD category, the most promising methods are subsequently identified and discussed in sequence—cathodic sputtering, plasma spraying, and magnetron sputtering—since these processes constitute the practical and technological backbone of most industrial solutions. They differ in the mechanisms of ionized flux generation, particle

energy, deposition rate, and characteristic defect formation, i.e., the parameters that ultimately define the achievable limits of friction and wear performance as well as the operational stability of multilayer architectures.

### Cathodic Sputtering

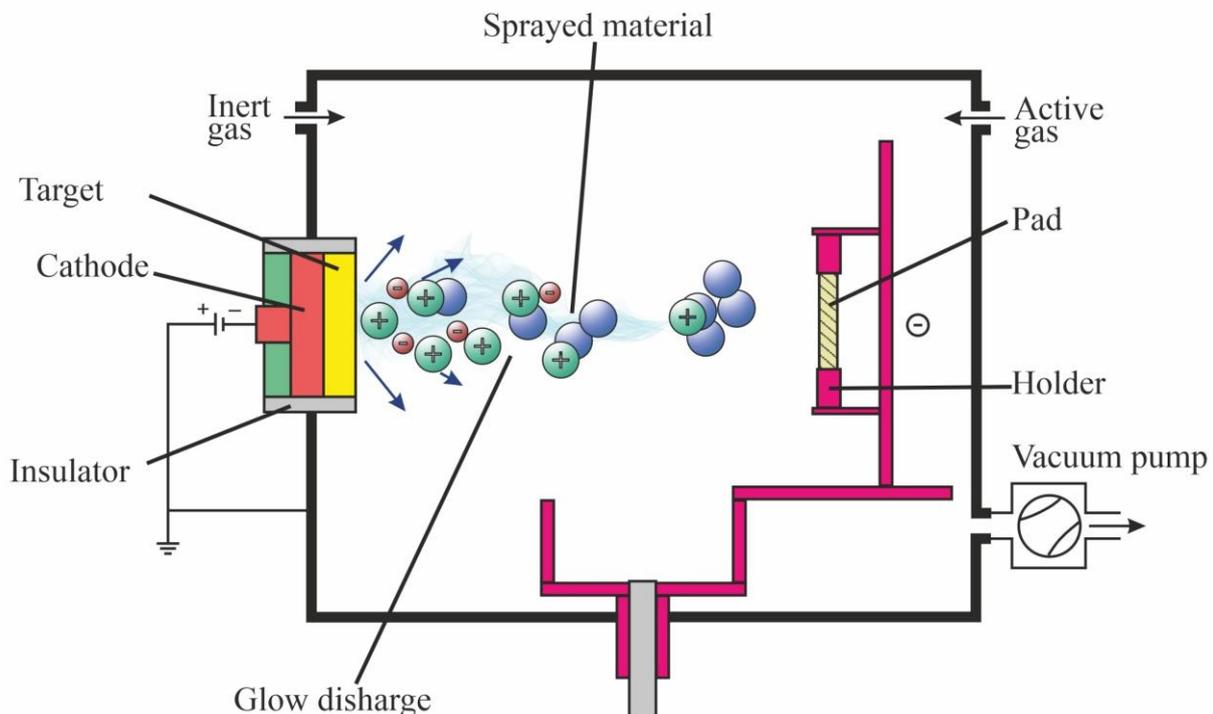
Cathodic sputtering is a fundamental PVD deposition technique in which material transport to the coating is driven by ion bombardment of a target under low-pressure discharge conditions. The method is technologically straightforward in implementation, yet highly sensitive to discharge parameters and the gas environment, as these factors govern the sputtering rate, particle energy at the substrate, layer density and defectiveness, and the reproducibility of interlayer boundaries during multilayer coating formation.

Figure 5 presents a schematic representation of a typical cathodic sputtering setup in a vacuum chamber. After evacuation, an inert gas—most commonly argon (Ar) – is introduced into the chamber, initiating a glow discharge between the cathodic target and the anode component of the system. Within the plasma, positively charged inert gas ions are generated and accelerated by the electric field toward the target surface. As a result of momentum transfer, atoms or clusters of the target

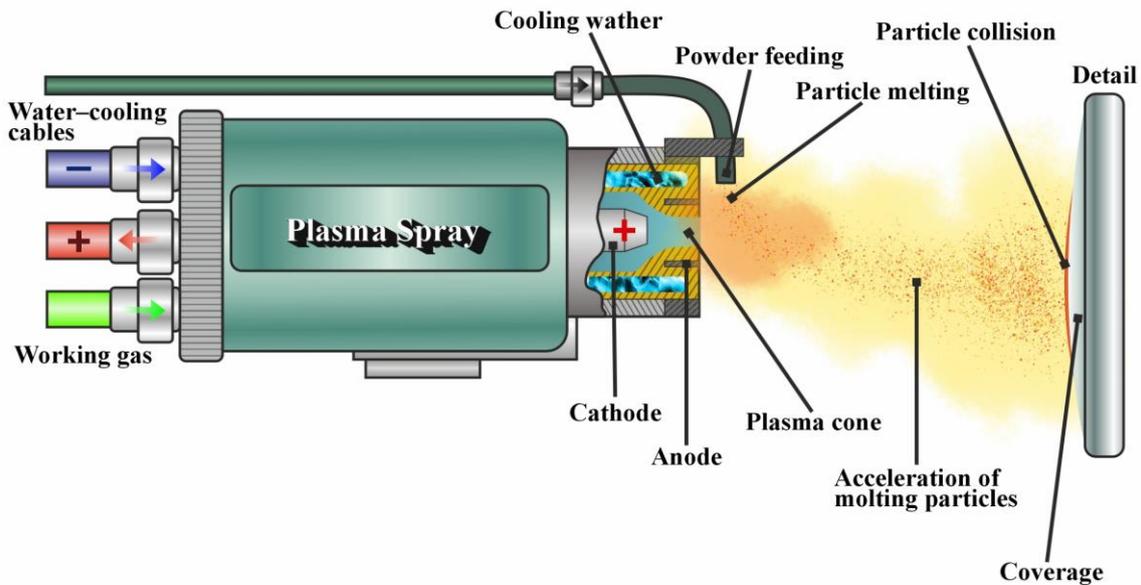
Materials are sputtered; the resulting flux of sputtered species is transported through the gas phase and condenses on the substrate mounted on a holder, thereby forming the coating.

The scheme also illustrates the reactive sputtering mode: upon the introduction of an active gas (e.g.,  $N_2$ ,  $O_2$ ,  $CH_4$ ), sputtered atoms react either in the gas phase and/or on the substrate surface, resulting in the formation of compounds such as nitrides, oxides, or carbides. In this configuration, two process variables dominate the outcome: the active-gas flow balance and discharge stability. Both directly govern the chemistry of the growing layer, the defect population, and the integrity of interlayer interfaces within multilayer architectures.

From an engineering standpoint, cathodic sputtering remains a workhorse for depositing metallic and compound layers when the key targets are reproducible thickness control and sufficiently sharp interfaces. The method, however, inherits the line-of-sight constraint typical of vacuum deposition routes, which degrades thickness uniformity on complex geometries. Reactive sputtering adds another layer of sensitivity. When gas delivery or discharge parameters drift, layer stoichiometry shifts and property scatter increases; in multilayer stacks, this manifests as poorer reproducibility of interlayer boundaries and a broader spread in tribological response.



**Figure 5** - Schematic diagram of cathodic sputtering in a glow discharge under inert/reactive gas atmospheres



**Figure 6** - Schematic representation of the plasma spraying process: powder feeding into the plasma torch, particle melting/acceleration, and coating formation on the component

### Plasma Spraying

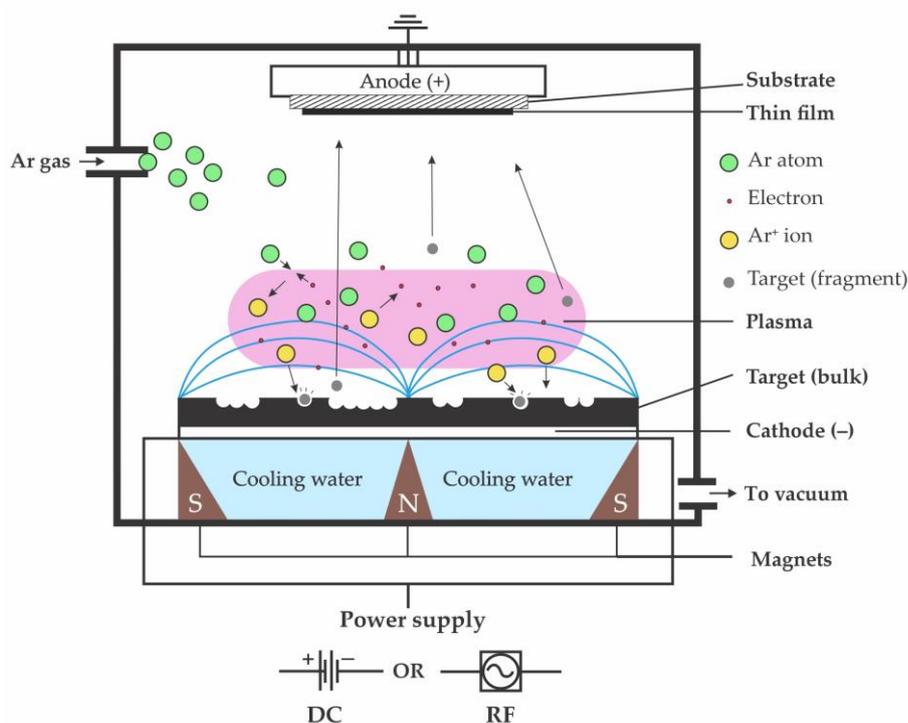
Plasma spraying is a thermal deposition route in which the feedstock arrives at the surface as molten or partially molten particles. This mechanism separates it sharply from cathodic or magnetron sputtering. Under sputtering, an atomic or ionic flux evolves in a vacuum environment and builds the film atom by atom; in plasma spraying, powder particles are heated, accelerated, and driven into the substrate, and coating growth proceeds through successive particle impacts. The resulting microstructure therefore tracks particle dynamics – temperature, velocity, and flight path – together with impact deformation and lamella formation/closure, rather than being dictated solely by plasma discharge settings.

Figure 6 schematically depicts the plasma-spraying setup. The process gas enters the torch, and an electric discharge between the cathode and anode sustains a high-enthalpy plasma jet (plasma cone). Water-cooling circuits protect the torch hardware, as indicated by the cooling lines. The powder feedstock is injected into the plasma region; particles heat to molten or semi-molten states while the gas stream accelerates them toward the workpiece. Collisions within the jet can occur, producing a spread in particle temperature and velocity before impact. On contact with the surface, molten particles flatten and solidify on short timescales, generating the coating. Layer continuity and thickness uniformity are then governed by spray distance, jet energy, and powder-feed conditions.

From the perspective of multilayer systems, plasma spraying is best regarded as a method for producing thick functional layers (tens to hundreds of micrometers or more), in which architectural control is implemented at the macroscale, while interface quality is governed by pass repeatability, thermal cycling, and the stability of particle kinetics. In tribological applications, this makes the method practical for protective coatings operating under abrasive wear, erosion, and high-temperature degradation conditions; however, it is not a direct analogue of PVD in terms of nanometer-scale control over interlayer boundaries and defect populations.

### Magnetron Sputtering

Magnetron sputtering represents an advanced form of cathodic sputtering in which a magnetic field is employed to stabilize and intensify the discharge by confining electrons near the target surface. As a result, the degree of working gas ionization increases, plasma density is enhanced, and sputtering efficiency improves at lower operating pressures. In practice, this translates into two outcomes that matter for multilayer tribological coatings. First, the process offers high deposition repeatability together with tight metering of individual layer thickness. Second, once the parameter window is properly tuned, it suppresses defect formation and promotes coating densification.



**Figure 7** - Schematic of magnetron sputtering: plasma localization by a magnetic field near the target,  $\text{Ar}^+$  bombardment, and deposition of sputtered material onto the substrate (DC/RF modes)

Figure 7 schematically outlines magnetron sputtering. Argon is admitted into the evacuated chamber, and a plasma is then sustained between the cathodic target (target, cathode  $-$ ) and the anode/substrate assembly (anode  $+$ , substrate). A magnet set placed behind the target establishes closed magnetic field lines that trap electrons near the cathode surface; the local electron confinement raises plasma density in the region immediately above the target.  $\text{Ar}^+$  ions accelerate toward the cathode and bombard the target, ejecting atoms (or target-derived fragments). These species traverse the chamber and condense on the substrate, where they coalesce into a thin film. The schematic also indicates that power can be supplied in either DC or RF mode, thereby extending the applicability of the method to different target materials and deposition regimes.

From an engineering perspective, magnetron sputtering is the primary PVD tool for constructing multilayer structures with high reproducibility, as it enables stable process operation in regimes that provide a favorable balance between deposition rate and coating quality. For multilayer architectures, a key advantage is the controlled formation of layers with predefined thicknesses and relatively sharp interlayer boundaries, as well as the capability to operate in reactive modes (with the introduction of  $\text{N}_2$ ,  $\text{O}_2$ , etc.) for the deposition of

nitride and oxide layers. The limitations are predominantly technological in nature, including geometric dependence (line-of-sight), the need to control substrate heating and plasma stability, and—in reactive sputtering—the sensitivity to active gas flow rates and discharge conditions, which directly affect the composition and defect density of the growing layer.

## Conclusions

This review demonstrates that the effectiveness of multilayer coatings in tribological applications is governed not by multilayering per se, but by the extent to which the selected deposition method provides reproducible control over three key parameters: layer density and defect population, adhesion to the substrate and/or interlayers, and architectural controllability through interface quality. Accordingly, the deposition technology should be regarded as a limiting factor for the attainable coating properties. Chemical processes are well-suited for conformal functional and barrier layers, yet are sensitive to interfacial blurring; hybrid and functional solutions enable multifunctionality at the cost of stricter requirements for structural reproducibility; and physical vacuum-based methods—particularly those of the PVD family—remain the foundational platform, as they offer

superior control over microstructure and interlayer boundaries, which constitute the primary mechanism underlying genuine architectural effects.

Future developments are expected to shift from merely expanding the range of coating materials toward interface and defect engineering. Key priorities include controlling interface sharpness and intermixing, mitigating critical defects (macroparticles, porosity, and growth-related imperfections), and managing residual stresses, all of which govern coating lifetime under contact fatigue and abrasive wear. Of particular practical relevance are targeted hybrid process routes, in which the deliberate combination of deposition methods compensates for specific limitations (conformality, density, adhesion, and interface stability), as well as the integrated framework linking “architecture–deposition regime–microstructure–tribological behavior,” validated by comparable tribological

testing and, where appropriate, supported by multiphysics modeling.

**Conflicts of interest.** On behalf of all authors, the corresponding author states that there is no conflict of interest.

**CRedit author statement:** **N. Bakhytuly:** Supervision, Investigation, Data curation; **K. Smailov:** Conceptualization, Writing draft preparation, Reviewing and Editing; **A. Kenzhegulov:** Conceptualization, Supervision; Validation, Data curation; **M. Kudabayeva:** Investigation, Data curation, Software. **A. Yessengazyev:** Supervision; Validation, Data curation; **D. Karim:** Data curation, Visualization, Software; **T. Arynbayev:** Conceptualization, Data curation.

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## Трибологиялық сипаттамаларды жақсартуға арналған көпқабатты қатты жабындарды тұндыру әдістері: шағын шолу

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### ТҮЙІНДЕМЕ

Көпқабатты қатты жабындар жоғары жанасу жүктемелері кезінде жұмыс істейтін бөлшектердің үйкелісі мен тозуын азайту сонымен қатар қызмет ету мерзімін ұзарту үшін ең тиімді инженерлік шешімдердің бірі болып табылады. Дегенмен, олардың практикалық тиімділігі көп қабаттылықтың өзіне емес, таңдалған тұндыру технологиясының үш негізгі параметрлері – қабат тығыздығы мен ақаулары, негізге және/немесе аралық қабаттарға адгезия, сондай-ақ интерфейстердің сапасы арқылы архитектураны басқару мүмкіндігін – қаншалықты тұрақты қамтамасыз ететініне байланысты болады. Бұл шағын шолуда трибологиялық қолданбалар үшін өзекті тұндыру әдістері жүйеленіп, олардың жалпыланған жіктелімі ұсынылған: химиялық процестерді қамтитын (sol-gel, газ фазасынан химиялық тұндыру (CVD), атомдық-қабаттық тұндыру (ALD), гидротермалдық синтез, электролиттік тұндыру, анодтау және электролитсіз тұндыру), PVD тобына жататын физикалық вакуумдық әдістер (магнетронды тозаңдату, катодты-доғалық тұндыру, қуыс катодты разрядтағы иондық тұндыру (HCD), ион-сәулелік көмекші тұндыру (IBAD) және т.б.), сондай-ақ гибриді және функционалдық шешімдер (PVD+CVD, композиттік, өздігінен майланатын және нанокөпозиттік жүйелер). Көпқабатты архитектуралар үшін тұндыру әдісін таңдау интерфейстердің тұрақтылығы мен жабынның ұзақ мерзімділігіне тікелей әсер ететін технологиялық шектеулерге негізделуі тиіс екені көрсетілген, оның ішінде тұндыру температурасының диапазоны мен конформдылығы, диффузиялық араласу салдарынан шекаралардың бұлыңғырлануы, қалдық кернеулер және кеуектілік, макробөлшектер мен өсу ақаулары сияқты критикалық кемшіліктер бар. «Архитектура – тұндыру режимі – микроқұрылым – трибологиялық сипаттама» байланысын үйлестіруге арналған практикалық бағдарлар ұсынылып, әрі қарайғы зерттеулердің негізгі бағыттары анықталды, соның ішінде интерфейстер мен ақаулар инженериясы, ішкі шектеулерді (конформдылық, тығыздық, адгезия және интерфейстердің тұрақтылығы) өтеу үшін тұндыру процестерін мақсатты гибридету және салыстырмалы трибологиялық сынақтармен расталған болжамды модельдеуді қолдану ұсынылған.

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## Методы осаждения многослойных твёрдых покрытий для улучшения трибологических характеристик: мини-обзор

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<p>Поступила: 20 января 2026 Рецензирование: 27 января 2026 Принята в печать: 29 января 2026</p>	<p><b>АННОТАЦИЯ</b></p> <p>Многослойные твёрдые покрытия остаются одним из наиболее эффективных инженерных решений для снижения трения и износа, а также для увеличения срока службы деталей, работающих при высоких контактных нагрузках. Однако их практическая эффективность определяется не самой многослойностью, а тем, насколько выбранная технология осаждения обеспечивает воспроизводимый контроль трёх ключевых параметров: плотности и дефектности слоя, адгезии к подложке и/или межслоевым прослойкам, а также управляемости архитектуры через качество интерфейсов. В данном мини-обзоре систематизированы методы осаждения, релевантные для трибологических применений, и предложена их обобщённая классификация, включающая химические процессы (sol-gel, химическое осаждение из газовой фазы (CVD), атомно-слоевое осаждение (ALD), гидротермальный синтез, электроосаждение, анодирование и безэлектролитное осаждение), физические вакуумные методы семейства PVD (магнетронное распыление, катодно-дуговое осаждение, ионное осаждение в разряде с полым катодом (HCD), ионно-лучевое ассистированное осаждение (IBAD) и др.), а также гибридные и функциональные решения (PVD+CVD, композитные, самосмазывающиеся и нанокompозитные системы). Показано, что выбор метода осаждения для многослойных архитектур должен основываться на технологических ограничениях, напрямую влияющих на стабильность интерфейсов и долговечность покрытия, включая температурное окно и конформность осаждения, диффузионное размывание границ, остаточные напряжения и критические дефекты, такие как пористость, макрочастицы и дефекты роста. Сформулированы практические ориентиры согласования «архитектура – режим осаждения – микроструктура – трибологическое поведение», а также обозначены ключевые направления дальнейших исследований, включая инженерию интерфейсов и дефектов, целенаправленную гибридизацию процессов осаждения для компенсации присущих ограничений (конформность, плотность, адгезия и стабильность интерфейсов) и использование прогностического моделирования, подтверждённого сопоставимыми трибологическими испытаниями.</p> <p><b>Ключевые слова:</b> многослойные твёрдые покрытия, CVD, PVD, магнетронное распыление, нитриды переходных металлов.</p>
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