An Overview of Corrosion Behavior and Surface Treatments of Metals: Applications in Medical Implants and Boiler Systems

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Abstract — The relentless degradation of metallic materials due to corrosion poses significant challenges across diverse engineering applications, ranging from the intricate environment of the human body to the harsh operating conditions within industrial systems. This paper provides a comprehensive overview of corrosion mechanisms affecting metals, highlighting the critical need for effective surface treatments to enhance their longevity and performance. While a primary focus is placed on the corrosion behavior of metallic biomaterials and the surface modifications employed to improve their biocompatibility and resistance to physiological environments, this review also extends to explore the corrosion challenges encountered in boiler systems. Specifically, it examines the application of thermal spray coatings as a prominent surface treatment strategy for mitigating corrosion in boiler steel exposed to high temperatures and aggressive chemical environments. By drawing parallels between the demands for corrosion resistance in medical implants and boiler components, this paper aims to provide a broader understanding of the principles governing material degradation and the versatility of surface engineering techniques in combating corrosion across seemingly disparate fields. The insights presented underscore the importance of tailored surface treatments in ensuring the long-term reliability and safety of metallic components in critical applications.

Keywords: Corrosion, Surface Treatments, Medical Implants, Biomaterials, Boiler Steel, Thermal Spray Coatings, High-Temperature Corrosion

I. INTRODUCTION

The degradation of metallic materials through corrosion presents a persistent challenge across a wide spectrum of engineering applications. From the intricate and reactive environment within the human body, where metallic biomaterials have been employed in medical implants since the 19th century [1], to the demanding operational conditions of industrial systems like boilers, the need for effective corrosion mitigation strategies is paramount. Today, metallic biomaterials such as 316L stainless steel, cobalt-chromium alloys, and titanium alloys are extensively utilized in bone repair, fracture fixation, joint replacements, and dental treatments [2], valued for their strength, inherent corrosion resistance, and biocompatibility. Emerging materials like magnesium and nickel-titanium (NiTi) also offer unique advantages such as biodegradability and shape memory effects, further expanding the possibilities in implant design [3, 4]. The selection of an appropriate metal is crucial for ensuring the safety, longevity, and successful integration of medical implants within the body [1].

The criteria for choosing metals in medical implants are stringent, emphasizing biocompatibility, resistance to corrosion and wear, adequate mechanical strength, and non-toxicity. Corrosion in this context can lead to implant failure through the release of detrimental ions into the surrounding tissues, necessitating surface modifications to enhance performance and extend the implant's lifespan. Despite significant advancements in materials science and surface engineering, a considerable number of implants still face failure within 12–15 years due to a complex interplay of chemical, mechanical, and biological factors. The long-term success of an implant is intricately linked to its compatibility with the physiological environment, the intrinsic properties of the material, and the overall health of the patient. This paper will delve into the underlying mechanisms of corrosion affecting metallic implants, categorize the common types of corrosion encountered, discuss their potential adverse effects, and explore various preventative measures, including the application of coatings, the formation of protective oxide layers, and other advanced surface treatments [2, 5].

Beyond the realm of medical implants, corrosion poses equally significant challenges in other engineering domains. Boiler systems, for instance, operate under extreme conditions involving high temperatures, elevated pressures, and exposure to aggressive chemical environments, making boiler steel susceptible to various forms of corrosion [6]

To combat this, thermal spray coatings have emerged as a vital surface treatment technology, offering a robust approach to enhance the corrosion resistance and extend the service life of critical boiler components. This review, therefore, broadens its scope to encompass the corrosion challenges encountered in boiler systems and highlights the role of thermal spray coatings in mitigating material degradation in these demanding industrial applications. By drawing parallels between the critical requirements for corrosion resistance in both medical implants and boiler components, this paper aims to provide a more comprehensive understanding of the fundamental principles governing metallic corrosion and the diverse yet often analogous strategies employed in surface engineering to combat it across seemingly disparate fields. The insights presented underscore the universal importance of tailored surface treatments in ensuring the long-term reliability and safety of metallic components in a wide array of critical applications.

A. *Reasons of Corrosion in Implants*

Corrosion in metallic implants happens due to chemical reactions between the implant and body fluids, which contain reactive substances like chloride ions, proteins, and oxygen. This reaction can lead to the release of harmful metal ions, which may cause inflammation, toxicity, or implant failure.

Factors such as changes in body pH, temperature, and mechanical stress like wear and cracking can increase corrosion risk [5, 2, 6]. Therefore, it is important to test implant materials for corrosion resistance before use, following standards like those set by ASTM.

B. *Classification of Distinct Type of Corrosion*

Corrosion in metal implants occurs in several forms, including uniform corrosion, where the entire surface degrades evenly, and pitting corrosion, which causes localized holes due to chloride ions breaking down passive oxide layers. Another severe type is stress corrosion cracking and fretting corrosion, which combine mechanical stress and electrochemical reactions, accelerating wear and structural failure under cyclic loads in the body. These corrosion mechanisms reduce implant lifespan and may trigger inflammatory or toxic responses due to metal ion release [7]. Corrosion testing is important to check how well implant metals can resist damage inside the body. ASTM standards like G61-86, G5-94, and F746-87 help test different types of corrosion, such as general, galvanic, and pitting corrosion in biomaterials. These tests ensure implants are safe and long-lasting in the body environment [8-11].

C. *Surface Modification for Enhanced Corrosion Resistance: Applications in Medical Implants and Beyond*

Surface modification plays a pivotal role in enhancing the corrosion resistance and overall performance of metallic materials across various critical applications, including the demanding environment of the human body and the aggressive conditions within industrial systems like boilers. For medical implants, where biocompatibility and long-term stability are paramount, various surface treatments are rigorously evaluated in simulated physiological solutions such as simulated body fluid (SBF), Ringer's solution, and artificial saliva [12-14]. These treatments aim to create a protective barrier against the corrosive bodily fluids and promote osseointegration.

II. Corrosion Challenges in Boiler Systems

Boiler systems present a uniquely aggressive environment for metallic components, characterized by high temperatures, pressures, and the presence of various corrosive species such as dissolved oxygen, carbon dioxide, and various salts. This leads to several forms of corrosion, including general wastage, pitting, and stress corrosion cracking, significantly reducing the operational lifespan of boiler steels. The continuous exposure to hot water, steam, and flue gases necessitates robust corrosion protection strategies. The economic implications of boiler corrosion, including costly downtime and potential safety hazards, highlight the critical need for advanced surface treatments.

A. *High-Temperature Corrosion in Boilers*

High-temperature corrosion in boilers primarily involves the oxidation and sulfidation of metallic surfaces exposed to hot combustion gases. At elevated temperatures, the protective oxide layers formed on boiler steels can become unstable, allowing for accelerated material degradation. The presence of impurities in fuel, such as sulfur, can lead to the formation of aggressive molten salts or gaseous sulfur compounds, further exacerbating corrosion. This phenomenon significantly compromises the structural integrity and efficiency of boiler tubes and other critical components, necessitating specialized surface protection methods to maintain performance and extend service life.

B. *Thermal Spray Coatings for Boiler Steels*

Thermal spray coatings offer a versatile and effective solution for mitigating high-temperature corrosion in boiler systems. Techniques like High-Velocity Oxygen Fuel (HVOF) and plasma spraying deposit dense, wear-resistant, and corrosion-resistant layers onto boiler steel surfaces. These coatings, often composed of ceramics, cermets, or metallic alloys, act as a barrier against aggressive environments, preventing direct contact between the corrosive media and the substrate. They provide superior protection against oxidation, sulfidation, and erosion-corrosion, significantly extending the lifespan and enhancing the reliability of boiler components under harsh operating conditions.The following subsections detail specific surface modification techniques commonly employed to improve the corrosion resistance of metallic materials, with a particular emphasis on their application in medical implants:

III. Surface Modification for Enhanced Corrosion Resistance: Applications in Medical Implants and Beyond

The following subsections detail specific surface modification techniques commonly employed to improve the corrosion resistance of metallic materials, with a particular emphasis on their application in medical implants:

A. *Sandblasting-Acid Etching (SLA) and Anodizing:*

Sandblasting and acid etching (SLA) is a widely adopted technique for titanium implants, primarily aimed at creating a rough and porous surface topography. This increased surface roughness significantly enhances bone cell attachment and subsequent osseointegration. Studies have demonstrated that SLA treatment yields a greater surface area and roughness compared to conventional methods. Complementary to surface roughening, anodizing is employed to grow a dense and protective oxide layer on titanium surfaces. This oxide layer acts as a barrier, effectively improving the corrosion resistance of the implant material in the physiological environment [15].

B. *Laser Surface Treatment:*

Laser surface treatment offers a clean, precise, and contactless approach to modifying implant surfaces. This technique allows for controlled alterations in surface morphology and texture, enabling the optimization of properties such as wear and corrosion resistance. By precisely melting, alloying, or coating the surface using laser technology, the performance of medical implants can be significantly enhanced. This method provides a high degree of control over the surface characteristics, contributing to improved long-term stability within the body [16].

C. *Electropolishing and Magneto-Electro polishing:*

Electropolishing (EP) is a sophisticated electrochemical polishing method that effectively removes surface defects, leading to a smoother surface finish and improved corrosion resistance. Unlike mechanical polishing, EP does not introduce surface stress or embed impurities, which can compromise the material's integrity. Magneto-electro polishing (MEP) builds upon the principles of EP by incorporating a magnetic field during the process. This synergistic effect results in an even smoother and more uniform surface, further enhancing corrosion protection and biocompatibility [17-19]. The highly polished surface minimizes sites for corrosion initiation and reduces protein adsorption, contributing to improved implant performance.

Boiler systems, the workhorses of power generation and various industrial processes, are inherently susceptible to a multitude of corrosion mechanisms due to their demanding operating environment [20]. The simultaneous exposure to high temperatures, pressurized steam, and combustion byproducts creates a highly aggressive atmosphere that can lead to significant material degradation. Steel alloys, commonly employed in boiler construction for their strength and thermal conductivity, are particularly vulnerable to oxidation, sulfidation, and attack by chloride and other aggressive chemical species present in the fuel and boiler water. This corrosion not only compromises the structural integrity and efficiency of the boiler, leading to costly downtime and potential safety hazards, but also necessitates frequent maintenance and component replacement. Understanding the specific corrosion challenges within different zones of the boiler, from the high-temperature furnace walls to the economizers and superheaters, is crucial for implementing effective mitigation strategies [21].

To combat the pervasive issue of boiler corrosion, a range of preventive measures are employed, with surface engineering techniques playing a pivotal role. Among these, thermal spray coatings have emerged as a versatile and effective approach for enhancing the corrosion resistance of critical boiler components [22-27]. By depositing a protective layer of specialized materials onto the steel substrate, these coatings act as a barrier against the harsh operating environment. Metallic coatings based on chromium or nickel alloys, for instance, can form protective oxide scales at high temperatures, preventing further oxidation of the underlying steel. Ni-Cr and Ni-Al based coating offered better corrosion resistance due to the development of Cr_2O_3 and Al_2O_3 oxide layer (protective layer) when subjected to harsh conditions [28-31]. Similarly, ceramic and cermet coatings offer excellent resistance to chemical attack and erosion [32-34]. The selection of the appropriate thermal spray technique and coating material depends on the specific corrosion challenges encountered in different boiler sections, allowing for a tailored approach to significantly extend component lifespan, improve operational efficiency, and reduce the economic burden associated with corrosion-related failures [35-37].

Considering the diverse and aggressive environments within boiler systems, the selection of an appropriate surface modification technique, including various thermal spray methods and coating materials [38-41], is paramount to effectively combat specific corrosion challenges encountered in different boiler sections [42, 43]. Reviews on surface modification techniques highlight the broad spectrum of available methods for enhancing material performance and corrosion resistance [38]. Understanding the fundamental mechanisms of corrosion and its control is crucial in selecting the most suitable preventive measures for boiler steel [39, 40]. Notably, surface modification techniques, particularly thermal spray coatings, play a significant role in enhancing the resistance of boiler steels against the combined threats of corrosion, erosion, and oxidation, ultimately contributing to extended component lifespan, improved operational efficiency, and a reduction in the economic burden associated with corrosion-related failures [41].

IV. Conclusion

Biocompatible metals are widely used in medical implants due to their strength, corrosion resistance, and compatibility with the body. However, they can still corrode in certain body environments, releasing harmful metal ions. To reduce this risk and improve implant performance, surface modification techniques like coating, anodizing, electro polishing, and laser treatment are used. These methods help improve corrosion resistance and support better healing. Continued research will help develop safer and longer-lasting implants for future medical use.

The persistent challenge of metallic corrosion necessitates a comprehensive understanding of its underlying mechanisms and the deployment of effective surface treatment technologies across diverse engineering domains. This overview has underscored the critical role of surface modification in enhancing the longevity and performance of metallic components, with a particular focus on applications in medical implants and boiler systems. In the realm of biomaterials, tailored surface treatments are paramount for achieving biocompatibility and resisting the aggressive physiological environment, thereby ensuring the safety and efficacy of implantable devices. Parallels can be drawn with the demanding conditions encountered in boiler systems, where high temperatures and corrosive environments necessitate robust surface protection strategies. The application of thermal spray coatings in mitigating corrosion of boiler steel exemplifies the versatility and effectiveness of surface engineering principles in addressing degradation challenges in high-temperature industrial settings. By examining and contrasting the surface treatment approaches employed in these seemingly disparate fields, this review highlights the fundamental importance of tailoring surface properties to specific operational demands. Ultimately, continued advancements in surface modification techniques are crucial for ensuring the long-term reliability, safety, and economic viability of metallic components in both life-enhancing medical applications and critical industrial infrastructure.

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