

$\bar{\phi}$	Volumetric film flux vector, m^2/s
$\delta\xi, \delta\eta$	Infinitesimal angular displacement components of rotor, <i>radians</i>
λ	Real part of s
A	Bearing number, $= 6(\mu VR)(p_a C^2)^{-1}$
μ	Gas viscosity, $Pa \cdot s$
\bar{v}	Outward normal base-vector of bearing surface
$\sigma_\tau, \sigma_C, \sigma_P$	Rarefaction coefficients for mid-film shear, Couette flux, Poiseuille flux
$\bar{\tau}$	Mid-film in-plane shear stress, <i>MPa</i>
ω	Rotational rate, <i>rad/s</i>
Ω	Ratio of oscillation rate to rotational rate, whirl ratio
Ω'	Damped natural frequency, <i>rad/s</i>
Mathematical symbols	
div	Divergence operator, $\equiv \text{grad} \cdot, m^{-1}$
grad	Gradient operator, m^{-1}
$h_{(\)}$	Jacobian derivative of film thickness with respect to the generic displacement ().
$\delta(\)$	Infinitesimal deviation of ()
j	Identifier of the imaginary part of a complex number, $= \sqrt{-1}$
$\bar{\nabla}$	Normalized gradient operator
Subscripts	
0	Pertaining to the steady-state
neutral	Pertaining to the neutral state of stability
m	Pertaining to the radius of the circle that separates textured and smooth annuli of spiral grooved thrust bearing, Fig. 4
x, y, z	Pertaining to linear perturbation along the respective Cartesian directions
ξ, η	Pertaining to angular perturbation about respective ground-fixed transverse s

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Self-Excited Shaft Whirl

- [Self-Excited Gas Bearing Instabilities](#)

Self-Lubricating Bearings

- [Porous Metal Journal Bearings](#)

Self-Lubricating Coatings and Composite Coatings

- [Self-Lubricating Treatment of Light Alloys](#)

Self-Lubricating Hard/Ultra-Hard Coatings

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Synonyms

[Hard self-lubricating coatings](#); [Hard/ultra-hard self-lubricating coatings](#)

Definition

Self-lubricating hard/ultra-hard coatings is a class of coatings, which usually exhibit low friction coefficients and relatively high hardness. The threshold of the hardness is roughly estimated to be around 20 GPa. And the threshold value of friction coefficient about 0.3 between solid lubricants and anti-wear coatings, close to typical friction values of metals.

Scientific Fundamentals

Introduction

Increasing demands for higher power density, longer durability, and greater efficiency in future mechanical systems are pushing current materials and coatings to their limits. Modern mechanical assemblies often operate under boundary-lubricated sliding regimes where asperity interactions can take place, as opposed to a thick fluid film separating the sliding surfaces and thus preventing direct contact. Furthermore, some industrial applications even require sliding contact without any type of liquid lubrication, thus exacerbating the situation. To achieve and maintain higher efficiency and durability under such increasingly more severe sliding conditions, protective and/or solid lubricant coatings are becoming prevalent. Low friction coefficients can effectively reduce the contact temperatures during boundary-lubricated and/or dry sliding and thus have a huge potential to reduce the thermal load for coating and substrate material. A lot of effort is being made to develop low-friction protective layers to act as solid lubricants with the goal to replace the commonly used expensive and hazardous coolant lubricants. Especially in high speed and dry cutting applications, low-friction and lubricating mechanisms of the coating itself are required in addition to excellent mechanical properties. However, the present commercially used hard transition metal nitride or carbide coatings lack lubricating properties and show, consequently, relatively high friction coefficients in the range between 0.4 and 1.0 against steel. Reducing the friction coefficient while retaining the high hardness and wear resistance of a hard coating, which means self-lubricating hard/ultra-hard coatings, could be achieved by the development of new coating concepts, architectures, and deposition methods in the field of hard coatings technologies (Mayrhofer et al. 2006).

The coating with immense potential in mechanical application is diamond-like carbon (DLC), which has both high hardness (often exceeding 20 GPa) and low friction coefficient. However, the strong dependence of the tribological properties of DLC on the environment

(especially on the presence of oxygen and water vapor), the significant stress levels in the coatings, the high wear rates when sliding against ferrous materials and degrading in high temperature (below 350°C) are among the most serious disadvantages of the DLC coatings. Intrinsic solid lubricants like metal oxides (PbO, TiO, NiO, CoMoO₄), inorganic fluorites (CaF₂, BaF₂), lambda structure material (transition metal dichalcogenide, MoS₂, WS₂, and graphite), or soft metals (Ag, Au, In) have lower hardness and poor wear resistance, which does not make them ideal for surface engineering applications in terrestrial environment. Currently, there is a challenge to acquire self-lubricating hard coatings with both high hardness coatings and low friction coefficient. Advanced coating approaches combine multiple materials in a single composite coating in an attempt to circumvent the shortcomings of individual solid lubricant materials (Hogmark et al. 2000).

The Classification of Self-lubricating Hard Coatings

Carbon-Based Self-lubricating Hard Coatings

Advances in coating science and technology have led to the introduction of hard and lubricious carbon-based coatings, such as diamond-like carbon (DLC), carbon nitride (CN_x), silicon carbide, boron carbide (nominally B₄C), and nanostructured DLC-based nanocomposites as preferred candidates for self-lubricating hard coatings (Robertson 2002). However, the friction and wear properties of these carbon-based coatings depend strongly on the environment. For example, during dry sliding between two hydrogenated DLC-coated surfaces in nominally dry nitrogen ambient, the friction coefficient is sensitive to the presence of water vapor and increases with time delay between sequential sliding experiments. On the other hand, in the presence of oxygen, acceleration of graphitization (i.e., conversion of sp³- to sp²-bonded carbon atoms) and oxidation of carbon may occur, leading to increased friction and wear. In some instances, counterface materials react with the carbon coating, forming softer components and resulting in wear of a nominally harder surface by a softer counterface. The environment and surface chemistry determine the friction and wear performance of carbon-based coatings.

Diamond-like carbon (DLC) is an amorphous carbon (a-C) or hydrogenated amorphous carbon (a-C:H) thin film material with a high fraction of sp³ carbon bonding. The great variety of DLC structures and compositions leads to a wide range of mechanical properties and

performance. The hardness varies from a few GPa up to more than 60 GPa, while the elastic modulus ranges from several tens of GPa up to several hundreds of GPa. Friction coefficients of DLC films, which typically range from 0.01 to more than 0.5, depend on the nature of the film and the conditions used for friction testing, such as test conditions (load and speed), test environment, temperature, and counterface material. And the friction behavior of DLC is controlled by an interfacial transfer layer formed during sliding. This transfer layer of low shear strength (sp^2 -type) is formed from the surface of the DLC coating and is responsible for the low friction coefficients. In ambient humid air at a relative humidity of 20–60%, hydrogen-free DLC films generally exhibit lower friction coefficients (<0.15) compared with hydrogenated DLC film. In a-C films, friction easily causes a local shear-induced graphitization (sp^3 – sp^2) in the contact zone as the high contact flash temperatures, resulting in reduced friction due to the formation of a thin graphitized tribolayer. The increase of the friction coefficient with increasing humidity can be explained by a condensed water layer at asperity contacts, which has a “cooling effect” at the contact zone, so that necessary temperatures may not be attained and, therefore, the graphitization process is expected to be suppressed. At very high humidity, no graphitization formation results in relatively high friction coefficients. In inert environments such as dry nitrogen and vacuum, the amount of hydrogen in the coating structure determines the tribological performance of the DLC coating, where the hydrogen atoms determine the contact bonding between the DLC film and the counterface. For hydrogenated DLC, friction coefficient depends strongly on the relative humidity. The friction coefficient below 0.05 is found in a vacuum and at low humidity and increases strongly at high humidity. Contact with a different surface causes a transfer layer of hydrogenated DLC to be formed on the other surface. Thus, the contact is between two basically similar hydrophobic hydrogenated DLC surfaces, and the friction coefficient is very low. High humidity is believed to interfere with the formation of the contact layer and cause it to become oxidized/hydrated, so that it no longer forms the van der Waals bonds. If the transfer layer does not form, the counter surface is no longer hydrophobic, and the friction coefficient is much higher (Donnet and Erdemir 2008).

To overcome the disadvantageous humidity sensitivity of DLC, metal atoms in the range of 10–40% can be added to the DLC film to obtain less humidity degradation compared with pure DLC films. DLC films has been made with many different metals, including Ti, Nb, Ta, Cr, Mo, W, Ru, Fe, Co, Ni, Al, Cu, Au, and Ag, mainly by

sputtering of metallic targets in the presence of acetylene or other hydrocarbon gas (Donnet and Erdemir 2008). In many cases, metals are in the form of small nanocrystallites of pure metal or metal carbide (depending on the nature and concentration of the metal) dispersed throughout the carbon network. Interesting optimum tribological properties may be obtained for each type of metal dopant, with a concentration that seems to depend on its nature. However, the tribological performances of the Me-doped DLC coatings can differ sharply from one another. For instance, addition of metals like W, Ti, Cr, Ta to DLC films forming nanocrystalline metal carbides embedded in the DLC matrix thus improve their performance in humid and dry conditions. Tribological tests in ambient air conditions always exhibit steady-state friction in the range 0.10–0.25 with a slight dependence on humidity and load for metal contents below 30 at.%. The addition of silicon to a-C:H improves its friction properties by allowing it to maintain its low friction coefficient from low up to high humidity. It is believed that this occurs because the Si changes the nature of the transfer layer, forming a silica-gel-like sacrificial layer. Furthermore, the real response of a coating in a specific application has to be determined by conducting field tests. To further overcome these variations in performance and to extend the applicability over a broader range of test conditions, researchers have been exploring novel coating architectures having multilayers, nanostructures, or composites. This can cause a coating that is optimized for a certain tribological applications to perform worse under other tribological conditions.

Amorphous carbon nitride (CN_x) is suggested as a superhard solid lubricant as the interesting mechanical properties of α -C₃N₄. The hardness of these coatings typically varies between 15 and 30 GPa. The friction coefficient of the steel-CN_x pair in unlubricated conditions was about 0.16. Similar to DLC, friction and wear properties of CN_x coatings are dependent on the atmospheric conditions, degrading with increased humidity in the testing environment. In pure nitrogen (without oxygen and water vapor), friction coefficients <0.01 are obtained with smooth surfaces and when both surfaces are coated with amorphous CN_x, either initially or through the formation of transfer films. Amorphous silicon carbide synthesized by plasma methods has relatively high hardness range from 10 to 25 GPa. The lubricating performance of this amorphous silicon carbide film is greatly improved by annealing at 800°C. When annealed at 800°C, all remaining hydrogen was liberated from the film. The dehydrogenation process results in the formation of graphite-like structures, leading to lower friction.

The low friction (friction coefficient ~ 0.01) was maintained until the film was worn out. Boron carbide (B_4C) films are characterized by high hardness (ranging from 25 to 45 GPa) and stress resulting in excellent wear resistance, however, they always show relatively high friction coefficients of 0.3–0.4. After annealing at $800^\circ C$, reduced friction coefficients of 0.03–0.05 due to oxidation of B_4C . This low-friction mechanism is based on the reaction of the boric oxide (B_2O_3) with ambient humidity to form a thin boric acid (H_3BO_4) film. The low friction coefficient of boric acid is associated with its layered triclinic crystal structure. The layers consist of closely packed and strongly bonded boron, oxygen, and hydrogen atoms, but the layers are widely separated and attracted by van der Waals forces. During sliding, these atomic layers can align themselves parallel to the direction of relative motion and slide easily over one another. The temperature sensitivity of boric acid, however, restricts the applications of low-friction B_4C coatings at elevated temperatures. Above $170^\circ C$, boric acid tends to decompose, thus losing its layered crystal structure and hence its lubricity. The use of boric acid as a low-friction coating is also limited to reasonably humid conditions, precluding its use in dry or vacuum applications (Erdemir et al. 1991).

Self-lubrication by Oxide Formation

Intrinsic solid lubricants like DLC, MoS_2 , and h-BN often begin to fail in their tribological effectiveness with increasing temperature, in humid atmosphere, or due to oxidation. However, several approaches have been suggested to improve the friction properties of hard coatings by self-adaptive lubrication mechanisms occurring during application, e.g., during dry cutting or by tailoring their oxidation behavior. Conventional lubricants that are a product of chemical reactions between coating and moisture of the ambient atmosphere, e.g., the formation of boric acid in B_4C , always begin to fail in their tribological effectiveness with increasing temperature, limiting applicability at elevated temperature (Erdemir et al. 1991).

Thus, a new concept of high-temperature lubrication was found in the use of lubricious oxide materials with easily moveable shear planes, also referred to as Magnéli phases. These phases exhibit good thermal stability, high resistance against tribo-oxidation, and low adhesion. The oxides of W, Mo, V, and Ti especially form homologous series with planar faults according to the common Magnéli phase principles Me_nO_{2n-1} , Me_nO_{3n-1} , and Me_nO_{3n-2} (Woydt et al. 1998; Mayrhofer et al. 2006). Such crystalline structures based on the rutile structure contain rutile-like chains of edge-sharing octahedral, interrupted by shear planes every n th octahedron.

Generally, these shear planes exhibit reduced binding strength. In comparison to common solid lubricants such as MoS_2 , where every second layer offers crystallographic slip ability, Magnéli phases might exhibit less promising lubrication performance, because here only every n th layer has a crystallographic shear structure. Solid lubricants based on these Magnéli phase oxides have not yet found wide use because of the difficulty in achieving and maintaining the very narrow range of oxide stoichiometry, which is necessary for good lubricity.

As VN is a potential candidate to add self-lubricious properties to existing hard thin films for advanced cutting applications, some effort has been made to develop TiAlN/VN superlattice films where the beneficial properties of both types of layers are combined (Mayrhofer et al. 2004). TiAlN/VN has proven to be an excellent candidate in protecting machine wear parts and cutting tools due to its high wear resistance and low friction. The mechanism of the low friction was laid on the formation and stability of V_2O_5 as it is known to transform to VO_2 via different V-oxides, which partly count as Magnéli phases. The TiAlN/VN superlattice films also achieve low friction coefficient at room temperature. During sliding, a V_2O_5 containing oxide with lubricious properties is formed at asperity contacts. The excellent tribological properties of TiAlN/VN superlattice films can thus be attributed to the formation of these particular oxides.

TiN deposited by PVD as well as by CVD exhibits a friction coefficient in the range of 0.4–0.8 against steel counterparts. Using PACVD, the friction coefficient of TiN could be decreased to a value of 0.17. These low values are attributed to a certain amount of chlorine in the coatings, which is incorporated as $TiCl_4$ and is used as a chloridic precursor in the PACVD process. Moreover, chlorine implantation into TiN coatings also decreases the wear loss and the friction coefficient. For coatings with a chlorine content below 3.2 at.%, the friction coefficient is stable at a value of 0.75 over the test period, whereas for higher chlorine concentrations a sharp drop to a value of 0.17 occurs. Low chlorine impurities are assumed to be incorporated into the TiN phase, whereas for concentrations exceeding 3.2 at.% chlorine also segregates to grain boundaries. PACVD TiN coatings exhibit grain refinement by continuous renucleation during growth, whereas, on the other hand, the formation of a thin rutile layer, in humid air, is stimulated at the topmost surface (Badisch et al. 2004). This Cl-induced low-friction effect has been demonstrated for several transition metal nitride coating systems, e.g., TiN and nanocomposite $Ti(B)N$, where the Cl addition was provided by the PACVD process or by Cl ion implantation, respectively. Summing up,

the self-lubrication properties of Cl containing PACVD TiN coatings can be explained by the in situ formation of the easily shearable rutile phase in the contact zone between the sliding partners (Aizawa et al. 2004).

State-of-the-Art Structure Self-lubricating Hard Coatings

The Architectures of Self-lubricating Hard Coatings

The development of the technique to make a hard, self-lubricated coating is interesting. In order to improve self-lubricating behavior, different methods have been employed, building on the composite structures that involve the combination of soft lubricating phase(s) within hard, wear-resistant phase(s). The state-of-the-art structure designs of self-lubricating hard coatings have been addressed using three different approaches as follows: (a) inclusion of metal doping in solid lubricant coating, (b) solid lubricant coating layer on top of hard coating layer in the form of multilayer, and (c) inclusion of solid lubricant in a hard matrix (Hogmark et al. 2000). Figure 1 shows possible architectures of state-of-the-art structure designs of self-lubricating hard coatings.

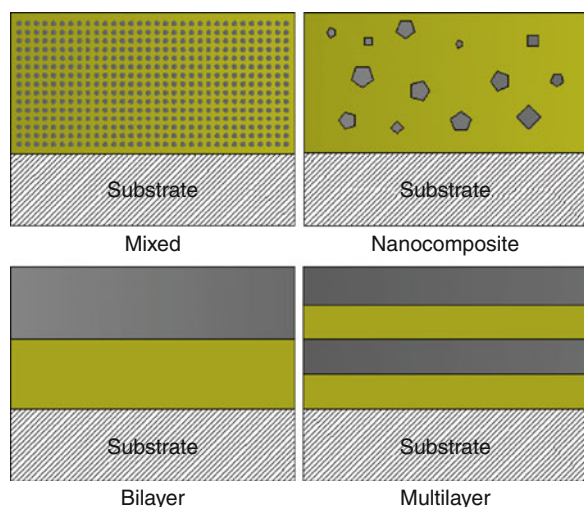
Mixed and Nanocomposite Coating Architectures

In the mixed coatings, the matrix and the dopant are mixed on an atomic level without any phase separation. The resulting solid solution is monophasic and can be amorphous or crystalline. In the composite coatings at least two phases can be distinguished. Clusters (mono-

polycrystalline or amorphous) of the solid lubricant with several nanometers magnitude in size are uniformly dispersed within the hard phase matrix (amorphous or crystalline). Some solubility of the solid lubricant in the hard phase and vice versa is also possible. The solid lubricant is to be present throughout the entire thickness of coating in order to maintain the low friction coefficient during its entire period of service. Furthermore, the mechanism of solid lubrication in the mixed and nanocomposite coatings can be easily predicted. As in the nanocomposite coating wear process, there are always reservoirs of solid lubricant in the nanocomposite coatings exposed at the surface of the wear track. These reservoirs provide solid lubricant, thus decreasing the friction coefficient. For the mixed coatings, when the coatings are rubbed, some re-orientation and re-crystallization of the coating materials takes place so that the coating surface might consist of a more crystalline material with a basal plane parallel orientation. Finally, low friction is achieved in the wear process.

Bilayer and Multilayer Coating Architectures

The bilayer and multilayer architectures are realized by the sequential of the constituents. The thickness of each individual layer can be controlled, from several nanometers to several micrometers. For the bilayer coating structure, once the top layer of the solid lubricant is worn, no further lubrication will be provided for the underlying hard phase. The multilayer structure can be useful in a real friction situation since such an effect, if constantly repeated many times throughout the multilayer coating wear life, can lead to the overall effect observed with the composite and probably the mixed coatings. If the individual layers of the solid lubricant and the hard phase are very thin, in the range of few nanometers, overlapping of the effects of each phase on the overall properties of the coating will take place. Furthermore, due to local fluctuations in friction conditions, the multilayer coatings never wear layer by layer in such a way that there is only one phase present at the entire surface of the wear track at any moment.



Self-Lubricating Hard/Ultra-Hard Coatings, Fig. 1 The architectures of self-lubricating hard coatings

The Classification of State-of-the-Art Structure Self-lubricating Hard Coatings

As mentioned above, the self-lubricating hard coatings consist of two components: a hard phase and a solid lubricant. The ideal candidate for the role of the hard phase in the self-lubricating hard coatings would possess good mechanical properties such as high hardness and low wear rate. Hard coatings, such TiN, TiC, Ti(C,N), (Ti,Al)N, (Ti,Al)(C,N), ZrN, CrN, Al₂O₃, diamond-like carbon (DLC) and others, possess high hardness (above 20 GPa),

low wear rate, and relatively high friction coefficients. Solid lubrication can be achieved using metal oxides (PbO, TiO, NiO, CoMoO₄), inorganic fluorites (CaF₂, BaF₂), lambda structure material (transition metal dichalcogenide, MoS₂, WS₂ and graphite), or soft metals (Ag, Au, In, Cu). This group of coatings has low friction coefficient and their wear-diminishing properties are brought about by providing solid lubrication. Significant disadvantages of the coatings in this group, however, are their relatively low hardness and low wear rate compared to the hard coatings. Classifying of self-lubricating hard composite coatings by lubrication phase is summarized below:

In the class of transition metal dichalcogenides, molybdenum disulphide (MoS₂) is the most popular lamellar solid lubricant. MoS₂ shows good friction performance in vacuum and under dry running conditions, but degrades quickly in moist and oxidizing environments. Friction coefficients of 0.002–0.05 can be observed in vacuum, dry, or inert atmospheres, which increase rapidly to 0.2 in humid air. MoS₂ coatings are soft (the hardness is about 4 GPa) with poor adhesion to metal substrate and, of course, are totally unsuitable for use in terrestrial conditions.

The development of the technique to make a MoS₂-based, hard, solid-lubricated coating is interesting. One way to achieve this goal is to deposit a soft-lubricated MoS₂ film on the hard films. MoS₂-based coatings usually deposit as a top layer on hard underlayers (such as TiN, TiC, CrN). A MoS₂-based coating on the hard CrN layer leads to a significant improvement in tribological properties. A maximum wear volume and coefficient of friction (COF) reduction of 95% is observed. However, when the top layer of the solid lubricant is worn, no further lubrication will be provided for the underlying hard phase. The decreasing friction and wear only act on the initial process when there is a layer of a solid lubricant on a hard coating. Since the bilayer coating system is practically improbable to obtain super low friction, hardness, oxidation, and wear resistance properties, another way to achieve this goal is to deposit a nanocomposite structure with the incorporation of a lubricious phase like MoS₂ into a harder matrix (e.g., TiN, TiB₂, CrN, CrB₂) in order to maintain a reservoir of solid lubricant throughout the coating thickness. Such hard solid lubricant film is effective in maintaining a coefficient of friction less than 0.3 through a long, stable lifetime without showing significant deterioration in hardness. The TiN–MoS_x composite coatings show very low friction characteristics (with friction coefficient less than 0.05) under normal atmospheric conditions. Incorporation of 8% MoS₂ in the TiN–MoS_x composite matrix

also shows significant reduction in friction coefficient (~0.2) while maintaining high hardness around 30 GPa. CrB₂–MoS₂ composite coating with 19% concentration of MoS₂ is attributed to the formation of an optimal nanocomposite structure and mechanical properties. In every case examined, separate MoS₂ peak is not found in the XRD spectra and hence it is postulated that the presence of MoS₂ is in the form of elemental Mo and S at grain boundary, which formed MoS₂ when put into a tribological application. The re-orientation and recrystallization of the elemental Mo and S with a more crystalline material with a basal plane parallel orientation in the wear surface cause the self-lubrication performance (Hogmark et al. 2000). Another effective method of increasing friction and wear properties of MoS₂ coatings is the addition of titanium atoms (up to ~20 at.%) to the MoS₂ structure. In this so-called MoSTTM structure (Teer 2001), titanium is thought to be in solid solution within the MoS₂. HRTEM investigations show that the Ti atoms actually also form nanocrystallites in a matrix of MoS₂ in the form of bundles of curved MoS₂ basal planes. The distortion due to the titanium atoms is responsible for an increase in hardness from ~4 GPa (pure MoS₂) up to 10 ~ 20 GPa, yielding improved wear resistance. Another advantage of titanium-doped MoS₂ compared with conventional MoS₂ is a reduced sensitivity of the coating to water vapor. Therefore, the applicability of these coatings is extended from dry conditions up to 50% humidity.

To combine the superior friction properties of DLC in humid air and WS₂ in dry conditions with the high wear resistance of transition metal carbides, a nanocomposite concept for tribological applications has been proposed by Voevodin et al. The nanocomposite coating within the W-C-S system consist of 1–2 nm WC and 5–10 nm WS₂ grains embedded in a DLC matrix. The WC/DLC/WS₂ nanocomposite exhibited chameleon-like self-adaptation to operations that occur in aerospace systems, providing friction reduction in both dry and humid environments (Voevodin and Zabinski 2005).

Soft metal coatings like lead, silver, gold, copper, nickel, and indium exhibit low shear strength over a large temperature range and excellent friction properties when kept sufficiently thin, but are susceptible to high wear, plastic deformation, and gross plowing during sliding causing rapid coating loss, increased friction, and irregular surface topographies. Inclusion of soft metals as solid lubricating phases in carbide, oxide and nitride matrix aims to improve tribological performance, as they possess sufficiently low shear strength as well as strong adhesion to the substrate, high film thickness, low surface roughness, enduring high load, and sliding speed.

The benefit of these nanocomposites, such as TiN/Ag, TiC/Ag, CrN/Ag, TiN/Cu, and yttrium-stabilized zirconia YSZ/Au systems, is that soft metals may act as lubricants at room temperature as well as high temperatures due to their low shear strength and stable thermochemistry.

Transition metal nitrides combined with soft metals are of particular interest as they are relatively easy to co-deposit by reactive magnetron sputtering and form nanocomposite structures, due to the lack of miscibility between the matrix and the lubricant. For instance, the incorporation of silver into the CrN coating tends to form a structure that consists of a matrix of CrN surrounding nanoparticles of silver, and offers the potential to modify the tribological properties. The self-lubricating nature of CrN/Ag coatings, combined with their high hardness and scratch resistance, makes them attractive for tribological applications (Mulligan and Gall 2005). Alloying TiN and TiC coatings with Ag also offers a high potential to enhance the tribological behavior in a wide temperature range and under varying environmental conditions. Ag containing nanocomposites is promising as it is expected that elevated temperatures will facilitate Ag diffusion to the surface, yielding a lubricious layer without wear of the hard matrix. The magnitude of this effect depends on the nature and quantity of the silver particles and their distribution within the coating matrix, which in turn are functions of the deposition parameters and the silver content of the film. Analogous to TiN/Ag coatings, incorporation of copper into the TiN film also results in a strong decrease of the friction coefficient, from high values of 0.6–0.7 corresponding to TiN films, to very low values of approximately 0.2. The hardness of the films ranges from 20 to 30 GPa (Musil and Vlček 2001). This means that the hardness of the TiN/Cu films is fully comparable with that of hard single-phase TiN films.

In another example, nanocrystalline yttrium-stabilized ZrO₂ (YSZ) grains encapsulated in a mixed YSZ-Au amorphous matrix showed interesting applications in aerospace (Voevodin et al. 2001). In this case, the large fraction of amorphous YSZ-Au grain boundary phase provided ductility by activating grain boundary slip and crack termination by nanocrack splitting. This provided a unique combination of high hardness and toughness in these coatings. The coating hardness was quite high, ranging from 18 to 30 GPa, while low friction coefficient of about 0.2 and high wear resistance are expected. Recently, this concept was expanded to high temperatures, where DLC and/or MoS₂ was combined with Au, providing high-temperature/low-temperature and dry/wet lubrication, and embedded in an yttria-stabilized zirconia (YSZ) matrix. Furthermore, advanced state-of-the-art

structures are designed to combine these composites with buried diffusion barrier layers and achieve surface self-adaptation during repeated temperature cycling. Recently, novel wear-resistant materials have been developed that combine nanocrystalline carbides (TiC, WC), oxide-based ceramics (YSZ and AlON), dichalcogenides (MoS₂, WS₂), and amorphous diamond-like carbon (DLC) into nanocomposite structures. Self-adapted coatings made of amorphous diamond-like carbon (DLC) matrix with incorporation of nanocrystalline TiC, WC, WS₂, and laser-processed MoS₂ reservoirs have demonstrated an order of magnitude improvement in toughness above that of single-phase carbides while maintaining the same level of hardness, a low friction coefficient in cycling from dry to humid environments, and an extremely long life in both ambient and space environments (Voevodin and Zabinski 2005). The surface chemistry, structure, and mechanical behavior of these nanocomposite materials are shown to reversibly change in the tribological contact, depending on applied loads and operational environment to maintain low friction and prevent wear.

Novel nanocomposite designs for self-lubricating hard coatings are very promising and provide a very attractive alternative to multilayer architectures. Nanocomposite coatings are more easily implemented, since they do not require precise control in the layer thickness and frequent cycling of the deposition parameters, as is required for fabrication of multilayer coatings. They are, however, relatively recent developments, and suitable scale-up of deposition techniques is currently under intense study.

Key Applications

Self-lubricating hard coatings with low friction coefficients and relatively high hardness have potential applications in industry. Their development will enable increased utilization of coatings in many types of applications including those in the automotive, tool, and aerospace industries where the operational environment is variable and severe. The typical use of advanced self-lubricating hard coatings has been proven to be very effective in improving the tribological performance of components such as cutting tools and ball bearings. On the one hand, requirements for personnel safety and low environmental impact in metal cutting/forming technologies today require using reduced amounts of or, in many cases, even no cooling/lubricating fluids. On the other hand, the requirements for low cost and high productivity set the necessity of using high-speed tools. Combining these two harsh demands has triggered a serious demands on the field of the self-lubricating hard wear-resistant coatings as a means to significantly reduce tool wear and friction in

dry cutting applications. There is also an increasing interest in the development of these advanced self-lubricating hard coatings that could provide low friction in vacuum environments, such as the applications in aerospace assemblies. Soft coatings commonly used in vacuum environment lubrication include dichalcogenides such as molybdenum disulfide and tungsten disulfide, and soft metals such as silver (Ag) or gold (Au). The incorporation of a soft metal within a hard transition metal carbide or nitride may therefore provide both high wear resistance and low friction in vacuum, even in a repeatedly switching atmosphere process.

Cross-References

- ▶ [Diamond-Like Carbon Coatings](#)
- ▶ [Doped MoS₂ Coatings and Their Tribology](#)
- ▶ [High-Temperature Solid Lubricating Materials](#)
- ▶ [Solid Lubricants, Ceramic-Based Self-lubricating Materials](#)

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Self-lubricating Metal Composite Coatings by Electrodeposition or Electroless Deposition

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Synonyms

[Electrochemical deposition for self-lubricating metal composite coatings](#); [Electroplating for self-lubricating metal composite coatings](#)

Definition

Electrodeposition or electroless deposition is used to prepare a self-lubricating metal composite coating that offers an in situ lubricating film without the need for an external supply of lubricant. This composite coating consists of at least two constituent parts, namely a metal matrix and fine particles of lubricant dispersed throughout the metal matrix.

Scientific Fundamentals

Background

Lubrication is a process used to reduce friction and wear between two surfaces in close proximity. The two surfaces can either be stationary or in motion relative to each other. The most effective way to reduce friction and wear is to separate the two surfaces by means of a third body in the form of a lubricating film. The lubricant serves the purpose of limiting contact pressure, reducing friction and wear, and preventing galling and seizure between two surfaces. This lubricating film can be in the form of a solid lubricant, a mixture of solid/liquid dispersion, or a liquid phase lubricant.

The introduction of a third body lubricating film between two surfaces may not be adequate in a number of applications, e.g., liquid lubricant is not suitable for applications in a vacuum environment or aerospace applications, at extremely high contact pressure, or at elevated service temperature. Solid lubricants would be a more appropriate choice for these cases and in dry environment applications, but they have a finite service life depending on the type, size, and dimension of the lubricant. Replenishment of solid lubricants may be possible but this approach is not always practical during service.