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Recent Advancements in Sealants Solutions for Surface Coatings: A Comprehensive Review

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Abstract

This review presents a novel and comprehensive analysis of various sealants used in diverse coating applications, focusing on their role in corrosion prevention. Sealants are crucial in shielding the coating materials from various environmental factors. This review categorizes the sealants into polymer, ceramic, inorganic chemical, and composite based. It delves into the significance of sealants in enhancing corrosion resistance and overall durability within coatings, drawing insights from an extensive literature analysis. By underscoring the pivotal role of sealants, this study serves as a unique and valuable resource for researchers and practitioners in coatings and materials science, emphasizing their significance in the ongoing battle against corrosion.

Keywords Surface coatings · Sealants · Corrosion

1 Introduction

Surface coating and sealing are abstract concepts and practical procedures in numerous industries, from manufacturing to construction. They enhance the performance, lifespan, and visual appeal of materials and products. This literature review not only delves into the reasons behind the necessity of surface coating but also underscores the practical significance of sealing as a subsequent measure, making the content more relatable and useful for the audience.

Surface coatings protect materials from environmental damage like rubbing, abrasion, corrosion, chemical wear, water, UV light, chemicals, and contaminants essential for substrate protection. They enhance material properties, functionality, and durability by acting as a barrier against damage [1–3]. Coating materials can effectively reduce corrosion rates, thus prolonging the life of metallic structures exposed to aggressive environments [4–7].

The role of coatings in enhancing the appearance and properties of products and structures was studied [8]. Various organic, inorganic, and metallic coatings are selectively applied to surfaces according to their environmental demands. These coatings play a crucial role in enhancing the resistance of materials against corrosion and wear, effectively extending their lifespan and performance under varying conditions [9, 10]. The application of hard coatings in cutting tools and machinery components, reducing wear, and extending the lifespan of these tools are reported [11]. However, porosity within the coating is a critical concern as it can facilitate the penetration of corrosive media toward the substrate through interconnected pores and defects within the coating structure. The wear and corrosion properties of alumina thermal spray coatings intended for pump piston applications are also studied [12]. Coatings also serve esthetic purposes, enhancing the visual appeal of objects and surfaces. In architecture and design, for example, coating materials can add color, texture, and gloss, contributing to the overall appearance of structures and products. The need for these processes is evident across various industries and applications, underscoring their significance in preserving and enhancing the integrity of materials and products [13–15]. The use of specialized coatings in art and design, illustrating their role in achieving visual effects and creative

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expression, is reported [16]. Beyond protection and esthetics, coatings can improve the functional properties of materials. Such functional enhancements are also observed in the automotive and electronics industries, where coatings contribute to increased durability and performance [17].

Sealants are of utmost importance in enhancing coatings' longevity, protective properties, and visual attractiveness in various sectors, such as structural, automotive, aerospace, and marine fields. The restoration of the insulating characteristics of the coating is of utmost importance. Therefore, it is necessary to apply a suitable sealant to seal existing open pores and cracks, if present, after surface modification [18]. Various organic sealants, including epoxy resins, phenolics, and silicon sealants, are commonly used to seal the coatings' micropores [19]. The sealing process ensures enhanced resistance against corrosion and wear, thus ensuring the enduring durability of coatings.

1.1 Classifications of Sealants

Different categories of sealants are available within this vast range, providing diverse options to meet specific requirements. Common types include

1.1.1 Organic Sealants

- Polyurethane Sealants: These are known for their strong adhesive properties and are used in many applications, including construction, automotive, and aerospace.
- Acrylic Sealants: They have good adhesion properties and are often used in construction to seal gaps and joints.
- Butyl Rubber Sealants: These sealants are particularly good at sealing against moisture and are used in applications where a watertight seal is critical, such as roofing and automotive.
- Epoxy Sealants: Epoxy sealants are known for their strong bonding capabilities and are commonly used in applications requiring a high-strength seal.
- Polyester Sealants: These are used in construction for sealing and bonding, particularly in applications where UV resistance is needed.
- Polysulfide Sealants: Polysulfide sealants have good chemical resistance and are used in applications like sealing joints in concrete and aircraft fuel tanks.

1.1.2 Inorganic Sealants

- Aluminum Silicate Sealants: Aluminum silicate sealants offer high-temperature resistance and are commonly used in furnace and kiln applications where they can withstand extreme heat and thermal cycling without deteriorating.
- Calcium Carbonate Sealants: These sealants are derived from calcium carbonate and exhibit excellent chemical resistance, making them suitable for sealing joints in chemical processing plants and industrial environments where exposure to harsh chemicals is common.
- Sodium Silicate Sealants: Sodium silicate sealants, also known as water glass sealants, are water-based sealants that form a rigid, waterproof bond when dried. They are used in sealing concrete, masonry, and pottery applications.
- Titanium Dioxide Sealants: Titanium dioxide sealants possess excellent UV resistance and are often used in outdoor applications, such as sealing exterior surfaces of buildings and structures, to prevent degradation from sunlight exposure.
- Zinc Oxide Sealants: Zinc oxide sealants are known for their anti-corrosive properties. They are often used in marine applications, such as sealing boat hulls and marine structures, to protect against rust and corrosion in saltwater environments.
- Magnesium Oxide Sealants: Magnesium oxide sealants offer fire resistance and are commonly used in fireproofing applications, such as sealing gaps and joints in fire-rated walls, doors, and windows to prevent the spread of flames and smoke.
- Sulfur Sealants: Sulfur sealants are highly resistant to chemical attack and are used in aggressive chemical environments, such as sealing joints in sulfuric acid storage tanks and chemical processing equipment.
- Graphite Sealants: Graphite sealants exhibit low friction properties and are used in high-temperature and high-pressure applications, such as sealing steam valves and flanges in power plants and industrial machinery.

1.1.3 Ceramic Sealants

- Nano-Ceramic Sealants: These create ultra-thin protective coatings against scratches, chemicals, and UV rays, enhancing surface appearance and offering long-lasting protection. They are commonly used in automotive detailing for paintwork, glass, and wheels.
- Ceramic Coating Sealants: Form a hard protective layer resisting abrasion, corrosion, and extreme temperatures, providing long-term protection for metal, glass, and plastic substrates in industrial and consumer products.
- Hydrophobic Ceramic Sealants: Repel water and other liquids, preventing moisture penetration and facilitating easy cleaning on buildings, vehicles, and porous materials like concrete and stone.
- Thermal Ceramic Sealants: Provide excellent heat resistance and thermal insulation for high-temperature applications in industrial furnaces, kilns, and exhaust systems.
- Anti-Fouling Ceramic Sealants: Prevent dirt and organic matter accumulation while inhibiting microorganism

growth, reducing maintenance, and extending equipment lifespan in marine and architectural applications.

1.1.4 Composite Sealants

Composite sealants are essential for providing enhanced protection and durability in various coatings. They are formulated using a combination of materials to meet specific performance needs, sealing pores, cracks, and imperfections to prevent moisture ingress, corrosion, and degradation. Polymers like acrylics, polyurethanes, and silicones act as binding agents, while resins enhance strength and chemical resistance. Fillers like silica and calcium carbonate reinforce the sealant matrix and control viscosity, improving mechanical properties.

Additives such as antioxidants, UV stabilizers, biocides, and cross-linking agents further enhance the sealant's performance, protecting against degradation and microbial growth and improving strength. Composite sealants are versatile and can be customized for automotive, architectural, marine, and industrial coatings, protecting against corrosion, environmental contaminants, and moisture damage. They have a significant impact on extending the lifespan and aesthetics of finished products, ensuring they withstand harsh conditions. Overall, composite sealants are vital for enhancing the properties of coatings and preserving the integrity of surfaces in various industries.

The choice of sealer and application method depends on specific requirements and conditions. Understanding these reasons is crucial for maintaining and improving the performance of sealed materials.

1.2 Applications of Sealants

Sealants are essential in various industries, improving performance and encompassing the product lifecycle. In construction, sealants seal gaps, enhance energy efficiency, and protect against damage. The automotive and aerospace sectors use sealants for watertight seals, which are crucial for performance and safety. In the marine industry, sealants strengthen boat structures against water and corrosion. Electronics rely on sealants to protect components from moisture and contaminants, ensuring reliability.

Sealants are also essential in electric vehicles to safeguard critical parts, such as batteries and electronics, from external elements. They maintain structural integrity and prevent leaks in energy storage material. Industrial machinery uses sealants to prevent leaks and shield delicate equipment, while sealants are also used in solar panel installations for renewable energy. Additionally, sealants are used in the upkeep and restoration of infrastructure to prolong the durability of essential buildings. Surface coating and sealing procedures are vital for enhancing material characteristics and longevity across different sectors.

1.3 Methods of applications of Sealants, Adhesives, and Related Products

Numerous approaches were used to apply sealants, glues, and correlated products [20]. Sealants and Glue include fluids, pastries, dust, movies, mixtures, hot melts, and solvent-located versions. Furthermore, these elements showcase approximately ten different mediums of setting. In mixture glues, the substrates dehydrate and take in water. In solvent-located glues, the substrates dehydrate and take in liquids. In the technology of glues, diverse proceedings enact pivotal roles. Heating curing of thermosetting glues entails administering warmth to commence the cross-connecting counteraction, solidifying the glue. Two-component glues bank on a chemical backlash amid their components to encounter bonding, underscoring the relevance of meticulous blending. Chilling is necessary for hot melt glues, as it solidifies them post-application. Glues and sealants also chemically interface with environmental humidity, impacting their curing process. Curing through ultraviolet (UV) or electron ray (EB) vulnerability is noteworthy since it provokes polymerization, solidifying the glue promptly. These proceedings collectively contribute to diverse adhesive applications and functionalities [21].

1.4 Properties of Sealants

To ensure effective sealing, the properties of sealants in both liquid and solid states are of utmost importance. In its liquid state, a sealant must penetrate the coating it is applied to deeply. Tailoring the curing system to suit the size of the sealed component is crucial, particularly when oven-curing significant components is not feasible. Stability is essential to prevent phase separation caused by capillary forces during penetration while minimizing curing shrinkage is paramount. Environmental factors must be carefully considered to avoid undesirable solvent evaporation. Proper removal of potential solvents during the curing process is necessary to prevent softening, and the sealant should ideally form a thin film to avoid additional post-grinding.

Once solidified, the sealant must meet specific criteria to maintain its effectiveness. It should exhibit chemical durability against environmental factors and demonstrate less diffusion of electrolytes and O_2 through its structure. Coating adhesion, temperature resistance, and retention or enhancement of the coated surface's functional properties are also essential. Lastly, the sealant should exert minimal tensile stress on the coating to preserve its structural integrity [22].

Various commercial and lab-made sealants were tested and their characteristics and curing methods are detailed in

Table 1. Notably, the solvent-based sealant D, formed via coalescence rather than cross-linking, does not shrink due to its polymeric nature. Commercial sealants B, C, and D exhibited reduced viscosities and wetting angles compared to laboratory-made sealants E to I while also showing a higher volume curing shrinkage. Improved penetration into the coating is achieved with lower wetting angles and viscosities [22].

Mei et al. [23] assessed the efficacy of Silicone Resin (SR) sealant and Aluminum Phosphate (AP) sealant by examining wetting properties. The contact angle measurements suggest superior wettability between the SR sealant and AS coating compared to the AP sealant. The contact angle's magnitude influences the contact area fraction between sealants and coated surfaces, impacting the effectiveness of the sealing process.

Moreover, the wetting characteristics of sealers, particularly regarding the solvents employed, were examined in relation to the coating. Table 2 presents contact angle values for various coatings exposed to water and MDS 250 (Commercially available sealant) at different temperatures, along with silhouette photos. Solvent selection plays an important role in finding the extent of wetting. Notably, coatings with high porosity, such as hydrophilic oxide materials, demonstrate advantages in inhibiting liquid penetration due to dewetting internal pore surfaces [24].

The correlation between the degree of wettability and contact angle is further illustrated in Fig. 1, where static contact angles between unsealed coatings and two different sealants, silicone resin and aluminum phosphate, are depicted. Lower contact angles indicate enhanced adhesion and the capacity to fill flaws, as observed with silicone resin [25–27]. Additionally, the hydrophobic properties of silicone resin are highlighted, as evidenced by its effective water repelling. Eliminating surplus sealant before conducting tests ensures precise assessment of sealed coatings' performance.

Zhang et al. [28] presented the contact angles of coatings in their as-sprayed state and after being sealed with stearic acid. Sealed coatings exhibited significantly higher contact angles than as-sprayed coatings, indicative of notable hydrophobic properties. This reduction in the interface between the solution and the coating can reduce corrosion rates.

Table 3 summarizes various sealing materials, sealing methods, coating materials, and findings from different studies. Some notable findings include the enhancement of thermal-sprayed coating versatility through vacuum sealing with silicone resin, the revolutionary use of ultra-high-molecular weight polyethylene particles for self-sealing anti-corrosion maritime coatings, the superior sealant properties of silicone resin over epoxy resin in blocking porosity in coatings, the significant improvements in mechanical properties achieved by sealing commercial polymer sealants, and the enhanced corrosion resistance and durability of Fe-based amorphous coatings through the use of modified sealant. Additionally, the table highlights various sealing techniques' effectiveness in improving corrosion resistance and mechanical properties of different types of coatings, such as ultrasonic excitation sealing, vacuum sealing, immersion sealing, and manual brushing.

2 Discussion

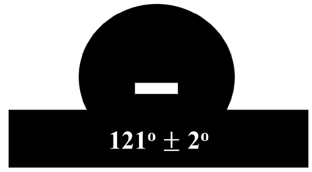
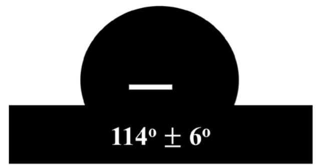
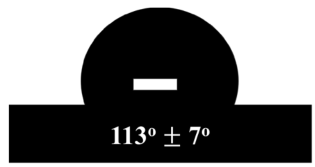
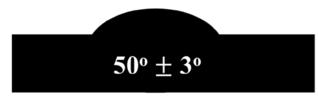
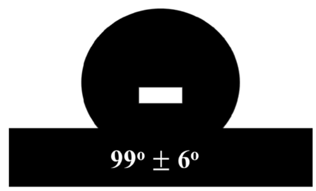
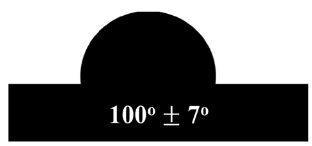
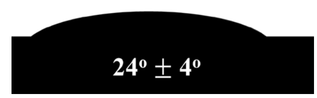
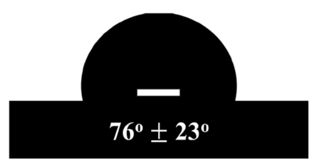
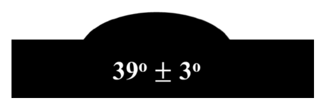
2.1 Polymer-Based Sealants

The efficiency of thermal-sprayed WC cermet coatings is hindered by flaws like pores and cracks. Wei et al. [29] developed a corrosion-resistant WC–Cr_3C_2–Ni coating using HVOF spraying and vacuum sealing with silicone resin. Based on the experimental results, it is evident that the SR successfully penetrates the imperfections found in the WC–Cr_3C_2–Ni coating. After extended exposure to salt spray corrosion, the sealed layer shows fewer pits

Table 1 Sealants and their properties [22]

Sealant	Base polymer	Curing parameters 200 °C/7 h	Wetting angle on γ-alumina, degrees	Viscosity, η, mPa/s	Curing shrinkage by wt%	Curing shrinkage by vol%
A	Inorganic aluminum phosphate	200 °C/7 h	97	505	48	–
B	Methacrylate(a)	60 °C/1 h	15	6.5	3.8	17.6
C	Methacrylate(a)	60 °C/1 h	15	8.6	2.6	5.3
D	Phenol(a)	RT	10	1.5	79.6	8
E	Epoxy	80 °C/2 h	39	162	0.1	0.2
F	Methacrylate(a)	UV	26	28	0.5	< 2
G	Epoxy	60 °C/2 h	42	179	1	0.1
H	Furan	60 °C/1 h – RT	67	626	2	2
I	Vinyl ester	60 °C/1 h – RT	83	319	0.6	2.4

Table 2 Selected results of the contact angle measurement of sealers on Cr_3C_2–NiCr coatings (HVOF) and Al_2O_3 coatings (Flame Spraying) [24]

Sl. no	Sealant/solvent	Temperature	Contact angle (°) for Cr_3C_2–NiCr	Contact angle (°) for Al_2O_3
1	Water	23 °C		0
		40 °C		0
		80 °C		
2	MDS 250 (commercially available sealant)	23 °C		0
		40 °C		
		80 °C		
3	Hydro (commercially available sealant)	23 °C	0	0
		40 °C	0	0
		80 °C	0	0
4	HTWG-S (commercially available sealant)	23 °C	0	0
		40 °C	0	0
		80 °C	0	0

'0' means complete wetting

than the unsealed layer. It is because the pores and fissures are blocked by silicone resin, preventing corrosion. The sealed coating displays a smooth surface, with fewer corrosion pits and cracks than its original sprayed state. Using vacuum sealing in conjunction with silicone resin is a promising approach to enhance the versatility of thermal-sprayed coatings. However, it is important to consider that a reduction in the quantity of sealant resulted in an elevated propensity for corrosion within the sealed coating, ultimately leading to pitting corrosion [29].

The preparation process route of the Sealed WC–Cr_3C_2–Ni coating is demonstrated in Fig. 2a. The research examined both unsealed and sealed coatings and their respective surface morphologies. Figure 2b and c illustrates the corrosion behavior of unsealed and sealed WC–Cr_3C_2–Ni coatings. Both varieties of coatings

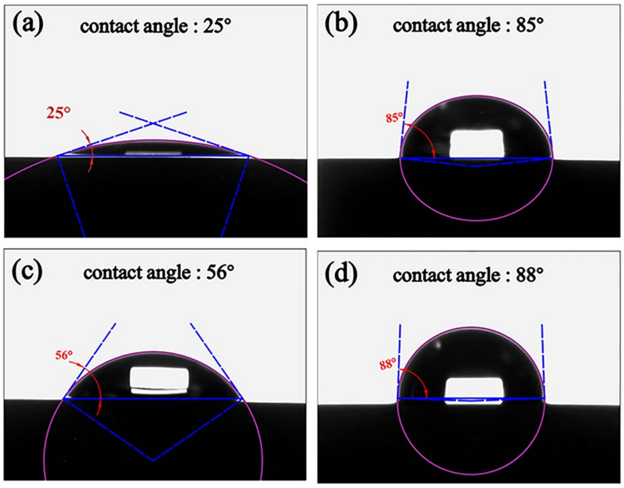


Fig. 1 Contact angle between the **a** coating and silicon resin sealant, **b** coating and aluminum phosphate sealant, **c** NaCl solution and coating, and **c**, **d** NaCl solution and VI-SR coating [69]

demonstrated dense and homogeneous structures characterized by minimal porosity. The unsealed coating primarily suffered from pitting corrosion, while the sealed coating initially showed lower corrosion tendency due to the protection of defects by the sealant. According to the findings presented in Fig. 3c, it can be observed that the application of a silicone resin sealant effectively fills the defects present during the vacuum sealing procedure. Furthermore, this sealant demonstrates the ability to impede the occurrence of pitting corrosion on the SWCN coating. However, over time, a reduction in the quantity of sealant resulted in an elevated propensity for corrosion within the sealed coating, ultimately pitting corrosion [29].

Xiaoxia Wang et al. [30] investigated aluminum (Al) coatings with the incorporation of ultra-high-molecular weight polyethylene (UHMWPE) particles, which served as both the coating material and the sealing agent for anti-corrosion purposes in the aquatic environment. The resulting composite coatings (Al-UHMWPE) exhibited a dense and uniform structure with well-dispersed particles of UHMWPE. This integration of UHMWPE particles led to an enhancement in corrosion resistance. The mechanism of anti-corrosion of the UHMWPE particle is exposed in Fig. 3a. Microstructure development coatings are shown in Fig. 3b. This innovative approach of producing composite coatings provides valuable insights into developing self-sealing anti-corrosion coatings for marine applications, with UHMWPE particles serving as a key component.

Plasma-sprayed coating of Cr_2O_3–8TiO_2 was applied to steel and subjected to sealing processes using Epoxy resin (ER) and Silicone resin (SR). The findings revealed that SR exhibited better sealant, blocking 91% of interconnected porosity in the coatings. It was capable of penetrating the coating depth of over 280 µm. Among the different sealants, SR sealed under vacuum exhibited the maximum corrosion resistance. Conversely, unsealed coatings exhibited the lowest corrosion resistance. Silicone resin was a highly effective sealant for Cr_2O_3–8TiO_2 coating by blocking a significant portion (91%) of interconnected porosity. The SR-sealed coating in a vacuum environment exhibited only about 1/26th of the cumulative weight loss compared to unsealed coating in a 240-h salt spray corrosion test [31].

An antimicrobial sealant was developed to address the issue of microbial attachment and degradation in humid environments. The sealant was formulated using a silane-modified polyether (SMPE) as the base material and TPOAC (3-(trimethoxysilyl) propyldimethyloctadecyl ammonium chloride) as the antimicrobial agent. The implementation of TPOAC was observed to expedite the sealant's curing mechanism. Various properties of antimicrobial SMPE sealants were investigated, including mechanical, bonding, thermal, and surface wettability characteristics. The mechanical behavior of the sealant was observed to be enhanced with an optimal TPOAC content of 1.5%. The thermal stability of the sealant was not significantly affected by the addition of TPOAC. Furthermore, the sealants became increasingly hydrophobic as the quantity of TPOAC was increased. The results indicated that including an antimicrobial agent (TPOAC) is a viable strategy for developing SMPE sealants with desirable antimicrobial properties. The study also revealed that TPOAC forms covalent bonds with the sealant matrix, potentially providing strong antimicrobial properties with a small quaternary ammonium salts (QAS) content. An innovative type of SMPE antimicrobial sealant with TPOAC was developed, and the study's findings laid the foundation for further exploration of the antimicrobial properties of this sealant in combating microorganisms in humid environments [32].

Hyung-Jun Kim et al. [33] explained the mechanical properties of Al_2O_3–13TiO_2 plasma-sprayed coatings, emphasizing the sealing process's impact. Three types of commercial sealants based on polymers were selected for sealing. The depth of penetration of this polymer-based sealant into the Al_2O_3-13 wt% TiO_2 coating was assessed through optical microscopy with a fluorescent dye, revealing a penetration depth ranging from 0.2 to 0.5 mm, depending on the type of sealant employed. This study showed significant improvements in several mechanical properties after the sealing. Nevertheless, it is crucial to mention that the degree of these enhancements differed based on the particular sealant utilized.

To improve the life cycle of atmospheric plasma (AP)-sprayed Fe-based amorphous coatings, Guangyu et al. [34] addressed the problem of porosity defects. A sealing was employed to increase the resistance to corrosion and extend the coatings' lifespan. An ultrasonic excitation and

Table 3 A brief review of the sealing on coatings

S. No	Sealing materials	Method of sealing	Coating material and technology	Findings	References
1	Silicone resin	Vacuum sealing	WC–Cr_3C_2–Ni and high-velocity oxyfuel (HVOF) spraying	Vacuum sealing with silicone resin could enhance versatility in thermal-sprayed coating	[29]
2	Ultra-high-molecular weight polyethylene particles	Manual	Al and cored wire arc spraying	UHMWPE particles are used in this revolutionary composite-coating method, which can help produce self-sealing anti-corrosion maritime coatings	[30]
3	Epoxy resin (ER) and Silicone resin (SR)	Manual	Cr_2O_3–8TiO_2 and Plasma-sprayed coating	The findings revealed that SR exhibited better sealant, blocking 91% of interconnected porosity in the coatings	[31]
4	Commercial polymer sealant	Coating	Al_2O_3–13TiO_2 plasma-sprayed coatings	Significant enhancements in various mechanical properties were achieved after the sealing process	[33]
5	Waterborne silicone-modified acrylic emulsion	Ultrasonic excitation and Immersion combination	Fe-based amorphous coating and Atmospheric plasma spray coating	The sealant effectively penetrated the Fe-based amorphous coating, improving corrosion resistance and durability	[34]
6	Epoxy-Polyester	Manual	85Zn–15Al and spray coatings	Epoxy-polyester-sealed coatings were more chloride-resistant	[36]
7	Silicone resin or Epoxy resin	Manual	Al_2O_3 and APS	Application requirements determined sealant choice: silicone resin or epoxy resin	[39]
8	Fluorocarbon resin	Spraying	Zinc and arc-sprayed (AS) coatings	Implementing this sealing agent successfully decreased the reaction surface area of the coating	[40]
9	Silicone resin	Manual	Al_2O_3 + 13TiO_2 Plasma spraying	Silicone resin sealing prevented corrosion and improved plasma-sprayed coating performance	[41]
10	Aluminum phosphate	Spreading and immediate heating	Alumina coating and Plasma spraying	The coating's stress and strain resistance changed due to pore sealing and changes in the aluminum phosphate sealant phase	[42]
11	Aluminum phosphate	Microarc Oxidation (MAO) process and vacuum impregnation	Al6063 and Microarc Oxidation (MAO) process	Sealing improved coating corrosion resistance	[44]
12	$AlPO_4$	Immersion	Fe amorphous coatings and HVAF process	The performance of aluminum phosphate sealing depends on the HCl solution concentration	[45]
13	$AlPO_4$	Manual	α-Al_2O_3 and metal–organic decomposition (MOD) method	The aluminum phosphate adhesive penetrated and filled holes and cracks in α-Al2O3 coatings	[46]

Table 3 (continued)

S. No	Sealing materials	Method of sealing	Coating material and technology	Findings	References
14	$AlPO_4$	Ultrasonic excitation sealing (UES), conventional impregnation sealing (CIS), and vacuum sealing (VS)	Fe-based HVOF coating	Long-term corrosion tests on the three sealed coatings showed that the UES technique produced the best results	[47]
15	$AlPO_4$	Ultrasonic vibration and vacuum heat treatment	Amorphous coatings and APS technique	Ultrasonic vibration and vacuum heat treatment made deep penetration easier	[48]
16	Cerium salts	Electroless	Ni–P coatings	Cerium-sealed Ni–P coating has no microcracks, unlike standard cerium conversion coatings	[52]
17	YSZ Abradable Sealing	Mixed solution precursor technology	YSZ and Plasma spraying	MSP technology can create nano-structured abradable sealing coatings with improved qualities promising for diverse applications	[43]
18	SiO_2	Sol–gel technology	ZrO_2-coated Cf/Mg and Supersonic atmospheric plasma spraying method	Sealing treatment reduced coating porosity and surface roughness by 37.33%. By making the sealing layer thick and hydrophobic, this treatment reduced surface porosity by 65.47% and boosted corrosion resistance	[57]
19	Various mixtures of SiO_2/B_2O_3	Sol–gel method	SiC-coated C/C composite and chemical vapor deposition (CVD) process	The observed sealing efficiency was attributed to a chemical reaction between B_2O_3 and SiC, leading to a consistent thick layer of SiO_2	[61]
20	Nano-Ti polymer sealant	Spraying equipment	Aluminum and Supersonic plasma spray technique	Utilizing the nano-Ti polymer in the sealing process played a crucial role in attaining higher corrosion protection	[63]
21	Epoxy resin with nano-TiO_2 particles	Immersion	TiN coatings and Reactive plasma spraying	Incorporating nano TiO_2 in the epoxy resin (ER) decreased porosity, enhanced the bond strength between the sealant and the TiN coating, and improved the epoxy's barrier qualities against the diffusion of solvents and gases	[64]
22	Al_2O_3 with $Al(PO_4)$ and P	Manual brushing	80Ni–20Cr and HVOF	Closing the pores within the coating was discovered to effectively mitigate hot corrosion in extreme settings during post-treatment	[66]
23	$AlPO_4$ and SR	Sol–gel method and ultrasound-assisted sealing	nano Al_2O_3-13-wt% TiO_2subsonic plasma spray coating	Nanostructured Al_2O_3–13TiO_2 coatings following ultrasound-assisted silicone resin sealing were more corrosion resistant than aluminum phosphate sealant	[67]

Table 3 (continued)

S. No	Sealing materials	Method of sealing	Coating material and technology	Findings	References
24	Phosphoric acid, phenol, and epoxy-based sealants	Manual Brushing	$Al_2O_3 + TiO_2$ and plasma-sprayed coating	Using phenol and epoxy-based sealants resulted in better results for making the products more corrosion resistant	[68]
25	$AlPO_4$ and SR	Ultrasound-assisted sealing	WC–Cr3C2–Ni/CNTs and HVOF spray coating	The coating wettability was better on SR than $AlPO_4$. Ultrasonic sealing helped sealants penetrate cracks and pores, especially the SR, which improved corrosion resistance	[23]
26	SR and $AlPO_4$	Conventional and Vacuum impregnation	WC–20Cr_3C_2–7Ni/MWCNTs and HVOF coating	Vacuum impregnation (VI) with SR sealant showed the most significant improvement in corrosion protection	[69]
27	Aluminum Isopropoxide And Isopropanol	Immersion	WC–12% Co and plasma-sprayed coating	The sealing process substantially decreased porosity, decreasing values from 3.51% to 0.75%	[70]
28	Phosphate-based sealant 8Y_2O_3–ZrO_2, Cr_2O_3 and ZrSiO4 layers	Manual a nd Detonation-gun spraying	Additive-loaded zirconia-based materials and Thick thermal barrier coatings (TTBCs)	Detonation-gun spraying could create denser ceramic top layers on conventionally sprayed TTBCs	[72]

immersion combination was utilized to seal the coating (illustrated in Fig. 4), as the commercial method of sealing failed to produce the desired result. An emulsion polymerization produced a waterborne silicone-modified acrylic (WA) emulsion for sealing. This emulsion was the principal film-forming agent to develop a WA sealant with anti-corrosive and sealing characteristics. The present study successfully developed a waterborne silicone-modified acrylic sealant with anti-corrosion and sealing characteristics. This sealant effectively penetrated the Fe-based amorphous coating, substantially enhancing corrosion resistance and an extended operation lifespan. The sealant's exceptional resistance to long-term corrosion and absence of solvent requirements create novel opportunities to advance functional coatings for waterborne applications.

Mateus R. D. Carneiro et al. [35] focused on the FeCr- and CoCr-based coatings on carbon steel and their performance of microstructure, adhesion, and corrosion properties. Uniformity of the deposited layers with minimal oxide content and defects was achieved, with both conditions showing low defect percentages. The coating condition labeled "Condition 1," which involved the deposition of FeCr + CoCr alloy with an intermediate bond of 95Ni5Al, demonstrated excellent overall performance. The corrosion resistance of samples that were sealed with epoxy resin was higher. The results highlighted the effectiveness of "Condition 1" and the positive impact of epoxy sealing on corrosion behaviors. The observed adhesion strength remained consistent under the various conditions that were tested.

Akinci and Yilmaz [36] aimed to assess the corrosion resistance of different metal-coated steel samples with epoxy-polyester top coating under salt spray conditions. Steel substrates were sprayed with Zn, Al, and 85Zn–15Al coatings of varying thicknesses and subsequently top-coated with an epoxy-polyester sealing layer. Test results indicated that the sealed Al spray-coated surfaces demonstrated better corrosion resistance than Zn spray and 85Zn–15Al-spray coatings. Zn and 85Zn–15Al-sprayed surfaces, even when sealed with polymer, experienced filiform corrosion, delamination, pitting, and severe damage. The corrosion resistance of Al-sprayed surfaces was notably higher compared to Zn and 85Zn–15Al-sprayed systems. The epoxy-polyester sealed system also provided more durability against chloride environments than the other systems. The study highlighted that the sealing treatment significantly improved substrate protection from corrosion attacks. Although the Al-sprayed epoxy-polyester system was the most durable, the sealing treatment effectively enhanced overall protection against corrosion for all substrate types.

In a comprehensive investigation of the peel strength of two different sealants, experiments were conducted using a modified peel specimen. The research encompassed five distinct peel angles, spanning from 90 to 180°, and seven

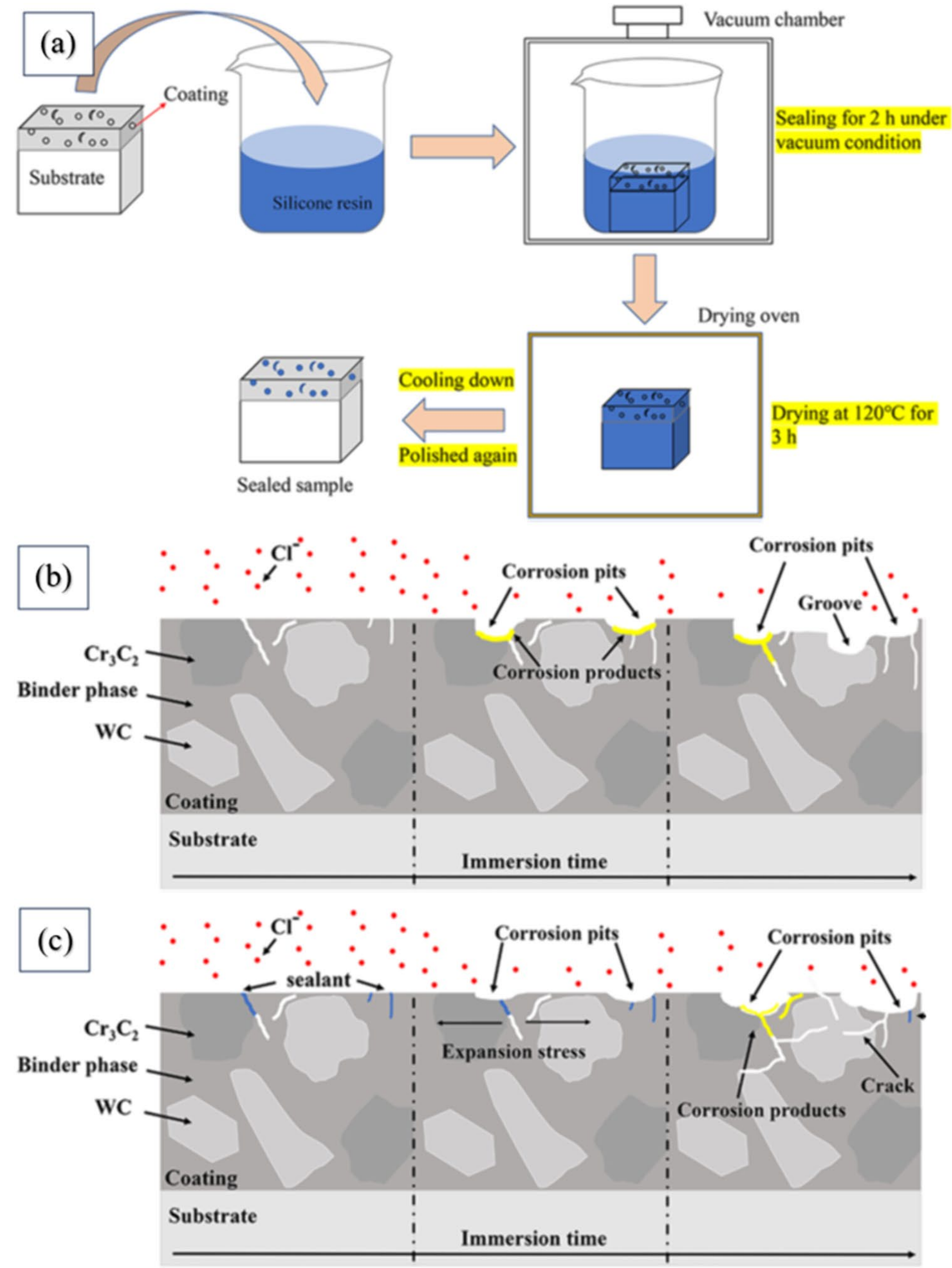


Fig. 2 **a** The fabrication process diagram of the Sealed WC–Cr_3C_2–Ni coating. Long-term corrosion mechanism of **b** unsealed WC–Cr_3C_2–Ni and **c** sealed WC–Cr_3C_2–Ni [29]

varying thicknesses of the sealant layer, ranging from 0.1 to 5 mm. Additionally, the effect of the peel rate was examined while the thickness of the sealant layer and the peel angle remained constant. The analysis primarily examined the influence of sealant layer thickness and peel angle on the measured peel energy, finding that both factors had a notable combined effect. Notably, this study found that with the sealant layer thickness increase, the peel energy exhibited a linear growth, and this increased rate intensified as the peel angle ranged from 90 to 180°. However, for very thin sealant layers (0.1 mm), the peel angle had no discernible effect on peel energy. These energy dissipation results during deformation and up to fracture lead to a proposed relationship for predicting peel energy [37].

Yu Zhang et al. [38] initially developed a spray coating process with TiN, Ti_3O, and $TiN_{0.3}$ phases. Subsequent heat treatment at 300 °C and 400 °C resulted in TiO_2 and Ti_2O phases, respectively. Moreover, the nitride phases underwent substantial oxidation as the heat treatment duration increased. Heat-treated coatings at 300 °C exhibited the lowermost porosity, representing 78.2% of the as-sprayed coating's porosity. However, the most significant finding of this study was related to the sealing process. The heat treatment altered the phase composition and reduced porosity in the

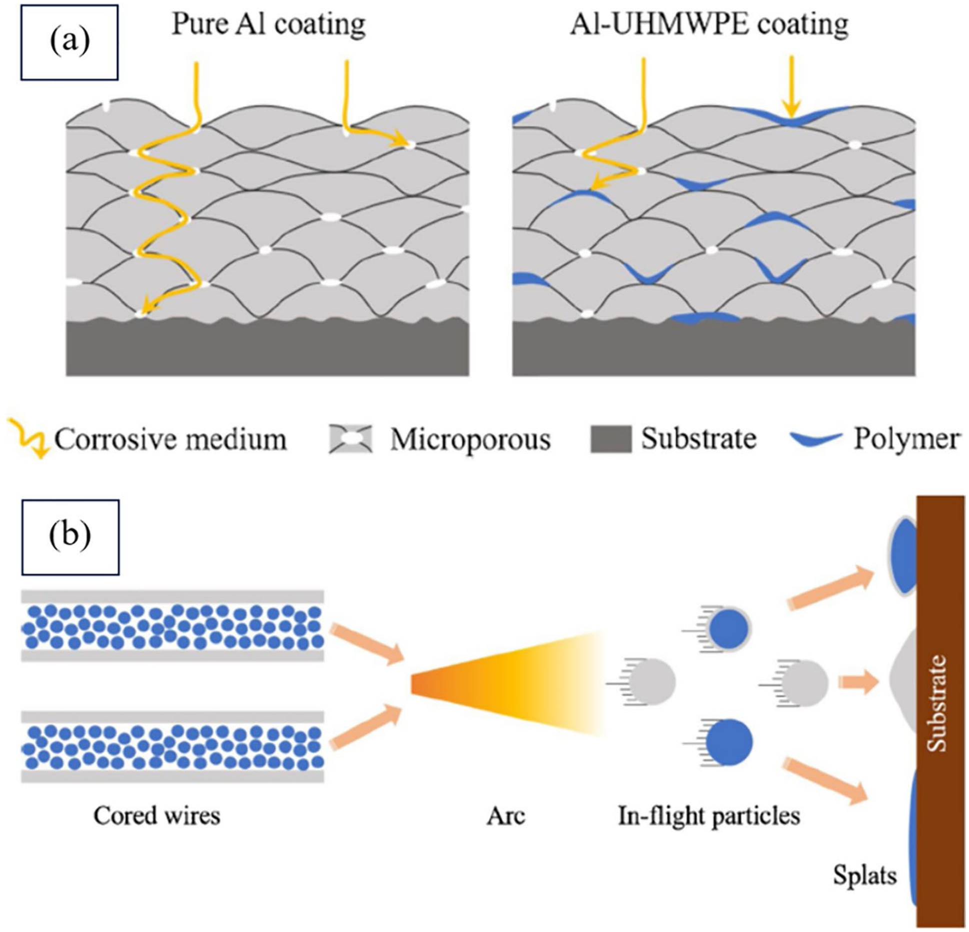


Fig. 3 **a** Anti-corrosion mechanism of UHMWPE particle; **b** UHMWPE particle microstructure evolution of coatings [30]

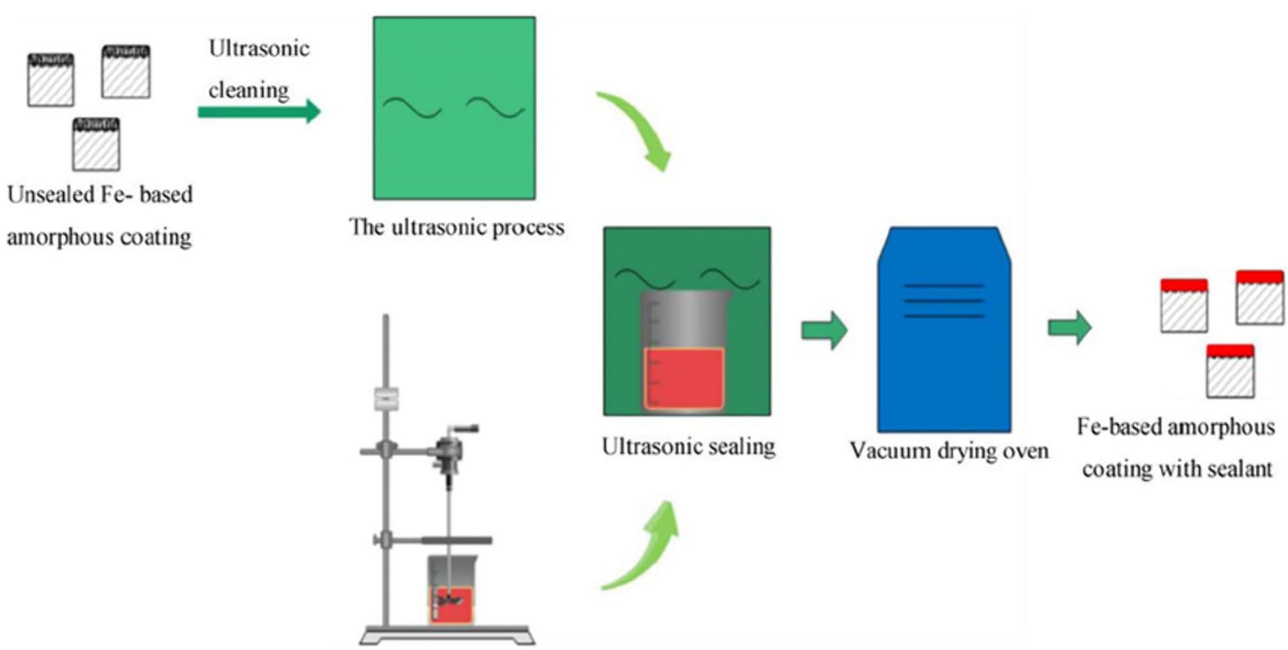


Fig. 4 Fe-based amorphous coating with sealant [34]

TiNx/TiOy coatings created via reactive plasma spraying. Sealing was pivotal in enhancing corrosion resistance, with or without heat-treated coatings. Therefore, the outcomes emphasize the significance of a two-step sealing approach for achieving superior corrosion resistance in heat-treated composite coatings.

Alumina (Al_2O_3) coatings were applied to aluminum alloy substrates using APS. Two different sealing treatments were executed to enhance the insulation properties of coatings, utilizing SR and ER sealants. SR sealant solidified at room temperature, while ER sealant required high-temperature curing, making it more suitable for applications with stringent insulation requirements. The sealing process involved in this study effectively improved the insulation properties of APS Al_2O_3 coatings by reducing their porosity and enhancing dielectric strength. The choice of sealant, whether silicone resin or epoxy resin, depended on the specific requirements of the application [39].

Using a simulated corrosion electrolyte, this study assessed the sealing treatment based on fluorocarbon resin on the corrosion properties of arc-sprayed (AS) zinc coatings. A sealing agent (fluorocarbon resin, based on fluoroethylene vinyl–ether copolymer as the binder) was applied to the coating by spraying under low-pressure conditions as part of the sealing procedure. The application of this sealing agent resulted in the effective reduction of the coating's reaction surface area. In addition, it prevented the deterioration of the outer coarse layer's pores and microcracks caused by corrosive elements penetrating them. The zinc coating's resistance to corrosion was considerably improved through this sealing procedure, as indicated by a reduction in corrosion and an increase in corrosion potential. During prolonged immersion in a corrosion solution, compared to the unsealed coating [40].

Plasma spraying created $Al_2O_3 + 13TiO_2$ ceramic coatings with a bond layer of NiCrAl. These coatings were characterized through various techniques, and silicone resin sealing was applied to assess its impact on corrosion resistance. The sealing procedure encompasses the infusion of filler materials into the pores, and microcracks are visible in the coating, thereby establishing a safeguarding ceramic layer that overlays the underlying substrate. On the contrary, the coating exposed corrosion by pitting at the bond layer–substrate interface. The sealing process with silicone resin played a crucial role in preventing corrosion and enhancing the performance of the plasma-sprayed coatings [41].

Polymer-based sealants are crucial for enhancing corrosion resistance and longevity in coatings. Different combinations, such as HVOF spraying with silicone resin vacuum sealing, can effectively seal imperfections in coatings, reducing corrosion. Aluminum coatings with UHMWPE particles show improved corrosion resistance, particularly in marine applications. Silicone resin outperforms epoxy resin in blocking porosity in coatings, enhancing corrosion resistance. Antimicrobial sealants, like SMPE with TPOAC, combat microbial degradation in humid environments. These sealants also impact mechanical properties, with significant improvements in coatings post-sealing. Choosing the right sealant is essential based on specific application needs. In summary, polymer-based sealants are critical in advancing coating functionality and durability across various industries.

2.2 Inorganic Chemical-Based Sealants

Vetrivendan et al. [42] investigated the aluminum phosphate sealing with varying P/Al molar ratios on plasma-sprayed alumina coating applied to Inconel 600 samples. The sealing process with P/Al molar ratios of 10 and 15 demonstrated a notable decrease in porosity, effectively sealing the lamellae boundaries and other non-fillings in the plasma-sprayed alumina coating. In contrast, a lower P/Al ratio sealing has limited sealant penetration, primarily addressing the surface and subsurface. XRD analysis confirmed the formation of aluminum metaphosphate (type B) as the dominant phase after curing across different P/Al molar ratios. The insulation resistance measurements demonstrated a significant enhancement in resistance, with an increase of up to two orders of magnitude, when the sealing process was conducted using a low molar ratio of P/Al of 3. However, thermal cycling studies revealed a significant deterioration in the thermal cycling life of the sealed alumina coatings. The sealing of pores, coupled with phase transformations in the aluminum phosphate sealant, altered the stress levels and reduced the strain tolerance of the coating. Overall, this study reaffirmed the enhanced insulation resistance value for sealing with a P/Al molar ratio of 3 and the substantial deterioration in the thermal cycling life of the sealings with molar ratios of 10 and 15. Interestingly, no significant variation in insulation resistance values was observed for P/Al molar ratios of 3 and 10 at voltages exceeding 300 V. Consequently, it can be presumed that intermediate P/Al molar ratios, such as 5 and 7, may not significantly enhance insulation resistance when compared to the P/Al ratio of 3.

Corrosion-resistant composite coatings were applied to Al6063 using Microarc Oxidation (MAO) and sealed with varying NaH_2PO_4 solution concentrations. The principal constituent of the sealing coating was determined to be $AlPO_4$. The sealing treatment was a crucial step in the process, effectively sealing the open surface pores and cracks. It is worth noting that the sealing coating produced with a NaH_2PO_4 concentration of 0.5 M displayed the least porosity of 1.554% and surface roughness of 5.352 µm. The coatings' resistance to corrosion was substantially enhanced using the sealing treatment. Electrochemical Impedance Spectroscopy (EIS) revealed a decrease in $|Z|_{0.01\ Hz}$ from 107 $\Omega \cdot cm^2$ during primary immersion to 106 $\Omega \cdot cm^2$ in later stages. At the same time, corrosion current (I_{corr}) in the Polarization Resistance (PDP) curve was measured at 3.881×10^{-7} $A \cdot cm^{-2}$. Both salt spray and hydrogen evolution corrosion tests confirmed the coatings' excellent corrosion resistance. Furthermore, the process of $AlPO_4$ adsorption onto the surface of the coating adhered to the Langmuir adsorption isotherm, with the 0.5-M NaH_2PO_4 sealing coating exhibiting a high maximum adsorption amount (K_{ads}) of 833.33. This result indicated superior corrosion resistance due to the substantial adsorption [44].

The HVAF process was utilized to apply amorphous coatings consisting of Fe onto SS304 substrates. These coatings were subsequently sealed with AlPO4 sealant to enhance their corrosion properties. The findings of this study indicate that the sealing process involving aluminum phosphate sealant extends the resistance to corrosion. This improvement in corrosion resistance is ascribed to the ability of the sealant to penetrate the coatings and effectively seal microcracks. As a result, the corrosive solution is prevented from infiltrating the microcracks and corroding the interface. Notably, the research demonstrates that the effectiveness of aluminum phosphate sealing is contingent on HCl solution concentration. The sealant will inhibit the penetration of the solution; however, an increased concentration of HCl reduces the resistance to corrosion of the material that has been coated. This study highlights the importance of the sealing process involving $AlPO_4$ sealant in extending the corrosion properties. The sealant can seal the pores and microcracks and avert the penetration of HCl solutions. It is highly effective, especially in lower-concentration HCl solutions. However, it is crucial to acknowledge that as the HCl concentration increases, the ability to repel corrosion of the sealed coatings could decrease [45].

Wei Zhang et al. [46] focused on α-Al_2O_3 coatings produced via the metal–organic decomposition (MOD) method and sealing using aluminum phosphate (AP). The approximately 51-μm-thick sealed coatings primarily comprised α-Al_2O_3 and $AlPO_4$ (orthophosphate phases). AP adhesive effectively penetrated the coatings, filling defects like pores and cracks within the α-Al_2O_3 coatings. The scratch tests demonstrated a robust bonding strength of over 100 N for the alumina coatings, unaffected significantly by the AP sealing treatment. Regarding permeation resistance, the aluminum phosphate sealing treatment showcased promise in enhancing the thick MOD coatings' hydrogen/deuterium permeation resistance. Both tests on hydrogen permeation with electrochemical methods and deuterium gas-driven methods, performed before and after the treatment, confirmed the possible effectiveness of the sealant.

The study by Liu et al. [47] aimed to mitigate porosity defects in amorphous coatings sprayed with Fe-based coatings using a high-velocity oxyfuel (HVOF) spraying technique. To achieve this, the researchers utilized three distinct sealing technologies: ultrasonic excitation sealing (UES), conventional impregnation sealing (CIS), and vacuum sealing (VS) utilizing aluminum phosphate sealant. The objective of the sealing procedure was to increase the durability of the coatings and prevent corrosion. The effects were evaluated through microstructural analysis and corrosion behavior investigations. The $AlPO_4$ sealant was utilized to penetrate coating defects during the sealing procedure, resulting in barrier layer formation consisting of $AlPO_4$, $H_2(AlP_3O_{10}) \cdot H_2O$, $Al_2P_6O_{18}$, and $AlPO_3$. This barrier layer is connected with the coatings to form an adhesive bond. Electrochemical tests showed that all three sealing methods reduced the corrosion rate for long-term corrosion compared to unsealed Fe-based amorphous coatings. The observed consequence was ascribed to the obstruction of corrosion media inward diffusion. In the following sequence: Coating with UES is superior to coating with CIS and VS. Using ultrasonic energy by UES facilitated enhanced sealant penetration into minute cracks and holes, thereby effectively sealing internal pores. This innovation contributed to the highest level of resistance to corrosion observed within the three sealing methods.

The study involved fabricating a nanocrystalline amorphous Al-based coating on aluminum alloy 2024 using high-velocity air-fuel spraying, resulting in a coating with a small porosity of 0.42% and an Al-based amorphous coating content of 80.3%. The amorphous matrix containing this thin coating precipitated α-Al, which demonstrated favorable resistance to short-term corrosion, as evidenced by an average icorr of 7.4 $\mu A/cm^2$. However, over time, the corrosion resistance decreased [28].

Kang et al. [48] investigated the production of amorphous coatings through the atmospheric plasma spraying (APS) technique. Subsequently, these coatings were sealed by aluminum phosphate. The sealing process entailed the utilization of ultrasonic vibration and vacuum heat treatment to achieve optimal penetration of sealant into the coating, thereby eliminating air from micro-pores and -cracks. As corrosion progresses, coating dissolution and corrosion product accumulation can cause pores, cracks, and peeling (Fig. 5a). After sealing treatment, many coating pores are filled with sealant, even reaching the substrate–coating interface. Sealing treatment can increase corrosion resistance by blocking electrolyte diffusion channels and slowing penetration (Fig. 5b). Additionally, pores and microcracks can initiate cracks in coatings. In layer-by-layer thermal-sprayed coatings, lamellar structure increases crack propagation along droplet interfaces. Due to weaker cohesion, cracks are more likely to form and spread along coating pores and microcracks. Under repeated stress during friction, cracks can expand and cause coating flaking when they reach a critical size, as shown in Fig. 5c. After sealing, the sealant

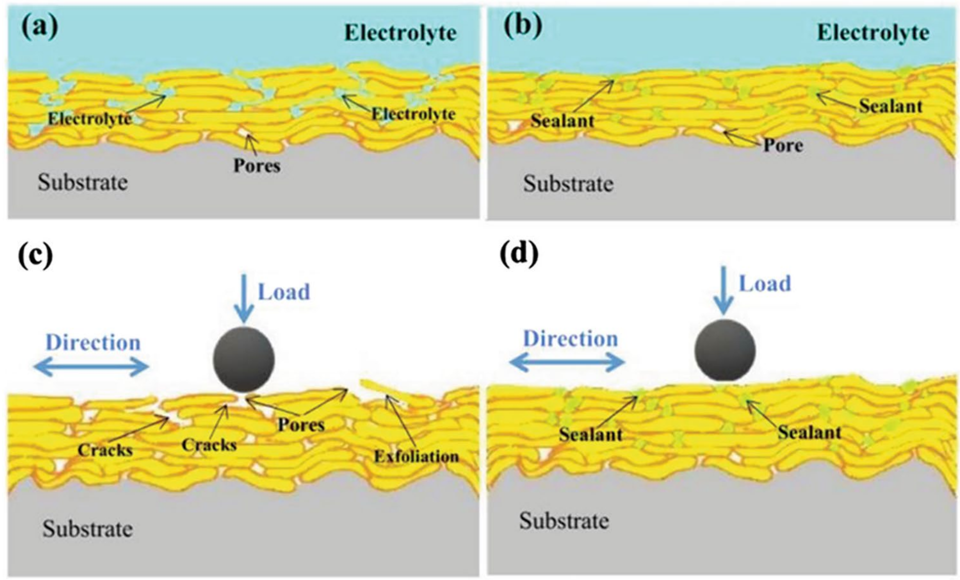


Fig. 5 Schematic sketch of **a**, **b** corrosion and **c**, **d** wear; **a**, **c** unsealed; and **b**, **d** sealed [48]

fills open pores and microcracks, forming a hard droplet binder after curing. Therefore, minimize open pores and microcracks in the coating, particularly on its surface. This reduces the likelihood of crack initiation and suppresses crack propagation along the micro-pores and -cracks, as shown in Fig. 5d. This is confirmed by worn morphologies, which show reduced delamination and smooth, flat surfaces of the sealed coating.

Therefore, sealing treatment significantly enhances the coating's ability to withstand wear. The research demonstrated that aluminum phosphate is an effective sealant for amorphous coatings, able to penetrate the micropores and cracks. Deep penetration was made easier by employing a process that combined ultrasonic vibration with a vacuum heat treatment. This sealing process significantly improved the coating's corrosion and wear resistance, making it a valuable technique for enhancing the performance of such coatings [48].

Figure 6 depicts the macroscopic images of the coating surface after various sealing treatments. The AS-sprayed

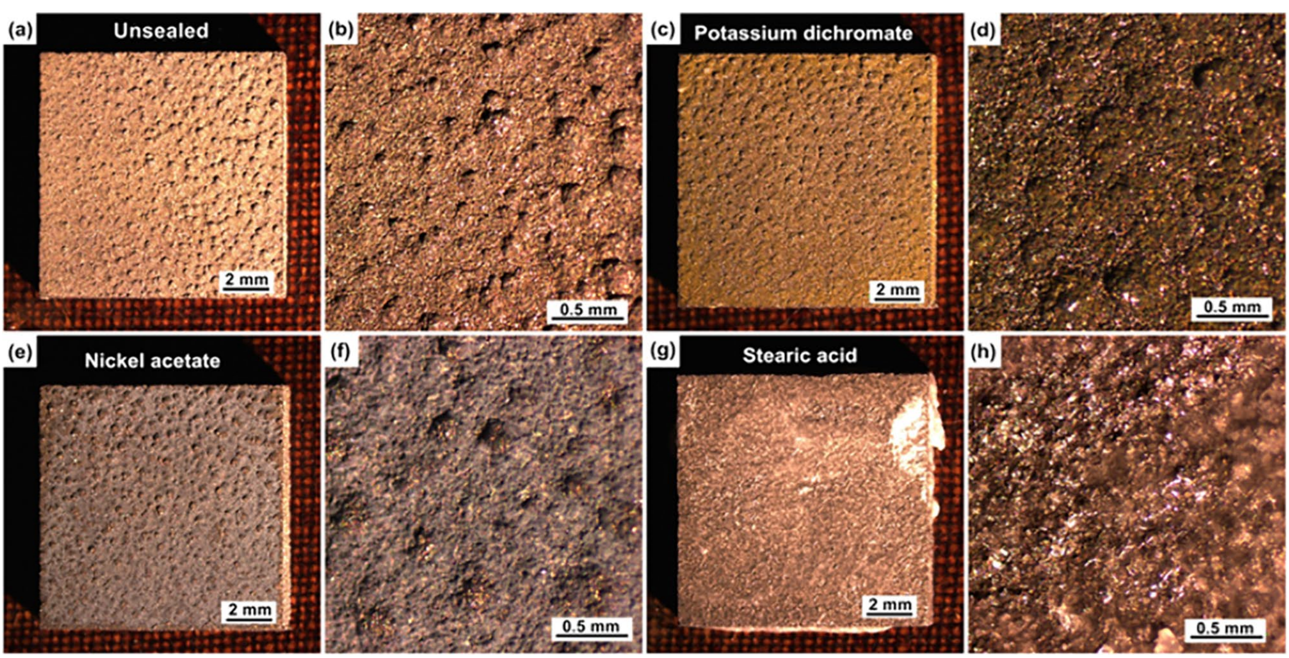


Fig. 6 The surface of the coatings after various sealing processes [28]

coating exhibits numerous craters on its coated surface, formed by the HVAF coating technique. Additionally, the entire surface displays a pale orange hue. The external surface color has undergone alterations after various sealing treatments—applying a potassium dichromate sealing treatment results in a dark orange coating. Conversely, when treated with nickel acetate, the coating surface transforms and appears brown. It is worth noting that the craters on the coating surface remain visible even after both sealing treatments have been applied. On the contrary, applying stearic acid sealing treatment maintains its original color. However, due to their concealment, the stearic acid layer renders the craters invisible.

The sealing treatment was found to be a crucial process in improving the corrosion resistance of the coating. Sealing effectively closed the connected pores and reduced the porosity defects in the coating. Due to its hydrophobic and impermeability characteristics, stearic acid exhibited the most substantial sealing effect among the evaluated sealants. Potassium dichromate also exhibited a good sealing effect by forming various compounds on the coating surface, preventing the penetration of corrosive ions. In contrast, nickel acetate had a weaker sealing effect, primarily because of unclosed macro-pores on the coating surface. Sealing treatment, with stearic acid being the most effective sealant, improved the corrosion resistance of the coating by reducing porosity defects. Potassium dichromate also showed good sealing effects, while nickel acetate had a weaker sealing effect of unclosed macro-pores on the coating surface [28].

Minnamari Vippola et al. [49] focused on the microstructural examination of AlPO4-sealed CrO_2 coatings by plasma sprayed to understand the strengthening mechanisms. The lamellar structure of the sealed CrO_2 coating was composed of columnar type α-Cr_2O_3 grains that protruded across its entire thickness. It was observed that the $AlPO_4$ sealants had permeated the coating, causing structural flaws, including cracks and pores among the lamellae. The sealant composition within the coating was determined to be 25% aluminum and 75% phosphorus, resulting in a molar ratio P/Al of 3, equivalent to metaphosphates $Al(PO_3)_3$. Importantly, no evidence of chemical reaction products between the sealant and the coating was observed. During the heat treatment process, an excessive amount of $AlPO_4$ sealant underwent dehydration, resulting in a mixture of $Al(PO_3)_3$ (metaphosphates) on the surface of the coating. The dominant phase observed in this mixture was cyclohexaphosphate $Al_2P_6O_{18}$, which corresponds to the B-type polymorph of $Al(PO_3)_3$. The sealing of chromium oxide coatings with aluminum phosphate appears in future primarily based on the adhesive strength due to the development of condensed phosphates for the coating rather than through chemical bonding after the coating and sealant reactions.

This study focused on enhancing tribo-corrosion properties of plasma spray coatings, which often suffer from porosity due to factors, like molten and semi-molten particles, pores, cracks, and oxide formation. To address this issue, a post-spray sealing process was applied to Cr_3C_2–NiCr/Al_2O_3–TiO_2 plasma-sprayed coatings, with a specific emphasis on the sealing agent known as $AlPO_4$, which contained Al_2O_3 nanoparticles. The sealing process involved using $AlPO_4$ containing nano-Al_2O_3, and the study assessed the penetration ability. The post-treatment with $AlPO_4$ containing nano-Al_2O_3 demonstrated superior workability in erosion–corrosion environments when the coating was sealed with $AlPO_4$ without nano-Al_2O_3. The post-treatment with $AlPO_4$ containing nano-Al_2O_3 nanoparticles reduced the coating porosity compared to sealed with $AlPO_4$ containing nano-Al_2O_3 alone. The sealing proficiency, determined by the proportion of the open pores, exhibited a notable increase when utilizing $AlPO_4$ incorporating nano-Al_2O_3, with closure rates exceeding 80%, in contrast to APP lacking nanoparticles, which achieved closure rates of approximately 60% [50].

Kumar et al. [51] investigated the feasibility of augmenting corrosion protection on Mg AZ31 alloy by integrating self-healing sol–gel coatings with a porous anodized layer. After a comprehensive characterization, the coatings applied to Mg AZ31 demonstrated enhanced adhesion strength and diminished thermal conductivity after the sol–gel sealing procedure. Corrosion behavior was evaluated through immersion and electrochemical studies, which showed a progressive improvement in corrosion resistance and decreased corrosion current for the alloy treated with inhibitor-loaded sol–gel coatings. Also, they conducted salt spray exposure tests with artificial scribes on the coatings. They observed a self-healing phenomenon through SEM analysis, which showed the development of Ce3 + and 8-hydroxyquinoline for the self-healing coatings. This sol–gel sealing process and anodization showed promise for various applications.

Cerium salts were utilized to develop a surface sealing method for electroless Ni–P coatings on aluminum-reinforced carbon fiber (Al/C_f) composites. The findings indicated that the Ni–P coating, which was cerium sealed, demonstrated the most pronounced resistance to corrosion and substantially enhanced the resistance of Al/C_f composites to corrosion. This Ni–P coating that was cerium-sealed significantly exhibited the absence of discernible microcracks, a characteristic frequently detected in traditional cerium conversion coatings. The lack of microcracks observed could be ascribed to the electroless nickel surface's comparatively uniform and homogeneous characteristics, in contrast to the surface of the Al/C_f composite surface, where the varying local coating thicknesses facilitated the formation of microcracks. The XPS analysis indicated that the Cerium-sealed coating predominantly comprised Ce3 + and Ce4 + species, with Ce4 + serving as the predominant oxidation state in Ni–P coatings sealed with cerium [52].

Multiple studies have explored the effectiveness of inorganic chemical-based sealants in enhancing different coating properties. For example, research by Vetrivendan et al. observed that aluminum phosphate sealing improved insulation resistance in alumina coatings, while NaH2PO4 sealing enhanced corrosion resistance in Al6063 coatings. Aluminum phosphate sealing on Fe-based amorphous coatings also increased corrosion resistance, with results dependent on HCl concentration. Studies on α-Al_2O_3 and CrO_2 coatings showed improved bonding strength and corrosion resistance with effective sealing penetration. Other treatments, such as stearic acid and potassium dichromate, demonstrated varying levels of effectiveness. Incorporating nano-Al_2O_3 in AlPO4 sealants showed superior sealing proficiency on plasma-sprayed coatings. Overall, these studies emphasize the valuable role of inorganic chemical-based sealants in enhancing coating durability against corrosion and wear.

2.3 Ceramic-Based Sealants

A plasma spraying technology has been developed to prepare 8YSZ-5-based abradable sealing coatings with nanostructures. The findings suggested that the 8YSZ-5 coating demonstrated exceptional thermal shock when subjected to a 200-cycle test at 1150 °C. Spallation was observed only at a small scale along the coating's edge, and the coating consistently maintained a stable phase with a tetragonal structure. The 8YSZ-5 coating's in-plane residual stress was compressive and increased during thermal shock. Microstructure showed spontaneous closure, reduced coating pores, and increased average grain size in the thermal shock test. Over some time, there was an increase in both the hardness and surface friction coefficient. However, the adhesive strength exhibited a reduction of 50% after the completion of 200 thermal shock cycles. Results suggested that potential ways to enhance the adhesion strength in thermal shock conditions, such as increasing density, altering crack characteristics, and further adjusting the coating's porosity [53].

Li et al. [54] developed the thermo-chemical reaction technique as an efficient low-temperature technique for sealing. This approach uses a coating slurry to deposit a compact α-Al_2O_3/$AlPO_4$ layer onto the coating surface at 500℃. This slurry also functions as a sealant, effectively filling the micro-pores and fissures in the coating. The increased confrontation of the sealed coating with hydrogen permeation confirms this enhanced sealing process. Furthermore, compared to a single-layer coating produced via the identical thermal chemical reaction method, the thermal shock resistance is substantially enhanced, approaching a level virtually equivalent to that of an unsealed coating.

The evaluation of bond strength of the unsealed and the sealed plasma-sprayed coating resulted in measurements of 12.3 MPa and 13.2 MPa, respectively, accompanied by a standard deviation of 0.76 MPa (Fig. 7). This slight increase in bond strength for the sealed coating indicates robust bonding, within the coating structure. The thermal chemical reaction method stands out due to its cost-effectiveness, low-temperature requirements, and ease of production. Bond strength tests revealed that the sealed coating exhibited slightly higher bond strength than the unsealed coating, indicating excellent bonding on the substrate, coating, and intermediate layers within the coating thickness. It has proved an innovative and efficient process for sealing, making it more practical for various applications [54].

The objective of the research conducted by Jingqi Huang et al. [55] was to create an YSZ-based abradable sealing coating (ASC) for SiC_f/SiC ceramic matrix composites (CMC) using plasma spraying. The thermal-environmental barrier coatings (T-EBC), comprising Si/$Yb_2Si_2O_7$/$LaMgAl_{11}O_{19}$ intermediate layers, were utilized to safeguard the CMC against recession and alleviate thermal expansion mismatch. The investigation encompassed thermal shock and isothermal exposure tests conducted at a temperature of 1200 °C. These tests induced significant alterations in the YSZ topcoat, such as the t'-ZrO_2 phase decomposing into c-ZrO_2 and t-ZrO_2 phases, the development of mud-cracks across the coating, and the identification of a $Yb_2Si_2O_7$ reaction layer in addition to thermally grown oxide (SiO_2). The bond strength of the coated samples was assessed to be 5.47 ± 0.85 MPa through measurement. It was observed that fracture took place primarily within the CMC substrate. Critical for readability, the Superficial Rockwell Hardness (HR15Y) increased marginally by 1.34 percent following 100 h of isothermal exposure at 1200 °C, indicating exceptional high hardness stability at higher temperatures. The

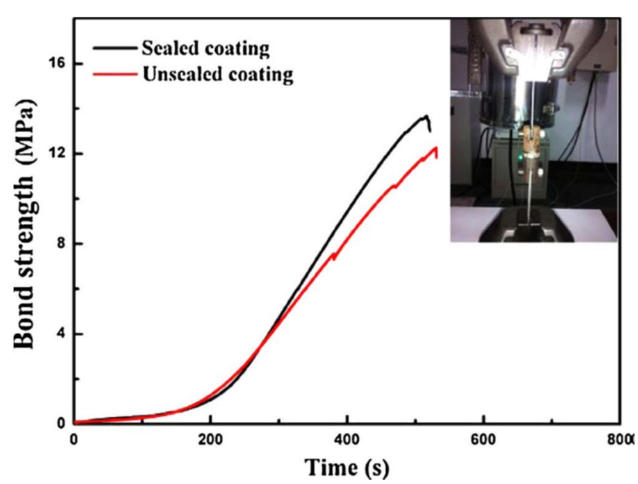


Fig. 7 Plot of bond strength [54]

readability was evaluated via a sliding wear test, demonstrating that fatigue wear was predominantly observed in Si_3N_4 ceramic balls with low thermal conductivity and hardness. The transitional layers and thermal-environmental barrier coatings (T-EBC) were meticulously planned to safeguard against thermal expansion and recession.

The study involved developing and testing a layered ceramic sealing coating comprising a "brick" layer created using APS and a "mud" layer made from polymer resin applied using a spray gun. The coatings were designed with varying numbers of "mud" layers and their thermal performance and failure mechanisms were analyzed. The "brick" layer contained 54.2% YSZ phase and had porous spherical structures, while the "mud" layer remained amorphous SiO_2 at ≤ 1100 °C. The fracture toughness of the "mud" layer exhibited a reduction of 72.3% compared to the "brick" layer, which aligns with an assumption of "weak" interlayer commonly observed in the layered structures [56].

The sealing process involved applying a SiO2 layer of 10–15 µm thickness through sol–gel technology onto the ZrO_2-coated Cf/Mg composites. The sealed ZrO_2 coating required three steps, as shown in Fig. 8a. Supersonic atmospheric plasma spraying method (SAPS) (HEPJ-2) was used to coat Cf/Mg composites with NiCrCoAlY buffer layer and ZrO_2 coating. The buffer layer was designed to improve matrix ZrO_2 coating bonding and endurance. The ZrO_2 layer mostly prevents composite deterioration. Second, generate SiO_2 sol by stirring ethanol absolute (20–30 vol%), tetraethyl orthosilicate (50–60 vol%), and deionized water (10–20 vol%) at 343–363 K. Mixed composites were placed in sol for 10–30 min after spraying ZrO_2 coating and then oven-dried at 70 °C for 8–12 h. The specimens were heated in argon at 200–300 °C for 1–3 h to complete. This treatment substantially reduced surface roughness by 37.33% and lowered the coating's porosity. This treatment effectively reduced surface porosity by 65.47% and increased corrosion resistance by enhancing the dense structure and hydrophobicity of the sealing layer [57].

Figure 8b and c shows an expected corrosion behavior of sprayed and sealed ZrO_2 coatings. In NaCl solution, unsealed and sealed ZrO_2 coatings behave differently (Fig. 8b1-b4 and c1-c4). Previous studies show that coating surface porosity considerably affects corrosion resistance. Adsorption and transferability of small Cl^- ions in corrosion solutions are high. The sprayed covering surface's pores and fissures let corrosive solution damage the matrix (Fig. 8b2). Flaws on

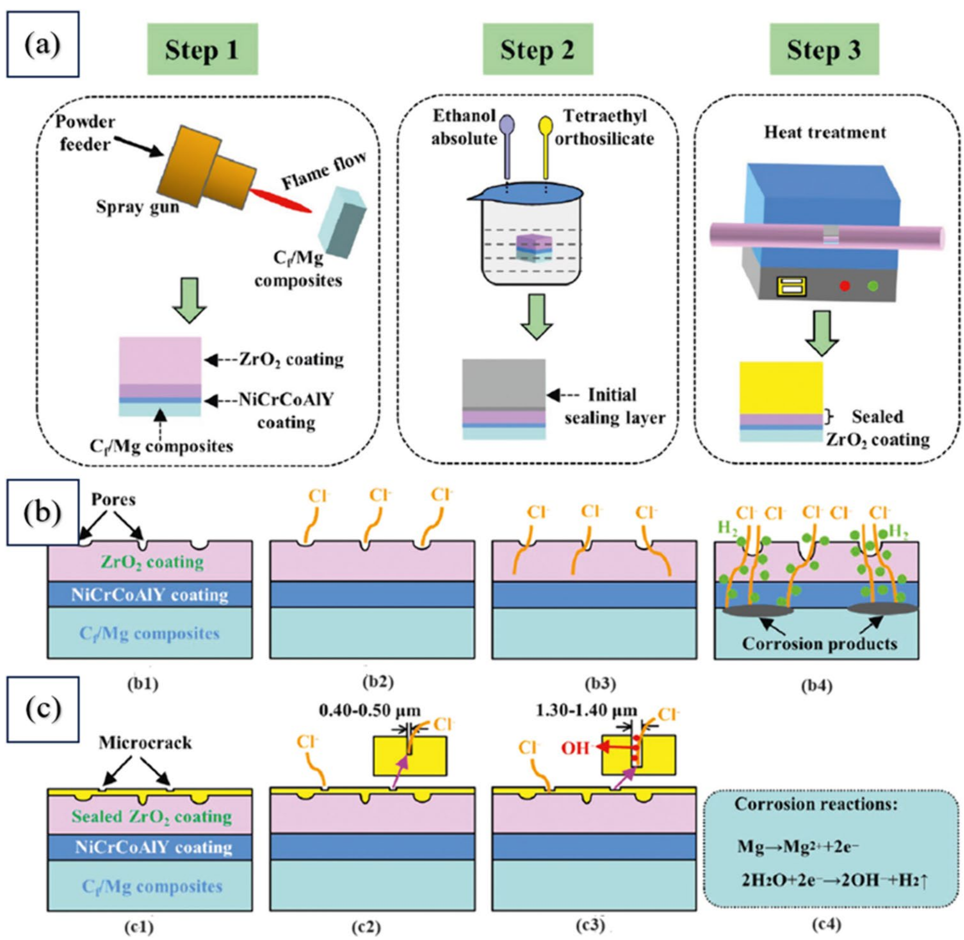


Fig. 8 **a** The preparation process of sealed ZrO_2 coating Corrosion protection mechanism of specimens in NaCl solution: **b** ZrO_2-coated Cf/Mg composites; **c** sealed ZrO_2-coated Cf/Mg composites [57]

the sprayed ZrO_2 layer allow solution Cl^- to enter easily (Fig. 8b3). Mg in the matrix loses electrons to Mg^{2+}, while ZrO_2 in the corrosive solution gains electrons to produce H_2. Released H_2 stirs corrosion solution. Longer immersion reduces ZrO_2 layer adhesion. ZrO_2 gets sandblasted because H_2 escapes, and the corrosive solution penetrates its pores. As ZrO_2 coating defects develop, its protective effect decreases (Fig. 8b4). Solute fluidity fills pores in sealed specimens, and heat treatment seals pores on the sprayed ZrO_2 coating (Fig. 8c1), protecting the matrix. SiO_2 sol–gel plugs ZrO_2 coating holes. The weakest locations accumulate corrosive solution due to sol–gel covering fractures near the surface (Fig. 8c2). Fluid corrodes the sealing coating slowly. The sealing layer fissures have more OH-ions due to their increased surface area exposed to the corrosive solution (Fig. 8c3). Figure 8c4 illustrates the primary reactions during the corrosion phenomenon.

The improved electrochemical performance indicated a notable increase in corrosion potential, a drastic reduction in corrosion current density, and a considerable decrease in corrosion rate. The enhanced electrochemical performance was attributed to the improved hydrophobicity and dense structure of the SiO_2 sealing layer, which effectively blocked corrosive solution penetration and improved the corrosion resistance of Cf/Mg composites [57].

Park et al. [58] examined the corrosion properties of thermal arc-sprayed Inconel 625 coatings in a natural seawater solution using a variety of sealing processes. The insufficient ability of the Inconel 625 coating to resist corrosion can be attributed to its porous nature and the reduction in chromium (Cr) content resulting from the formation of chromium oxide during the thermal spraying process. The Zinc sealing offered consistent cathodic protection; however, anodic polarization experiments revealed localized corrosion damage attributable to weak interparticle bonds and excessive dissolution reactions. Although hybrid sealing resulted in enhanced sealing, interconnected microcrack defects on the surface caused corrosion damage. On the contrary, ceramic sealing demonstrated superior corrosion properties due to its elevated sealing proficiency and diminished surface damage, impeding the progress of flaws in the Inconel 625 coating.

Jiachen Li et al. [59] aimed to overcome the drawbacks of conventional HfC, ZrC, and HfC–ZrC coatings. These coatings cannot withstand prolonged ablation temperatures exceeding 2100 °C because of the brittle structure of their oxides (HfO_2 and ZrO_2) and their inadequate ability to prevent oxygen infiltration after ablation. A novel HfC–ZrC–TiC multiphase coating, capable of securing the loose oxide structure during ablation, was developed to address this issue. The supersonic atmospheric plasma spraying was utilized to produce the coating, which underwent ablation testing at 2.38 MW/m^2 heat flux. The linear and mass ablation rates decreased from 2.58 μm/s to 0.71 μm/s and 0.85 mg/s to 0.18 mg/s, respectively, over 30 to 120 s. The observed upward trends in coating thickness suggest that C/C composites are protected for 120 s. Throughout the initial 120 s of ablation, an oxide m-(Hf, Zr, Ti)O_2 skeleton comprised most of the coating surface. As ablation continued, these oxide skeletons were progressively demolished through mechanical denudation. A liquid phase of TiO_4 formed beneath the oxide skeletons to fill the pores, resulting in a denser oxide layer 120 s later. The coating's capacity for self-healing substantially enhanced the ablation strength of C/C composites operating at temperatures exceeding 2100 °C. Superior resistance to ablation was exhibited by multiphase coating, which was fabricated via supersonic atmospheric plasma spraying. This coating successfully shielded C/C composites from elevated temperatures for over 120 s. The improved efficacy of the coating in safeguarding C/C composites during high-temperature ablation can be attributed to several factors, including the accumulation of a dense phase, the upward trajectory of ablation rates, and the self-healing capability of the coating [59].

The trivalent chromium coating process (TCCP) plays an important role in sealing the anodic coating on AA2024-T3. It forms a protective layer and penetrates the oxide pores, enhancing corrosion resistance and providing both anodic and cathodic corrosion resistance. The results confirmed the effectiveness of TCCP sealing in comparison to other sealing methods, demonstrating stability even in harsh environments. After the revelation of a 14-day salt spray test in the neutral condition, TCCP-sealed specimens remained free from significant damage, starkly contrasting to unsealed anodized specimens that exhibited extensive corrosion and pitting. The sealing process with TCP is instrumental in preserving the integrity and longevity of the anodic coating [60].

The investigation focused on identifying a crack sealant that effectively protects an anti-oxidation of C/C composites at approximately 1500 °C. While B_2O_3 is known to be effective as a sealant, it rapidly evaporates at temperatures exceeding 750 °C. To address this issue, various mixtures of SiO_2/B_2O_3 at different ratios were examined for their high-temperature durability. The research confirmed that pure B_2O_3, when applied as an overcoat on a SiC-coated C/C composite, displayed sufficient sealing ability up to 1500 °C. This sealing effectiveness was attributed to a chemical reaction between B_2O_3 and SiC, resulting in the establishment of a uniform SiO_2 thick layer of SiC [61].

Smeacetto et al. [62] focused on incorporating ceramics in solid fuel oxide cell stacks, particularly addressing the challenges of joining dissimilar materials (ceramics and metals) for reliable long-term operation. The primary emphasis is on the mechanical characterization of glass–ceramic sealant used to join a high-temparature ferritic stainless steel (Crofer22APU) metallic interconnects and its interaction with pre-oxidized Crofer22APU. In conclusion, the ceramic glass sealant exhibited exceptional sintering characteristics, thermo-mechanical integration, and adhesion properties when applied to pre-oxidized Crofer22APU.

Innovative ceramic sealants have been developed, with advancements in thermal shock resistance and sealing efficiency. One method uses plasma spraying to create coatings with nanostructures, showing exceptional thermal shock resistance and phase maintenance. Another technique involves a thermo-chemical reaction to deposit a compact, enhancing thermal shock resistance significantly. Research also focuses on developing sealants for ceramic composites and other materials, showing improved corrosion resistance and ablation strength. Efforts are ongoing to develop crack sealants for high-temperature applications and integrate ceramics into solid fuel oxide cell stacks, emphasizing mechanical characterization and long-term reliability.

2.4 Composite-Based Sealants

Bo Wang et al. [63] deposited an aluminum coating on an AZ91 substrate via supersonic plasma spray; a Ti nano-polymer sealed the Al-coating pores. A range of characterization methods and corrosion testing were utilized to evaluate the material structure and composition and find Al coating and composite-coating corrosion properties. These results were subsequently compared to those of the reference AZ91 alloy.

The diagram illustrating the model of the protective mechanism of the coating in its as-prepared state is presented in Fig. 9a and b. Micro-pores were observed in the Al coating (Fig. 9a), produced using supersonic plasma spraying technology. Consequently, the Al coating experienced the infiltration of invasive ions, namely H_2O, Cl^-, and O_2, which entered through pores and defects, thereby initiating the corrosion process. The study demonstrated that the combination of SP-sprayed Aluminum coating and the nano-Ti polymer sealant enhanced the corrosion properties of the composite coating (Fig. 9b), making it highly effective in protecting the substrate material over extended periods. The sealing process involving the nano-Ti polymer was instrumental in achieving this enhanced corrosion protection [63].

According to Liu et al. [64] reactive plasma-sprayed TiN coatings underwent a sealing process using epoxy resin (ER) with nano-TiO_2 particles to evaluate the sealing process's impact on the corrosion behavior of TiN coatings when exposed to seawater. EIS analyses revealed that the modified ER effectively blocked micro-pores and -cracks in TiN coatings, inhibiting the diffusion or transfer of electrolytes and some products from corrosion during immersion. This blocking effect extended the coating material's lifetime. The nano-TiO_2 in the ER reduced porosity, improved bond strength between the sealant and the TiN coating, and enhanced the epoxy's barrier properties against solvent and gas diffusion. After sealing, the coatings exhibited reduced porosity and significantly improved corrosion resistance in simulated seawater. The study's findings revealed that the potential for corrosion of TiN coatings exhibited an increase. In contrast, the corrosion current density experienced a decrease of approximately two orders of magnitude after the sealing treatment. Significantly, the efficacy of the modified epoxy resin in terms of sealing was found to be twice as effective when compared to that of the pure ER [64].

Modified montmorillonite (OMMT) was incorporated into an epoxy resin to seal a Fe-based amorphous metallic material (AMC) coating. The preparation of the OMMT involved a two-step procedure that consisted of octadecylamine modification followed by intercalation with 2-mercaptobenzimidazole (MBI). The study examined the

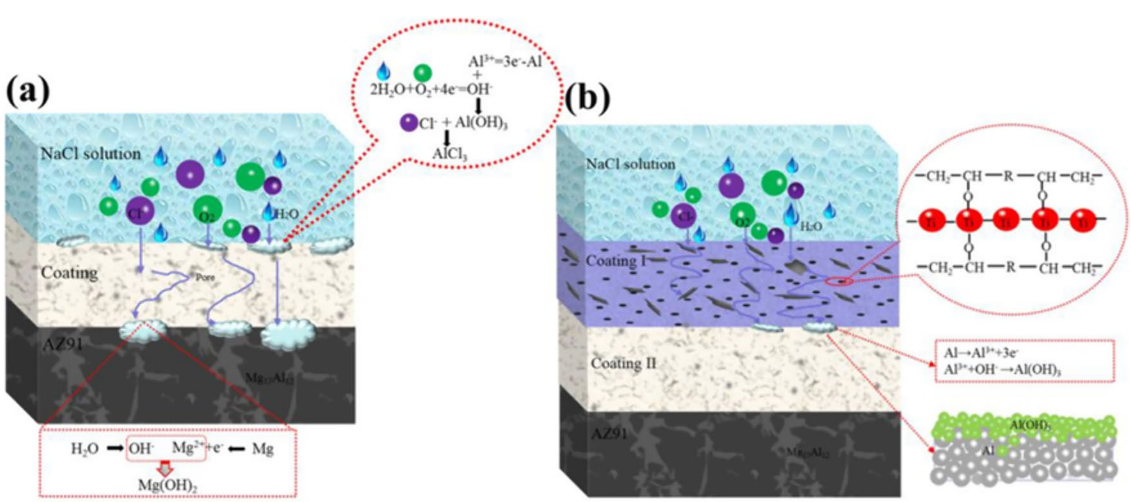


Fig. 9 Schematic representation of corrosion protection mechanism of **a** Al coating and **b** composite coating [63]

corrosion resistance of Fe-based AMCs in their as-prepared and sealed states through electrochemical impedance spectroscopy and salt spray tests. The study's findings indicate that using OMMT-loaded epoxy in the sealing process significantly improved the corrosion resistance of the Fe-based AMC. The observed enhancement can be ascribed to a confluence of multiple factors. The combination of epoxy sealant and thin layer-structured OMMT demonstrated a notable capacity to provide adequate protection against corrosive substances.

Furthermore, the MBI compound, released from the OMMT interlayer, exhibited a significant capacity to impede the corrosion process. The experiment effectively incorporated octadecylamine and 2-mercaptobenzimidazole into the interlayer of OMMT, resulting in an expansion of the basal spacing of OMMT with a monolayer of slices. A corrosive milieu impacted the liberation of MBI from the OMMT interlayer. Applying sealing treatments led to a reduction in structural defects observed in the Fe-based AMC. The order of corrosion resistance for the coatings was as follows: the OE-sealed coating exhibited the highest resistance, followed by the BE-sealed coating, and finally, the unsealed coating. The enhanced corrosion resistance of the original equipment (OE)-sealed coating can be attributed to two main factors. Firstly, the uniform dispersion of organically modified montmorillonite (OMMT) in the epoxy sealant contributes to effective shielding against corrosion. Secondly, the OMMT interlayer releases a corrosion-inhibiting substance known as MBI, which actively protects against corrosion [65].

Singh et al. [66] explored the combined heat treatment and sealing process on the performance of 80Ni–20Cr coating deposited via HVOF on austenite steel under hot corrosion conditions. Introducing the 80Ni–20Cr coating improved the hot corrosion resistance of T347H austenite steel, possibly owing to the development of protective oxides of NiO and Cr_2O_3, as confirmed by SEM analysis showing good adhesion between the coating and substrate. Sealing post-treatment was found to provide good hot corrosion in severe environments by sealing the pores within the layer.

Multiple studies examined composite-based sealants to improve the corrosion resistance of different coatings. Wang deposited aluminum coatings on AZ91 substrates and sealed pores with a Ti nano-polymer, leading to better corrosion properties compared to the reference alloy. Liu et al. sealed TiN coatings with epoxy resin containing nano-TiO_2 particles, significantly improving corrosion resistance in seawater and incorporating modified montmorillonite (OMMT) into epoxy resin enhanced the corrosion resistance of Fe-based metallic coatings. Singh investigated heat treatment and sealing processes on 80Ni–20Cr coatings, effectively protecting against hot corrosion in severe environments. Overall, composite-based sealants were shown to enhance corrosion resistance in various coatings.

2.5 Comparative Study of Sealants

$AlPO_4$ and SR were used with ultrasound-assisted sealing of a subsonic plasma-sprayed nano-Al_2O_3–13wt% TiO_2 coating to increase the coating's corrosion resistance. The ultrasonic environment provided the suitable sealant's penetration, improving the polarization resistance of Al_2O_3–13TiO_2 coating. In particular, when $AlPO_4$ and SR were utilized to seal the material, the polarization resistance increased by around 6.3 and 119.6 times, respectively, compared to the nano-Al_2O_3–13TiO_2 coating as it was sprayed. Notably, the sealing process had varying effects on the two sealants. Heat treatment stabilized the $AlPO_4$ sealant, but water evaporation caused microcracks and formed pits, which reduced the sealing effect. The silicone resin demonstrated distinct advantages, such as better elasticity and a lower drying temperature, resulting in a dense sealant structure and an effective sealing process. It confirmed the extraordinary effect of sealing without damaging the coating. Consequently, the nano-Al_2O_3–13TiO_2 coatings demonstrated enhanced resistance to corrosion when compared to those sealed with $AlPO_4$ after ultrasound-assisted sealing with SR [67].

Sugehis Liscano et al. [68] focused on enhancing the corrosion properties of plasma-sprayed $Al_2O_3 + TiO_2$ coatings, which typically exhibit high open porosity, making them vulnerable in aggressive environments. In order to address this issue, various types of sealants were employed to seal the as-deposited coatings. The sealing treatment effectively reduced the interconnected porosity of the substrate, ultimately increasing the corrosion properties. The results demonstrated that phenol and ER sealants effectively increased the corrosion resistance of the ceramic coatings compared to phosphoric acid in aggressive environments.

In this study, HVOF-sprayed WC–Cr_3C_2–Ni/CNTs coatings were applied to SS430. These coatings were subsequently sealed using two different techniques: sol–gel-based $AlPO_4$ as an inorganic sealant and silicone resin (SR) as an organic sealant, both of which were applied with an ultrasound-assisted sealing process. The ultrasound-assisted sealing experiment was executed for 2 h at room temperature and pressure using an ultrasonic generator, as illustrated in Fig. 10. The results showed that sealing with both the $AlPO_4$ and SR sealants efficiently filled the micro pores and cracks, which enhanced corrosion resistance. The corrosion current densities of the sealed coatings exhibited a notable reduction, accompanied by increased resistivity, thereby enhancing corrosion resistance. The SR showed better wettability with the coating compared to the $AlPO_4$. Furthermore, ultrasonic sealing facilitated the penetration of the sealants into the cracks and pores, with the SR being more effective in enhancing corrosion resistance [23].

Jiyue Qin et al. [69] prepared WC–20Cr_3C_2e–7Ni/MWCNTs coatings using high-velocity oxyfuel (HVOF) spraying,

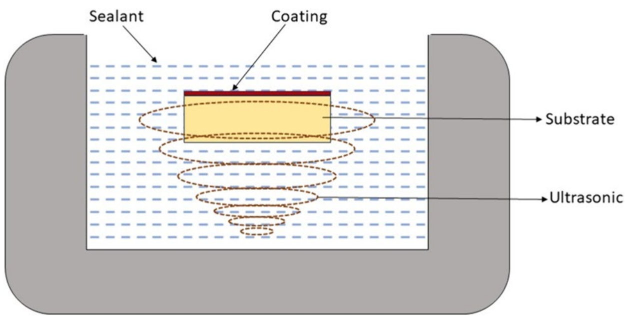


Fig. 10 Schematic representation of sealing apparatus

followed by the sealing process with two sealant types, SR and $AlPO_4$, employing both traditional and vacuum impregnations techniques. As demonstrated by the outcomes, each of the four sealing techniques enhanced the coatings' resistance to corrosion. The vacuum impregnation process facilitated filling these defects with sealants by extracting residual air from pores and microcracks. On the contrary, aluminum phosphate sealants adversely impacted sealing by thermal stress-induced defect formation due to the vanishing of certain water content during treatment under heat. Vacuum impregnation (VI) with SR sealant exhibited the most substantial enhancement in corrosion resistance compared to the other sealing techniques. The corrosion mechanisms of sealed coatings, as depicted in Fig. 11, are influenced by the sealing process and the characteristics of the sealants. Conventional impregnation sealing encountered challenges due to air hindering sealant penetration, resulting in inadequate depth and penetration, especially for aluminum phosphate compared to silicone resin sealants. The aluminum phosphate sealant's heat treatment-induced defects and stress disparities led to cracks between the coating and sealant. Although the coating's multi-walled carbon nanotubes (MWCNT) hindered crack propagation, new cracks could still form. During testing, excess sealant removal affected the aluminum phosphate sealant more than silicone resin due to their distinct structures, impacting their corrosion resistance differently. Vacuum impregnation showed superior penetration but revealed differences in the effectiveness of the two sealants: silicone resin enhanced corrosion resistance with deeper penetration—and excess aluminum phosphate led to poor surface sealing. The results suggest that the VI-SR coating excels in corrosion resistance. Conventional and vacuum sealing methods depend on the sealant's nature [69]. Overall, the choice of sealant and sealing technique significantly impacted the corrosion resistance of the coatings.

2.6 Other Sealants

Ashraf et al. [70] focused on improving the corrosion resistance of plasma-sprayed WC–12% Co coatings, commonly used in applications requiring robust mechanical properties but suffer from poor corrosion resistance due to their high porosity. The research aimed to enhance these coatings' corrosion resistance by refluxing the optimized aluminum isopropoxide-isopropanol mixture using the sol–gel sealing method. The sealing process involved filling the pores in the coatings with a sol–gel solution. The results were promising,

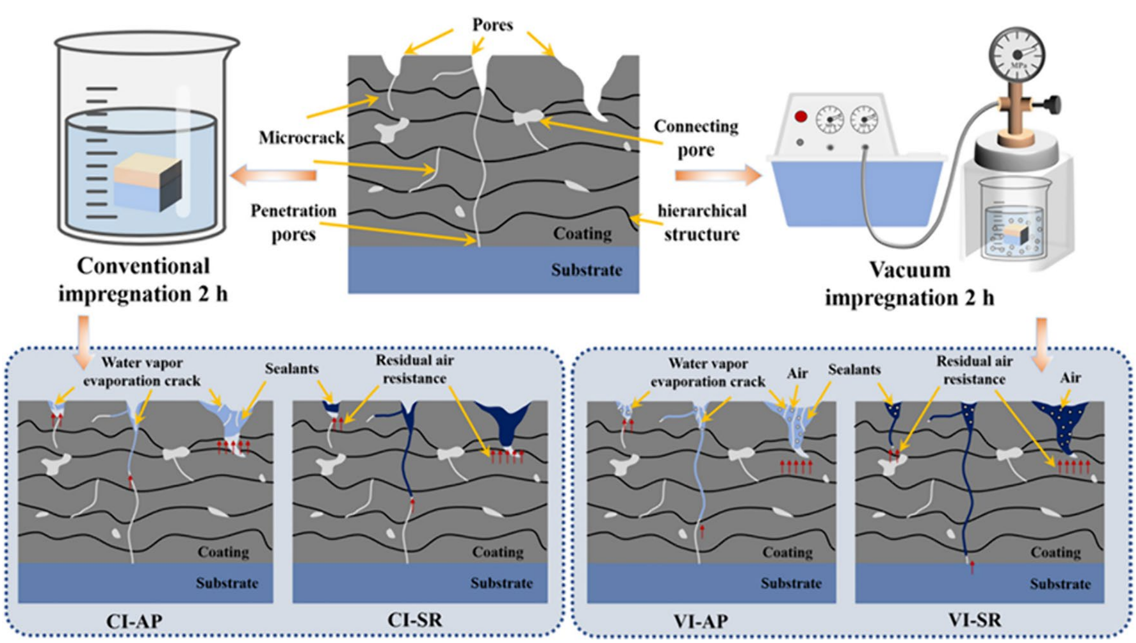


Fig. 11 The sealed coatings' corrosion mechanism [69]

with a substantial reduction in porosity (> 75%) observed in the sealed coatings compared to the unsealed (as-sprayed). Additionally, the results of the corrosion tests revealed that the sealed coatings had a higher corrosion resistance. These characteristics underscore the superior corrosion resistance of these coatings.

SiC-C/C composites were coated with yttrium silicate coatings of various compositions via plasma spraying; an outer borosilicate glass layer was subsequently deposited onto the surfaces of the yttrium silicate coatings. For C/C composites, the SiC/yttrium silicates/glass coatings demonstrate efficacy as oxidation protectors. An increase in the gradient of yttrium silicates within the interlayer resulted in a substantial enhancement in the resistance against oxidation. The C/C composites were effectively protected against oxidation at elevated temperatures, exhibiting reductions in weight of 1.65% at 1500 °C and 1.77% at 1600 °C. An activation energy of 132.2 kJ/mol was ascertained for this process [71].

3 Applications of Sealants in Various Fields

Surface coatings are commonly sealed to increase environmental resilience. In marine applications, hull coatings are sealed to resist saltwater corrosion. Sealing helps improve the adhesion strength of the coatings. In the automotive industry, sealing processes ensure the paint coating adheres well to the vehicle's body, preventing peeling or delamination. Sealing further enhances chemical resistance. In the petrochemical industry, sealing coatings applied to storage tanks protect against chemical spills and leaks, preventing environmental disasters. Sealing is necessary to integrate sensors and monitoring devices in real-time applications, such as aerospace and critical infrastructure. Sealed coatings protect the underlying structure while allowing for the installation of sensors to collect real-time data on structural integrity and performance.

Three distinct sealing techniques were examined for thick thermal barrier coatings (TTBCs) composed of additive-loaded zirconia-based materials [72]. The coatings under investigation were those designed for implementation in gas turbines and diesel engines to improve their resistance to hot corrosion and mechanical characteristics. The TTBC was subjected to a set of sealing procedures. The densified top layers produced by these sealing techniques varied in thickness from 50 to 400 µm. Phosphate-based sealing treatment-induced minor phase changes and reaction compounds were known via XRD analysis. In the 8Y coating, laser glazing induced phase changes and crystal orientation in the coatings. In every case, the outer sealed coating layer porosity decreased, increasing microhardness values.

Morończyk et al. [73] explored the thermally sprayed coatings to improve the corrosion resistance of AZ91E alloy, particularly for aircraft applications. They employed a thermal spray technique termed Warm Spraying (WS) to coat titanium onto an AZ91E. The key advantage of WS is its capability to control the particle temperature by adjusting the nitrogen flow rate (NFR), thereby influencing the porosity of the WS coatings.

Figure 12 displays the cross-sectional analysis of WS Ti coatings after post-treatment. The ER creates a dense upper layer on the coating surface with varying thickness. Additionally, it effectively seals the pores within the coatings, as indicated by the black arrows. This observation is particularly evident in the Ti_1.0 + E and Ti_1.25 + E coatings, providing further evidence of the interconnected nature of the pores. The research demonstrated that the initial as-sprayed Ti coatings exhibited poor protective properties due to galvanic corrosion and interconnected pores. However, the post-treatment process, which involved sealing the pores with an ER polymer coating, significantly improved the corrosion properties and durability of the coating materials, ultimately protecting the base substrate material in a corrosive environment [73].

The use of coatings in fluidized bed boilers under harsh conditions is explored, primarily due to the challenges posed by high temperatures and the use of fuels like biomass containing high levels of chlorine and alkali. These conditions lead to significant material degradation in the boiler's metallic parts. Thermally sprayed coatings have been considered a protective measure, but they face issues like substrate corrosion due to voids and oxides in the coating structure. The solution proposed is the sealing of these coatings to address these concerns. The research entails applying laser treatment and thermal spraying to affix commercially available sealing agents to metallic coatings. The findings highlight the importance of selecting the right sealants to protect the

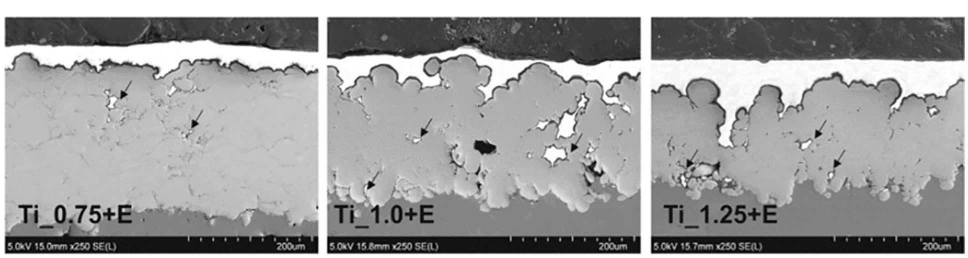


Fig. 12 SEM cross-sections of epoxy resin-sealed WS Ti_0.75, Ti_1.0, and Ti_1.25 coatings [73]

coatings and suggest potential improvements in laser treatment parameters for enhanced corrosion and erosion resistance [74].

The offshore sector encounters difficulties with the corrosion resistance of hydraulic cylinders that are deployed in marine environments [75]. Thermal spray coating is a promising solution to replace electroplated coatings in these applications. Nevertheless, in extremely corrosive environments, the performance of thermal spray coatings must be improved. To address this issue, a novel sealing technique for HVOF-sprayed WC–CoCr coatings has been evaluated for use on hydraulic cylinders in marine environments. This sealing method is achieved by applying a sol–gel solution that can permeate, fill, and seal the pores and fissures in the coating. Despite its limited penetration into the coating, the proposed sealing process holds promise for direct application to industrial components. Further, industrial-related tests are required to authorize the laboratory test results and optimize the sealing procedure for real-world applications in marine environments.

This study investigated ZrO_2-thick thermal barrier coatings (TTBC) of $8Y_2O_3$–ZrO_2 and 22MgO–ZrO_2, each with a thickness of 1000 µm, for their potential use in diesel engine applications. The principal aim was to increase the resistance to hot corrosion of the porous TTBC coatings. Ahmaniemi et al. [76] examined three discrete methods of sealing thick thermal barrier coatings: impregnation with a sealant phosphate-based on the surface, surface melting using laser glazing, and detonation gun spraying of a dense top coating. The research also included characterizations of coating microstructural properties and the study of thermal and mechanical properties. Some key findings from the study included variations in thickness, microhardness, and phase structures, particularly in laser-glazed coatings, and changes in the magnesia-stabilized zirconia phase structure. The results demonstrated that these coatings, specifically the 8Y and 22 M variants, were robust enough to pass the engine test, with only phosphate-sealed coatings exhibiting minor vertical microcracks during testing; despite this, spallation was not observed. In addition, the outermost layer porosity of the coated surfaces was decreased by each sealing technique, resulting in increased microhardness values. Notably, all coatings passed the engine test without vertical cracks and spallation [76].

Vakhrusheva et al. [77] examined the characteristics of U-30MES-5NT and VITEF-1NT sealants (Commercially available sealants), which were implemented in agricultural aircraft to seal joints and structural components. The sealants were exposed to various pesticides and fertilizers for 10, 30, and 90 days to assess their durability on different paint and varnish coatings. Polysulfide sealants, based on Thiokol-type oligomers, are commonly used in aviation equipment due to their resistance to aggressive environments. The findings suggest that the U-30MES-5NT and VITEF-1NT sealants retain their mechanical, adhesive, and physical characteristics in the presence of agricultural pesticides. Among the tested sealants, Chlorophos is the most aggressive, causing the greatest deterioration in the material's characteristics and the sealant's appearance. To guarantee consistent sealant adhesion and safeguard aluminum alloy, the 265 system is suggested.

4 Conclusion

This review comprehensively analyzes various studies on sealants' corrosion properties across different coated materials. The consistent findings underscore the significant potential of sealants in enhancing corrosion resistance. Extensive research indicates that sealants are crucial for prolonging the lifespan of coated materials, effectively improving their durability. Polymer-based sealants offer remarkable adaptability when combined with various coating materials, while ceramic sealants demonstrate exceptional performance in extreme temperatures and harsh environments. This versatility and resilience make sealants indispensable in preserving and protecting coated surfaces, ensuring their longevity and functionality even in the most demanding conditions. Inorganic chemical sealants, such as silanes and phosphates, effectively passivate surfaces and halt corrosion.

Furthermore, composite sealants blend materials harmoniously, creating unique characteristics that enhance corrosion protection. Sealants are integral components in coatings, pivotal for safeguarding surfaces, prolonging coating lifespans, and optimizing performance across diverse industries like construction, automotive, aerospace, and marine. By sealing surfaces, they fortify coated materials against environmental hazards, such as the corrosive effects of saltwater on a marine coating, thus ensuring prolonged durability and effectiveness.

5 Future Scope

The manuscript on the review of sealants used in coatings presents a comprehensive insight into the current landscape of sealants while offering a glimpse into the exciting future directions within this field. The trajectory of sealants in coatings appears promising, primarily due to the continuous evolution of materials science and engineering. One of the most exciting possibilities is the development of self-healing seals, which use novel materials to repair damage on their own. The most recent advances in nanotechnology are predicted to dramatically transform sealants, providing superior barrier properties and significantly increased endurance. Future study may focus on developing self-repairing sealants. These are essential for creating longer coatings, particularly in tough or high-stress environments. Functional fillers such as carbon nanotubes, nanographene, and nanoclays are incorporated to enhance the strength of sealants, imparting superior mechanical, thermal, and barrier properties to the coverings. Their growing popularity across various industries stems from their diverse benefits, including resistance to fouling, corrosion, flame retardancy, and UV protection. Their outstanding endurance and multifarious performance make them increasingly desirable for applications that require such features. Adding intelligent elements to composite sealants is one aspect of this paradigm shift. These features allow the sealants to respond to stimuli like pH, temperature, or light sensitivity, which can help control the release of active ingredients or adapt to changing external conditions. The main goal for the future will probably be to create eco-friendly composite-based sealants that come from renewable, recyclable sources. In this quest, bio-based polymers and natural fillers are being looked into as ways to make coatings less harmful to the environment. Coatings will soon be improved with smart materials that can detect degradation and generate a self-sealing reaction in the sealer to prevent further breakdown. More research will define the future generation of coatings and sealants, ushering in a time of innovative, long-lasting, and environmentally responsible solutions.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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