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Effect of Coatings on Mechanical, Corrosion and Tribological Properties of Industrial Materials: A Comprehensive Review

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Abstract
The implementation of coatings on industrial materials has a significant impact on their tribological, corrosion, and mechanical properties. This review examines the impact of coatings on these essential material properties, and the challenges of the implementation mechanisms are discussed. In industrial applications, coatings are essential for lowering friction, wear, and surface damage and enhancing the tribological performance of materials. The ability of several coating processes to improve the wear resistance and lubricity of materials is being investigated. Also, the study cuts across the review of literature on physical vapour deposition (PVD), chemical vapour deposition (CVD), and thermal spray coatings. Furthermore, using protective coatings can considerably increase the corrosion resistance of industrial items. The suitable coating materials and methods must be used to prevent corrosion over the long term effectively. Additionally, coatings significantly affect the mechanical qualities of industrial materials, such as toughness, strength, and hardness. Hard coatings like nitride-based coatings can considerably increase materials' surface hardness and wear resistance. Additionally, by mixing various materials with complementary qualities, tailored multilayer and composite coatings can improve mechanical capabilities. To customise coatings for particular applications, it is crucial to comprehend how coatings interact with industrial materials. Furthermore, challenges such as coating-substrate compatibility, durability, and cost-effectiveness are addressed to ensure the successful implementation of coatings in industrial applications. Overall, the review highlights the significant role of coatings in improving industrial materials' tribological, corrosion, and mechanical properties and emphasises the need for further research and development in this field.

Keywords Industrial materials · Mechanical properties · Corrosion properties · Tribological properties · Industrial coatings

1 Introduction

Industrial materials, which offer a wide range of qualities to match the varying needs of many industries, are essential elements in modern manufacturing processes. Industrial materials can be divided into several categories depending on their composition and characteristics, as presented in Fig. 1. Due to their remarkable strength-to-weight ratios, metals like steel and aluminium are widely employed and suitable for structural applications [1]. Metals and alloys are widely used in various industries due to their excellent mechanical strength, conductivity, and corrosion resistance [2]. Steel is used exclusively in the construction of skyscrapers and bridges due to its high tensile strength and durability, while Aluminium, with its lightweight nature and excellent corrosion resistance alongside composites which are composed of two or more materials, combine the desirable properties of each component, making them valuable in industries like aerospace, automotive, and sporting goods [3]. Carbon fibre-reinforced polymers (CFRPs), among other composite materials, have become common substitutes for conventional materials. Due to its high strength-to-weight ratio, CFRPs are excellent for applications such as sporting goods and automotive components. CFRPs combine the high strength of carbon fibres with the flexibility of polymers to produce lightweight and durable materials [4]. Polymers and ceramics are also essential components in industrial applications. Ceramics are ideal for use in engine parts,

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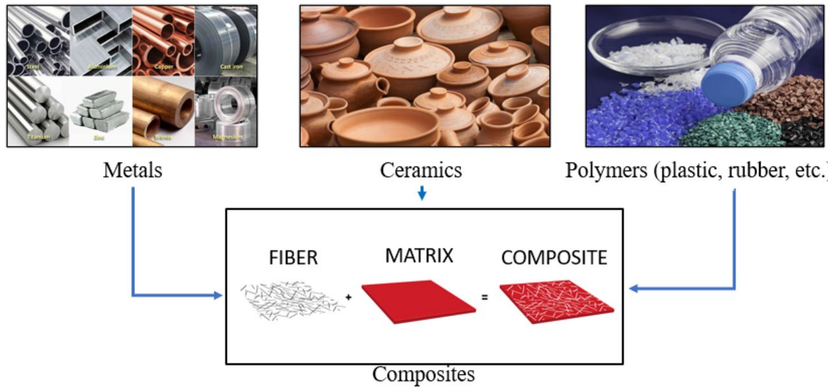


Fig. 1 Various industrial materials

cutting tools, and electrical insulators because of their outstanding resistance to high temperatures, wear, and corrosion [5]; they also find use in the electronics, aerospace, and energy sectors because of their high-temperature stability and electrical insulation [6]. Polymers like plastics and rubber are lightweight and adaptable, making them appropriate for packaging, construction, and automotive industries [7]. Developments in materials science have facilitated the production of specialised materials with distinctive features for particular uses. Aerospace, Defence, and high-temperature applications use high-performance materials such as shape memory alloys, carbon fibre-reinforced composites, and superalloys [8]. Electronics, energy storage, and medicinal fields use nanomaterials, including nanoparticles and nanocomposites, since they possess more excellent qualities [9]. Manufacturers can produce goods with particular qualities suited to their various industries because of the wide variety of industrial materials. These qualities include tribological, corrosion, and mechanical properties.

The mechanical properties of industrial materials play a crucial role in determining their behaviour and performance under various loading conditions. A material's response to mechanical forces is described by various qualities known as mechanical properties. Young's modulus, often known as the elastic modulus, measures a material's stiffness and elastic deformability, whereas Toughness measures a material's ability to absorb energy before fracture [10]. A material's resistance to deformation and failure is indicated by its strength, which includes tensile, compressive, and shear strength [11]. According to Meyers et al. [12], ductility is the capacity of a material to endure plastic deformation before fracture. According to [13], a material's hardness reflects its resistance to being scratched or indented. Different materials have various mechanical properties as a result of these qualities. The inherent strength and ductility of metals like steel and aluminium make them ideal for structural applications. Although polymers are flexible and lightweight, they typically have lower mechanical strengths than metals. Ceramics are very stiff and rigid but typically fragile [12]. According to the composition and placement of components, composites combine the desirable qualities of many materials to provide a wide range of mechanical characteristics. The different materials' characteristics shown in Fig. 2a affect the stress–strain, such as ultimate strength and yield and determine the fracture point as debited in Fig. 2b.

The corrosion properties of industrial materials refer to their susceptibility to deterioration and degradation when exposed to corrosive environments. Material contact with the environment is a key component of the complicated electrochemical process termed corrosion. Corrosion can happen in various ways, according to Chen and He [14], including uniform corrosion, pitting corrosion, crevice corrosion, and stress corrosion cracking. Each mechanism has unique difficulties and calls for specialised corrosion mitigation techniques. A material's microstructure, surface quality, and composition affect its corrosion resistance. Because alloying elements like chromium and nickel are present and form a passive oxide layer on the surface of stainless steel, they have high corrosion resistance [15]. Similarly, using corrosion-resistant alloys, including nickel-based or titanium alloys, may enhance the resistance to corrosion in particular environments [16]. Tribological properties describe the friction, wear, and lubrication that occur when surfaces move about one another. Understanding the tribological properties of industrial materials is crucial for optimising their performance and ensuring efficient operation. Key tribological characteristics, such as friction and wear resistance, influence the barrier to motion between two surfaces and define a material's capacity to tolerate surface deterioration and material loss. According to Sahoo and Satapathy [17], the coefficient of friction determines how easy or difficult it is to slide between surfaces. In mechanical systems, high friction can result in energy losses, more wear, and less efficiency. Li et al. [18] pointed out that elements like hardness, surface roughness, and the presence of protective coatings have an impact on wear resistance. Superior wear-resistant materials provide less material loss and longer service life.

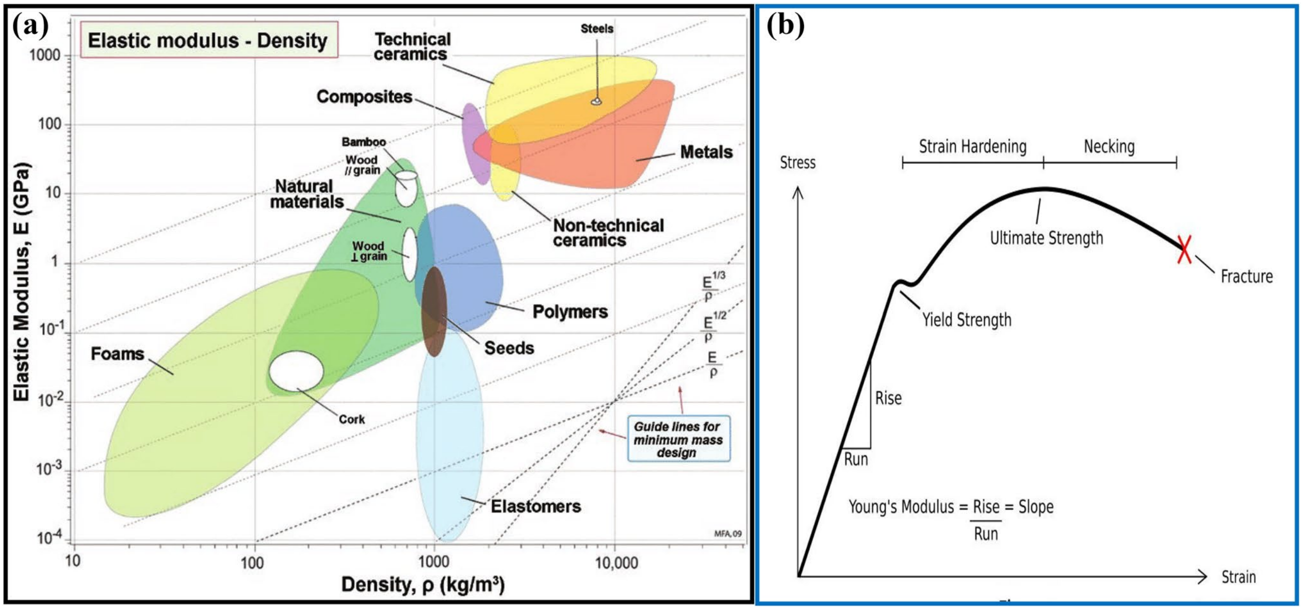


Fig. 2 **a** Material property chart and **b** Stress–Strain curve for materials [12]

Industrial coatings fall into two categories: organic and inorganic. Due to their adaptability, simplicity of application, and attractive finishes, organic coatings, including polymer-based paints and coatings, are frequently employed [19]. These coatings offer improved aesthetics, chemical resistance, UV protection, and corrosion resistance. They are frequently used in consumer products, construction, and the automotive industry. On the other hand, Metallic and ceramic coatings are examples of inorganic coatings. Metallic coatings offer superior corrosion resistance, wear protection, and enhanced surface hardness [20]. Examples of these coatings include electroplating and thermal spray coatings. Applying thick coatings with improved mechanical and corrosion properties is made possible by thermal spraying techniques, such as plasma spraying, high-velocity oxygen fuel (HVOF) spraying, and flame spraying [21]. These coatings are widely employed in industries where toughness and resilience over severe conditions are essential [22]. They provide superior wear resistance, muscular bond strength, and improved fatigue life. Ceramic coatings offer some unique qualities of abrasion resistance, thermal barrier capabilities, and high-temperature stability [23]. They have uses in the aerospace, energy, and automotive sectors where resistance to oxidation, wear, and high temperatures is crucial.

Preparing and implementing industrial coatings involve various materials, methods, and techniques. Some standard coating application techniques are spraying, dipping, roller coating, and electrostatic deposition, as debited in Fig. 3a–c. Because of their effectiveness, consistency, and simplicity of usage, spraying techniques, including airless and electrostatic spraying, are often used [24]. Methods like dipping or immersion provide for homogeneous coating application and are suited for objects with complicated shapes. For big, continuous surfaces, roller coating is frequently used. According to Ghasemi et al. [25], the most popular procedure is the dispersion of coating components in an appropriate solvent, followed by application methods including spraying, brushing, or dipping. A common technique for applying metal coatings is electroplating, depositing a metal layer onto a substrate using an electrochemical process [26]. To ensure adequate adherence between the coating and the substrate, surface preparation is a crucial step involving cleaning, surface roughening, and primers or adhesion promoters. The type of coating, desired thickness, and type of substrate all play a role in choosing the best coating technique. The coating thickness is also unnecessary because it influences the coating's durability and protective qualities [27]. The thickness, content, and structure of coatings can be precisely controlled using cutting-edge processes, including chemical vapour deposition (CVD) and physical vapour deposition (PVD), as shown in Fig. 4. A thin layer is deposited on the substrate surface due to a chemical reaction between gaseous precursors in CVD. Contrarily, PVD entails the evaporation or sputtering of solid coating ingredients afterwards deposited onto the substrate surface. The benefits of thin films are excellent wear resistance, reduced friction, and increased hardness [28]. These nanoscale coatings can be customised through various deposition processes to fit particular needs [29]. However, the application of multiple layers of coatings is know as multi-layer coatings. The majority of multi-layer coatings are just many repetitions of two layers, one tougher and one softer. They could be comprised of two separate

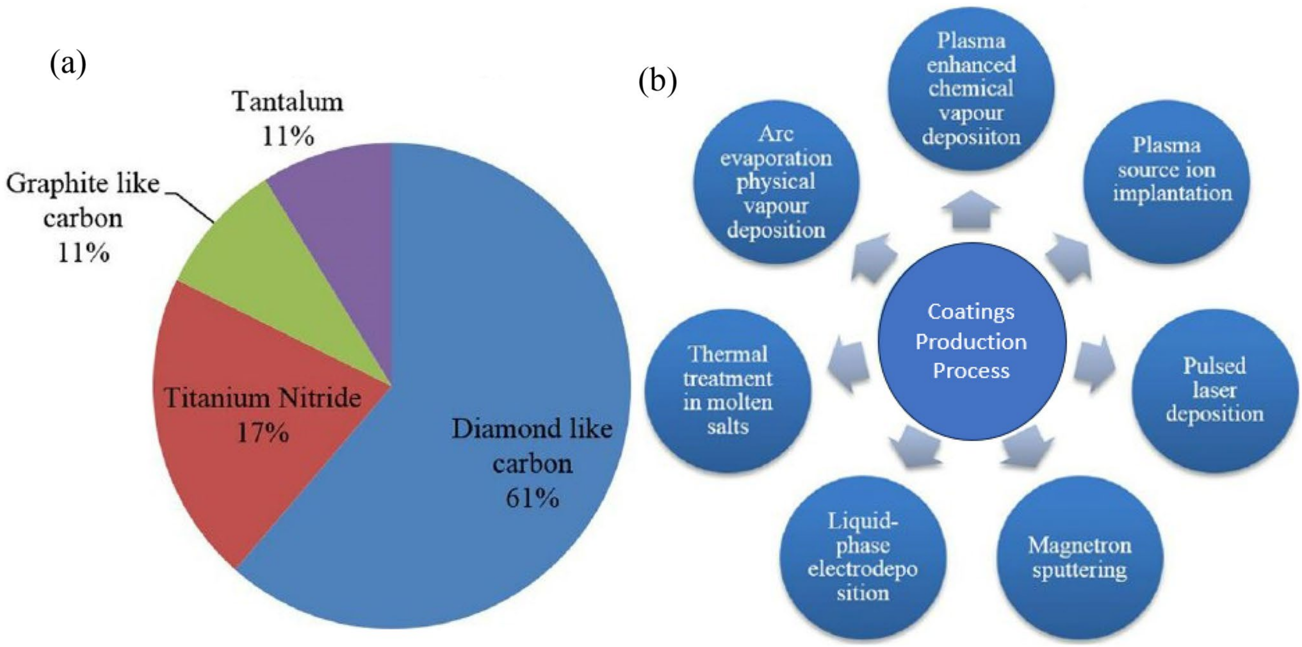
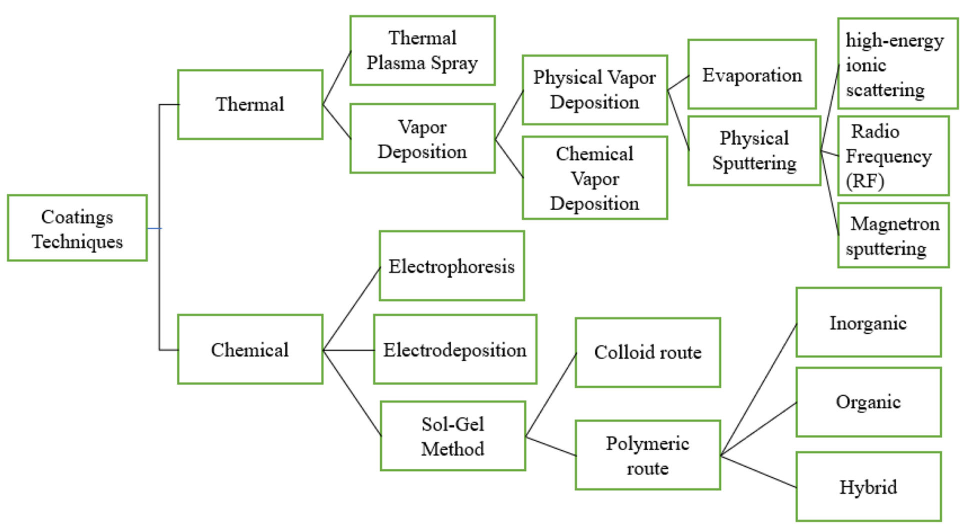


Fig. 3 **a** Materials for coatings developmsent and **b** different method to produce [26]

Fig. 4 Coatings techniques for implementation [27]



ceramic layers or a combination of ceramic and metallic layers. Layer material characteristics affect the characteristics of multi-layer coatings.

Specialised coatings have emerged as a result of coating technology. For instance, functional coatings, such as self-cleaning or anti-fouling, have been developed to meet industrial needs [25]. These coatings offer extra features like water and oil repellence or microbial growth resistance, which have uses in various industries like healthcare, electronics, and food processing. The application of coatings successfully depends on considering some variables, such as the application's specific requirements, the surrounding environment, and the intended performance characteristics. Therefore, this study aims to review the literature on the effect of coatings on industrial materials' mechanical, corrosion and tribological properties. Also, the study discusses the significance of coating and its challenges in the manufacturing industry.

2 Study of the Impact of the Implementation of Coating on the Mechanical Properties of Industrial Materials

The mechanical qualities of materials, such as hardness and fatigue strength, are greatly enhanced by coatings. According to Zhang et al. [30], coatings can greatly increase the hardness of a material, offering resistance to abrasion and surface damage. They also help to improve a material's wear resistance by reducing friction and the impacts of wear operations. According to Li et al. [31], coating application permits the adjustment of surface roughness and topography, which can affect mechanical properties, including adhesion and friction. Figure 5 shows that the ASP30 and D2 tool steel substrates have higher roughness than H11 steel. After polishing the D2 and ASP30 tool steel substrates, shallow protrusions (about 8 nm in height) appeared at the sites of carbide inclusions, while no such protrusions were observed in the case of H11 tool steel. This suggests that coatings can increase the fatigue strength of industrial materials. Coatings also serve as barrier layers that can prevent crack initiation and growth, extending the material fatigue life [31]. The bonding of coatings to the substrate is a crucial factor that impacts the mechanical properties. It is crucial to adequately prepare the surface and use the appropriate coating materials to obtain good adhesion and prevent delamination or cracking [32]. Physical vapour deposition (PVD) and chemical vapour deposition (CVD) are two advanced techniques that precisely control coating thickness and characteristics, affecting mechanical properties. Table 1 shows a summary of the effect of coatings on the mechanical properties of some industrial materials. The mechanical properties of industrial materials guide the design and engineering of components to ensure optimal performance and reliability. Jones [33] emphasises the importance of considering the mechanical properties of materials, such as strength, stiffness, and toughness, when designing structures, as it ensures that the materials can withstand the applied loads and forces without failure. The mechanical properties of industrial materials can be modified through various procedures, including alloying, heat treatment, and processing methods. According to Ashby et al. [10], alloying elements can increase strength, hardness, and corrosion resistance. Quenching and tempering are heat treatment techniques that can alter the microstructure and improve mechanical characteristics. The material's grain structure and mechanical behaviour can be affected by processing techniques such as forging, casting, and extrusion. All these mentioned properties of industrial materials can be modified using industrial coatings.

While coatings offer potential benefits in enhancing the corrosion resistance of industrial materials, it is essential to consider their associated drawbacks. One major disadvantage is the potential reduced material ductility and toughness due to a coating layer [34]. Research studies have

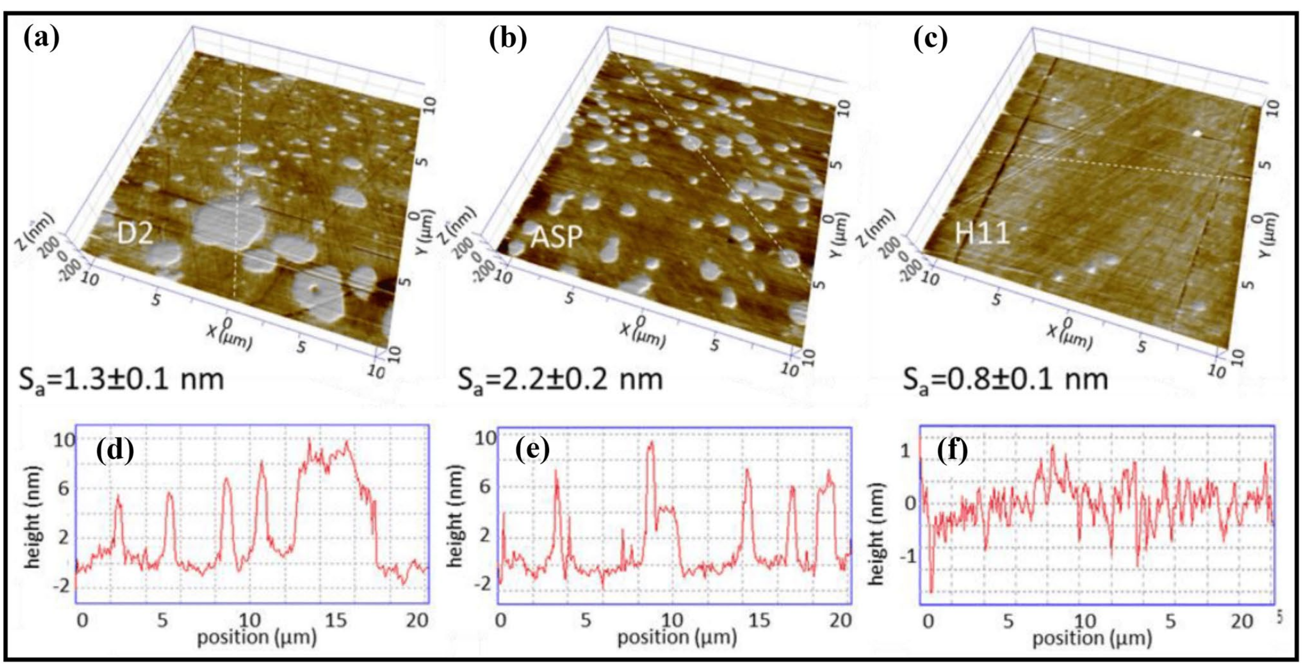


Fig. 5 Atomic Force Microscope images and surface roughness (Sa) of uncoated D2 (**a**) ASP30 (**b**) and H11 (**c**) tool steel substrates after polishing [34]

Table 1 Summary analysis for coating effects on mechanical properties of industrial materials

Authors details	Type of coating materials used	Industrial materials	Mechanical properties study	Modes of application	Findings
Verdi et al. [35]	Cr3C2 + Inconel 625 alloy	Ferritic steel substrate	Microstructure, mechanical; Local wear behaviour	Laser cladding	Evenly distributed Cr3C2 particles in coating microstructure
Rambabu et al. [36]	Zirconium Oxide	Aluminium alloy Al7075	Tensile and impact strength	Spraying method	Enhanced Tensile strength, Impact strength and hardness
Dileep et al. [37]	Zinc	Aluminium 7075 alloy	Surface hardness, tensile strength and fracture toughness tests		Improved hardness; Increased yield stress; Unchanged brittleness
Ravi et al. [38]	Nickel, Zinc, and Cadmium	Al 7075	Hardness and tensile	Time-dependent electroplating method	Nickel coating provided better hardness and tensile strength than zinc and cadmium. 20 µm Nickel-coated alloy exhibits the highest hardness number of 102 HRB
Mohseni et al. [39]	Ti/TiN	Ti–6Al–4V	Surface hardness	PVD magnetron sputtering technique	14% enhancement in surface hardness
Zalnezhad et al. [40]	Titanium Nitride coating	Al7075-T6 alloy	Surface hardness, adhesion, surface roughness	Magnetron sputtering technique	14% increase in surface hardness, 4.15% increase in adhesion, and 9.43% reduction in surface roughness
Çiçekler et al. [41]	Precipitated Calcium Carbonate (PCC) and Ground Calcium Carbonate (GCC)	Fluting paper	Tensile and burst strength	Ring crush test (RCT), corrugating medium test (CMT), corrugating crush test (CCT),	13.9% increase in tensile strength; 6.05% increase in burst strength; No significant impact on the CMT values
Abdulrahaman et al. [42]	Carbon nanotubes	Mild steel	Tensile strength, yield strength, hardness value	Conventional chemical vapour deposition reaction using bimetallic Fe–Ni catalyst	Increased tensile strength, yield strength and hardness
Jarząbek et al. [43]	Thin Cu layer of SiC particles	Ni/sic composites	Composite interface microstructure; Bonding strength	co-electrodeposited method	The Cu/Ni had good quality but rough interface; The sic/Cu had good quality and smooth surface; The sic/Cu interface was weak; Low tensile strength of the composite
Al-Juboori and Albtoosh [44]	Titanium (Ti) and Nickel (Ni)	Thin aluminium (Al7075-t6)	High stress and the resistance to deformation of aluminium alloy AL7075-T6	Electro-deposition of composite coatings	Nickel coating has shown more significant improvements in comparison with Titanium coating
Zhao et al. [45]	Cu	Carbon fibre-reinforced aluminium matrix (Cf/Al) composites	Tensile strength; Elastic modulus	Ultrasonic vibration-assisted plating technique	Improved tensile strength and elastic modulus: tensile strength of 169 Mpa, an elastic modulus of 80, and an elongation of 4.2%

Table 1 (continued)

Authors details	Type of coating materials used	Industrial materials	Mechanical properties study	Modes of application	Findings
Alten et al. [46]	Ni	Al-6063 alloy	Hardness tests	Electroless technique	The mechanical properties of composites are badly affected by higher coating thicknesses
Tung et al. [47]	Polydopamine and graphene	3D printed polyurethane	Hardness	Dipping	Increase in compressive strength and Young's modulus
Chen et al. [48]	Dopamine-modified graphene oxide (D-GO)	Waterborne polyurethane (W-PU)	Tensile stress and yield strain	Water solution blending	Improved elongation at break and increased Young's modulus
Heck et al. [49]	Commercial silica	Commercial waterborne polyurethane (PU)	Mechanical resistance	Blending method	Increased mechanical resistance
Lee et al. [50]	0.5 vol% polyethylene terephthalate (rPET) fibres	Mortar	Fracture energy		Increased tensile strength and fracture energy

indicated that coatings can increase brittleness and decrease crack propagation resistance, compromising the material's mechanical strength and fracture resistance [51]. Another drawback is the possibility of coating delamination or debonding from the substrate. Delamination can occur due to poor adhesion, thermal expansion mismatch, or mechanical stress, significantly weakening the material and reducing its load-bearing capacity [52]. Additionally, applying coatings can introduce residual stresses in the material, which can arise during the coating process and affect its mechanical properties. These stresses can lead to dimensional instability, warping, or microcracking, impairing the material's structural integrity [53]. The thickness and uniformity of the coating layer also play a role in the material's mechanical behaviour. Non-uniform or excessive coating thickness can introduce stress concentrations and uneven load distribution, potentially resulting in premature failure or localised deformation [54].

Moreover, certain coating materials may not be compatible with the operating conditions or environment in which the material is utilised. Exposure to harsh chemicals, high temperatures, or corrosive agents can degrade the coating, compromising its protective function and accelerating material degradation [55]. The cost and complexity associated with applying coatings can be significant. Coating processes often require specialised equipment, skilled labour, and time-consuming procedures, increasing production costs and potentially limiting their feasibility in specific industries or applications [56].

3 The Effects of Coating on the Corrosion Behaviour of Industrial Materials

Coatings and surface treatments play a crucial role in improving the corrosion properties of materials. Protective coatings, such as organic coatings or metallic coatings, create a physical barrier between the material and the corrosive environment [57]. Surface treatments like passivation or anodising can modify surface properties and enhance corrosion resistance. In addition, environmental elements like temperature, humidity, pH, and the presence of corrosive compounds affect how materials behave when they encounter corrosion. For instance, exposure to chloride ions or acidic conditions can accelerate corrosion. To choose materials that can endure corrosive difficulties, it is essential to understand the individual environmental conditions—coatings shield Materials from corrosive conditions, which serve as protective layers. Corrosion resistance is unsatisfactory for several coating materials, including polymers, ceramics, and metallic alloys [58]. Implementing coatings on industrial materials significantly impacts their corrosion properties, providing an effective barrier against corrosive environments and enhancing their durability. Coatings serve as protective layers that can considerably increase the ability of a material to resist corrosion, prevent direct contact, slow down corrosion and give good finishing. Figure 6 shows the primary layers of coating material and their functions. Kim et al. [59] claim that coatings build a physical barrier between the material and the corrosive environment. For example, ceramic coatings, such as oxide or nitride, provide good corrosion protection due to their excellent chemical stability and inertness. These coatings produce a shielding oxide layer that prevents corrosive species from penetrating and offers long-term corrosion protection. Additionally, coatings can alter the electrochemical characteristics of a material, improving corrosion resistance. Li et al. [60] state that coatings can change a material's corrosion potential and current density, preventing corrosion reactions. As seen in Fig. 7, an additional layer of defence against corrosion is offered by coatings such as organic coatings and inorganic films.

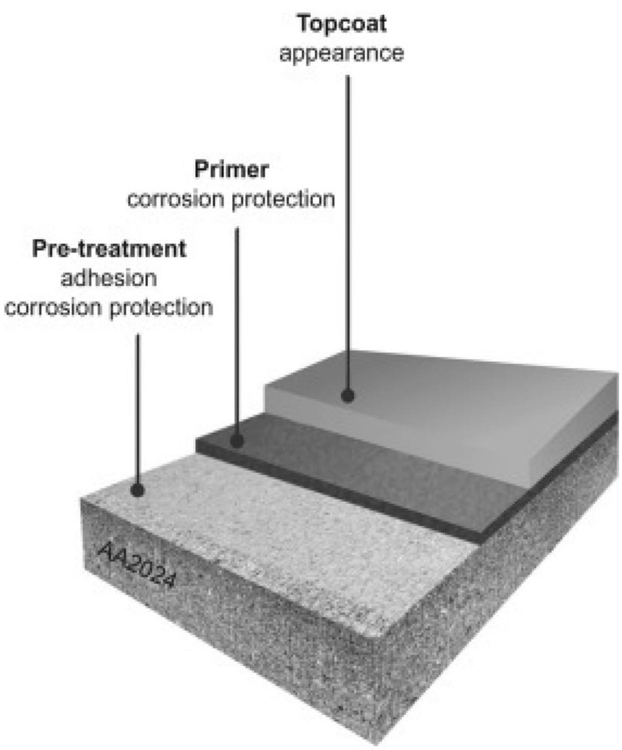


Fig. 6 Idealized scheme of a coating system for barrier protection of AA2024 [59]

A significant factor affecting the corrosion characteristics is the adherence of the coating to the substrate. Proper surface preparation and coating application processes are crucial to maintaining strong adhesion, reducing the chance of coating delamination and preventing the substrate from corrosion [61]. To achieve long-term corrosion protection, choose suitable coating materials and application methods [62]. For example, Zhang et al. [63] emphasised using corrosion-resistant coatings, such as zinc-based or aluminium-based, to provide long-term protection against corrosion. The combination of suitable coating materials and practical application techniques ensures enhanced corrosion resistance and extends the service life of industrial materials. Table 2 illustrates a summary of the effect of coatings on the corrosion properties of some industrial materials.

The thickness and uniformity of coatings play a significant role in determining the corrosion properties of materials. The choice of deposition method can influence these factors. Research has indicated that deposition techniques such as electroplating and electrochemical deposition offer the advantage of producing precise and controlled thickness coatings, leading to enhanced corrosion resistance [78]. Conversely, spray or dip coating methods may result in uneven coating thickness, potentially undermining the protective barrier against corrosion [79]. The bonding strength between the coating and the substrate is a critical factor that impacts corrosion performance. Specific deposition techniques like physical vapour deposition (PVD) and chemical vapour deposition (CVD) facilitate interfacial solid bonding, thereby contributing to improved corrosion resistance [80, 81]. In contrast, improper adhesion caused by inadequate deposition methods can result in coating delamination and accelerated corrosion [82]. Additionally, the microstructure and porosity of coatings play a crucial role in determining their corrosion properties. Techniques such as sol–gel processing or electrodeposition can produce coatings with a

Fig. 7 Effect of the corrosion potential in the topcoat and bond coat layers [60]

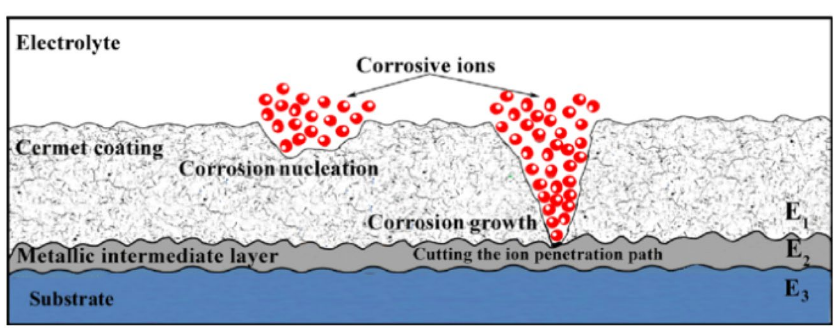


Table 2 Summary analysis for coating effects on corrosion behaviour of industrial materials

Authors details	Type of coating materials used	Industrial materials	Corrosion analysis	Mode of applications	Findings
Mukhopadhyay and Sahoo. [64]	Ni–P, Ni–P–W and Ni–P–Cu	Fe-600 rebar	Mitigation of corrosion in 0.5 M sulphuric acid	Electroless technique	Uncoated rebar showed severed cracking and corrosion pitting; The Ni–P–W coating showed the highest corrosion resistance
Khodair et al. [65]	MgO nanoparticles	Mild steel (in various aqueous media)	XRD: weight loss sem	Dipping	Increase in corrosion rate with temperature. Increase in corrosion rate with salt concentration; Decreased CR with PH values. Significant reduction of corrosion rates in acidic solution due to coating
Mukhopadhyay and Sahoo [66]	Ni–P–W	Rebar steel	Potentiodynamic polarisation in chloride environment	Electroless technique	Negligible damage to the Ni–P–W coated rebar
Alsamuraee and Ameen [67]	Zinc, tin, and lead	Steel reinforcement in concrete	Accelerated corrosion Test ASTM 109 g; electrochemical polarisation. Microstructure and visual inspection	Electroplating and hot dipping	The results for the corrosion rates are listed below (worst-to-best): Galvanized CRS showed the worst corrosion rate; Followed by untreated CRS
Banerjee et al. [68]	Autocatalytic Ni–P	Magnesium nanocomposites (AZ31-2WC)	Energy dispersive X-ray analysis (EDAX), and X-ray diffraction analysis (XRD)	Electroless technique	Improved corrosion resistance and enhanced surface quality;
Chen et al. [69]	Nickel-phosphorus (Ni–P) plated composite film	LZ91 Magnesium alloy	Potentiodynamic polarisation test	Micro-arc oxidation (MAO) and electroless plating	Better protection for LZ91 magnesium alloys
Chen et al. [70]	Ni–P composite	Magnesium (Mg) alloy AZ31B	Corrosion tests	Plasma electrolytic oxidation (PEO) and electroless plating	Superior corrosion protection of the Mg substrate by the PEO/Ni–P coating
Zhang et al. [71]	Ni–P coating and Ni–Cu–P bilayer composite film	L360 pipeline steel	Erosion corrosion method and electrochemical test	Electrodeposition and Two-step electroless plating	Improved corrosion resistance and decelerated surface corrosion
Shamshirsaz et al. [72]	Ni–Al_2O_3	316L Stainless steel	Corrosion resistance	Spraying	20% increase in corrosion resistance
Lakkimsetty et al. [73]	Nano coatings (Tio_2: Zone: Polyamide (PA)	Steel substrate (304L SS)	Weight loss method	Thin-film technology	Higher and prolonged corrosion resistance
Sajid et al. [74]	Soy-protein and corn-derived polyol-based coatings	Cement mortar embedded. Soy Protein Isolate (SPI) coated rebars	Rapid macrocell corrosion test	Fusion-bonded epoxy (FBE) coating	Reduced corrosion current density; Improved corrosion rates; Stable corrosion potential

Table 2 (continued)

Authors details	Type of coating materials used	Industrial materials	Corrosion analysis	Mode of applications	Findings
Castro et al. [75]	ZrNxOy	Film substrate 316 l	Potentiodynamic polarization and electrochemical impedance spectroscopy	Reactive high-power impulse magnetron sputtering	Corrosion tests showed that the film densification controlled the corrosion resistance
Rybin et al. [76]	Zirconium dioxide and titanium dioxide coated	Basalt fibre	Weight loss and electrochemical sol–gel method	Immersion process of deposition	Solid corrosion products might vary in form and composition depending on the kind of alkaline medium
Mittal et al. [77]	Carbon nanotubes (CNTs)	Woven-type basalt fabric	Electrochemical impedance spectroscopy and linear polarisation resistance	*Chemical vapour deposition*	Implementing carbon nanotube coating on basalt fabric improves the material's corrosion resistance

dense and compact structure, thereby minimising the penetration of corrosive species [83, 84]. Conversely, thermal spraying can introduce porosity, allowing corrosive agents to reach the substrate. The chemical composition and phase of the coating can also be influenced by the deposition method, thereby affecting its corrosion behaviour. Specific deposition techniques enable the formation of protective oxide layers on the coating surface, contributing to enhanced corrosion resistance [85, 86].

Furthermore, the deposition atmosphere and conditions impact the corrosion properties of the coatings. Vacuum-based methods such as PVD provide a controlled environment, reducing the risk of contamination and ensuring improved corrosion resistance [87]. Conversely, atmospheric deposition methods may introduce impurities or moisture, which can affect the performance of the coating.

4 The Effects of Coating on the Tribological Properties of Industrial Materials

The tribological properties of industrial materials are significantly impacted by the application of coatings, influencing friction, wear, and lubrication. Enhancing the tribological performance of materials is greatly helped by coatings. Coatings significantly influence the tribological behaviour of materials by reducing friction and wear. They act as protective barriers, minimising direct contact between mating surfaces [88]. Balint et al. [89] assert that coatings with low friction coefficients can greatly minimise energy losses and increase the effectiveness of mechanical systems. As shown in Fig. 8, where a polymer-based coating is used on metal, coatings can reduce friction and wear by acting as a protective layer between interacting surfaces. Additionally, coatings can make industrial materials more resistant to wear.

According to Xia et al. [90], coatings with high hardness and strong adhesion can withstand wear processes such as abrasion, adhesion, and erosion. Coatings also play a role in enhancing the lubricating capabilities of materials. Coatings can be lubricants in sliding contact applications, decreasing wear and friction. They can also integrate solid lubricants or lubricant-infused layers to offer continuous lubrication and lessen the requirement for external lubrication [91]. According to Xie et al. [92], effective coating reduces the direct contact between surfaces by generating a thin film that separates them. Lubrication also plays a key function in lowering friction and wear between contacting surfaces. Additionally, proper lubrication enhances tribological performance by minimising wear and friction. Several lubrication mechanisms, such as boundary, mixed, and hydrodynamic lubrication, may be employed. Industrial materials' tribological characteristics are also influenced by surface topography. Due to the increased contact area and potential for abrasive

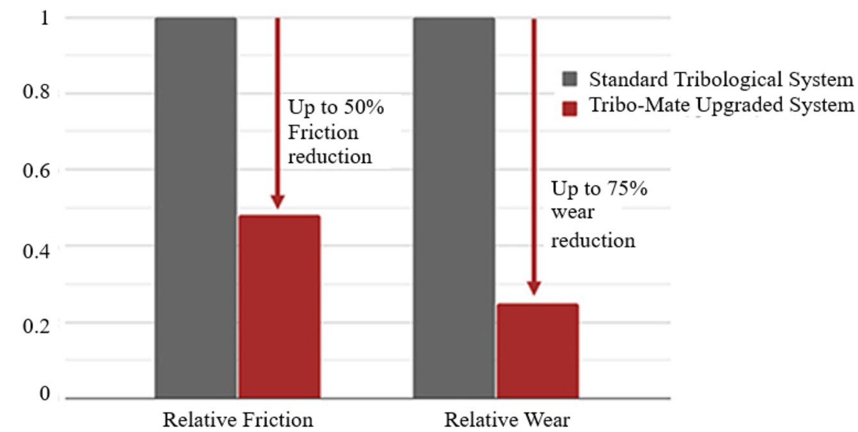


Fig. 8 Generalised effect of polymer-based coating on the tribological properties of metals [89]

interactions, rough surfaces may experience more wear and friction. The surface topography can be optimised to improve tribological performance using surface modification procedures like polishing or coating. Factors such as coefficient of friction, wear resistance, lubrication mechanisms, and surface topography all contribute to the overall tribological performance of industrial materials. The tribological properties of coatings are significantly influenced by their adherence to the substrate. To promote strong adhesion and ensure the longevity and integrity of the coating, it is essential to prepare the surface and choose the suitable coating materials properly. The choice of coating material and deposition technique plays a crucial role in determining the tribological properties of the coated surfaces [93]. Table 3 highlights some coatings, their application methods and their effect on the tribological properties of the substrate.

Diamond-like carbon (DLC) coatings have emerged as a promising coating option for preserving the tribological properties of industrial materials. DLC coatings exhibit desirable attributes such as exceptional hardness and low friction, rendering them suitable for applications where wear resistance plays a vital role [108]. Research findings have consistently indicated that DLC coatings can effectively sustain low levels of friction and wear, thereby minimising any adverse effects on the tribological properties of the base materials [109]. Certain ceramic coatings have demonstrated limited impact on the tribological properties. Notably, alumina (Al_2O_3) coatings have exhibited exceptional wear resistance and low friction coefficients, positioning them as viable options for applications where tribological performance is paramount [110]. Likewise, titanium nitride (TiN) coatings have exhibited favourable tribological characteristics by maintaining low levels of friction and wear [111]. Furthermore, certain polymer-based coatings, including polytetrafluoroethylene (PTFE) coatings, have demonstrated negligible influence on tribological properties. PTFE coatings are characterised by their low friction and impressive wear resistance, rendering them well-suited for applications necessitating low friction and lubrication [112]. Moreover, self-lubricating coatings, like molybdenum disulfide (MoS_2) coatings, have exhibited encouraging outcomes in preserving the tribological properties of industrial materials. MoS_2 coatings possess exceptional lubricating properties and can mitigate friction and wear across various operating conditions [113].

From the various studies, one of the significant coatings employed to reduce friction and wear rate is silicone coating made of resin, additives, solvent, pigment and fillers, as shown in Fig. 9. All these components of the coating agent assist in improving the performance of coatings in engineering applications.

5 Effects of Coating on the Tribo-corrosion Mechanism of Industrial Materials

Tribo-corrosion is the word used to describe the mechanisms of surface deterioration resulting from the interaction of mechanical wear with chemical and electrochemical reactions [114]. Time-dependent and nonlinear mechano-electrochemical interactions occur every day in tribo-corrosion. Research on tribo-corrosion has recently focused on the need to choose or create new surfaces for equipment in the future and how to reduce operating costs and increase the lifespan of machinery and medical equipment already in use [115–120]. The research area thus covers the interactions between corrosion and erosion (solids, liquid flow, and droplet impingements or cavitation bubbles) and processes such as abrasion, adhesion, fretting, and fatigue wear. Tribo-corrosion is frequently associated with the interaction of mechanical and environmental forces and the consequent synergy or antagonistic consequences [121]. For instance, chemical influences frequently impact the adhesive dissipation of energy during friction. Panda et al. [122] Studied the tribo-corrosion circumstances of iron boride coatings on carbon steel (CS) made through thermal diffusion, and

Table 3 Summary analysis for coating effects on tribological properties of industrial materials

Authors details	Type of coating materials used	Industrial materials	Tribological properties	Mode of applications	Findings
Lakavat et al. [94]	Nano Al_2O_3 + Ni–P–B	AZ91D magnesium alloy	Surface morphology	Electroless plating	Increases specific wear rate; Lowers average friction coefficient
Ghavidel et al. [95]	Ni–P	AZ31 Magnesium alloy	Corrosion resistance	Electroless plating	Improved corrosion resistance at 300 °C
Aydeniz et al. [96]	Ni–B–W	Steel	Wear resistance	A ball-on-flat test	Wear resistance of the coating increased with heat treatment
Li et al. [97]	Ni–Co–P/Si_3N_4 composite coatings	Aluminium–silicon (Al–Si) alloy	Wear performance	Pulse-current electroplating	Improved anti-wear properties compared to the uncoated Al-Si
Fiołek et al. [98]	Polytetrafluoroethylene/polyetheretherketone (PTFE/peek 708)	Ti–6Al–4V titanium alloy	Wear resistance and wear rate	Electrolytic plating	1900 times lower wear rate; Improved wear resistance
Moskalewicz et al. [99]	Polyetheretherketone-based tin nanocomposite	Ti–6Al–4 V titanium alloy	Wear resistance and friction reduction	Cathodic electrophoretic deposition	Reduced coefficient of friction from 0.70 to 0.65; Highly improved scratch resistance; No adhesive or cohesive cracks for loads up to 30N; 650 times lower wear rate
Cooke et al. [100]	Ni/Al_2O_3 + TiO_2	Ti–6Al–4V	Pin-on-plate wear testing	Electric arc	100% improvement in wear resistance
Kganakga et al. [101]	Tin nanoparticles	Ti–6Al–4V	Erosion wear	Spark plasma sintering technique	The coated alloy was wear-resistant
Carrillo et al. [102]	Ni–P–TiO_2	AZ91D magnesium alloy	Wear performance	Direct electroless method	Decreased wear rate
Wu et al. [103]	Ni–TiC	Titanium grade 2 (TA_2)	Wear resistance	Electron beam remelting	Significant improvement in wear resistance; The coefficient of friction reduction from 0.61 to 0.33
Zuo et al. [104]	Borocarburized (FeB, Fe_3C, and Fe_2B) and Sulfurized layers (FeS and Fe_2S)	2Cr13 stainless steel	Ball-on-disk friction test	Pack cementation method	Significant decrease in coefficient of friction; Improved wear resistance
Gao et al. [105]	Ni–P alloy	Polyetheretherketone (PEEK) 30% carbon-fibre-reinforced	Adhesion properties of the surface roughness morphology	Electroless	The maximum coating adhesion was produced at a surface roughness Ra of 0.4 m. Furthermore, fibres-reinforced PEEK adhered to coatings better than plain PEEK
Biswas et al. [106]	Polysiloxane and polysilazane based polymers	Glass Fiber	Tensile properties	Impregnation of fibre with a solution of polymer in a padder	According to the experimental findings, coated GF roving had much better tensile characteristics than uncoated GF roving

Table 3 (continued)

Authors details	Type of coating materials used	Industrial materials	Tribological properties	Mode of applications	Findings
Silva et al. [107]	PVD -CrN/TiAlCrSiN nano-structured multilayer coating	Glass fibre–reinforced plastics	Wear resistance	sputtering	The TiAlN monolayer coating demonstrated the best wear resistance performance in laboratory wear testing, whereas the CrN/TiAlCrSiN nanostructured multilayer coating demonstrated the best performance in industrial wear tests

it was contrasted with that of bare CS and 316L stainless steel. The reciprocating tests used in the tribological trials had a ball-on-flat geometry and were conducted under dry sliding and tribo-corrosion conditions. The coatings showed improved wear resistance because the iron boride protective layer is harder and more chemically inert. Compared to CS, a multi-layered structure of h-BN or other BN-based compounds over boronised steel reduced the potential for crack propagation and helped reduce the friction coefficient (COF) by about 20% to 40%. Evaluation of the worn surfaces' microstructure and surface morphology helped clarify the tribo-corrosion mechanisms in the studied samples.

Beliardouh et al. [123] created multilayer thin coatings using reactive radio frequency magnetron sputtering with a thickness of around 3 m on a Ti–6Al–4V substrate for biomaterial applications. Hard zirconium nitride and pure tantalum are combined to create films, which are utilised to control interfacial tension and prevent crack development. A biomimetic design (nacre-inspired materials) alternates hard/ductile material. A ball-on-disk reciprocating tribometer was used for tribo-corrosion testing in Hank's solution at 37 °C and open circuit potential. All the samples had a propensity to have strong corrosion resistance. Coatings with a top ZrN layer 100 nm thick demonstrated more significant noble potential and decreased wear rate and friction coefficient during the sliding phase. The wear process appears to consist of three main steps: (i) Rubbing under applied OCP (and normal load), (ii) causes the coating covered by a tribo-corrosion layer to thin, which causes fractures and rifts, and (iii) causes pieces to develop and separate (coating delamination), which allows the electrolyte to access the substrate as presented in Fig. 10.

6 Interaction Study of Coatings Materials and Industrial Material Surfaces/Substrates and Pretreatment

In general, there are interactions between the coating materials and the substrate of the industrial materials. Different materials behave differently during the deposition of the coatings on the substrate [124]. Regarding mechanical, corrosion and tribological properties, the substrate has to be well-prepared to have a firm grip on the coating materials. Also, the thickness of the coatings plays a vital role in the coated materials having viable properties in terms of adequate hardness, high resistance to wear rate and corrosion properties of the coated substrate [125]. The deposition of the coating assists in improving the surface morphology of the industrial materials either by physical or chemical deposition process. The plasma-sprayed coated of different substrates' tribological characteristics are discovered to be only somewhat superior in different

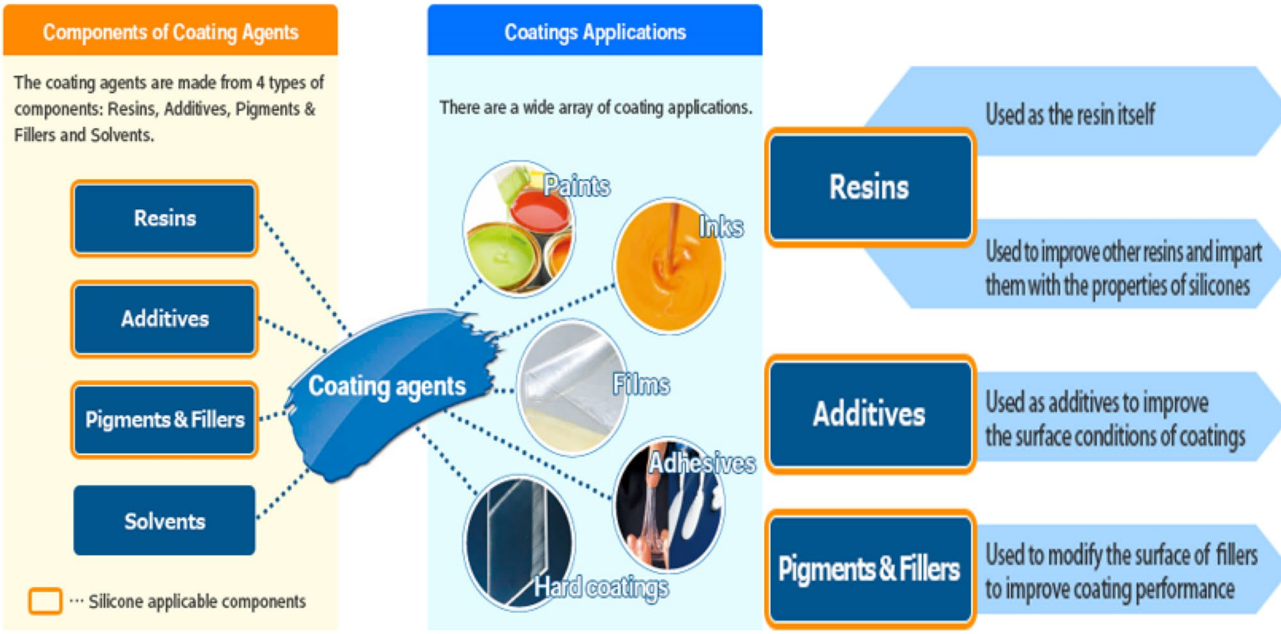
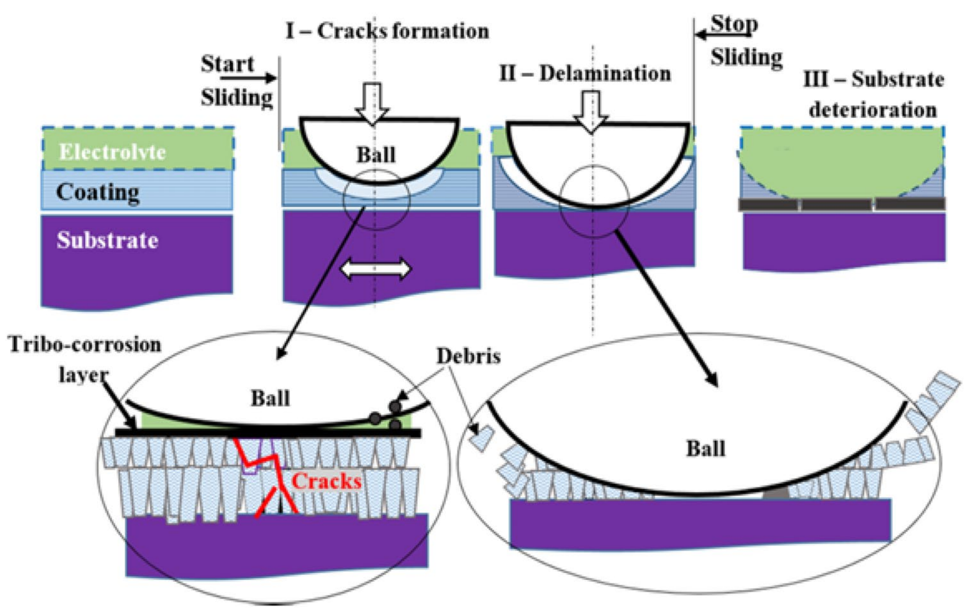


Fig. 9 Coating agent and applications [103]

Fig. 10 The illustration of the tribo-corrosion mechanism [116]



concentrations on the substrate. This might be because of mechanical stability and strong atomic coherence connection between physical and chemical properties, as reported in books [126–128]]. Lowered Atomic coherence corresponds to diminished coating's chemical connection. The contracting microstructure characteristics include grain size, density, and porosity. Process parameters impact these; for instance, the coatings produced by PVD and thermal spraying processes differ significantly [129].

Every effective pretreatment procedure for coatings application on a substrate starts with a straightforward cleaning step. The stages that should be completed before any other procedures are.

i. The cleaner stage
ii. The rinse stage
iii. The dry-off oven
iv. The conditioning stage

v. The zinc phosphate stage
vi. The sealer stage
vii. Shot blasting as pretreatment
viii. Shot plus primer

After this general pretreatment stage, other pretreatment and functional agents have also been involved in the coating's application of industrial materials, as presented in Fig. 11.

7 Challenges of the Implementation of Coatings on Industrial Manufacturing Products and the Way Forward

Key issues must be resolved when using industrial coatings on manufactured items for practical application and optimal performance. The compatibility of coatings with the substrate material is one of the primary challenges. Numerous

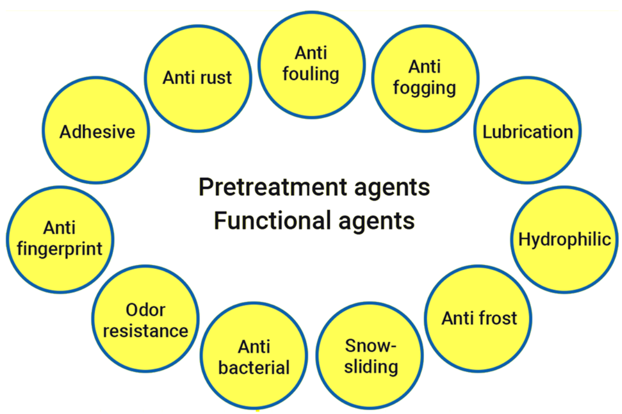


Fig. 11 Different types of pretreatments and functional agents [129]

materials, including metals, polymers, and composites, each with unique qualities, are used to create various manufacturing products. Long-term performance depends on adequate adherence and compatibility between the coating and the substrate material [130]. Adhesion and compatibility can be improved using effective surface preparation processes, such as cleaning, roughening, and applying primers or adhesion promoters. The coating resilience and lifespan in challenging operating environments is another issue. Industrial items frequently operate in hostile conditions, including extreme heat, corrosive chemicals, and abrasive wear. In order to remain protective over time, coatings must be resistant to certain elements [131]. Advanced coating technologies, such as multilayered structures or nanocomposite coatings, offer increased performance and endurance in harsh environments.

Another difficulty is ensuring constant and uniform coating application throughout extensive manufacturing processes. The coating thickness, coverage, and uniformity are essential elements that affect the coated product's general performance and appearance. To obtain consistent and uniform coating, methods like robotic coating application, automated spraying systems, and dip coating can be applied [132]. Coatings can increase production costs overall. As presented in Fig. 12, The market for industrial coatings, which had a value of USD 97.33 billion in 2021, is anticipated to expand at a Compound annual growth rate (CAGR) of 3.1% during the next five years. Figure 13 debited the global analysis of coatings and paint. The increased requirement for improved aesthetics combined with rising general industry, automotive, and aerospace demand is anticipated to accelerate the product's uptake. Due to growing concerns and awareness about environmental and health risks, the demand for ecologically friendly coatings is anticipated to rise throughout the prediction period [133]. Thus, weighing

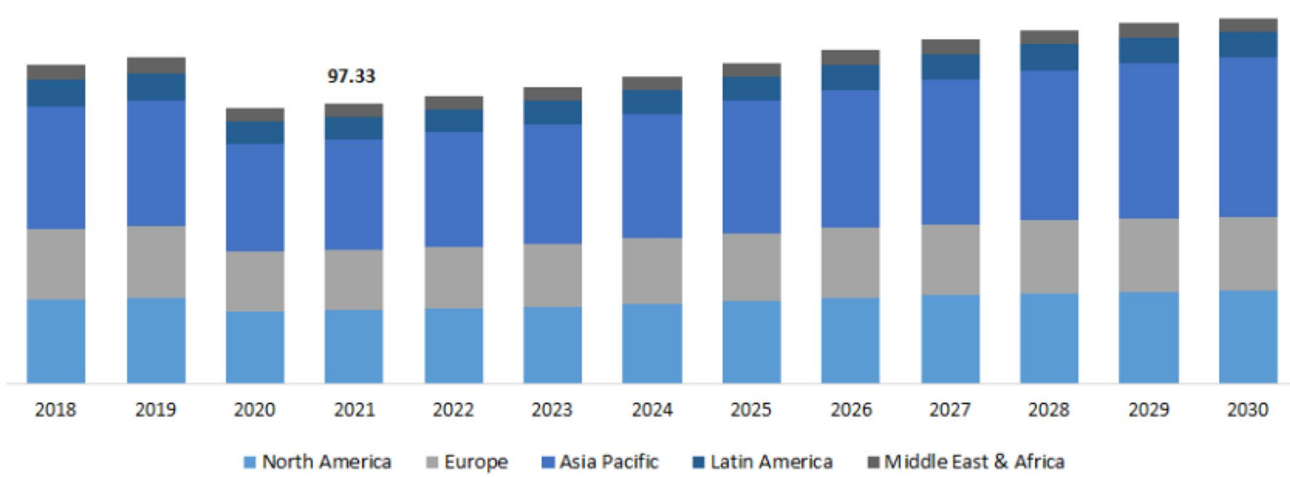


Fig. 12 U.S industrial coating market from 2018 to 2030in USD billion [132]

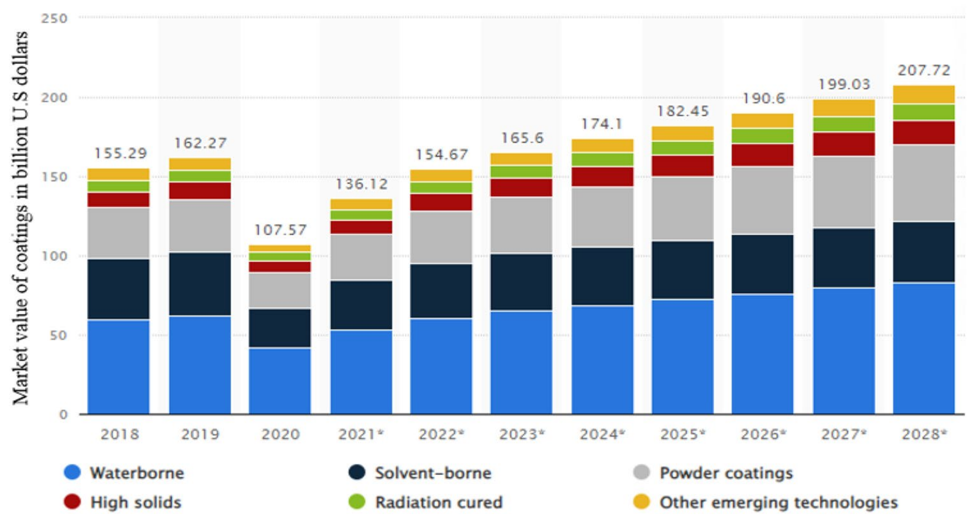


Fig. 13 The global market for paints and coatings from 2018 to 2028 [133]

the advantages of better performance against the related costs is crucial. Cost-related issues can be reduced by investigating cost-efficient coating materials, streamlining coating procedures, and considering life cycle cost analyses [134].

Collaboration between researchers, manufacturers, and coating suppliers is essential to address these challenges [135]. The creation of specialised coating solutions that are adapted to particular product needs and manufacturing techniques can be facilitated by close collaboration. Additionally, there are promising possibilities for application in the future owing to continuing research and development in coating technologies, such as sophisticated surface modification methods or self-healing coatings. Future research may also focus on developing novel coating materials, exploring advanced deposition techniques, and evaluating the long-term performance of coatings in diverse industrial applications [136].

8 Conclusion

The important influence of coatings on the mechanical, corrosion, and tribological characteristics of industrial materials has been underlined in this research. In many industrial uses, coatings have demonstrated their effectiveness in improving materials' performance, toughness, and durability. The study of several research tests has shown that various coating types, such as organic, metallic, and ceramic coatings, each offer special benefits in enhancing particular material attributes. Metallic coatings offer sacrificial protection, ceramic coatings demonstrate great chemical stability, and organic coatings offer a defence barrier against corrosive chemicals. Coating application requires careful consideration of coating choice, surface cleaning, adherence, and thickness. Additionally, it is important to regularly inspect and maintain coated surfaces to detect and resolve any symptoms of wear, corrosion, or damage. Emerging trends in coating technologies, such as Nanocomposite and self-healing coatings, can potentially improve industrial material characteristics and extend their service life. The findings from this study highlight how crucial it is to incorporate coatings in developing and producing industrial materials. Industries can increase the overall performance of their goods, minimise friction and wear, and reduce the harmful effects of corrosion by using the right coatings. Industrial materials' mechanical, corrosion, tribological and tribo-corrosion properties can be continuously improved and optimised if more studies investigate innovative coating materials, deposition methods, durability assessment methodologies and multilayer coatings methods which consisting of using pure metallic and ceramic layers with different designs thickness, to improve the wear rate and corrosion rate of the industrial materials.

9 Recommendations

Based on extensive research on the effect of coating on the tribological, corrosion, and mechanical properties of industrial materials, it is advised to carefully analyse the use of coatings in various industrial applications. These material qualities have seen considerable advancements thanks to coatings, which have improved performance, dependability, and durability. The following recommendations may be considered further to optimise the properties of industrial materials by coating:

i. First, the particular needs of the application and the anticipated operating conditions should be considered while choosing the right coating type and material. Different organic, metallic, and ceramic coatings have unique advantages. Thus, they should be selected as such.

ii. Secondly, proper surface preparation and application techniques are essential to guarantee adequate adherence and uniformity of the coating. To achieve the best performance, adherence to industry standards and recommendations for surface cleaning and coating application is strongly advised.
iii. Regular inspections should be done to find any indications of wear, corrosion, or damage, and the coated surfaces should undergo routine maintenance and examination. The intended qualities can be maintained, and further deterioration can be avoided by promptly repairing or recoating damaged areas.
iv. Following up with the most recent developments in coating technology is also essential. The tribological, corrosion, and mechanical qualities of industrial materials can be further improved by new trends such as nanocomposite coatings, self-healing coatings, and enhanced deposition processes.
v. Lastly, cooperation with coating producers, industry professionals, and research organisations can offer helpful insights and direction in choosing, using, and assessing coatings for particular industrial applications.

Following these recommendations can help industries take advantage of the benefits of coating and improve their materials' tribological, corrosion, and mechanical characteristics, resulting in better performance, a longer service life, and lower maintenance costs.

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Declarations

Competing Interests The authors declare that they have no competing interests. The corresponding authors claim no conflict of interest on behalf of the authors.

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