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Review Article

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Advances in Surface Modification Techniques for Enhanced Corrosion Protection of Steel: A Comprehensive Review

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Abstract

Corrosion is a serious issue in the steel industry because of its negative consequences on structural integrity, safety, and economic losses. To address this issue, different surface modification techniques have been developed to improve steel corrosion resistance. Surface modification methods have received a lot of attention since they offer a versatile and effective way to change the surface properties of steel. This paper reviews different techniques in surface modification used to improve steel corrosion resistance. It discusses the fundamentals of several surface modification technologies, such as conversion coatings, chemical passivation, electrochemical surface treatment, and organic and inorganic coatings. The impact of these changes on steel corrosion resistance are explored in terms of increased barrier characteristics, improved adhesion, and lower corrosion rates. Furthermore, this paper addresses the challenges involved with surface modification approaches and looks ahead to the future of creating enhanced corrosion protection methods for steel.

Keywords

Steel, Corrosion, Chemical surface modification, Corrosion resistance

Introduction

Corrosion is a natural occurrence and the main reason why steel constructions used in daily life deteriorate [1]. In severe circumstances, a structure's reduced ability to support its own weight causes catastrophic failure, such as collapse. Infrastructure failure is ultimately brought on by steel deterioration. It is an important consideration during the design phase of these infrastructures because it affects structural resistance as well as economic calculations because it necessitates expensive maintenance throughout the exploitation phase [2, 3].

Corrosion of metals is an electro-chemical process in which the presence of an electrolyte (such as water or moist soil) close to the metal surface causes an electrical circuit to be formed, which in turn causes the metal to corrode [4]. Due to material contact with the environment, corrosion mostly affects metal and alloys and causes deterioration. The features of the material were changed by corrosion, which also has an impact on the mechanical functioning. Furthermore, there are significant dangers to both human health and the environment if these structures fail [5]. For instance, if a foundation collapses, it may cause the structure it supports to fail as well or cause the leakage of hazardous materials, which may then result in hazardous explosions. Due to its detrimental effects on structures, corrosion has always been a problem in the industrial field [6, 7].

For reasons of safety, the environment, and the economy, corrosion damage must be addressed because it can also result in situations that pose a threat to human life [8, 9]. These types of issues plague most steel structures in India, necessitating scientific research initiatives to extend their useful lives. Steel corrodes due to an electrochemical process that degrades the substance. Corrosion occurs in steel structures exposed to harsh weather, particularly in coastal and heavily polluted industrial environments [10-12]. The traditional method of assessing residual capacity is visual inspection of the corroded parts and classification of the members based on the severity of the corrosion [13] (Figure 1).

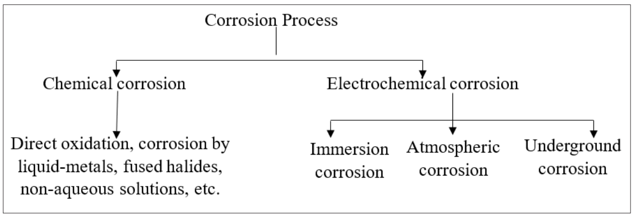

Figure 1: The various types of corrosion processes are as follows.

One of the best ways to deal with corrosion is through surface coatings. Due to competing demands for various features, surface coating on steel substrates has remained a difficult task for researchers. Components with varying quality are required for engineering applications, particularly surfaces exposed to harmful electrochemical, mechanical, thermal, and frictional interactions [14]. Therefore, this damage cannot be rectified without controlling and monitoring the tribological and corrosion activities.

The aerospace, automotive, power, missile, biomedical, electronic, petroleum, textile, chemical, petrochemical, power, steel [15], machine tools, cement, and construction sectors all employ surface coating techniques. Various functional qualities, such as chemical, physical, electrical, magnetic, electronic, mechanical, corrosion-resistant, and wear-resistant properties, can be developed at the needed substrate surfaces using surface coating techniques. It is possible to coat nearly any sort of material, including ceramics, metals, composites, and polymers [16] on other materials, whether they are related or unrelated. The process of surface coating of steel surface is shown in figure 2.

In this review we highlight different surface modification techniques used for corrosion protection of steel.

Surface Modification Techniques

Surface modification techniques are of great significance in the customization of material properties for various purposes. The approaches employed in this study are characterised by their versatility, as they involve the modification of surface composition and structure to produce improved properties, including better adhesion, wettability, biocompatibility, and corrosion resistance. Functionalization is a fundamental process that entails the attachment of functional groups onto surfaces by the utilisation of silane coupling agents [17]. The process of plasma treatment produces reactive species that alter the surface energy and adhesion characteristics [18]. Chemical vapour deposition is a technique that allows for accurate film deposition and is commonly used in the field of semiconductor fabrication [19]. Atomic layer deposition provides precise manipulation of thin-film growth at the atomic level, which is of utmost importance for the development of nanoscale electronics [20]. Self-assembly monolayers (SAMs) are known to form highly compacted organic layers, which have a significant impact on both wettability and resistance to biofouling [21].

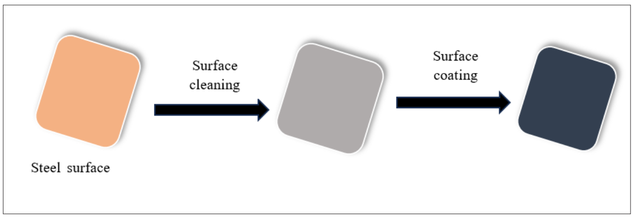

Figure 2: The process of surface coating of steel surface.

Electrochemical techniques, including as anodization and electroplating, are employed to deliberately induce regulated surface oxidation or reduction processes to improve specific qualities, such as corrosion resistance [22]. Sol-gel coatings offer thermal and chemical durability by undergoing a conversion process from precursor solutions into solid networks [23]. Polymer coatings, which are commonly applied using processes such as spin coating and spray coating [24], can regulate mechanical strength and biocompatibility [25]. The process of crosslinking involves the establishment of covalent connections between polymer chains, hence enhancing their stability. These approaches have been widely utilised in several disciplines such as electronics, biomaterials, and medical devices. Figure 3 shows the surface modification agents for steel.

Conversion coatings

Conversion coatings are those that are created by treating a metallic surface electrochemically or chemically with coating solutions. A portion of the metal surface is changed throughout the conversion process into a protective surface layer. Metals are coated with conversion coatings to increase their corrosion resistance, encourage the adhesion of organic coatings, or, ideally, achieve both goals [26]. They are applied in a multistep procedure that starts with cleaning the metal

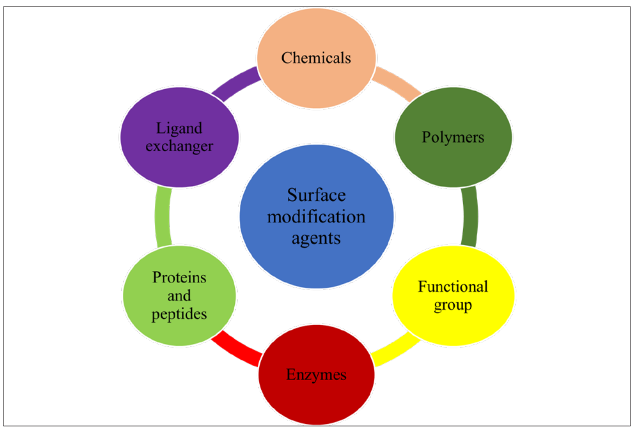

Figure 3: Surface modification agents.

to get rid of contaminants such organic matter, dirt, surface microstructures and surface oxide that could prevent the coating from forming or reduce performance. Conversion coating is a direct substitute for anodizing for several metals [27]. Conversion coatings can be categorised in a variety of ways, such as according to their environmental impact, chemistry, health risks or mode of application but one of the most helpful classifications is separating them into phosphate-based coatings and other coating types [28]. Prior to recently, chromate would have been the main substitute for phosphate, but due to its carcinogenic properties, it has been banned and substitutes are now being sought after [29].

When a metallic object is submerged in a chemical solution, either with or without the application of electrical current to the object, conversion coatings are created. The growth of a coating layer from the substrate surface is the result of the material's reaction with the chemical solution. The coating is incorporated into the surface of the component and is not only put on top of the surface. As a result, the coating's mechanical interaction with the underlying material is not clearly defined.

Chemical conversion coatings include phosphate coatings applied to zinc or steel [28], chromate coatings applied to iron, zinc alloys, steel, and copper [30] and oxide coatings applied to aluminum, copper, cadmium, silver, and magnesium [31].

Phosphating

Phosphating is a conversion coating process in which through electrochemical processes, the surface of a metal is converted into an adherent and insoluble phosphate coating during the phosphating process, which uses phosphate-salt aqueous solutions or diluted phosphoric acid. The metal surface is given helpful qualities by the phosphate coating that was created [32].

The process of forming an insoluble phosphate layer on a metal surface through dipping, spraying, or any other means is referred to as phosphate coating. In order to achieve surface pickling on the metal and the right pH, this sort of coating requires the prepared solution's hydrogen ion, phosphate anion and at least one metal cation.

One of the most crucial methods for metal surface treatment is phosphating, without which many contemporary metal finishing processes would not be possible. There are five stages of the phosphating sequence are typically as follows: (i) cleaning and degreasing, (ii) descaling and derusting, (iii) activation, (iv) phosphating, and (v) post-treatment.

Chromating

In chromate conversion coating (CCC), metals and alloys are often treated electrochemically or chemically in a solution that contains hexavalent chromium (Cr(VI)) and other components. This procedure creates an amorphous protective coating that can be sprayed on or immersed onto different metals (such as aluminium or steel) [33]. CCCs are used to increase the corrosion resistance of unpainted or painted surfaces, increase the adhesion of primer coatings or paint, and give metallic surfaces an attractive aesthetic finish. The base metal, trivalent chromium (Cr(III)), Cr(VI) water, different oxides and a few other substances like sulphates, fluorides and phosphates are the key ingredients of the solutions used to create CCC films. CCCs offer the metal excellent corrosion protection, whether it is painted or unpainted. The type of substrate metal, the type of chromate coating utilised, and the weight of the chromium coating all affect the level of protection provided by CCCs. Numerous experts have looked into the process by which Cr(VI) protects against corrosion during the past few decades. A general agreement on the mechanism by which CCCs reduce corrosion has been put forth by numerous researchers over the past ten years.

CCCs have demonstrated exceptional corrosion inhibition over the past few decades, and their substitutes have not fared as well. The Cr(VI) compound is a well-known carcinogen and toxin to the environment as well as to individuals [29]. Chronic exposure to Cr(VI) compounds raises the risk of lung cancer. Ingestion of soluble species can irritate the stomach and/or intestines and lead to stomach and/or intestinal ulcers. Due to this reason chromate conversion coatings came to an end.

Anodizing

Anodizing is the process of electrolytically oxidising a surface to create an oxide scale that is thicker than the naturally occurring coating and tightly adhering. Aluminum serves as the anode during the electrochemical process known as anodizing. The metal surface is changed into a strong aluminum oxide by the electric current flowing through an electrolyte. The oxide coating is a part of the metal substrate, as opposed to being a metallic coating deposition, which is the distinction between plating and anodizing [34]. The oxidised surface offers some corrosion protection and is tough and abrasion resistant. An additional layer of protection, usually in the form of painting, is frequently necessary because anodizing cannot be depended upon to offer corrosion resistance to corrosion-prone alloys.

Some alloys of magnesium, aluminum [35], zinc and titanium anodizing that converts the surface to a metal oxide. The component must be immersed in an acid solution and electrical current must flow through it for it to act as the anode in the electrical circuit [36]. This process is illustrated in figure 4.

Fortunately, the anodic coating offers a superb surface for adhesive bonding as well as painting. Anodic coatings degrade chemically in both very alkaline (pH > 8.5) and highly acidic (pH 4.0) conditions. Additionally, because they are very brittle and prone to cracking under stress, additional protection—such as painting—is crucial for alloys that are susceptible to

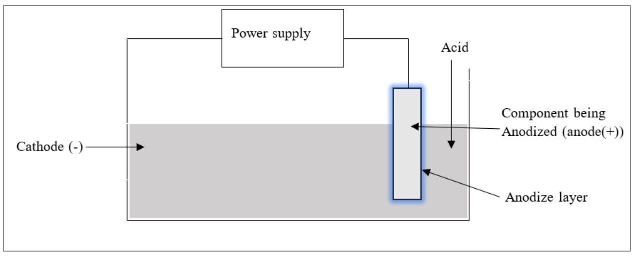

Figure 4: Anodizing process.

stress corrosion [37]. The considerations and the industries that use them are as follows: abrasion resistance, heat absorption, appearance, and non-galling.

Chemical passivation

Passivation is a popular technique for metal polishing that prevents corrosion. In the passivation process, citric acid and nitric acid are used to remove free iron from steel's surface. The chemical procedure creates a passivation film, also known as a protective oxide layer, which lessens the possibility of corrosion due to chemical reactions with air. Steel that has been passivated resists rust. A chemist recognised the effects of passivation in the middle of the 19th century. In contrast to iron that had not received the treatment, iron that had been exposed to powerful nitric acid showed little to no chemical reactivity, according to his research. He called this lack of chemical reactivity the "passive" condition. As the practise of passivating steel with nitric acid grew in the 1900s, environmental and safety issues about the substance became more and more apparent. The Adolf Coors Brewing Company in Germany conducted studies and found that citric acid was a great replacement [38]. In the 1990s, numerous businesses began adopting citric acid as a safer and greener alternative to nitric acid. Nitric acid, nitric acid with sodium dichromate, and citric acid are the three forms of passivation. According to Wang et al. [36], the work demonstrates the deposition of ferric hydroxide on substrates made of iron and passivated film. Due to the poor contact between the hydroxyl groups in -FeOOH and ferric hydroxide, he concluded that the deposition may be done on the surface of iron rather than on ferric hydroxide [39]. Nitric and citric acids were utilised by Parsons and colleagues [37] to evaluate the impact of passivation on the environment. To substitute nitric acid and keep the same level of corrosion resistance, citric acid is naturally created through fermentation. Utilizing citric acid has both advantages and downsides for the environment, according to the attributional life cycle assessment [40].

Electrochemical surface treatment

Anodizing and microarc oxidation

Anodizing is a well-known electrochemical oxidation technique that creates a stable and thick oxide film on alloys and metals to increase their resistance and hardness to corrosion and wear. The electrochemically created oxide layer can also be used as a superb base to increase paint coating adherence and infuse dyes for decorative or architectural purposes. These oxide coatings also have high dielectric strength, improved thermal stability, and improved optical characteristics, heat resistance and thermal shock resistance [41]. Mg, Al, Ta, Ti, Nb, Zr and their alloys are frequently treated with anodizing.

Electrolytic cathodic plasma deposition

Cathodic plasma electrolytic deposition technique that combines galvanic processes and plasma chemical phenomena was created by Paulmier et al. [42] in 2007. It runs at atmospheric pressure. The main idea behind this technique is to apply a high voltage between an anode and a cathode that are both submerged in an electrolyte solution and have an anodic-to-cathodic area ratio of 0.08:1. The creation of a vapour sheath around the cathode is triggered by the significant Joule heating caused by the high electric field near the cathode. The voltage drop occurs predominantly within the vapour layer because it has a substantially poorer electric conductivity than the liquid solution, which causes a strong electric field to develop inside the separated bubbles. The vaporised electrolyte will dissociate and form a continuous coating on the cathode if the applied voltage is high enough to generate a plasma glow discharge inside the bubble. The main benefits of this technology include the capacity to create homogeneous and thicker coatings, high deposition rate, direct synthesis of crystalline coatings without the requirement for annealing after deposition and operation at atmospheric pressure.

Electrodeposition

Metals, alloys, metallic oxides, ceramics, and composites can all be deposited using the flexible and economical technique known as electrodeposition. By appropriately adjusting the deposition potential/current, it offers the special benefits of allowing control over chemical composition and coating thickness. The window of opportunity for this technology to manufacture high-quality coatings is extended by using a pulsed current mode as opposed to the usual direct current mode [43]. Electrodeposition is a versatile and cost-effective.

Organic coatings

Organic coatings act as corrosion barrier between the corrosive environment and the underlying metal. They keep structures strong and resist the humidity, elements abrasion, toughness, visual appeal, and chemicals [44]. The mechanical characteristics of the coating system, the type and concentration of suspended inhibitors, pretreatment of the metal surface, adherence of the coating to the underlying metal base, and other additives that prevent substrate corrosion all affect how effective an organic coating is. The most popular technique for preventing corrosion in metallic objects is organic coatings, which are particularly significant in the transportation and infrastructure sectors. However, despite more than a century of study and experimentation, the mechanisms underlying coating failure remain relatively hazy. Solvent, resin (the binding agent), pigment, filler, and additives are typically found in coating formulations [45]. They offer a continuous, homogenous coating when applied to the underlying metal, preventing cracking and structural collapse due to stress, water penetration, and ageing. To be cost-effective, protective coatings need to have low permeability, good corrosion stability, and long-lasting aesthetics. On steel and other substrates, organic coatings have been utilised for hundreds of years to fulfil both ornamental and protective purposes.

Polymer-based coatings

These are a well-known class of protective coatings for metals and alloys in terms of preventing corrosion. The polymer films tend to deteriorate, and when coated on metallic substrates, this deterioration makes it easier for oxygen and moisture to enter, weakening the adherence of the polymer film to the substrate and exposing it to harsh conditions that could cause corrosion. To improve protection and adhesion, inhibitors, colours, and other compatible mixes are added to the formulations of polymer coatings. Inhibitors are encapsulated using a variety of approaches to avoid leakage and to give a controlled release in response to the corrosion trigger, preventing the potential deterioration of inhibitor-spiked polymer coatings [16]. Numerous polymeric compounds have evolved into essential elements of coatings for preservation and aesthetics. Polymers' flexibility has also made it possible to use additional materials to improve the performance of coatings.

Conducting polymer coatings

Due to their electrochemical and mixed ionic/electronic conductivity capabilities, conducting polymers are of tremendous interest. They are frequently employed as host matrices in the production of different composite films. When particles are added to conducting polymers, they change certain characteristics like morphology, physical characteristics, and conductivity. Depending on the requirements of the final application, such as corrosion prevention, the particle may be inorganic or organic. Some polycrystalline nanocomposites with conductive polymers in them shown unique features [25]. Low quantities of nano-particulate dispersions of organic metal polyanilines also had notable impacts on corrosion prevention in a variety of paints. To lessen mild steel corrosion, González et al. [46] created several structural forms of polyaniline and related nanocomposites using graphene as functional fillers.

Polyurethane coatings

Polyurethanes are adaptable polymers made of precursors to isocyanate and polyol. Their high demand as industrial coatings materials has been fuelled by their exceptional physical, chemical, and mechanical qualities. Applications for polyurethane include the production of, adhesives, paints, shoes, foams, auto parts, insulating plates, etc. Polyurethanes that are water- and solvent-borne can be used in the manufacture of coatings. Due to their resilience to water, chemicals, and other solvents, however, solvent-based polyurethanes are highly relevant in applications for coatings and fibers, foams, elastomers, and adhesives. Their importance is greatly influenced by their adherence and adaptability to a variety of substrates, and resistance to abrasion [47]. However, one of its environmental issues is the evaporation of volatile organic molecules. Water-borne polyurethanes are therefore favored even though they have a difficult time rapidly propagating microcracks after physical damage. Numerous characteristics of polyurethane coatings, including their resistance to solvents, high mechanical strength, abrasion, flexibility at low temperatures and corrosion, have led to their widespread use in industry. Neem oil polyester amide-based polyurethane coatings have demonstrated promising results in preventing rust on mild steel. The proof of the anti-corrosive efficacy of polyurethane coatings with various composition percentages while submerged in 3.5 weight percent sodium chloride solution. Neem acetylated polyester polyol has also been researched and has tremendous promise for preventing corrosion in mild steel.

Coatings based on epoxy

Epoxy coatings are produced using thermoset epoxy resins, which are widely used to provide protective coatings for structural and speciality metallic components. Epoxy resins can be easily modified and can be used as solvent-free or solvent-based matrices. As composites or films, epoxy technology is used in a variety of industries, including manufacturing, aircraft, household goods and automobiles to name a few [48]. Epoxy coatings made of solvents are inexpensive and offer benefits such as high chemical resistance, adherence to metallic surfaces and outstanding processability. Epoxy resins can be produced in a variety of ways with different cure times. The curing substances could be quaternary phosphonium salts, cationic salts, amine-boron trihalide complexes, oxygen, sulphur, or nitrogen-containing compounds. Epoxy resins were first made in the 1930s by reacting bisphenol A and epichlorohydrin. Epoxy resins have been utilised for castings and coatings ever since. They are frequently used for binders, potting, adhesives, and encapsulating. Aromatic glycidyl amines, phenolic glycidyl and cycloaliphatics ethers are the classes of commercially available and widely used epoxies, respectively [49]. Based on its shape (liquid, solid, or semi-solid), equivalent weight, the number of reactive sites per molecule, and viscosity, commercialised epoxy resins go by many brand names. Epon 828, DER 661, MY 720, CY 179, Epon 1001, GY 250, E44, KER 828, E-20-75, WSR 6101, and other commercially available epoxies are frequently used for coating purposes. Among the commercially available curing agents are Epikure, CRAYAMID 140C, D-3282, Versamid 115, HY 951, Anquamine 615, etc. These curing agents vary in curing temperature and may comprise amides or amines, such as, aromatic amines, polyamides, triethylenetetramine, diethylenetriamine, etc. However, the hardener-to-epoxy ratio affects how well these two-part epoxy systems cure. The thermal and mechanical properties are also impacted by this ratio.

Nanocomposite organic coatings

One of the active and quickly evolving fields is nanocomposite coatings, which uses many techniques and facets of nanoscience and nanotechnology to design and create various kinds of surface coatings with increased durability and higher performance at a reduced cost [50]. Additionally, nanocomposite coatings allow for the incorporation of novel and varied capabilities, opening the door to the potential of creating creative qualities through the engineering of clever multifunctional coatings [51].

Anticorrosion coatings offer the metal surface a barrier function against the corrosive species that are present in the environment. The development of flaws and micropores that weaken the organic coating's barrier function and start corrosion can be speed up by external conditions including humidity, the presence of hostile chemicals and temperature. The phase separation between the solid inorganic macroparticles and the polymeric/organic liquid phase in the created coating dispersions is more pronounced with standard organic coatings that contain macro sized particles. The strong interactions between the inorganic nanoparticles and the host organic matrix, which lead to lower cracking potential and lower porosity of the formulated nanocomposite coatings, make it possible for nanocomposite protective coatings to provide robust, long-lasting, and superior corrosion protection performance. Figure 5 shows the characteristics of nanocomposite coatings [52].

SAMs

SAMs have been thoroughly researched for their possible application in corrosion prevention. SAMs have the potential to function as strong barriers between the environment and the metal surface, assisting in the prevention of corrosion. They have several benefits as corrosion protection coatings, including the capacity to create well-ordered and extremely dense structures on the metal surface and the flexibility of their surface characteristics [21]. SAMs can be utilized in the following ways to prevent corrosion: customised surface properties, barrier protection, passivation, ecologically friendly, and self-healing properties.

Some SAMs have the capacity to heal themselves. The remaining SAM molecules can travel and recombine to restore the damaged location if the SAM is damaged or removed locally, offering continuous corrosion protection. Because SAMs frequently use less energy and less toxic chemicals than conventional corrosion prevention techniques, they can be designed to be ecologically friendly.

SAMs have several promising qualities, however there are some issues to consider while employing them to prevent corrosion: durability, compatibility, scale-up, and compatibility.

Inorganic coating

Chemical reactions, without or with electrical help, can form inorganic coatings. The treatments transform the metal's immediate surface layer into a compound film or metallic oxide that has superior corrosion resistance than the natural oxide film and serves as an efficient foundation or key for additional protection, such as paints. These treatments could occasionally be used as a cleaning step before painting. Inorganic coatings include "anodizing, surface conversion, metallic coatings, enamelling, and more" ("Inorganic coatings") [52]. These coatings are produced chemically, turning the metal's surface layer into a metallic oxide compound or film, which lessens corrosion.

Ceramic coating

To combat corrosion, heat, wear, friction, and insulation, alloys and metals can be coated with ceramic coatings to create high-performance oxide layers. Plasma spray coating, thermal spray coating, dry-film lubricants, sputter coating and various wet electrochemical and chemical coatings are examples of ceramic coatings. Depending on the coating techniques and its uses, ceramic films can have a thickness of 50 nm to several micrometre metres. Due to their superior thermo-mechanical properties, novel nanoscale ceramic coatings including silicon carbide, silicon nitride, cerium oxide, and boron nitride have recently been taken into consideration in alloy and metal coatings to generate promising high-temperature structural materials [53]. Numerous benefits of ceramic coatings include corrosion prevention, increased component lifetime, reduction of heat on high-temperature components, halting acidic and thermal corrosion, improved surface attractiveness and reduced friction. Although ceramic coatings have many benefits, they also have some drawbacks, including difficult to repair, extremely fragile, the possibility of de-bonding during contraction and expansion, the ease with which corrosion can form at cracks, the fact that they weigh more than organic coatings, and the fact that applying them requires additional materials, labor, and tools. The chemically linked phosphate ceramic coatings on AISI 304 L stainless steel are created by altering aluminium dihydrogen phosphate through organic-inorganic *in-situ* hybridization.

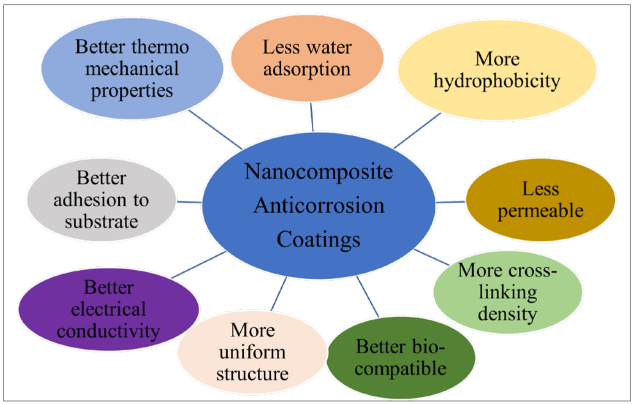

Figure 5: Characteristics of nanocomposite coatings.

Sol-gel coating

Sol-gel generated films have a great deal of promise as alternatives to the harmful chromate metal-surface pre-treatment techniques. Metals and organic paint can be painted on with good adherence thanks to inorganic sol-gel generated coatings [54, 55]. However, because of their significant crack-forming potential, they are unable to offer appropriate corrosion protection. When an organic component is added to an inorganic sol-gel system, more flexible, thicker functionalized films are created with improved compatibility to various organic top coatings. because of their reduced cracking propensity and lower porosity, nanoparticles are added to hybrid sol-gel systems to improve mechanical qualities as well as corrosion protection [23]. Additionally, the integration of inorganic nanoparticles can create corrosion inhibitor nano reservoirs that are ready for "self-repairing" pre-treatments with controlled release characteristics [56]. There has been a significant amount of research on sol-gel based protective coatings, primarily for metals, because of the benefits of sol-gel coatings, including benign conditions of deposition (e.g., relatively low temperatures) and the ability to produce coatings on complex shapes without the need for machining or melting (hence no expensive equipment) [57]. Since the turn of the century, research has exploded due to the simplicity of application as well as the necessity to develop ecologically benign alternatives to the conventional chromium- and/or solvent-based anti-corrosion coatings. Under the brand name "Boegel," Boeing's anticorrosive sol-gel coating, which consists of zirconium n-isopropoxide and 3-glygodopropyltrimmethoxysilane, has been commercialised to give metal superior barrier qualities without the need for an additional anticorrosive layer. Waterborne siloxane compositions are sold by the German company Evonik

Industries AG to prevent corrosion on a variety of metallic substrates [58].

Effects of Surface Modification

Surface modification can have a variety of consequences on materials. Following are some specific instances of chemical surface modification's impacts [59, 60]:

Improved adhesion and interfacial bonding effect

Surface modification can enhance the interfacial bonding of different materials, such as metals and polymers by introducing chemical functionalities that promote interfacial bonding [61].

Superhydrophobic or superhydrophilic surfaces

Depending on the needs of the application, surface modification might produce superhydrophobic surfaces with extremely high-water repellency or superhydrophilic surfaces with great water affinity.

Antibacterial and anti-biofouling properties

Impact to lessen bacterial adhesion and biofilm development, surface modification can introduce antibacterial agents or generate anti-biofouling surfaces.

Controlled drug release

Surface modification of drug delivery systems can regulate the rate at which drugs are released, enhance drug stability, and facilitate targeted drug delivery.

Corrosion resistance

Surface modification can create passivation layers or protective coatings that can shield metals from corrosion [62].

Better biocompatibility

Surface modification can make materials used in biomedical implants and devices more biocompatible, lowering the risk of adverse responses and accelerating tissue integration.

Tuned optical properties

Surface modification can change a material's optical characteristics, including light absorption, emission, or transmission, for application in optical devices and sensors.

Conclusion

This paper concludes by offering a thorough analysis of the numerous chemical surface modification methods employed in the steel industry to improve steel corrosion resistance. These techniques provide a flexible and powerful means of modifying the surface characteristics of steel and addressing the major problems of corrosion, which can damage structural integrity, raise safety issues, and cause financial losses.

Conversion coatings, chemical passivation, electrochemical surface treatment, and organic and inorganic coatings are just a few of the techniques mentioned that have shown promise in terms of enhancing barrier properties, enhancing adhesion, and lowering corrosion rates. These adjustments successfully prevent corrosive substances from penetrating and shield the underlying steel substrate from corrosion.

The paper also emphasises the difficulties of chemical surface modification methods, though. These difficulties could include problems with compatibility with various steel grades, environmental issues with some chemicals employed, and assuring the durability of the protective coatings under difficult circumstances.

With an eye towards the future, this report sets the path for additional study and research to develop cutting-edge corrosion protection techniques for steel. The negative effects of corrosion on the steel industry can be lessened in the long run by further research and development in chemical surface modification techniques.

This study concludes by highlighting the substantial advancements made in the field of chemical surface modification for steel corrosion resistance and encouraging continued efforts to successfully address this pressing issue. By using these protection techniques, the steel industry will experience significant financial gains in addition to improved safety and dependability of steel structures.

Challenges and Limitations

- Surface contamination and cleanliness: For surface modification to be successful, a clean and contaminant-free surface is essential. Poor surface modification outcomes can be caused by impurities such as residual oils, rust, or other pollutants interfering with chemical reactions and bonding processes.
- Challenges with reproducibility and uniformity: It can be difficult to guarantee consistency and reproducibility of surface modification during large-scale production. Inconsistent outcomes may be caused by variations in the surface properties, chemical treatments, and environmental influences.
- Challenges with steel alloy compatibility: Finding a general technique that is successful on all types of steel is difficult because different steel alloys may respond differently to chemical surface modification techniques.
- Surface sensitivity: The surface properties and pre-treatment procedures can have a significant impact on the efficacy of specific chemical surface modification approaches. The success of the alteration can be dramatically impacted by even little changes in surface preparation.
- Durability and corrosion resistance: However, they might not offer the same level of durability as other surface treatments like physical coatings or plating's. Some chemical surface modification techniques may increase corrosion resistance.
- Cost and complexity: Industrial-scale chemical surface modification procedures can be difficult and expensive to implement since they call for specialised tools, qualified labour, and meticulous process management.

- Environmental issues: Some chemical surface modification procedures contain risky chemicals, which, if not managed appropriately, can cause environmental and safety issues.

Future Prospects and Outlook

Future possibilities for chemically altering steel's surface to improve corrosion resistance look bright, since continuous research and development efforts are concentrated on enhancing current methods and examining novel ones. The future of this field is anticipated to be shaped by several important areas of interest.

Solutions that are environmentally benign and sustainable

These are becoming more and more in demand for corrosion protection. To create surface modification strategies with little environmental effect and good corrosion resistance, researchers are investigating green chemistry methodologies and ecologically safe compounds. Utilising bio-based coatings, non-toxic passivation agents, and waste-reduction techniques are a few examples of this.

Smart coatings and nanotechnology

Surface modification is becoming more and more possible because to nanotechnology. For proactive and responsive corrosion protection, self-healing nanocoating's and smart coatings are being developed. These coatings considerably increase the lifespan of steel buildings by being able to heal damage and stop future corrosion on their own.

Hybrid coatings and multifunctional materials

By combining various methods of surface modification or adding various kinds of nanoparticles to coatings, corrosion protection can be improved. Improved barrier capabilities, greater adhesion, and other desirable characteristics may be provided by hybrid coatings and multifunctional materials to successfully reduce corrosion.

Understanding corrosion mechanisms

New findings in corrosion research and materials science will expand our knowledge of the fundamental processes driving corrosion. With this knowledge, scientists will be able to create surface modification methods that are more specialised and effective against corrosion dangers.

Applications in industry

The use of chemical surface modification techniques will spread throughout a range of sectors, including the infrastructural, automotive, aerospace, and marine ones. The need for efficient corrosion protection solutions will increase as industries work to increase the durability and dependability of their buildings and machinery.

Standardisation and quality control

As chemical surface modification techniques proliferate, there will be a greater demand for standardised testing and quality control procedures. The dependability and effectiveness of corrosion protection coatings and treatments will be ensured through the development of industry standards.

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Conflict of Interest

None.

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