

Review Article

Study on Developments in Protection Coating Techniques for Steel

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Steel, also known as iron alloy, is found 35% of the whole mass of the Earth. It is found in many applications due to its unique properties. Alloying elements provide the backbone support for iron, improving its mechanical, physical, chemical, and structural properties. Failure of steel is due to chemical reaction i.e., corrosion, and it is unavoidable, but it can be prolonged. Applications such as marine have a salt corrosive environment. High-temperature applications such as power plants, gas turbines components, and combustion engine components accelerate air oxidization at higher temperatures. Protection coating alters the chemical composition of alloy surfaces by using techniques like conversion coating, mechanical alloying, ion beam implantation, laser cladding, and thermochemical treatments. Protection coatings adhere to the steel surface and prevent steel from direct contact with the environment, which is formed by chemical vapor deposition, physical vapor deposition, electroplating, chemical bath, sol-gel, thermal spraying, and hot-dip coating. These coatings are used to reduce the chemical reaction in accelerated corrosion environments so that the life span of the steel is further enhanced, thereby decreasing the replacement cost. These coating methods and coating materials play a vital role in corrosion and other corrosion-associated failure protection. The coating materials like chromium and cadmium produce carcinogenic gases. Coating methods such as thermal spraying, hot-dip coating, and thermochemical treatment produce by-products that affect the environment by releasing pollutants. It is essential to choose coating materials and methods that do not influence the environment and ecosystem. In this work, processing techniques available to prepare the protective coating for steel are discussed. The methods used to enhance the properties of steel and the various real-time characterizations are also discussed. In addition, challenges and opportunities in the proposed scope are also included.

1. Introduction

Steel is the iron alloy that has been used in a wide range of applications since 2000BC [1]. Steel is earth-abundant than any other metal, which leads to more vital interest

than other metals in areas such as construction, manufacturing, automobiles, shipping, chemical industries, oil and gas industries, food and beverage industries, power plants, gas turbines, piping, household appliances, and so on [2].

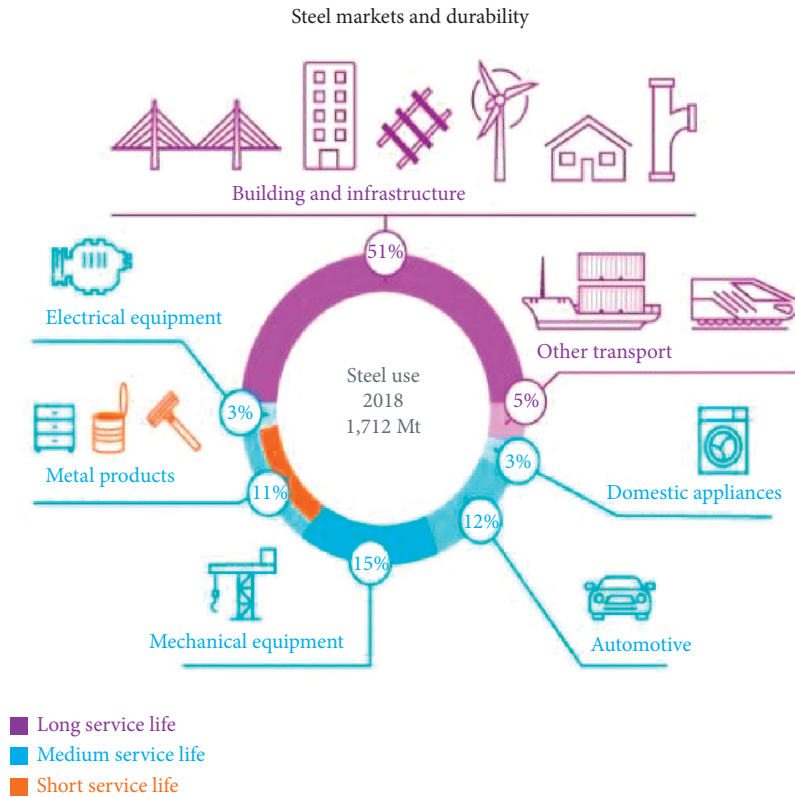


FIGURE 1: Conception of Steel in various applications. Reprinted with permission of World Steel Association (worldsteel).

Figure 1 shows the steel usage in 2018 in various applications. Even though it has broad availability, it has a notable setback of corrosion, which is unavoidable. Steel corrosion is due to electrochemical reactions or chemical reactions with its surrounding environment. Corrosion in pressure vessels, boilers, metallic containers for toxic chemicals, and turbine blades leads to failure with catastrophic consequences for safety. Corrosion loss is divided into two types: direct and indirect loss. In direct loss, the loss is associated with the replacement of corroded components, whereas in indirect loss, the loss is due to shut down in power plants, loss of product in oil and gas refineries, and loss of efficiency in machines and equipment. Based on reports, the cost of corrosion globally is in the range of 3–4% of the Gross National Product [3]. Reports say that corrosion depleted the world's 20% global energy [4]. Corrosion was found to be the leading cause of failure, along with other causes such as erosion, wear, and hoop stress [5]. The corrosion driving force of steel was prolonged or nullified by adding alloying elements such as chromium and nickel, which formed their oxides and acted as a corrosion protection layer.

Predominantly, the majority of the components in power plants consist of steel-based components [6]. The higher operating temperature of the power plant decreases the activation energy and results in oxidization; in general, oxides are brittle, which is why they easily wear out. In a coal-based power plant, sulfur penetrates through the chromium oxide layer at a higher temperature, causing high nickel alloy to experience localized pitting corrosion, and so the alloying element is found to be unworthy [7]. Coal-fired power plants in India produce a large amount of ash, about

50% [8], and 20% of ash is deposited over boiler components, which leads to hot corrosion and erosion [9]. Corrosion, along with erosion, leads to a volumetric reduction of components, reducing their lifetime and thereby increasing their maintenance and replacement cost [10]. Protective coating overcomes the accelerated failure rate by acting as a barrier for corrosion and erosion. The coatings process is divided based on the method of the coat as follows: vapour deposition, galvanic, thermal spraying, metallic coatings, diffusion techniques, polymeric and glass coatings, and high-density beam and ion implantation [11]. This report critically reviews the various protective coatings and methods employed for steel and discusses them in detail.

2. Experiment

2.1. Vapour Deposition. The vapour deposition method vaporizes the coating material and allows it to coat the substrate. The chemical reaction between the gaseous reaction species results from the formation of a coating on a substrate. Vapour deposition is categorized into two types: chemical vapour deposition (CVD) and physical vapour deposition (PVD).

2.1.1. Chemical Vapour Deposition. Chemical vapour deposition involved four steps. Initial step: precursor and inert gas are introduced into the chamber, then the substrate absorbs it, and thermal energy activates it. In the third step, gases undergo surface diffusion, and decomposition on the

substrate leads to nucleation. With time, the nucleation site grows to form the required thin film on the substrate.

At the final stage, the by-product formed in the chamber inside is carried away [12]. Chemical vapour deposition on steel substrate is majorly carried out inside a fluidized bed reactor to form a deposition of metallic and metal oxide coating [13, 14]. Sánchez et al. used additives to improve the coating thickness, morphology, and properties [15]. Post-coating heat treatment with an inert or air atmosphere increases the bond between the coating and steel substrates [16, 17]. Marulanda et al. prepared coating followed by a heat treatment process can be done with a one-step of placing the HF heater inside the reactor itself, which is very useful for direct application. Simulation software is used to predict the possible chemical formation upon the air, gas, and thermal oxidization testing [13]. Corrosion resistance property studies by steam oxidization, thermos cyclic oxidization, coal environment oxidization, corrosive gas environment oxidization at a temperature above 600 °C [15, 17, 18]. Saarivirta et al. used a whirling arm fluidized bed rig used for hot erosion and wear tests on the coated sample [19].

2.1.2. Physical Vapour Deposition Process. In the physical vapour deposition process, coating material is converted from the solid-state to the gaseous phase at an ultra-high vacuum condition. The heat source for phase transformation is from laser beam or arc discharge, ion sputtering, ionisation, and plasma decomposition. The nucleation of gaseous species follows layer growth, Stranski–Krastanov growth, and island growth techniques [20]. Figure 2 represents the physical vapor deposition process.

Baker et al. prepared PVD on the steel substrate with cooling or heating, resulting in different morphologies of coating material [21]. Pech et al. identify amorphous nature and nanostructured coating material to show excellent mechanical properties [22]. Jarmo and others used PVD coating for filling the pinholes on coated substrates [23]. Lamastra et al. studied residual stress in thin-films determined by XRD studies using the $\sin^2\psi$ method [24]. The mechanical properties of the substrate are increased by the PVD-assisted coating of ceramic materials on steel substrates. Molten salt corrosion, salt corrosion, and air oxidization are carried out to obtain surface property enhancement [25, 26].

2.2. Galvanic Techniques. Electrodeposition, the dissolving of coating material salt into the electrolyte, upon applying an electric field to the electrode, initiates the electrochemical reaction and results in the metal ions or coating suspension present on the electrolyte being coated uniformly over the electrode [27]. Metal oxides added to the electrolyte to form a colloidal suspension along with metal ion species paved the way for the coating of oxides on a steel substrate. Figure 3 illustrates the galvanic techniques.

Electrodeposition is carried out using pulsed current, direct current, and galvanostatic method [28–30]. Xu et al. used optimization techniques to determine the best process parameters for deposition [29]. Nanostructured material is also

coated using electrodeposition techniques [28, 31–33]. Additives used to reduce the pitting, buffers used for stabilizing the coating, and surfactant used for reducing the water contact angle of coated material on a steel substrate [34, 35]. Nano-sized material is used for filling the pores, gaps, and cavities formed during electrodeposition [33, 35]. Surfactants reduce the agglomeration of nanoparticles, with ultra-sonication employed to obtain uniform dispersion [31, 36]. Postheat treatment is carried out to obtain an excellent adherent, dense layer, and increased hardness on the coating [32, 37].

2.3. Ion Implantation Technique. Ion implantation is a surface modification process that increases roughness, surface hardness, and corrosion resistance. Ion implantation associated with other coating techniques increases the adhesive strength of the coating and steel substrate [38]. Figure 4 is a pictorial representation of the ion beam implantation techniques. The ion implantation technique enables an environmentally friendly and clean method for carcinogenic coating materials such as chromium and cadmium on steel substrates [39, 40]. Hatada et al. carried out surface pretreatment and preheating to increase the adhesion of the coating [41]. Sudjatmoko and others used ion implantation to increase the hardness of coated material and identified that implanted ion reacting with surface atoms result in multiphase formation, which increases hardness, wear, and physical/chemical properties on a steel substrate [42]. Hartwig et al. carried out postheat treatment and implantation energy to increase the surface properties. Surface energy and the nature of coating material play a significant role in corrosion property [43].

Mello et al. identified an amorphous phase coating that shows higher mechanical properties than the alloy phase coating [44]. Eshghi et al. found that increases in ion concentration decrease the corrosion resistance due to surface damage caused by irradiation [45]. Ovchinnikov and others prepared mono, double, and three-layer coatings by ion implantation techniques [40].

2.4. Thermal Spraying. The coating is carried by heating the coating material followed by spraying towards the steel substrate and allowing it to adhere through the thermal spraying process categorized as flame spraying, plasma spraying, and high-velocity oxygen fuel spraying [46].

2.4.1. Flame Spray Process. In the flame spray process, or powder flame spray process, the powder particles are heated to near melting point and welded with the steel substrate when encountered on the substrate surface. The result is a coating of powder on the steel substrate through the flame spray process [47]. Ball milling is used to obtain the coating material at the required composition [48]. Pacheco et al. used bond coating and preheat treatment to improve the adhesion between the substrate and coating material [49]. Bonetti et al. prepared flame spray-coated steel substrate coating contains porosity due to less cohesion between nearer coating materials [50].

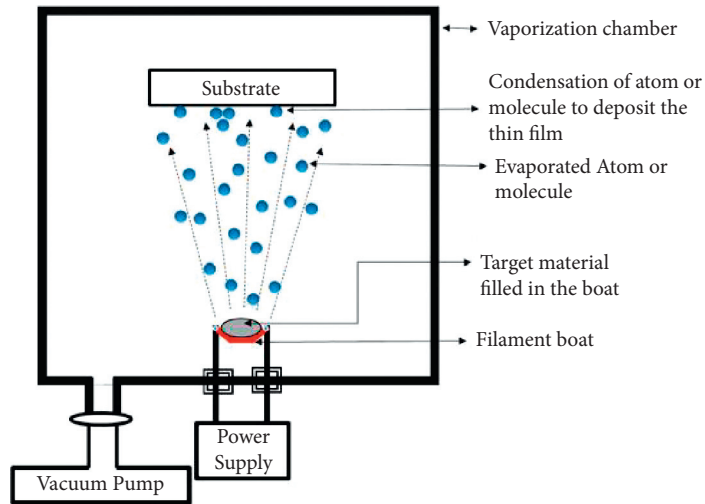


FIGURE 2: Schematic diagram of physical vapour deposition process.

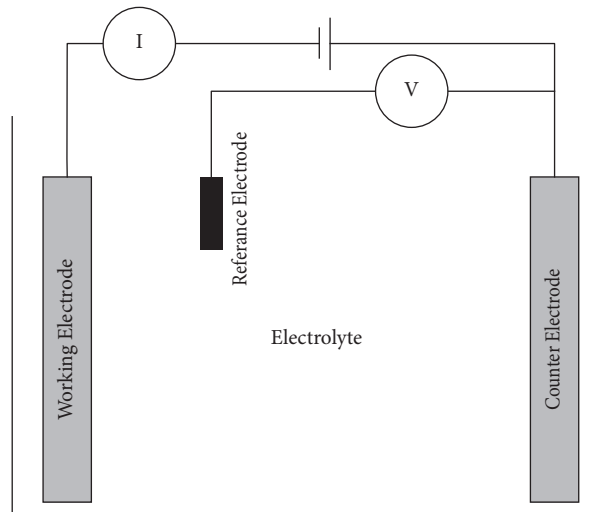


FIGURE 3: Schematic diagram of Electrodeposition process.

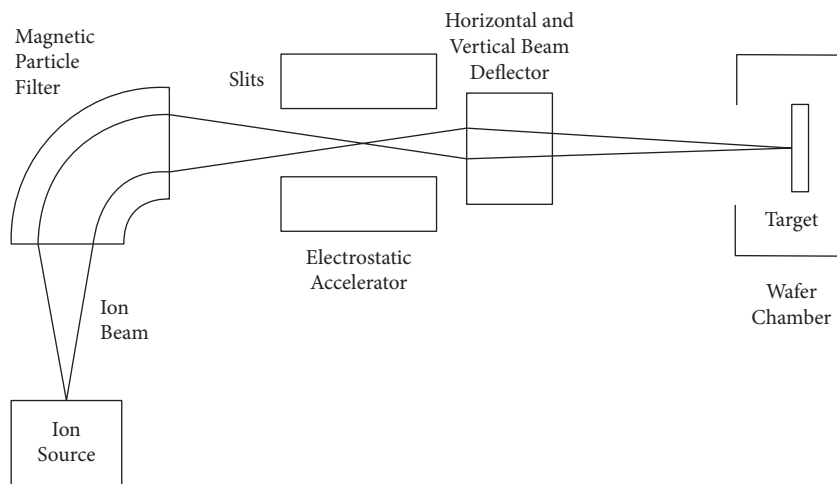


FIGURE 4: Schematic diagram of ion beam implantation technique.

2.4.2. Plasma Spraying Process. Plasma spraying process is similar to the flame spraying process in which the heat source is a plasma thruster, an inert gas used for powder carrier. The coating properties are based on the coating material, gas flow rate, power supply, nozzle torch shape, spray distance, and spraying angle [51]. Kiahosseini et al. identified surfaces to be coated as being sandblasted and preheat treated before coating to increase the adhesion between steel and coating material [52].

Ghahabi et al. used iron powder mixed with a coating material to improve adhesion [53]. Kiahosseini et al. identified grain growth increases with thickness increases so that the hardness of the coating decreases [52]. HO and others. prepared WC coating above 2 mm thickness using RF low-pressure plasma spray and DC vacuum plasma spray method [54].

2.4.3. High-Velocity Oxygen Flame Process [HVOF]. The HVOF process is similar to the thermal spray process in that the coating material is deposited over the steel substrate through thermal and kinetic energy. HVOF form thick coating increases hardness, erosion, wear resistance, and corrosion resistance on steel substrates [55]. Steel substrate preheat treatment, grit blasting, and shoot peening are carried out to improve coating adhesive property. Fatigue strength of the coated sample increases with coating and steel substrate by pretreatment like shot peening and grit blasting [56, 57]. Figure 5 and Figure 6 show schematic diagrams of the DC vacuum plasma spray system and the RF low-pressure spray system. Monticelli et al. studied the coating consisting of interporosity, which reduces the corrosion resistance and induces scale spalling off and cracking [58]. Kuroda et al. reported that postheat treatment reduces porosity [59].

2.5. High-Density Beam. Laser cladding coating material is sprayed over the substrate using a solvent binder after completely drying the substrate, which is then laser irradiated to obtain the coating layer. Figure 7 represents the schematic diagram of the laser cladding system.

Laser cladding coating properties vary with the beam diameter, beam overlapping, beam feed, and power. Laser cladding coating reduces porosity, provides uniform coating, and increases hardness, wear-resistance, and corrosion resistance [60].

Nickel primary coating increases the adhesion between the steel substrate and coating material [61, 62]. Coating material prepared at the required composition by using mechanical milling [63]. Coating material is mixed with binders to form a slurry and sprayed over a steel substrate before being laser cladded [64, 65]. Xiong et al. identified laser cladding, followed by friction stir processing, as increasing the adhesion between coating and substrate by forming mechanical interlocking [66]. Li et al. found beam overlapping forms a uniform coating, increases laser beam power, and beam diameter reduces the hardness of the coating material. Higher coating thickness results in a pore and crack-free coating [67].

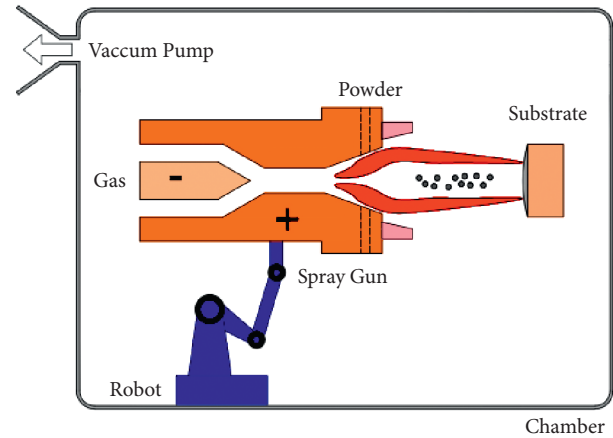


FIGURE 5: Schematic diagram of DC vacuum plasma spray system.

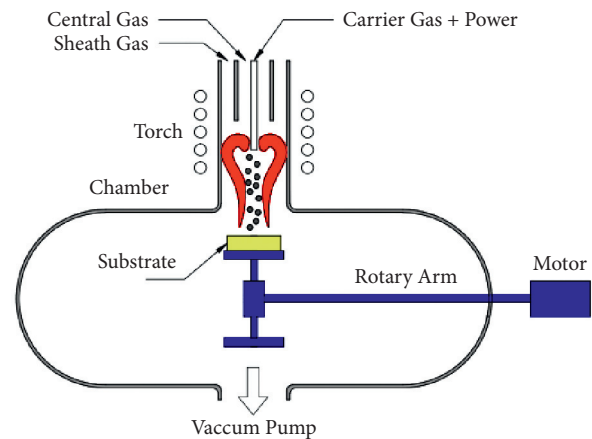


FIGURE 6: Schematic diagram of RF low-pressure plasma spray system.

2.6. Polymeric or Vitreous Coating. Sol-gel coating is also known as glass coating/vitreous coating, carried out by dip coating, spin coating, and spray coating. Dip coating, coating thickness based on withdrawal rate, steel substrate surface wettability, and sol viscosity. Spin coating, coating thickness based on rotation speed, duration of coating, surface wettability, and sol viscosity [68]. Steel substrates are preheated by sandblasting, shot peening, and prereduction heat treatment to improve the coating adhesion [69–71]. Prepared sol is allowed to age at room temperature for 24h, obtaining the uniform monomer formation [72, 73]. Dip coating the steel substrate immersed in a sol solution to obtain the coating sol stabilization with a substrate [74].

Liu et al. prepared coated samples dried in the air at a temperature range from room temperature to 150°C to remove the solvents such as ethanol and water. Postcoating heat treatment is carried out to obtain the dense coating with increased microhardness and grain size. Heat treatment results in microcracks and pores due to the densification of sol molecules at higher temperatures, which results in shrinking of the coating [69]. Ezz et al. carried out laser sintering to reduce the formation of cracks, unlike the heat treatment [75]. Functionalized nanoparticles increase

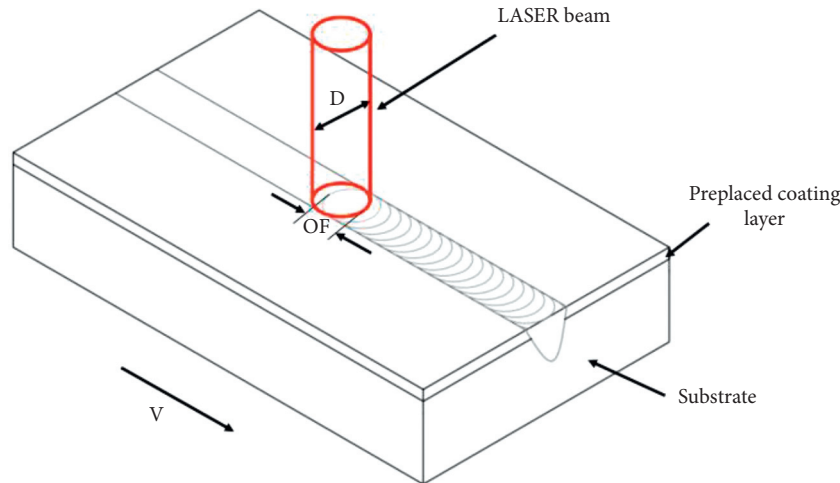


FIGURE 7: Schematic diagram of laser cladding on substrates.

adhesion between the substrate and coating, hardness, and Young's modulus [76, 77]. Liu et al. used sol-gel coating as a filler coating for pores formed on HVOF coating [78]. In general, sol-gel coating is the passivation type of coating, which results in corrosion resistance, increases in contact angle, and hardness increases on the substrate of steel.

2.7. Diffusion Techniques. Thermochemical treatment creates a diffusion coating that provides mechanical interlocking between the coating and the steel substrate, so the adhesion strength is fair enough to avoid delamination of the coating and substrate. The parameters such as heat, duration, and the chemical composition of the substrate and coating material alter the surface mechanical properties [79]. Liu et al. carried out thermochemical treatment on steel surfaces to increase the surface hardness, mean grain size, Young's modulus, and corrosion resistance [80].

Marteau and others identified sample substrate pretreated by shot peening to improve surface creep properties and provide mechanical interlocking of coating to improve coating adhesion on a steel substrate surface [81].

2.8. Metallic Coatings

2.8.1. Mechanical Alloying. Mechanical alloying on the steel substrate with mechanical ball milled alloy powder results in the cold-welded dry coating. The impact of a ball on the substrate increases the creep resistance of the substrate. Long-duration mechanical alloying results in a thick coating with uniform grains. Mechanical alloying creates the diffused alloy phase due to stress deformation caused by ball milling on a steel substrate, and alloy powder results in increased coating adhesion [82]. Steel substrate to be coated is subjected to preheat treatment and postcoating heat treatment to obtain excellent adhesion between substrates and coating materials [83, 84]. Aykut and others identified increasing milling duration results in increases in coating thickness decrease in hardness, lower roughness, form uniform coating, increase porosity, and increase the wear ratio [85].

Canakci et al. found that through XRD characterization coating material forms a multiphase compound formation between steel and coating material, which is responsible for the adhesion of coating material to a substrate [83]. Figure 8 is the schematic representation of mechanical alloying method.

2.8.2. Hot-Dip Coating. Hot-dip coating is unlike other methods, where the coating material or alloy is in a molten pool, which allows the steel substrate to dip into it and adhere to the coating material on its surface. Coating material, upon cooling, solidifies on the surface with uniform grains along with diffusion. Hot-dip coating of zinc provided galvanic corrosion resistance to the steel substrate, which is found in the vast application. Likewise, aluminum, silica, and the mixture of aluminum, silica, and zinc are also used as molten metals. Both materials, based on the properties of steel substrate, increase [86].

Huilgol et al. prepared an aluminum molten bath coating on MDN 321 stainless steel and carried out a hot corrosion test [87]. Prashant and others also prepared an aluminum molten bath coating on AISI 321 steel and analyzed diffusion heat treatment studies to find Fe_2Al_5 , $\text{Al}_{13}\text{Fe}_4$, NiAl , and AlFe four different layers [88]. Sehrish and others. prepared Al-Si molten bath coating on SS 316L and analyzed coating corrosion and mechanical properties [89].

3. Challenges and Opportunity

Based on the above study, the use of oxides and carbides as coating materials provides a significant improvement in surface properties. The novel coating techniques such as ion implantation, mechanical alloying, and vapour deposition techniques are compared to other techniques requiring substantial power consumption and taking a longer duration for coating materials. Thermal spraying and electrodeposition are widespread techniques. The electrodeposition of oxide-based materials is more complex than that of conductive materials. Thermal spraying results in the porosity of the coating, which reduces the coating performance. The use

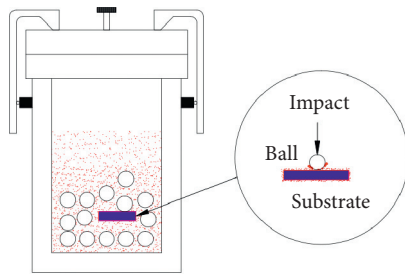


FIGURE 8: Schematic diagram of mechanical alloying method [85].

of metal matrix and nano-based oxide composites as a coating material on electrodeposition is to pave a new way to develop metal and metal oxide-based composite coatings on steel. The use of a sol-gel-based coating over the plasma sprayed coating capsules the pores present on the surface of the coating.

Multi-layered coatings and functionally graded coatings are also promising methods to nullify the porosity-induced effects on coatings. Combining thermal spraying and sol-gel, electrodeposition, and ion implantation-based coatings decreases the negativity of one over another.

4. Conclusion

Steel protective coating for various techniques, starting from coating precursors used, parameters followed, and research outcomes. The work enables us to correlate the relationships among these coatings for application aspects, technical significance, and compatibility of combined coatings. The review concluded that the coating performance is purely based on the coating material compatibility with the steel substrate in terms of wettability, adhesiveness, thermal expansion coefficient, crystal structure, crystallinity, and diffusion phenomena. The defects associated with coatings are unavoidable without adding filler material in nanoscale materials, using sacrificial coatings, and using additional filler coatings. Coating delamination is one of the significant phenomena that occur due to surface defects and thermal conductivity mismatch. To avoid delamination, pretreatment such as shot peening, sandblasting, precoating heat treatment, and precoating chemical etching was carried out on the steel surface to improve the adhesive strength. In the case of thermal spraying, a bond coat is applied. In the present day, environmental consideration plays a vital role in avoiding the coating process by-products toxic to the environment and living organisms. Therefore, those environmentally sustainable coating methods such as ion beam implantation, sol-gel techniques, electrochemical deposition, chemical deposition, LASER cladding, and mechanical alloying provide zero-emission toxic chemicals into the environment.

5. Future Scope

The above review found that the use of rare-earth-based nanoparticles as coating materials proved to have the best enhancement of corrosion, erosion, and wear resistance

properties. The thermal spraying method is the most widespread method among all other methods for power plant applications and is often found to be the easiest method to repair or replace the coating. The coating material based on rare earth oxides and the thermal spraying technique provides a promisingly significant improvement of all the surface properties of the steel components.

That is the scope for the budding researchers to focus their attention on the consent applications.

Data Availability

The data used to support the findings of this study are included in the article. Further data or information will be available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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