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A Comprehensive Analysis of Coating Technology and Thin Films

V. Basil Hans*

Abstract

In contemporary materials science, thin film and coating technologies are essential because they allow for the improvement of surface characteristics, including electrical conductivity, hardness, corrosion resistance, and optical performance. These technologies use physical, chemical, or hybrid deposition techniques to deposit materials in layers that range in thickness from a few nanometres to several micrometres, depending on the required functional properties and application areas. The content, thickness, and microstructure of films can now be precisely controlled because of recent developments in processes like sputtering, chemical vapour deposition (CVD), physical vapour deposition (PVD), and atomic layer deposition (ALD), which offer exceptional uniformity and reproducibility. These advanced methods make it possible to tailor materials at the nanoscale level, ensuring that films exhibit enhanced adhesion, durability, and overall performance under various operating conditions. The basic ideas, production processes, and characterisation methods of thin films and coatings are reviewed in this study to provide a comprehensive understanding of their scientific and technological significance. Their uses in electronics, optics, energy devices, and protective surfaces are highlighted, along with new developments in nanostructured coatings and ecologically friendly deposition techniques that support sustainability and environmental protection. The conversation focuses on how advancements in thin film technology are propelling the development of high-performance materials and cutting-edge industrial applications, ultimately enabling innovations in sectors such as microelectronics, photovoltaics, aerospace, and biomedical engineering, where thin films play a vital role in achieving superior efficiency, functionality, and long-term reliability.

Keywords: Slender films, methods of deposition, nanostructured coatings, nano-coating, biomedical engineering

INTRODUCTION

The word "thin film" was mentioned in around a million scientific articles totalling about 32 million pages between 1920 and 2020, according to Scopus. The following analytical overview offers a succinct but thorough review of thin film and coating science, including the fundamentals of film formation and coating generation techniques, the qualities that contemporary industrial coatings and thin films demand, their use in protective and functional coatings, and modelling, testing, and life-cycle assessment techniques that aid in the creation of long-lasting coating solutions.

Coatings offer functionality like catalytic activity, electric conductivity, and optoelectronic qualities, as well as improved surface qualities like wettability and adhesion, and resistance to wear and corrosion. In addition to offering a greater range of protective capabilities, thin films and coatings can form multilayered stacks that enable additional

***Author for Correspondence**
V. Basil Hans
E-mail: vhans2011@gmail.com

Research Professor, Srinivas University, Mangalore, Karnataka, India

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functionalities and other process alternatives with added value. Almost every area of human endeavour uses coatings, including the automotive, aerospace, optical, electrical, and medicinal industries [1].

PRINCIPLES OF THIN FILMS

Layers of material with thicknesses ranging from a fraction of a nanometre to several micrometres are called thin films. They are widely used in astrophysical research, spacecraft protection, photovoltaic and optoelectronic devices, optics, food packaging, oxidation barriers to prevent polymer degradation, and nanotechnology, among other contemporary technologies. For thin films to be used effectively, their thickness must be precisely measured. A number of approaches, including optical methods that can be used during or after film deposition, have been developed for measuring the thickness of thin films [2].

Thin films can be categorised according to their thickness or composition. They can be binary, ternary, quaternary, elemental, etc., based on their composition. By thickness: micro-scale thin film (>1 to 10 μm); nanometer-scale thin film (1 nm to 1 μm); and ultra-thin film (<1 nm). It is important to note that the characteristics of the material and the intended use determine what constitutes a thin and thick film. Although the term "coating" is also associated with thin films, it is frequently used to describe coatings whose substrate is a whole system. It is possible to think of coating procedures as disposal procedures that will come to an end [3].

Classification and Definitions

Layers of material that range in thickness from a few nanometres to several micrometres are called thin films. In optoelectronics, they are used to coat mirrors and lenses to reduce reflection and improve transmission; in the food packaging industry, protective aluminium coatings are used to prevent oxygen ingress; in solar cells, zinc oxide/n-type silicon junctions are formed; in astrophysical research, they are used to study ices such as carbon dioxide and nitrogen; in spacecraft protection, aluminium oxide and silica layers are applied; and silicon oxides are deposited to protect polymers from photo-oxidative degradation. In each of these applications, it is essential to measure the film thickness, which is the distance between opposing surfaces measured perpendicularly. Both contact and non-contact optical techniques, which can be used during or after film deposition, are among the many methods developed for determining film thickness.

The terms coating and thin film are frequently used interchangeably. A coating is a more generic phrase that also includes the functional qualities attributed to an applied material, such as the ornamental or protective functions of paint, varnish, or ink, whereas a thin film just refers to the thickness of a layer. Because coatings are often thicker than films, deposited layers that are a few micrometres or tens of micrometres thick are typically considered coatings. The composition of thin films and coatings (polymeric, metallic, dielectric, etc.), the layer thickness (very thin, thin, or thick), and the type of deposition environment (vacuum, atmospheric pressure, etc.) can all be used to categorise them [4].

Mechanisms of Deposition

Numerous industries, including semiconductors, optoelectronics, optics, aerospace, and machine tools, use thin film technology extensively. In order to reduce the formation of contaminants and scattering centres in the deposited films, deposition procedures are occasionally carried out without the presence of any background gases. This method may result in the subsequently adsorbed species having a high enough specific kinetic energy to arrive at the surface far from thermodynamic equilibrium. The mechanisms by which thin films form on surfaces from gaseous precursors are investigated, beginning with the fundamental definitions of thin films and coatings and their classification according to composition, thickness, and deposition environment. These mechanisms' governing parameters, including deposition-flux control, adatom mobility, and supersaturation, are described. Correlations with substrate type, temperature, and deposition rate are also clarified, and the growth modes Frank-van der Merwe, Volmer-Weber, and Stranski-Krastanov are compared [5].

Modes of Growth and Film Morphology

Since surface morphology is intrinsically linked to numerous significant features, including surface roughness, porosity, and microstructure, it is a crucial consideration in the analysis of thin-film growth. For example, the film's surface appearance, which is further connected to the underlying growth process, directly affects the amount of light reflection or transmission. Additionally, the microstructure of films and coatings affects their electrical conductivity. Because managing these stages can greatly improve the final thin-film materials, a basic understanding of the very first stages of thin-film formation is still relevant [6].

Based on the examination of actual thin-film-growth processes, statistical and thermodynamic models of film-growth processes incorporate kinetic equations for the temporal evolution of film morphology, including facets and roughness. The explicit time development of a developing interface is described by kinetic equations. The deposition rate of the deposit species, the necessary contributions to the free-interface formation energy, and the diffusion of the deposit species to free surfaces are all used to directly calculate the temporal variation of film thickness or surface profile as a growth-rate function [7].

METHODS OF EXPERIMENTAL THIN FILMS

With a distinction between *in situ* and *ex situ* methods, three categories of experimental approaches for characterising and tracking thin films during growth are compiled. Along with surface morphology and structural integrity assessments, models that relate deposition parameters to the resultant film properties, and plasma-assisted processes that alter the film morphology and microstructure, the implications for data validity and reproducibility are also covered. Measurements of optical and electrical properties are also described, along with the pertinent interpretation models that enable the establishment of connections between the composition, attributes, and conditions of film deposition.

When many deposition techniques and precursors are available, a range of deposition technologies, the number of participating species, and thermodynamic or kinetic conditions can be investigated, reflecting the basic understanding of thin-film materials and growth mechanisms. For extensive bibliographic reports, these models that forecast the composition, structure, and properties of films allow for the quick screening of multilayer sequences or hybrid coatings made up of various material vectors and assist in selecting the best procedure before the start of experimental work.

Ex Situ and *In Situ* Description

The ability to track the development of the deposited thin film and related morphological changes in real time is one of the most impressive aspects of physical vapour deposition (PVD) techniques. Under vacuum conditions in the deposition chamber, such *in situ* analysis can be carried out with minimal impact on the growth process. There is new potential for optimising deposition parameters and establishing more accurate correlations between them and the properties of deposited films when the characterisation technique is restricted to the growing environment [8].

The two most used industrial PVD processes are e-beam evaporation and unbalanced magnetron sputtering. Because of the high energy of the incident species, these processes are followed by a significant increase in adatom mobility, which is frequently incompatible with glass or polymer substrates. Therefore, it is necessary to execute the deposition of additional layers beneath electrical insulation in various applications, such as architectural or automotive glass. Then, in order to extract quantitative parameters and ensure accurate data repeatability, the employment of *ex situ* techniques like SEA, AFM, and ellipsometry becomes crucial.

Structural and Surface Analysis

Numerous surface and structural characteristics of thin films are indicative of their deposition conditions, chemical makeup, and growth mechanism. As a result, one of the most used methods for describing thin films is surface and structural analysis. The development of numerous sophisticated characterisation methods, including atomic force microscopy (AFM), scanning electron microscopy (SEM), transmission electron microscopy (TEM), grazing incidence small-angle X-ray scattering (GISAXS), and X-ray diffraction (XRD), has made it possible to conduct thorough and accurate analyses of functional thin films. GISAXS is a potent technique for figuring out the film morphology from an alternative viewpoint. Studying the thin-film growth process requires precise knowledge of the roughness and film structure, including thickness, which is provided by the resulting curve. High-resolution three-dimensional surface profiles are frequently obtained using AFM. It offers parameters including the autographic lattice peak (ALP) roughness coefficient, surface roughness coefficient, and root mean square (RMS) roughness. Important details about the shape and aggregation of particles are shown by the 2D and 3D surface pictures. For nanostructured materials, the AFM-obtained pictures and profiles are especially helpful in clarifying the mechanism governing the growth process. SEM makes it possible to compare the growth process and film morphology directly. The films can be exposed to differentially polarised light to further examine the structural evolution during growth, which is an added benefit of this quick and easy procedure that produces high-quality photos. The structure of nanocrystals can be seen, and flaws can be observed by TEM investigation of cross-sectional samples. Both SEM and TEM pictures can be used to assess the film thickness. By figuring out the pattern's peak position, full width at half-maximum (FWHM), and peak intensities, XRD and grazing-incidence XRD (GIXRD) can be used to ascertain the phase composition, crystal structure, and growth or deposition rate of the thin film [9].

Measurements of Optical and Electronic Properties

Characterising thin films and organic electronic devices requires measurements of optical and electrical characteristics. The optical bandgap, conductivity, extinction coefficient, and refractive index are all significant characteristics [10]. The particular coating material and thickness affect the measurements of optical and electrical properties. For instance, time-synchronized measurements with a single laser can expand the spectroscopic range into the ultraviolet/near-infrared region. Finding the film's thickness, roughness, and inhomogeneity is one of the most important aspects of its characterisation. The increasing need for such measurements has led to the development of non-destructive approaches based on envelope and transmission spectra.

COATING TECHNIQUES AND TECHNOLOGIES

A variety of technologies and techniques can be used to deposit thin films and coatings onto a substrate surface. The two most common physical vapour deposition techniques are evaporation and sputtering. In evaporation, solid atoms are released from a target material in the gas phase, while at the target surface, thermally induced particle transitions from solid to vapour occur [11]. The impact of various Ar gas pressures and an 18 cm target-substrate distance on the growth dynamics of long-period superlattices on a single Si wafer has been studied using sputtering in particular. These two factors alter the film densification and growth shape as well as the particle arrival energy onto the substrate. Furthermore, the Ar pressure also affects the amount of energy that the sputtered particle brings to the surface, which has a significant impact on the deposit's grain size and film densification. *In situ* spectroscopic monitoring of different materials and deposition settings has been used to study the growth and shape of films.

A precursor reacts with the surface to be coated at a specific temperature in the chemical vapour deposition method. This process is repeated until the surface is saturated and the growth precipitates as a coating. The time-scale for homogeneous coating is influenced by gas-phase transport; growth then takes place on the substrate surface as well as throughout the pre-deposited material, resulting in a multi-dimensional growth [12]. Numerous precursor compounds, including MoO_3, TiO_2, ZrO_2, SiO_2, W, and graphene, are accessible for depositing various coating materials. It becomes crucial to choose the right precursor when decorating delicate materials. The intended technique of deposition on the negated specimen at a high temperature must be consistent with the chemistry of the precursor molecule. Online flexible and transparent polymer-coated circuits can be created by digital ink-jet printing with a UV-curable polymer solution and a preprogrammed pattern. The general temperature window for the deposition coating onto flexible polymer substrates is largely determined by the choice of precursor.

The growth process transitions to clustering, which is essentially a monolayer transport deposition (MTD), and then to the atomic layer deposition regime when the size of the initially deposited particles becomes considerable in relation to the mean-free-path length of the gas. An atomic layer deposit approach has successfully completed the task of conformally coating a complicated three-dimensional (3D) microstructure with a sub-micron or nano-scaled thickness through a self-limiting reaction. The physical vapour deposition mechanism is used to co-deposit materials. The cluster monomer is under good control, and during growth, the cluster's size can be independently changed. Depending on the type of e-beam evaporator being utilised, the chemical makeup of the thin films that are deposited can vary from binary, tertiary, and quaternary alloys to pure metals.

Deposition of Physical Vapour

Coating operations carried out in a partial vacuum, in which at least one depositing species is atomised from a solid, are referred to as physical vapour deposition (PVD). Temperature-sensitive materials can benefit from PVD's low deposition temperatures and potential for plasma assistance. With exact control over the coating-substrate interface and development, the process allows metals, alloys, and ceramics to be deposited on a variety of substrates [13]. Sputter PVD ejects surface atoms by subjecting the coating material to a high-energy ion bombardment. The two main methods are magnetron sputtering and cathodic arc evaporation [14].

For the PVD process to provide the best possible material adherence on the substrate, certain vacuum and humidity levels are needed. The choice of target material has a big impact on tribological and mechanical characteristics. Consult the literature on advanced functional coatings for a thorough examination of PVD applications, including thin-film coating modelling and surface ion interaction.

Deposition of Chemical Vapour

Since the 1960s, chemical vapour deposition (CVD) has been used to build thin films using materials intended for optical applications. In order to chemically deposit the film and deposit a secondary polar solvent for droplet formation, CVD uses a volatile, non-polar precursor that can be either liquid or solid. A volatile precursor that dissolves in polar solvents served as the basis for the development of a gas-phase chemical vapour deposition (CVD) technology. Time-resolved examination of coating development is made possible by the system under a variety of experimental settings, including standard and vacuum air pressures, substrate temperatures of 60 or 150°C, and precursor concentrations of 0.005, 0.1, and 0.5 M. Both capillary and hole-drilling techniques have been developed to increase film uniformity and CVD on irregularly shaped solid objects. Furthermore, doped C60 thin films based on azobenzene-based precursors were deposited from a precursor capable of UV light-induced colour change for security applications. Particles as small as 500 nm in diameter have been coated by CVD utilising non-volatile resol-type resins at low temperatures and atmospheric pressure. Using diffraction patterns and spectrum shifts, optical non-linear spectroscopy was used to track the formation of films on glass slides. Four growth modes were identified: 3 (70–120 s), droplets coalesced and film phase grew by further liquid deposition and diffusion; 4 (120–240 s), film phase growth slowed down and coverage increased only by continuing droplet deposition; 2 (20–80 s), droplets coalesced and surface diffusion became important; and 1 (0–10 s), thin liquid films and/or small droplets formed. CVD has also been used to deposit the fluorinated acrylic CF2–C3 phase, which has been demonstrated to be a viable material for 3D micro-patterning. Based on a corrected particle-kinetic model, the kinetics and mechanisms of multi-stage thin film growth were successfully predicted for a number of systems, including the formation of alloyed, stable n-type and p-type doping in inkjet-printed thin films from Ag1.2Cu0.8Te and Cu1.18Sn0.4Se2 precursors, CVD of three different precursors in capillary and aerosol-assisted systems, gas-phase degradation of in outlets and inside a Teflon capillary, and CVD of oxidised precursors at atmospheric pressure [15]. All precursor solutions were made of commercially available materials. The progressive chemical growth method of the organic thin film formed from aqueous solution has been established by CVD of 3-thiophene-CHO. The cavity size of capillary-type devices with a coating approach has been discovered to considerably affect polymer film uniformity on electrically insulating and hydrophobic surfaces in the development of aqueous CVD from new fluorinated acrylic and stilbenic acid isomers. The development of ultra-broadband transparent coatings for hard and flexible substrates has advanced, and CVD of azobenzene-based polymers from the aqueous phase has been expanded. In addition to a newly developed resin that can change colour when exposed to UV light, CVD on arrayed needle substrates, and realistically simulate droplet condensation on three-dimensional structures, CVD of highly hydrophobic films from novel resins and fluorinated acrylics at atmospheric pressure, low temperature (20–60°C) has been established. Condensation in Ar happens by different pathways during CVD, and it was discovered that the gelation of polyfluorinated acrylate droplets significantly delayed the production of coating layers. Using a small-angle laser beam, CVD of azobenzene C60 derivatives from volatile monomers capable of undergoing a UV-induced colour shift, as well as the droplet formation behaviour of aqueous films from three distinct resins, have been studied. Through a methodical investigation of functional coating fine-tuning using aerosol-assisted chemical vapour deposition (AACVD), it is now possible to establish a clear link between coating formation at different phases and the improvement of thin film functionalities.

Atomic Layer and Cluster Processes

An effective substitute for traditional atomic layer deposition (ALD) techniques is the deposition of clusters (<=2 nm diameter) rather than atomic monolayers. By delivering numerous atoms per cluster and relying on size-controlled cluster production, cluster layer deposition favours growth over nucleation. Growth below traditional monolayer (M) concavities is made possible by self-limiting processes with regulated cluster size, which may carefully manage thin-film sub-monolayer nearly-saturation regimes [16].

Methods Assisted by Electrodeposition and Plasma

The electrochemical parameters of current density (defined as the charge passed through a unit area per unit of time) and chemical parameters (related to the pH, temperature, and concentration of the plating bath composition) govern the electrodeposition process, which deposits coatings on the substrate by electrochemically reducing the ions present in the electrolyte or electrolyte mixture, which is the plating bath. By varying the current density and the deposition time, coating thicknesses ranging from tens of nanometres to micrometres can be deposited by electrodeposition. The type of electrolyte and plating bath also affects the coating's thickness.

In coating techniques, the coating material can be supplied as a liquid, slurry, or powder. To increase their mobility and dispersion across the surface to be coated, these materials are frequently encapsulated and fluidised. It has been demonstrated that the coating quality is enhanced by the addition of surfactants whose surface tension is lower than that of the feedstock (such as liquid coating material).

Neutral atoms, ions, radicals, and electrons are among the many species in plasma that are applied in plasma-assisted processes. These species interact with the surface to be coated in the form of a discharge, significantly lowering the process temperature and enabling the deposition of coatings on substrates that are sensitive to temperature. The coating's morphology and structure are altered as a result. There are several types of plasma-assisted coating techniques, including high-pressure hot gas plasma spraying, low-pressure liquid and dielectric barrier discharge, atmospheric-pressure fluidised, and low-pressure atmospheric plasma jet deposition [17].

COATINGS' CHARACTERISTICS AND FUNCTIONALITY

Coatings significantly increase environmental resistance, corrosion resistance, and wear resistance. Coatings can boost performance, extend service life, and even raise value. They can provide chemical passivation, serve as a sacrificial layer, or provide a barrier, depending on the application. Important factors include the level of protection needed, the corrosive environment, the substrate's composition, applications where contact or liquid exposure is anticipated, and service parameters like temperature.

Additionally, location should be taken into account. If only used indoors, the choices might differ from components exposed to salt or parts used exclusively in hot conditions. Additionally, interior components may occasionally be painted and need to work well together. Colour coating is another issue. Darker hues are not completely out of the question, but white might be suggested for some areas. To assess appropriateness, it could be wise to speak with corrosion specialists to better interpret and comprehend the surroundings.

Dielectric, resistive, conductive, anti-reflective, and absorption are the five main categories into which the functional and protective requirements for coatings applied to electronic circuits fall. Semiconductor chips are the primary use for dielectric coatings. They guarantee electrical insulation between copper and aluminium sections and isolate and shield chips and connections from water intrusion. Moreover, they are used to stop oxidation, which makes it possible to use other materials under certain restrictions. Given that practically every surface, like diesel, air de-charger, etc., is transformed into water, water penetration poses the most challenging problem.

Tribological and Mechanical Behaviour

The mechanical properties of thin films, coatings, and multilayers have been the subject of extensive research. Elastic modulus, hardness, ductility, and wear resistance are frequently assessed criteria in these kinds of investigations. Thin films first grow in a free-standing manner after being put onto a substrate. The substrate material and interface characteristics affect the microstructure as the film thickness gets closer to the substrate-film contact limit. The overall mechanical behaviour of the coated structure is dominated by the thin film's adherence to the underlying layer. According to experimental research, a number of variables, including thickness and average grain size in relation to film thickness, deposition temperature, or kinetic energy, and interface quality, significantly affect thin-film mechanical properties [18].

Apart from distinct damping processes and elastic properties, thin films also have particular tribological features that, depending on the application, might be beneficial or detrimental. Thin films may have greater static and kinetic friction coefficients than bulk materials coated or deposited on the same substrate [19]. This phenomenon has been ascribed to either a greater impact of the soft and viscoelastic polymeric substrate underneath the films to be examined, or to a decrease in the number of asperities in contact between two thin films. The average coefficient of static friction of coupled thin films of silicon oxide, silicon nitride, or silicon oxynitride deposited by plasma-enhanced chemical vapour deposition on soft polymeric materials is dependent on the film's thickness and composition, according to nanotribological studies conducted using atomic force microscopy. The kinetic friction of soft substrates is decoupled from the inherent characteristics of thin-film materials, as evidenced by the fact that the kinetic friction of the identical linked thin films was found to be highly dependent on the polymeric substrate on which they were placed. When thin-film fragments separate due to interfacial debonding between the thin film and the polymer substrate, the thin-film stack fails. It is possible to trap residual static dust particles when a thin film is being deposited.

Thermal, Electrical, and Optical Characteristics

Thin solid films are essential parts of integrated circuits and optical filters, and they are important in both electronics and optics. Mechanical engineers are also interested in them because of their capacity to promote energy conversion and transfer. These films' rough surfaces can improve optical and radiative qualities, which can affect temperature management systems and photovoltaic devices. Therefore, a comprehensive understanding of these radiative properties is essential for many industrial applications. However, because of concurrent light scattering and interference events, transmittance and reflectance prediction is still a challenging tasks. Numerous modelling techniques have been put forth, such as the coupled Maxwell equations, differential quantity perturbation theory, and scalar scattering theory; however, their applicability is frequently limited to certain materials and surface conditions.

For some materials, including silicon and diamond, scalar scattering theory has shown promise as long as the surface is suitably rough and the wavelength of interest stays within the visible spectrum. A number of theories, including spectral averaging, have been investigated in relation to partial coherence effects, which are typically crucial for precise modelling. However, they have not yet been appropriately instantiated for the situation of smooth films. Since optical, electrical, and thermal studies of thin films are often subject to competing limitations depending on the intended application, they should be taken into consideration separately [20].

Environmental Resistance and Corrosion

The performance, security, and dependability of thin-film coatings and applications depend on their long-term endurance. Reduced film adherence and degraded functioning may arise from material changes and property degradations in thin-film coatings brought on by corrosion, environmental conditions, or wear. Protective or optical coatings may be used in the design of the final product or gadget in order to ensure good long-term functioning. Increased corrosion resistance in harsh settings can be achieved with a variety of inorganic and organic protective coatings [21].

INDUSTRIAL APPLICATIONS

Numerous industrial fields, including optics, food packaging, solar cells, astronomical research, space science, and polymer protection, heavily rely on thin films. The increasing miniaturisation of devices requires a precise control of the basic processes, their modelling, and coating technologies, as well as a comprehensive grasp of film properties.

Protective and functional coatings can be customised to satisfy the requirements of certain industrial applications in terms of wear, corrosion, adhesion, and environmental resistance. Similarly, the dielectric or semiconductor behaviour of the corresponding films is used to build low-emissivity coatings and electromagnetic shielding.

Coatings that are Both Functional and Protective

The service life of parts and entire systems is increased by protective and functional coatings, which shield underlying materials from wear, corrosion, and other environmental degradation events. Even for the replication of a common core function under a variety of degradation conditions, surface coating technologies are frequently chosen based on projected wear mechanism, ambient conditions, and chemical environment of contact; these specifications typically result in very different material choices. Coatings are commonly applied to wear-contact surfaces, including gear teeth, dynamic seals, and sliding or rolling bearing tracks. Whether a longer overall service life can be achieved using micro-coated systems instead of a normal change cycle depends on the coating application. However, because relatively significant wear occurs before mechanical replacement, leading to the initial generation of paring particles that deteriorate seals or previously deposited portions, even the best coating methods cannot prevent loss of utility [22].

Coatings employed in many devices, whether electromechanical, optoelectronic, or merely mechanistic, must have functional qualities in addition to wear, corrosion, or oxidation resistance. Furthermore, in terms of adhesive bond strength, surface coatings whose main objective is to alter the bulk substrate material's direct environmental reaction typically come close to meeting the requirements of obviously significant coatings. For instance, nonwettability in hydrophilic-hydrophobic adjustments is still effective after significant surface weathering, but realignment at the nanoscale, which is much below observable wear lift-off, accelerates the whole-session nonwettability ease following exposure to dusty air. For functional systems that need at least some substrate interaction, the overall coating-thickness limit rarely goes above the 6–8 μm range.

Photonics and Electronics

Integrated circuits and optical filters are two common applications for thin solid films in electronics and optics. They are also used in the transfer and conversion of energy. Thermophotovoltaic devices are a promising low-cost substitute for solar cells since they transform thermal radiation into electrical energy. Rough surfaces in thin films have optical and radiative qualities that can improve energy conversion efficiency. Light scattering and interference at the microscale make it difficult to accurately model transmittance and reflectance. Though its applicability to other surface conditions and semiconductor materials, like silicon, has not yet been thoroughly investigated, scalar scattering theory has demonstrated a respectable degree of agreement with certain observations. For accurate modelling of thin-film radiative properties, partial coherence theories are required; partial coherence theory has been effectively applied to smooth films. An alternate method that yields results similar to partial coherence theory is spectral averaging [23].

DC sputtering was used to create thin films of inorganic compounds, including tin-doped indium oxide, titanium oxide, and niobium-doped titanium oxide, onto glass and PET substrates. X-ray diffraction, scanning electron microscopy, spectrophotometry, spectroscopic ellipsometry, and surface profilometry were used to characterise the films. Transmittance, reflectance, refractive index, extinction coefficient, energy gap, and dielectric constants were among the optical metrics that were measured. Depending on the substance and substrate, the films' average transmittance ranged from 85 to 91%, indicating strong transmittance in the visible spectrum. XRD examination showed that the structure was amorphous. These substances are employed as transparent electrodes in optoelectronic devices, including liquid-crystal displays, organic light-emitting diodes, solar cells, and flexible electronics. Sol-gel, spray pyrolysis, chemical vapour deposition, pulsed laser deposition, and sputtering are methods for creating transparent thin films; DC sputtering has garnered attention recently for lower-voltage processing at room temperature.

Energy Storage and Biomedical Coatings

Coatings that are electrically conducting, biocompatible, and bioactive have garnered a lot of interest for use in energy storage and medicine. Better fixation, biocompatibility, and biodegradability are necessary for bone implants. Widely used coatings have been created from bioactive materials such as hydroxyapatite, bioactive glass, and bioactive glass-ceramic $ZrTiO_4$; bioactive glass coatings could chemically interact strongly with bone and metal. Additional bioactivity augmentation is demonstrated by three-component $ZrTiO_4$/bioactive glass/hydroxyapatite coatings. Through the formation of mineralised material, bioactive coatings also aid in the regeneration of injured bone tissue [24]. In turn, electrochemically stable and electrically conductive covering materials are required for devices such as Li-ion batteries and supercapacitors. While organic conducting polymers may contain hazardous substances, conventional materials frequently have a limited voltage window. For safe substitutes, carbon-based conductive polymers like polyaniline are being studied for chemical vapour deposition [25].

RELIABILITY, DURABILITY, AND DEGRADATION

The resilience, deterioration, and dependability of thin films and coatings can be strongly impacted by mechanical, environmental, and operational pressures. As a result, adhesion, delamination, ageing, fatigue, and the associated failure modes and service life estimation are all directly tied to thin film technology [26].

When the adhesion between the film and the substrate becomes intolerable, coatings typically break down mechanically. A critical tensile or shear stress at the contact or through the material system's thickness is frequently used to determine adhesion [27]. The failure of coating and thin film structural integrity may or may not be significantly influenced by residual stresses; yet, interfacial fracture mechanics is typically used to characterise the conditions for delamination. Both the substrate and coating materials, as well as the environment and the circumstances surrounding their surface preparation and treatment, can affect adherence. Adhesion models are essential for determining how long coatings will last. A coating is deemed "safe" if the environment does not significantly change the film's mechanical, chemical, or physical characteristics or cause it to age.

Adhesion, Stress, and Delamination

In thin film materials, stress, adhesion, and delamination are important variables. A physical structure or interface that divides two distinct media with varied material properties is referred to as a "thin film". It is possible to define thin films philosophically, geometrically, or in terms of service and function. A thin film, according to geometrical criteria, is a layer of a solid, liquid, or gas that is thin in relation to the substrates' macroscopic dimensions. When thin film technology creates a thin film on a substrate with predetermined dimensions, this geometry criterion is applicable. A thin film is defined geometrically in a more basic way when the process or structure's characteristic length is significantly greater than the thickness under consideration. Although depositing a single component onto a substrate is the standard definition of generating a thin film, the deposition can take the form of the same phase or a different phase. The terms "single layer" and "multilayer" can also be used to describe thin films; a multilayer can also consist of the same material's atomic layer or phase deposited alternately, for example, metallic/oxide/metallic.

The terms "coating" and "film" are not synonymous. A coating, also known as a coated layer, is a layer that is purposefully created on a substrate, substance, or surface in order to alter its qualities. Even if a substance has a certain thickness, it is not referred to as having a coating if it has a poor melting point or sticks to a device. It indicates that a certain deposited or coated structure does not, according to science, qualify as a thin film. Another way to classify coatings is as thin or thick; a "thick coating" is typically defined as being either over 100 μm or over 1–100 μm. A second thin film does not include a coating that is created on top of any thin film that has already been deposited, such as surface-grafted and ion beam-aided deposition thin films.

A number of methods have been developed to describe thin-film adhesion on interfacial bonding. Blister tests, four-point bending tests, indentation mechanics, and laser spallation procedures are some of the ways that adhesion is measured. Research has focused on dynamic delamination of patterned thin films, examining the effects of plasticity and segregation on interface adhesion, and experimentally quantifying interface strength. Many techniques in micro/nano fabrication cause unwanted defects on the surface of thin films, leading to premature micro/nano structure breakdown. Additionally, research examines the decohesion of thin films from brittle substrates, mixed-mode failure, and interfacial fracture behaviour between elastic layers. Insights into interfacial failure processes have been gained through modelling of cohesive bonding in thin film segments and multiple cracking and decohesion of thin films on polymer substrates [28].

Fatigue, Failure Modes, and Ageing

Thermal barrier coatings (TBCs) are used to minimise substrate temperature and thermal-mechanical fatigue, boosting surface durability and extending component life. The breakdown and failure mechanisms of TBC have been the subject of extensive inquiry. The dependability of durability estimates has increased as a result of thorough lifespan prediction studies. Characterization techniques have evolved to enable baseline property measurements and follow the temporal evolution of structural and property changes [29].

Thermal fatigue holds the most essential TBC damage and failure mechanism and continues to be a heavily investigated topic. Although TBCs can endure high-temperature oxidation, thick oxides can considerably minimise degradation rates. The TBC lifetime is inversely related to elevated-temperature oxidation kinetics in the bond coat. Conventional modelling of degradation techniques conforms to documented thermal progression equations and incorporates coating and substrate change.

For service life studies, several TBC configurations provide comparison models. Quantitative experimental evidence provides strong support for failure predictions centred on macroscopic TBC degradation. Pulsed thermography helps with design and process completion by characterising film ageing and predicting remaining life.

Quicker Procedures for Testing

For thin films and coatings used in electronic, photonic, medicinal, and energy storage devices, service life and long-term performance become crucial. In order to simulate long-term performance in an experiment with an arbitrary short duration, accelerated testing techniques are sought [30]. Plotting of the collected data is frequently done using the Coffin-Manson law or the Weibull distribution. Because the extrapolated service duration is not always appropriate, accelerated tests have limitations [31].

SIMULATION AND MODELLING IN THIN FILM TECHNOLOGIES

Despite significant absolute variations in every parameter, nearly every work in the literature on thin-film technology makes the assumption that processes and attributes are approximately unchanging in time at a specific temperature. Despite the frequent coverage of kinetic descriptions for growth in 0, 1, and 2 dimensions, expansions beyond these traditional frameworks are rarely considered. Crack formation, blistering, and other large-deformation events are frequently disregarded, even by skilled practitioners. Seldom are multiscale models that address such a wide range of topics as hydrodynamics, elasticity, optics, transport, mechanics, and precipitation stated. However, they are present in some portions of the literature and provide insightful information. Numerous transport problems that are regularly explored in variational calculus have close connections to both classical and contemporary continuum ideas. Seldom is "architecture" understood to refer to the stuff contained within a unit as well as the matter's orientation, shape, spacing, and direction. Moreover, it is uncommon to observe evanescent and time-harmonic events, including in Fourier space.

Another important class of technologies is machine-learning-based techniques, which rely on ever-increasing volumes of data. In order to reduce dimensionality to a tolerable level, algorithms that extract information from high-dimensional archives frequently use early-stage feature identification and extraction. The estimated governing size and form of any ruling set of equations can often be found using the available data. Furthermore, assessing sensitivity in relation to structural or system factors aids in determining which alterations have the greatest impact on goal values, a practice that is frequently used in the engineering, physical sciences, and biological sciences fields.

Growth Kinetic Models

By anticipating the morphological characteristics of the resulting films, kinetic models of thin film growth characterisation allow for the construction of customised methods and the elimination of trial-and-error testing.

The creation of kinetic equations with predictive power based on variables like substrate temperature and deposition flow is made possible by quantitative theoretical modelling of thin film growth. These growth models can be divided into two categories: atomistic (or particle) models and continuum models. Growth rate equations for continuum models are derived from macroscopic factors such as adatom response mechanisms, the local kinetic equation, and conservation of mass. The Cahn-Hilliard model, the Kuramoto-Sivashinsky equation, the Mullins' model, the Belanov-Mizgireu model, and the Larkin model are some of the methods for adapting the continuum model that allow for an analytical solution under particular circumstances. Molecular dynamics simulations are commonly used to help determine the coefficients of the continuum equation. By dividing the surface area into islands with a limited number of atoms and assuming that growth happens through a stochastic or deterministic mechanism, atomic or particle models simulate kinetic equations. In the creation of thin films and deposits, the size variations of individual islands provide a foundation for connecting microscopic processes to macroscopic kinetic equations.

Laplace pressure sheds light on the connection between the vapour medium's supersaturation, nucleation rate, and film thickness. The film thickness evolution follows the Boltzmann solution of the rate equations after a time lag due to the nucleation phase, whereas the steady state is obtained in a system of islands corresponding to a random or deterministic deposition process. With a focus on oscillatory structures, the study of multilayers draws attention to the potential for controlling their geometry and design.

Multiphysics and Multiscale Methods

In order to optimise coating design and deposition technique, computational modelling and simulations have become indispensable tools. By linking the atomic to the continuum scales and establishing the connection between kinetic and continuum models, there is better knowledge of transport processes difficult to investigate experimentally. The design process now heavily incorporates the thorough integration of the material, deposition, and environmental history into the modelling prediction of post-deposition parameters. By adjusting the deposition strategy applied to the material to coat, models of transport-driven evolution events on a solid surface under different combinations of deposition and environmental variables offer insights for customising desired features. Real-time remission of a whole design is made possible by optical modelling's capacity to tie the deposition history to both the coating microstructure and its transmission spectrum. In order to control the morphological creation of shadowing films, the model additionally incorporates diffusion-limited growth of nanostructures in air and vacuum [32].

Predicting and Optimising Properties

It is possible to pursue performance optimisation through surrogate models, parameter sensitivity, and experiment design that would be impossible with a complete 3D simulation of complex development or gas-solid interaction. By describing all parameters in terms of a set of prominent material and layout factors that govern the dimensional geometry of film structure, these methods may handle property prediction modelling as an inverse issue. For instance, these parameters include temperature, gas-phase velocity, deposition rate, film density, and shadowing fraction in the context of physical vapour deposition. A framework for the inverse problem of predicting the tribological behaviour of PVD coatings on engineering materials Wear, friction coefficient, and adhesion are the three factors that capture tribological performance; the first two are dependent on the deposit's properties, namely coating material and thickness, adhesion energy, and intrinsic wear. In order to demonstrate how deposition temperature, evaporated metal, and substrate stiffness affect the final aspect ratio of nanostructures in an E-beam evaporation process of metal films deposited on a polymer substrate, parameter-sensitivity analyses on a simplified growth-diffusion model [33].

STANDARDS, ECONOMICS, AND SUSTAINABILITY

Today, governments place a great deal of attention on technical processes that are both economical and environmentally benign, making sustainability a significant component of industrial development. The technology related to coatings and thin films is being included in the sustainability agenda. The market segment focusing on solar energy equipment, as well as coatings for antimicrobial and anti-corrosion reasons, is expanding quickly due to the rising use of these coatings on micro-electronic components, television and mobile phone screens, and solar energy panels. The market for hard chrome coatings, which are commonly utilised for hard, corrosion-resistant, and wear-resistant coatings in automotive and aerospace applications, is a significant portion of the metal processing sector. Furthermore, chromium coatings significantly improve mechanical qualities like hardness and wear resistance in addition to corrosion resistance, when compared to other coatings now available on the market. However, carcinogenic hexavalent chromium compounds are used in standard electrodeposition techniques to create deposits from chromate passivation baths or aqueous electrolytic processes. Magnetron sputtering and other alternatives to chrome coatings are thought to be more ecologically friendly technologies. While attempts to elucidate the firm's potential benefits of magnetron sputtering as a chrome plating alternative either targeted the entire TEA or welcomed discussions with regard to process fundamentals, such as standardisation and the establishment of uniform performance metrics) [34], the life cycle and techno-economic analysis (TEA) of hard chrome coatings elaborated three environmental effects associated with electrodeposition under residence time of coating production exceeding 10 min.

Considerations for the Life Cycle

Products with improved coatings may be recovered by selective disassembly or recycling instead of disposal after use. Within their functional operating limits, more functions, longer use cycles, and fewer material changes enhance sustainability, regardless of potential decreases in overall or relative material-use volume. These coatings show significant protection against scratches and wear when compared to uncoated parts, allowing for increased service life. Coatings should be viewed as aspects of a product-function cycle and continue to work on parts that are close to or beyond service limits. An economy-technology perspective allows for an informed assessment of investment-worthiness and capability-opening merits by applying economic models to new production processes and quantifying improvements in performance and service duration, lower energy consumption, and lower pollutant emissions.

Cost Implications of Process Scaling

Process scalability, capital and operating costs, and yield optimization remain important difficulties for the commercial implementation of innovative thin-film technologies and materials. Variations in surface coverage, morphology, precursor interactions, and deposition rates present scale-up difficulties [35]. The properties of the precursor materials, chemical reactions, and physical interactions that occur during the deposition process all have a major role in determining the scalability of the process. Understanding solvent evaporation, pre- and post-deposition interactions, and other precursor interactions is essential for successful scale-up, even when novel deposition processes show promise for high-performance coating of 2D materials.

Metrology, Standards, and Quality Assurance

The most widely used standards that are pertinent to coatings and thin films in general are ISO 4540:1983 on terminology for film thickness measurement personnel, ISO 2858:1987 on lubrication grease film thickness measurement, and ISO 2942:1998 on equipment calibration specifications for infrared radiation-based film thickness measurement. Transmission electron microscopy, scanning electron microscopy, microhardness, inductively coupled plasma-atomic emission spectroscopy, and Fourier transform infrared spectroscopy measurements have all been used to analyse PS coatings deposited on polycarbonate substrates.

The curvature method is frequently used to quantify the intrinsic residual stress of thin films; the values of this stress obtained for Al films grown on W substrates of varying thicknesses demonstrate that it is highly dependent on the thickness of the W buffer layer [36].

CONCLUSION

In contemporary technology, thin films and coatings are essential. Although they were first established in the 19th century, our knowledge of growth mechanisms is relatively new. *In situ* characterisation techniques have improved our understanding of the deposition process and, as a result, the engineering of film properties. Early in the 20th century, deposition materials were the subject of research. Later, the coating procedure came into prominence, with a particular emphasis on substrate preparation. The focus of current trends is on atomic-level growth control. Growth is influenced by a number of variables, including the geometry, deposition rate, substrate temperature, and material characteristics. Selective surface alterations known as coatings enhance usefulness while maintaining the material characteristics of the substrate. To achieve complete coatings with many functionalities, multilayer structures and composite coatings must be prepared.

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