THERMAL SPRAY COATINGS:
MATERIALS, TECHNIQUES & APPLICATIONS

Editors:
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Bentham Books

Thermal Spray Coatings: Materials, Techniques & Applications

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Thermal Spray Coatings: Materials, Techniques & Applications

Editors: Santosh Kumar, and Virat Khanna

ISBN (Online): 978-981-5223-55-2

ISBN (Print): 978-981-5223-56-9

ISBN (Paperback): 978-981-5223-57-6

First published in 2024.

Bentham Science Publishers Pte. Ltd.
80 Robinson Road #02-00
Singapore 068898
Singapore
Email: subscriptions@benthamscience.net

BENTHAM SCIENCE

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PREFACE

Thermal Spray Coatings: Materials, Techniques, and Applications is a comprehensive book that discusses the development, application, and future scope of thermal spray coatings. In this book, the authors try to explore the techniques, materials, and applications of thermal spray coatings in various industries, including power generation, aerospace, medical, and automotive.

The first chapter of the book is dedicated to the historical development of thermal spray coatings, providing a detailed account of the evolution of this technology. It also outlines the various types of thermal spray coatings and the materials used in their production. The second chapter discusses the latest trends in coatings, including the use of new materials and techniques to enhance the performance and durability of coatings. The third chapter focuses on reliable surface modification techniques and how they can be used to improve the functionality and performance of various materials. We explore the different types of surface modification techniques, including thermal spray coatings, and how they can be used to enhance the properties of materials. In the fourth chapter, we examine the high-temperature corrosion of coal-based thermal power plants, gas turbines, and steam turbines, and how thermal spray coatings can be used to mitigate these issues. We also discuss the challenges associated with using thermal spray coatings in high-temperature applications. Chapter five explores how thermal spray coatings can be used to combat corrosion, wear, erosion, and abrasion in hydropower plants. This chapter outlines the different types of thermal spray coatings used in hydropower plants and how they can improve the efficiency and performance of the equipment. The sixth chapter provides a comprehensive review of the thermal spray coating technique, its applications, future scope, and challenges. It covers the basics of thermal spray coating, including the various techniques used in the process, the materials used, and the properties of the coatings produced. Chapter seven is dedicated to cold spray coating of nano-crystallization material, providing a critical review of the method, properties, and challenges associated with this technique. We examine the benefits and limitations of cold spray coating and the potential applications of this technology. In chapter eight, we provide an overview of orthopedic implant materials, the problems associated with these materials, and the different coating materials that can be used to enhance the biocompatibility and corrosion resistance of these implants. Chapter nine examines the issue of corrosion in medical devices and the different detection methods used to identify and prevent corrosion. This chapter provides an in-depth analysis of the different types of corrosion that can occur in medical devices and the impact they can have on patient safety. Finally, chapter ten explores how thermal spray coatings can be used to enhance the corrosion resistance and biocompatibility of implants. We examine the different types of coatings used in this application, their properties, and their potential impact on patient outcomes.

Overall, this book provides a comprehensive overview of thermal spray coatings, including their historical development, recent trends, and future scope. It explores the different techniques, materials, and applications of thermal spray coatings in various industries and provides critical insights into the challenges associated with this technology. It is hoped that this book will serve as a valuable resource for researchers, engineers, and professionals working in the field of thermal spray coatings.

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CHAPTER 1

Introduction: Thermal Spray Coatings and their Historical Developments

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Abstract: Thermal spray coatings are a method of surface modification in which various metallic and non-metallic materials are sprayed in molten, semi-molten, or even solid state on a prepared substrate. The coating material is present in two forms: wire or powder. The most common thermal spraying techniques include cold spray, electric arc spray, plasma spray, detonation gun spray, flame spray, and high-velocity oxy-fuel spray. The coating's thickness, which is calculated in millimeters or microns and has distinguishing features from the base material's surface, is acceptable in many industrial sectors and is ideal for on-site industrial applications. These processes also offer affordable solutions in many industrial sectors and are capable of providing surface modification approaches with enhanced surface properties comprising better texture and high mechanical strength in terms of hardness, scratch resistance, and porosity. This chapter presents the evolution of coatings developed during the last few decades using various coating processes and materials for the protection of service components. Coating measures are developed for use in thermal power plants, gas steam, and the automotive industry for the treatment of components, able to work in harsh environments of flue gases and chemicals.

Keywords: Coating evolution, Cold spraying, Coating structure, Coating thickness, Flame Temperature, Feedstock material, Oxidation resistance, Particle velocity, Surface treatment, Surface modification, Thermal power plant, Thermal spray coatings.

INTRODUCTION

Thermal spraying (TS) is a coating process that develops coatings by depositing finely divided metallic or non-metallic surface components in a melted or semi-molten state on a prepared substrate [1]. The foundations of the schematic thermal spray method are depicted in Fig. (**1**). Surface modification needs the employment of surfacing material in powder, rod, or wire form depending on the mode of heat

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Santosh Kumar and Virat Khanna (Eds.)

generation: combustion or electrical [2]. Plasma jets (non-transferred direct current arcs or induction discharges), wire arcs, and transmitted arcs are examples of electrically driven thermal sprayed coatings. Plasma jets, as opposed to wire arcs, which are formed across two consumable, automatically extending wires, require powdered or liquid precursors [3]. For both techniques, the substrates made of metal, glass, ceramic, composite, and plastic are held much below their melting point. In contrast, the transferred arc technique welds the finished coating to the metallic substrate while the surface material is still in powder form [4].

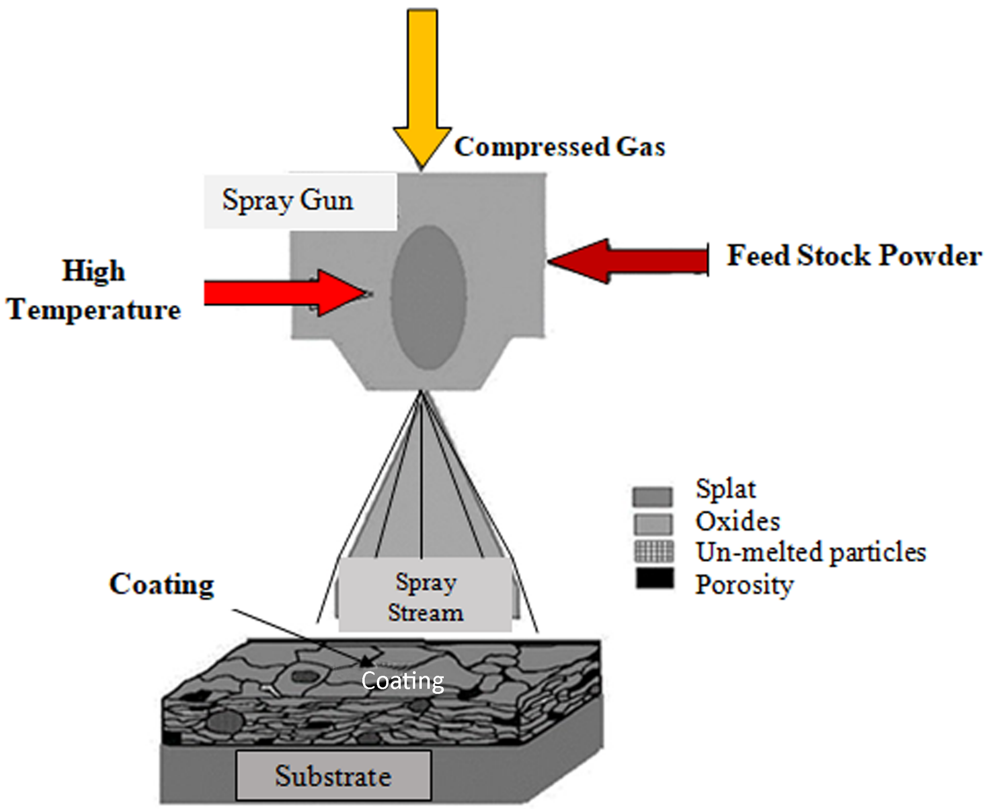

Fig. (1). Schematic of fundamental thermal spraying technique.

Thermal spray coating is a versatile technique used to apply protective or functional coatings to a wide range of surfaces. It involves heating coating materials to a molten or semi-molten state and then propelling them onto a substrate to form a coating. Hybrid approaches combine thermal spray with other deposition methods, such as physical vapour deposition (PVD) or chemical vapour deposition (CVD), to create coatings with unique properties. These techniques leverage the advantages of both methods to achieve improved adhesion, thickness control, and coating quality. Some thermal spray methods allow *in-situ* alloying of the feedstock materials, enabling the creation of tailored compositions and properties. Additionally, composite coatings can be produced by mixing different materials in the spray process, resulting in coatings with customized combinations of properties. Novel thermal spray coating methods also focus on reducing environmental impact. This includes exploring greener propellant gases and alternative feedstock materials and improving the efficiency of the process to minimize waste. The development of coatings for medical implants, free-standing shapes, thermal insulation or barriers, oxidation protection, corrosion or oxidation resistance, abradable seals, electrically conductive or insulating materials, dimensional restoration or manufacture, and wear protection is now mainly owing to these techniques. Application, cost (related to the cost of process investment), and economic viability of the method all influence the coatings that should be sprayed [5]. The parts utilized in various applications function under varying load circumstances and come across a wide range of problems. Surface modification by these thermally sprayed techniques allows the deposition of almost every class of material, such as metals, alloys, ceramics, and composites, with better thickness and potential coating characteristics to protect these components operating in hostile conditions [6]. A coating is formed by laying distinct compacted particles, one on top of the other. Compacted particles, known as lamellae or splats, develop preceding surface structures nearby that are cool and hardened. A precise morphology and metastable phases produced by the rapid solidification rate of 1 million °C/sec exhibit properties that are not attainable with conventional material production procedures. The deformation of the particle affects the flattening of the particles or droplets. The flattening rate (disc diameter vs. initial particle size) for molten particles can reach a maximum of 5. Less flattening is produced by operations at lower temperatures. The material being sprayed and the deposition method both affect how close together the granules or drips are. When heated, a class of substances called self-bonding materials demonstrates an exothermic reaction that provides the heat needed to create an interfacial connection. Most materials lack the ability to form a chemical connection combined with the base, so the surface must be toughened using method, such as grit blasting, to establish a foundation for mechanical bonding. Plastics, glass, ceramics, metals, paper, and composites are the surfaces that can be coated. The compact ability of the coating's structural components and the coating's bonding strength to the supporting base material are what determine the coating's toughness. Compact ability is determined by material qualities as well as porosity inside the coating. Its porosity comprises voids between flattened particles as well as micro fractures in ceramics. As porosity correlates to a loss in strength, it has been the subject of more sophisticated coating techniques that can, if necessary, reduce porosity.

CHAPTER 2

Comprehensive Study on Production Methods and Applications of Functionally Graded Coatings

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Abstract: Surface modification of metal substrates by coatings has remained a challenging research topic because of the conflicting demands for various properties. Functionally graded coatings (FGCs) have recently attracted the attention of researchers all over the globe owing to their mechanical, electrical, thermal and tribological characteristics in a variety of advanced engineering applications. These coatings are usually characterized by low porosity, good adhesion and base material compatibility, which includes temperature and geometry. However, coatings often experience some problems like variable thermal expansion coefficient (TEC) as compared to their base metals. Thus, to overcome this issue, the functionally graded material (FGM) layers may be employed. Hence, the purpose of this chapter is to describe a general idea of FGM coatings, including classifications of production methods and their diverse applications.

Keywords: Functionally graded coating, Mechanical and tribological properties, Process parameters, Thermal spray.

INTRODUCTION

A novel family of composites, termed functionally graded materials (FGM), offer a graded pattern of microstructure and material composition. These materials provide the qualities of two raw materials that are combined, with a continually graded component distribution. FGMs find wide applications in piezoelectric sensors, energy harvesting and phononic materials [1]. To enhance the surface performance of distinct parts in the biomedical, electronics, aerospace, marine, automotive, gas pipelines, and electronics fields, it is necessary to develop a new group of surface coatings that protect the surface parts in these applications and

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satisfy the competing criteria for essential characteristics. However, due to the simultaneous demand for opposing features in the same coating, surface coatings on several components have remained a challenging issue for researchers. FGCs have gained popularity in recent years and are frequently used to protect surfaces by obtaining certain properties in various locations suitable for various operating circumstances. A flexible and effective method for improving the features of the base material, particularly to enhance its functionality and lifetime, is the deposition of FGCs with gradient behaviour and high precision on its surface [2]. Due to their superior mechanical behaviour, FGM coatings are especially valued for high-temperature applications. A synopsis of FGM's application in many sectors is shown in Fig. (**1**) [3].

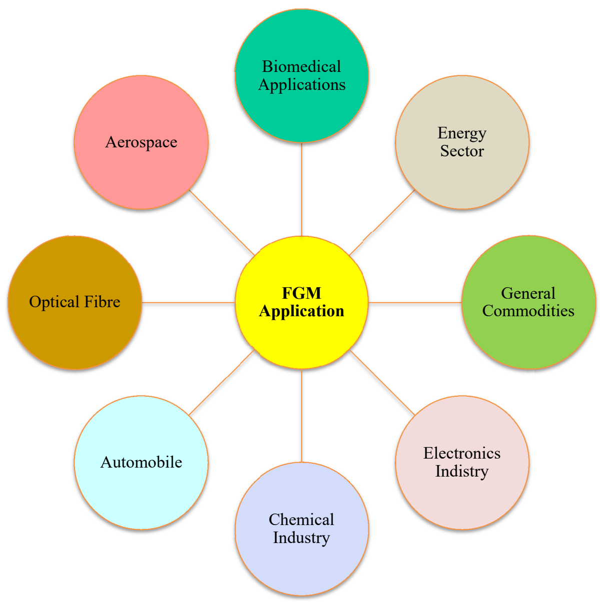

Fig. (1). Distinct applications of FGM.

In engineering applications, the components need graded qualities from region to region, specifically, surfaces exposed to frictional, thermal, mechanical, chemical, and electrochemical interactions that affect the components in the application [4, 5], Unless the tribological and corrosion events are regulated and observed, this damage is irreparable [6]. Because of their unique characteristics due to their graded properties, FGMs have recently made substantial contributions to several engineering applications [7, 8]. In a variety of applications, this graded behaviour reduce breakdown and increase part reliability [9]. A wire or powder coating material is heated by a mechanical technique called thermal spray coating. The substance is then melted into droplets and rapidly sprayed over a surface.

Typically used on metal substrates, thermal spray coating is also known as spray welding, plasma spray, HVOF, and flame spray [10].

Across all significant engineering industry areas, thermal spraying methods have been employed extensively for many years as a means of component preservation and reclamation. Thermal spraying methods have recently gained technical legitimacy thanks to advancements in equipment and material quality, which has led to substantial expansion in new markets like biomedical, electronic and dielectric coatings. As a result, the equipment for thermal spraying, materials for coatings, and gas selection options available to the spray coating supplier are numerous, but they typically depend on the environment to which the coating will be exposed [11]. Thermal spray coatings are used to extend machine part life by reducing friction and wear. This method may be applied to a variety of substances, such as pure metals, alloys, carbides, ceramics, and even composites. Among the thermal spray coating methods, HVOF, Plasma Spray, and electric arc spray are the most widely used. Light metals now have additional features, including dielectric characteristics, wear resistance, corrosion resistance, and bioactivity, thanks to the widespread usage of thermal spray coatings. The oxidation of metal alloy particles, the generation of splats and coating pore characteristics are all examined. Furthermore, characterization of the coating microstructure is the primary method for controlling cohesion, adhesion, and coating characteristics [12 - 15].

A method for enhancing or mending the surface of a solid materialis thermal spraying. Using this approach, a diverse assortment of components and materials may be coated to resist wear, cavitation, erosion, corrosion, heat and abrasion. Moreover, thermal spraying can produce lubricity, sacrificial wear, high /low friction, chemical resistance, and a range of other desirable surface characteristics. In many sectors, thermal spraying is the recommended technique. The lifespan of upgrades may be significantly extended. Tried-and-true methods are used to replace or repair worn-out or broken components [14].

Thermal spraying refers to the application of hot or melted materials to surfaces. Chemical or electrical heating (via plasma or arc) is utilized to heat the "feedstock". In contrast, other coating methods like electroplating, PVD, CVD, and thermal spraying create thick coatings over a vast area at a high deposition rate (the approximate thickness range is 20 microns to a few mm, based on the feedstock and process). This technique can be employed to apply coatings on a wide variety of materials, including metals, ceramics, alloys, polymers, and composites. They are accelerated as micrometre-sized particles while still in a molten/semi-molten state towards substrates after being fed as powder or wire. Typically, combustion/electrical arc discharge is the source. It is possible that the

CHAPTER 3

Reliable Surface Modification Techniques

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Abstract: Loss of material due to corrosion, erosion, wear and oxidation is a major problem in various industries. Recently, various surface modification methods have been employed to improve the service life of distinct engineering parts by improving their resistance to corrosion, wear and erosion. These methods boost thermal and biocompatibility in addition to the mechanical and physical qualities. To offer a thorough review of surface modification techniques, including mechanical, chemical, and thermal procedures, this chapter has three main objectives. Overall, this chapter provides a detailed study on working principles, merits, demerits, and applications of various surface modification techniques.

Keywords: Corrosion, Challenges, Metallic substrate, Nano-coating, Parameters, Surface protection, Thin film.

INTRODUCTION

Surface modification is the act of changing a substance's surface by including physical, chemical, or biological elements that are not already there. The structure and content of surface layers affect a metal's capacity to resist corrosion or wear. Over the last few decades, new methods for changing surface layers have been created. In the subject of material science, the numerous modification processes are crucial tools. Surfaces can be altered using one of three broad techniques, *i.e.*, adding material, removing material, or changing the material currently there [1]. Different metals, including 316L SS, Co, Cr, Mo, Ti, and its alloys, are used as either temporary (such screws and pins) or permanent implants, depending on the metal implant devices (such as joint replacement) [2 - 5]. The success rate of bio-

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implants is based on how well the body absorbs and is compatible with the implant [6]. However, the corrosion behaviour of implants has a significant impact on their biocompatibility [7]. As a result, the likelihood of severe effects increases as implant corrosion increases and poisonous ions are routinely discharged into the body [8]. A practical way to increase the dispersion stability of nanoparticles in various liquid media is to chemically modify the surfaces of the particles [9]. The primary causes of metal part deterioration in mechanical industries are corrosion and wear, which drive up the sector's overall operating costs. According to studies, the failure of metal parts caused by corrosion and wear costs mechanical companies between 40 to 60 percent of their maintenance budgets. The problems are not just limited to mechanical businesses; they also affect the electronic and automotive sectors. Fig. (**1**) displays the numerous surface modification techniques employed by distinct approaches in the industries.

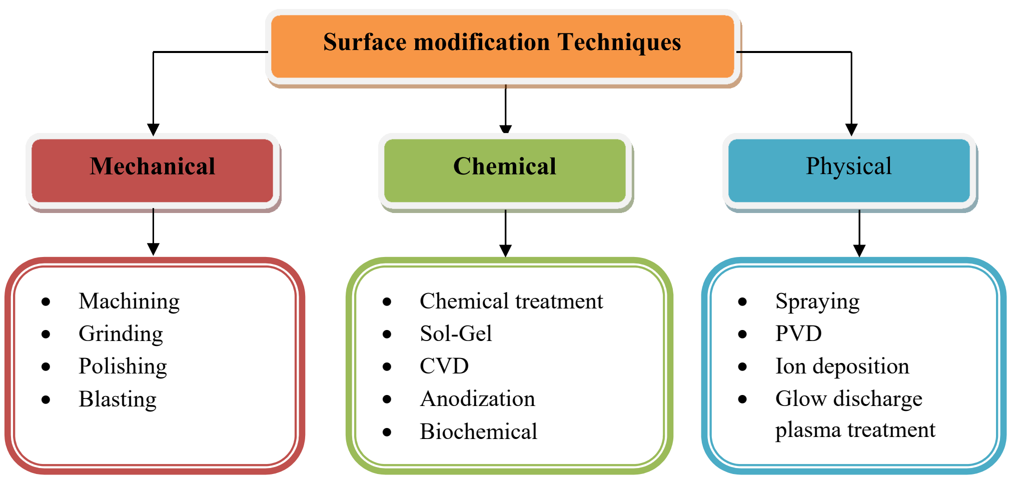

Fig. (1). Surface modification techniques.

Mechanical Method

The surface quality of manufactured components used in mechanical engineering and other sectors is greatly impacted by technical concerns in addition to design factors. The key goal of mechanical alteration is to produce certain surface topographies and surface roughness on implantation surfaces utilizing machining, grinding, and blasting procedures. These subtraction techniques allow us to improve the surface of metal-based objects by up to one µm [10, 11]. When you specify the surface requirements, you can make early decisions about the materials and manufacturing processes because the desired surface properties have an impact on the layout and geometry of the component, the functionality of the final product, as well as its haptic and aesthetic qualities. The schematic diagram for the determination of surface requirements is shown in Fig. (**2**) [11].

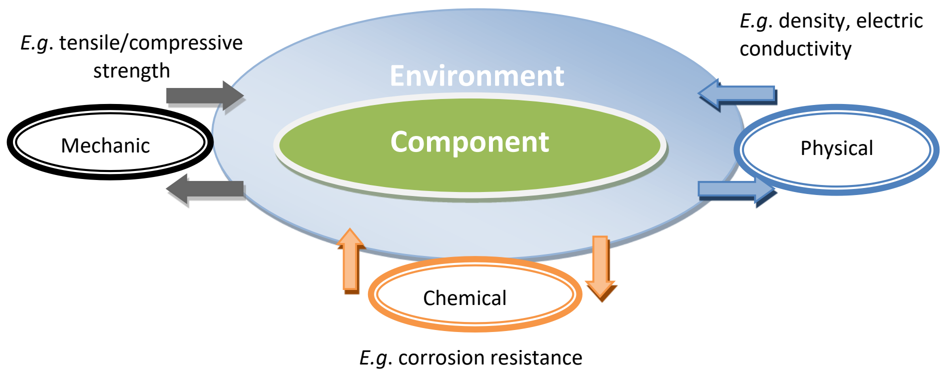

Fig. (2). Schematic representation of determination of surface requirement.

Machining

The majority of items in mechanical industries are created *via* the machining process. With the help of a hard instrument, the material is removed from the parent surface in this process. The material removed using this procedure only has a roughness value in the 0.8 µm to 6 µm range [12]. When it comes to generating high-quality products, manufacturing organizations rely heavily on machining. This process incorporates the atmosphere, lubricants, and other machine settings (including cutting speed and tool feed). Government rules urge the manufacturing sector to use environmentally friendly machining methods in their operations as a result of environmental pollution. EDM, ECM, AJM, AWJM, as well as other efficient machining processes, are being used for manufacturing in industries. These processes are used to create a range of equipment and goods connected to many different sectors, such as nuts and bolts, auto parts, flanges, drill bits, and plaques. One of the finest methods to help your metals work more effectively is through machining. Turning, drilling, and milling are the three main types of machining. Shape-changing, planning, boring, broaching, and sawing are further activities that fall into various categories. The workpiece, tool, and chip all serve as the fundamental components of machining.

Grinding

After every machining operation, grinding is utilised to combine excellent surface quality with dimensional precision. To remove stock in this process, abrasives are bound and attached to paper, plates, or wheels with a precision of up to 0.2 µm [13]. To remove material from a workpiece, a grinding wheel is used in the

CHAPTER 4

Recent Trends in Coatings

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Abstract: With the demand for high-fidelity coating involving metallic, multilayer, protective, and ceramic-based coatings, deposition methods have been introduced to achieve quality coatings. High temperatures cause erosion-corrosion wear, oxidation, and hot corrosion in materials operating in corrosive conditions. Among the various methods used to protect surfaces from deterioration, the method of applying coatings by high-velocity oxy-fuel spraying deserves special mention because it creates coatings with increased hardness and resilience, low (less than 1%) porosity, and high erosion-corrosion and wear resistances. Deposition of these coatings using a typical thermal spray process finds applications in the protection of base material in automobile, aerospace, orthopaedic, thermal power plant, and gas pipeline sectors. We present the potentials of the coatings and their respective protective properties. This chapter provides the optimization and overviews of the use of various recently used coating materials developed for the application in automotive, power plant, defence, gas and steam, and orthopaedic sectors.

Keywords: Automobile sector, Biomedical coatings, Ceramic material, Corrosion and wear resistance coatings, Gas turbine, Metallic coating, Multilayer, Optimization of coating material.

INTRODUCTION

In the early development stage, thermal spray (TS) technology was used mainly for repairing works and protecting the components from corrosion and wear. Thermal spraying is used for coating more easily worked and less expensive base materials with high-performance components made of metals, alloys, ceramics, cermets, and carbides [1]. Plasma spraying is a type of thermal spraying, a collection of techniques wherein finely ground metallic and non-metallic substances are sprayed on a prepared surface in a molten or semi-molten state. The most popular technique for creating ceramic coatings that are frequently utilized in mechanical uses to increase wear resistance, corrosion, oxidation, and

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erosion is plasma spraying. Al_2O_3/TiO_2 plasma-sprayed coatings, for instance, are frequently used in the printing, machinery, and textile industries to provide wear resistance. Aluminium oxide (Al_2O_3) is a widely utilized and reasonably priced material that is applied as coatings or sintered monolithic components (as wear inserts) in various tribological applications. Al_2O_3 ceramic coatings are frequently used to prevent frictional wear and erosion from solid particles because of their excellent hardness, chemical stability, and refractory nature [2].

These materials have a wide range of uses, including those for cutting tools, grinding wheels, and some essential motor parts like piston rings. When it comes to applications that call for strong tribological characteristics, increased hardness, and excellent thermal resistance, alumina-based ceramic coatings work well as an alternative. When titanium oxide is added to brittle alumina, a balanced equilibrium of characteristics results, preserving a sufficient level of hardness while greatly enhancing coating toughness [3, 4]. Since alumina grains are bound together by titanium oxide, the melting point is lower, and coatings with a higher density are produced.

In recent years, thermal spray coatings have gained significant traction as a crucial technology in the field of surface engineering and material protection. This trend can be attributed to several factors that highlight the versatility and effectiveness of thermal spray coatings across various industries. One notable trend is the growing emphasis on environmental sustainability and energy efficiency. Thermal spray processes, such as high-velocity oxy-fuel (HVOF) and cold spray, are being increasingly utilized to apply coatings with reduced environmental impact, lower material waste, and improved coating adhesion. Additionally, the expanding demand for advanced materials with enhanced functional properties has driven the adoption of thermal spray coatings. Industries such as aerospace, automotive, energy generation, and biomedical applications are benefiting from these coatings, which offer attributes such as high-temperature resistance, corrosion protection, wear resistance, and thermal insulation. The integration of novel materials, including nanostructured powders and cermet compositions, into thermal spray processes is another emerging trend, enabling the production of coatings with tailored microstructures and superior performance characteristics. As research and development efforts continue, it is anticipated that thermal spray coatings will continue to evolve, addressing new challenges and applications while contributing to the advancement in surface engineering technologies [4].

In the research community, the HVOF has drawn a lot of attention for its use in the thermal spraying procedure to deposit bioactive bioceramic coatings. HVOF is a method that creates a high-speed flame using either gas or liquid fuels (such as propylene, propane, hydrogen, and kerosene) and only pure oxygen. The operating principle of the technique and additional details can be found in the authors' other publications. The HVOF process produces thick, well-bonded coatings with lower oxide levels due to the increased particle velocity. Because of the high particle velocity associated with the HOVF procedure, the particle flight duration time is reduced. As a result, the oxidation reaction only takes place in the particles for a short period. Many research teams have successfully created nanostructured ceramic coatings during the last ten years utilising thermal spraying techniques, including plasma spraying. Studies on nanostructured materials have recently demonstrated that they may exhibit excellent features that differ noticeably from those of their usual bulk materials [5].

WEAR AND CORROSION-RESISTANT COATINGS

Without removing the debris produced, under dry sliding conditions, wear tests are conducted by wear testing equipment with a pin-on-disc setup. Both materials show a change between a light and heavy wear regime, which is indicated by a rapid increase in wear proportion. The moderate wear regime is extended because the nano coating's transition pressure is raised. A typical splat microstructure, which is frequently seen in thermal spray coatings, can be seen in both conventional and nanostructured coatings [6, 7]. Fig. (**1**) presents a Fig. outlining the nanostructured coating's layered microstructure and comparing it with the traditional coating. When a material's importance (owing to broad use and/or strategic relevance) is paired with high supply risks, it is said to be essential to the economy. In fact, under these conditions, the economy is particularly susceptible to changes in supply or volatility in prices. Alternative sources, trade agreements to ensure supplies, increased internal recyclability, or non-critical replacements for a number of its applications are some ways to do this. It is possible to lessen the likelihood that a raw material will be crucial.

In-depth inventories of essential raw materials have been made by developed countries such as the European Union and the USA (CRMs). Tungsten and cobalt stand out among these partially overlapping lists as the two most significant CRMs that depend on strong metal coatings for wear and corrosion resistance. WC-Co hard metals and Co-based hard-facing alloys, like Tribaloys and Stellites, are utilized in sizable amounts during cladding, using thermal spray to protect industrial machinery and equipment parts.

So, the unique situation of protective coatings can also be addressed using broader tactics to lessen an economy's reliance on CRMs. For instance, several articles have examined the potential of recycling WC-Co-type hard metal wastes to create feedstock material for thermal spray and cladding techniques, frequently with positive outcomes. Nonetheless, it may seem even more desirable to substitute

CHAPTER 5

High-temperature Corrosion of Coal-based Thermal Power Plants, Gas Turbines, and Steam Turbines

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Abstract: Hot corrosion is a critical challenge in the designing and functioning of coal-based power plants, gas turbines and steam turbines. The economic loss due to hot corrosion is very high. Many researchers are working to combat hot corrosion, but only a few researchers have reduced hot corrosion to some extent by various surface modification techniques. However, coatings deposited by the thermal spray process offer better results in combating hot corrosion. Thermal spray techniques are a promising way to apply dense, defect-free adherent coatings to components, increasing both their performance and lifetime. Thus, the core objective of this chapter is to provide a review of different thermal spray coating methods, coating materials, advantages, and disadvantages. Finally, the most recent industrial advances in thermal spray technologies to combat corrosion in high-temperature applications are provided.

Keywords: Hot corrosion, Thermal spray techniques, Thermal power plant recent advances.

INTRODUCTION

India is a major energy consumer globally. The energy demand has more than doubled since 2000. We are already well aware that global warming has adversely affected climate change, resulting in catastrophic consequences. The power generation industries play a major role in environmental pollution.

India's energy requirements are generally fulfilled by three fuels: oil, coal, and solid biomass. Coal is the largest single fuel in the energy mix, underpinning the development of electricity production and industry requirements. According to the

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Ministry of Power of the Indian government, 57.9% of total energy requirements are met by fossil fuels [1], as shown in Fig. (**1**).

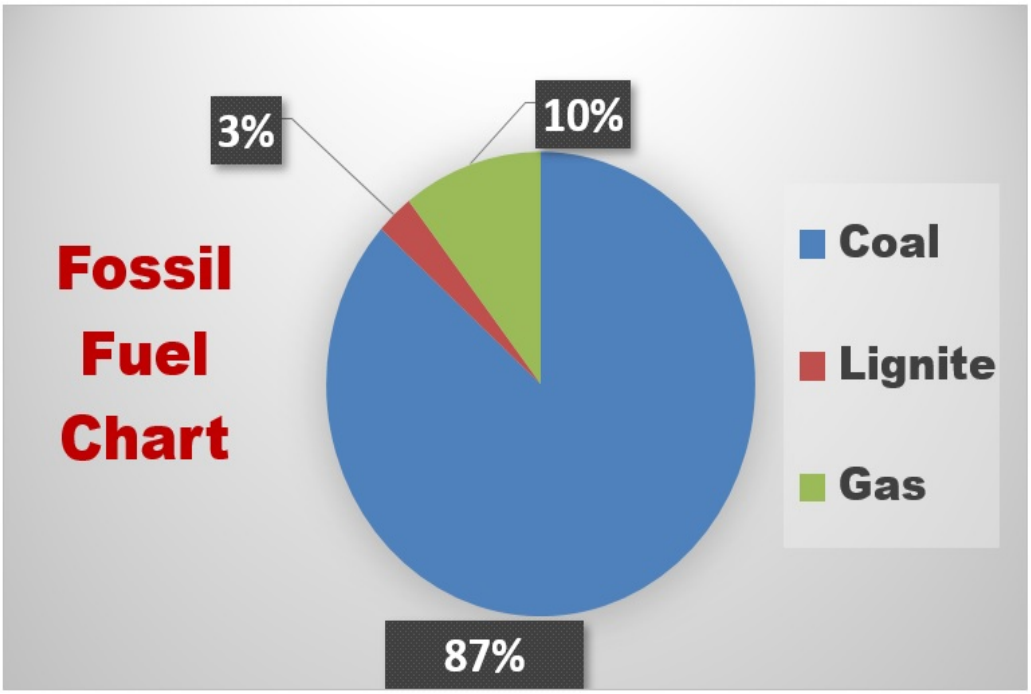

Fig. (1). Shows that fossil fuels meet 57.9% of total energy requirements.

The corrosion of the water walls of the superheater and other components of power plants is accelerated by the burning of biomass and waste fuels, which produces a significant quantity of corrosive chemicals like hydrogen chloride, chlorine, moisture, and alkali chlorides. Alkali chlorides that build up on the boiler's components affect the rate of heat transfer, and they are a major source of corrosion. Large-scale material and economic losses are brought on by corrosion, including tube failures, leaks, unscheduled shutdowns, and decreased component life cycles [2].

HOT CORROSION

Oxidation, sulfidation or both play a vital role in the "hot corrosion" phenomenon. The most significant method of material degradation, specifically when materials operate at extremely high temperatures, is hot corrosion. Due to the substrate's absence of a solid layer, degradation happens quickly. Boilers, gas turbines, industrial facilities, jet engines, and other components are some of the most typical targets of hot corrosion attacks [2].

The sulphate then coats the heated components, such as boiler tubes and rotor blades, speeding up oxidation. Commercial jet engines and marine gas turbines have very little sulphur in their fuel, yet it can still corrode metal surfaces.

High-temperature hot corrosion (HTHC) and low-temperature hot corrosion (LTHC) are two categories of hot corrosion phenomenon that occur when a deposit is in the form of liquid from the commencement or when a solid deposit turns into liquid as a result of a reaction with the surroundings [3 - 6].

Fig. (**2**) shows the stages of hot corrosion.

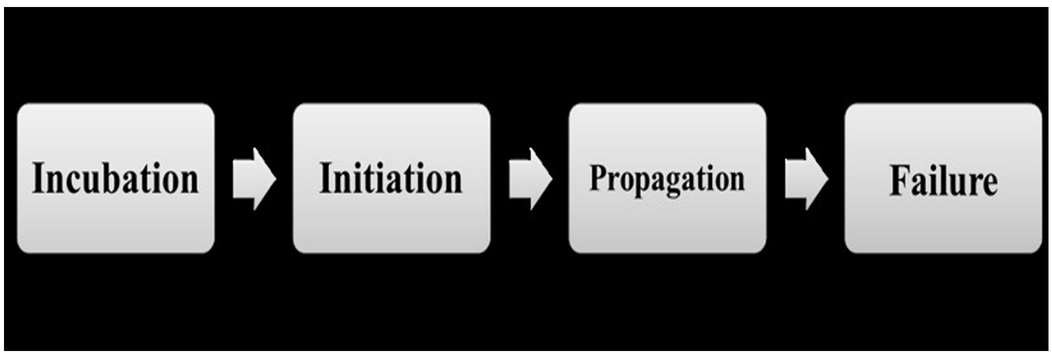

Fig. (2). Stages of corrosion.

Type I hot corrosion attacks occur at temperatures between 800°C and 900°C, with the melting point of the salt deposit serving as the minimum threshold. The salt dew point is assumed to be at the higher temperature; an incubation period during which the rate of attack is sluggish as the oxide layer develops, followed by a rapid acceleration of the rate. At temperatures ranging from 670 °C to 750 °C, type II hot corrosion is distinguished by a pitting attack with a relatively little attack beneath the surface. In maritime turbines and industrial gas turbines, type II hot corrosion is typical. The research on hot corrosion can be conducted using a variety of tests. They consist of manufacturer-used burner rig testing, salt-coating procedures, and immersion or crucible testing [4]. Fig. (**3**) depicts various deposits and corrosion products that are produced during hot corrosion.

PREDICTION OF HOT CORROSION

The development and stability of oxides must be predicted to estimate high-temperature corrosion in gaseous environments. High-temperature corrosion can be quickly predicted using the Pilling and Bedworth Ratio (PBR) [7, 8].

CHAPTER 6

Corrosion, Wear, Erosion, and Abrasion in Hydropower Plants by Thermal Spray Coatings

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Abstract: Hydropower plants, thermal power plants, offshore, chemical, food processing, oil sectors, *etc.*, all have difficulties with erosion, abrasion, and corrosion regularly. These issues impact a variety of hydraulic equipment and pipeline circuit components (pipelines, elbows, reducers, separators, tees, and seals). One application where these three issues consistently arise is a hydropower plant. However, one of the main issues with Indian hydropower facilities is silt erosion in the hydro-turbines and their parts. Hard particles like quartz, feldspar, and other minerals may be found in Indian rivers. More than 50% of the quartz in the silt contributes to several issues with hydro-turbines, including sediment erosion, leaky flow, disruptions in secondary flow, *etc.* As a result, these issues have an impact on the hydro-power plant's overall performance. The numerous failures of the components placed in hydropower facilities' impulse and response turbines are discussed in this chapter. Additionally, this chapter provides information on different turbine materials and their characteristics. Based on silt characteristics, material properties, and flow phenomena in various hydro-turbines, several numerical models of erosion abrasion are addressed. Different thermal spraying methods for turbine materials are compared and contrasted. To regulate wear and safeguard hydro-turbines, this chapter reviews the literature on wear mechanisms, models, pilot plant loops or rigs/testers, and protective strategies.

Keywords: Erosion, Thermal spray coatings.

INTRODUCTION

Energy demands are continually increasing globally, putting all energy sources under immense pressure. The most commonly used form of energy is derived from fossil fuels, which are non-renewable. According to an estimate, the storage of these fossil fuels is likely to be diminished by the end of the present century [1 - 3]. Moreover, with the use of fossil fuels, a lot of by-product gases are produced,

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which are harmful to nature. It has been observed that these harmful gases candirectly alter the climate other than causing several health-related problems [4 - 7]. Renewable energy is expected to supplement our increasing energy demand to a greater extent shortly. However, basic knowledge of utilizing hydropower was available even in the mid-1770s, as evidenced by the work of French engineer Bernard Forest de Bélidor, who presented the working designs of horizontal and vertical hydraulic machinery [8 - 10]. However, the first hydropower-driven turbine came into existence in 1878 at Cragside in Northumberland, England, developed by William George Armstrong. Thereafter, the Schoelkopf power station in 1881 and the Edison hydroelectric power plant in 1882 in Appleton, Wisconsin, started to produce electricity from water (http://www.usbr.gov/power/edu/history.html). This was followed by rapid development, resulting in around 200 hydropower stations in the U.S. alone by the end of 1889 (http://www1.eere.energy.gov). A remarkable achievement was made in 1928 with the development of Hoover's Dam, with an initial capacity of 1345 MW. It remained the largest hydropower plant until 1936, when it was surpassed by the 6809 MW Grand Coulee dam in 1942 (www.worldwatch.org). The struggle to produce larger hydropower plants went on, and in 1984, a plant having a generation capacity greater than 10 GW came into existence. The Itaipu dam, a joint venture of Brazil and Paraguay with a capacity of 14000 MW, was built. Guri Dam in Venezuela, with a capacity of 10200 MW, was initiated in 1963 and is presently the third largest dam in the world. Three Gorges Dam in China, currently the largest hydroelectric plant with a capacity of 22500 MW, began working in 2008 (www.hydroworld.com). Today, China is the largest producer of hydroelectricity, with 721 terawatt hours generated in 2010. Some countries, such as Norway, the Democratic Republic of the Congo, Paraguay, and Brazil, are blessed with large water resources with the potential to produce the bulk of their energy requirements from hydropower (www.worldwatch.org). Paraguay generates 100% of its energy requirements from hydropower. It is also a source of national income for Paraguay, with 90% of its generation being exported to Brazil and Argentina. Norway also generates 98% of its energy needs from hydropower. At present, almost 16% of the total generated energy in the entire world is from hydropower. This *Fig.* is bound to increase with the initiatives of Asian and African continents, where many of the hydropower resources remain unexplored. In 2010, China alone added 16 GW of hydropower generation capacity and added another 140 GW in the year 2015 [8 - 10].

In the current scenario, India is among the top ten hydroelectric power-generating countries. Out of its total installed capacity of 174 GW in 2011, 21.6% was contributed by hydropower, as mentioned in Fig. (**1**). By the end of the year 2012, the hydroelectricity generation improved to 39 GW (by~2GW) (http://powermin.nic.in/). However, the percentage contribution of hydropower appears to have reduced marginally, as can be observed in Fig. (**1**). Nevertheless, major projects which are under process are surely expected to improve this figure. To mention a few, the hydropower plants at Siang, Upper (11000 MW) and Lower Subansiri (2000 MW) are some of the future projects that could help India gain significant momentum in the field of hydropower generation. In Fig. (**2**), the trend followed in hydroelectricity generation with the total installed capacity of India since 1947 can be found (http://powermin.nic.in/). It can be observed that hydropower has shown a steady and gradual rise since 1947. Indian rivers have a large potential for hydropower, a significant portion of which remains untapped. Large potential lies in the Bharamputra, Indus, and Ganga basins, which need to be explored. In terms of installed generation capacity of hydroelectricity, India stands sixth worldwide (www.worldwatch.org). An idea about the hydropower potential of the country can be obtained from the fact that India has 150000 MW hydropower capacity, which, at 60% load factor, amounts to around 84000 MW. Out of this, India has been able to harness only 39339 MW till now(Fig **3**) (http://powermin.nic.in/). Additionally, 15834 MW has been estimated from small hydropower projects. This provides an idea about the growth that could be expected in this sector [5].

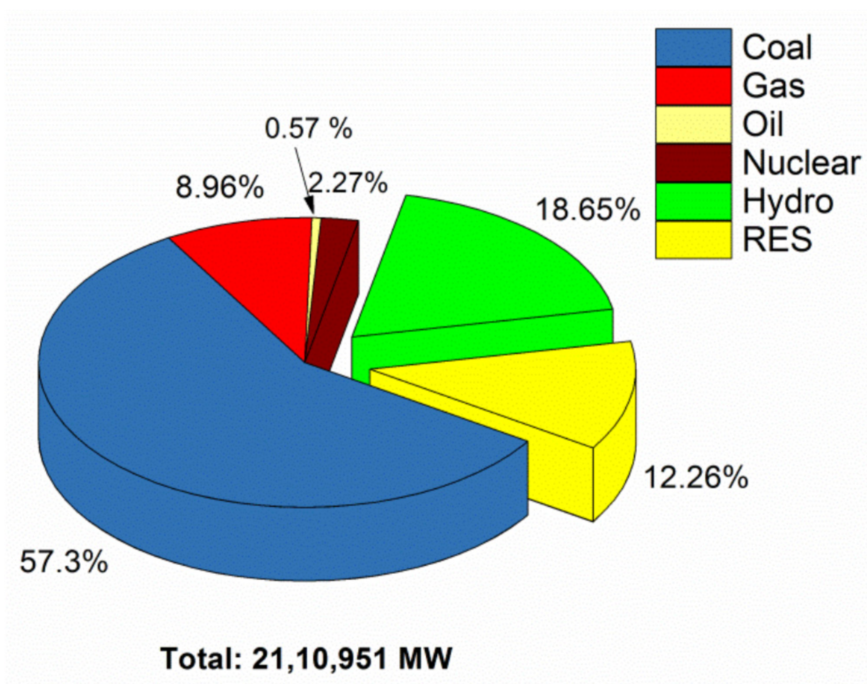

Fig. (1). This distribution of India's power-producing capacity by 2012 makes use of a variety of energy sources, and RES stands for other renewable energy sources.

CHAPTER 7

Overview of Corrosion in Medical Devices and Detection Methods

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Abstract: Corrosion is a major issue that can cause implant failure, leading to adverse reactions in the surrounding tissue and sometimes causing systemic complications. Several researchers are currently exploring ways to enhance the corrosion resistance of orthopedic implants, which is essential to improve their performance and longevity. The most common strategies used to enhance the corrosion resistance of orthopedic implants are selecting corrosion-resistant materials, surface treatments, coatings, and improved implant design. Surface treatments, such as passivation, anodization, and micro-arc oxidation, can also create a thin oxide layer on the surface of implants to act as a barrier against corrosion. Coatings (hydroxyapatite, diamond-like carbon, metal oxide coatings) and good implant design can also be used to provide a protective barrier and alter the surface chemistry. Further research can be focused on developing new materials and surface treatments that are more corrosion-resistant, as well as advanced implant designs that can minimize stress concentrations and enhance load distribution. By implementing these strategies, orthopedic implants can provide better treatment for patients with a higher level of safety and efficacy. This chapter mainly focuses on corrosion types, causes, merits, demerits, corrosion detection methods and remedial actions.

Keywords: Anodizing, Biomaterial, Corrosion, Coatings, Detection, Implants, Material, Merits, Scope, Types.

INTRODUCTION

Biomaterial is a material that is used to make devices to replace a part or a function of the body in a safe, reliable, economical, and physiologically acceptable manner. These devices and materials are used in the treatment of

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disease or injury and include sutures, tooth fillings, needles, catheters, bone plates, and more. Biomaterials can be synthetic materials designed to replace parts of a living system or to function in intimate contact with living tissue. The Clemson University Advisory Board for Biomaterials has defined a biomaterial as a "systemically and pharmacologically inert substance designed for implantation within or incorporation with living systems". On the other hand, biomaterials are specialized materials that are designed to interact with biological systems, either as a replacement for damaged or diseased tissue or as a means to support the body's natural healing processes. Some of the general characteristics of biomaterials are given below [1].

There are several properties of biomaterials. Some important properties with examples are shown in Fig. (**1**).

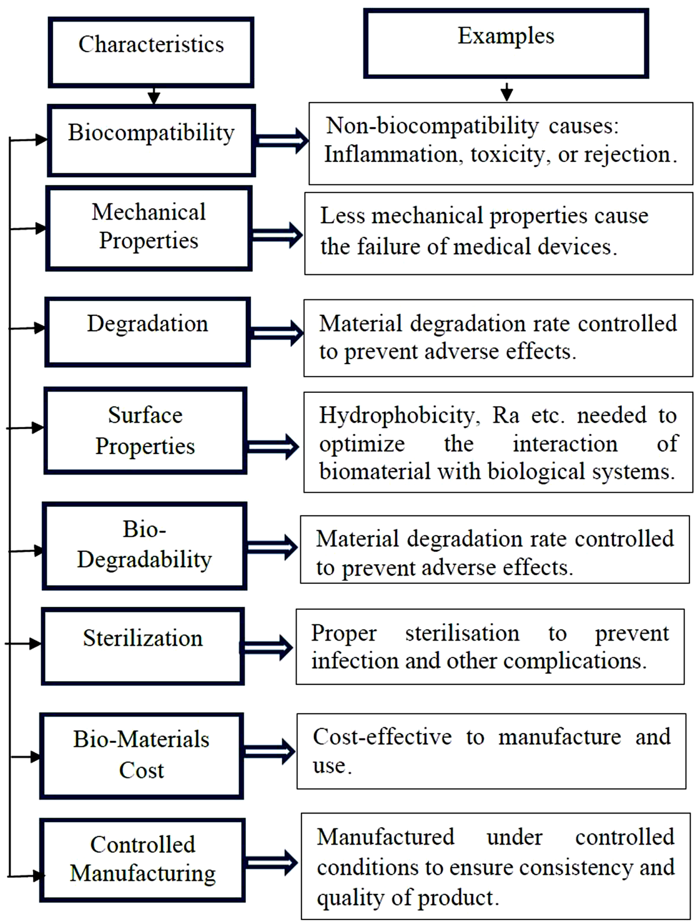

Fig. (1). Properties of biomaterials [1].

TYPES OF BIOMATERIALS

Generally, biomaterials are classified into different classes because each class has unique properties that make it suitable for specific medical and biological applications. These materials are carefully designed and tested to ensure biocompatibility, durability, and effectiveness in their intended applications. The biomaterials and their composition of each class are illustrated in Fig. (**2**).

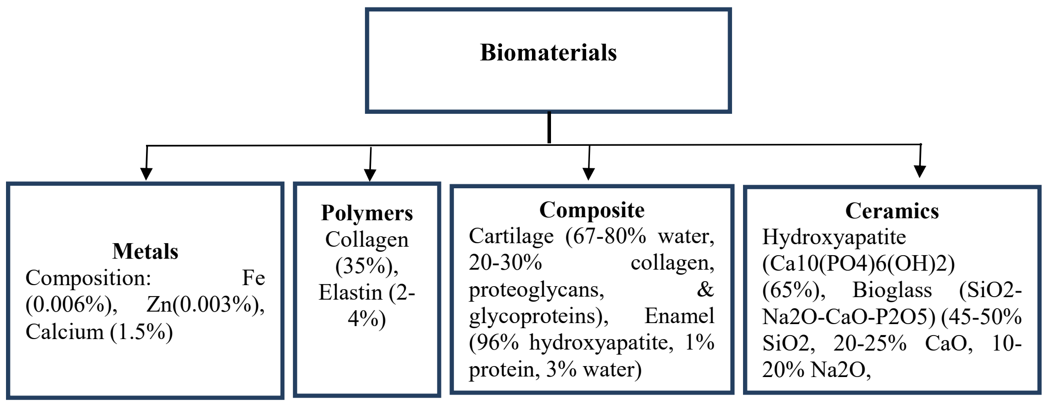

Fig. (2). The types of biomaterials and their composition [2].

Some merits and demerits with examples are described below.

• Metals: Metals such as iron, zinc, and calcium are used in the body for various functions such

as structural support, oxygen transport, and enzyme activity. The advantages of metals are their strength and durability, but a disadvantage is that they can corrode over time.

• Ceramics: Ceramics such as hydroxyapatite and bio-glass are used in the body for bone replacement and repair. The advantages of ceramics are their biocompatibility and resistance to wear and tear, but a disadvantage is their brittleness.

• Polymers: Polymers such as collagen and elastin are used in the body for various functions, such as providing structural support and elasticity. The advantages of polymers are their flexibility and versatility, but the disadvantages are their susceptibility to degradation and ageing.

• Composites: Composites such as cartilage and enamel are made up of a combination of different materials, including polymers and ceramics. The

CHAPTER 8

Enhancement of Corrosion and Biocompatibility of Implants by Thermal Spray Coatings

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Abstract: In the recent era, distinct metallic materials such as titanium, stainless steel, titanium alloys, and Co-Cr alloy are widely used for implant manufacturing. But for successful implantation, these biomaterials require good biocompatibility, corrosion resistance, low elastic modulus, which is required closer to actual human bone, high strength, and non-cytotoxic. These biomaterials have primarily been used in specific applications such as orthopaedic fixation devices, dental implants, and cardiovascular stents. The corrosion of metal implants, on the other hand, determines the service period of implantation due to the release of incompatible metal ions into the human body, which may cause allergic reactions. As a result, the focus of this chapter is initially on metal biomaterials and their properties. The causes of implant failure are then highlighted, with a focus on corrosion mechanism details. Finally, various surface modification techniques, such as thermal-based surface modification techniques, are discussed in detail, as are their applications in improving corrosion resistance, biocompatibility, and osseointegration of various biomaterials.

Keywords: Biocompatibility, Bio-materials, Corrosion, Coatings, Implant, Medical devices, Mechanism, Osseointegration, Surface modification methods, Wear.

INTRODUCTION

Biomaterials can be defined as substances or nonviable materials that are used in medical devices (implants and instruments other than a drug)to replace damaged tissue or organs or to help restore human body functions. Biomaterials are essen-

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tial because they enhance an individual's quality of life, health, mobility, and functionality [1]. The most common orthopaedic procedures in the United Kingdom in 2019 were hip and knee replacements, with close to 112,000 and 118,000 implants, respectively. In these procedures, the joint is replaced with a biomaterial implant to lessen discomfort and enhance joint functionality [2, 3]. Osteoarthritis becomes more common as people age, but lifestyle choices are increasing the disease's prevalence among younger people, with 35% of all surgeries of knee and hip replacement conducted in the United Kingdom by the NHS in 2013 being performed on patients under the age of 65 [4]. This shift is primarily due to rising obesity rates among young people in the United Kingdom. Early-onset osteoarthritis is caused by cartilage degeneration that is accelerated by the additional mechanical stress placed on the joints by excess weight. Osteoarthritis is seven times more common in people with a BMI of 30 kg/m^2 than in people who have a healthy weight [4]. The need for orthopaedic implants is growing as the world's population ages, with the proportion of people over 60 expected to double by 2050 [5]. Furthermore, advances in orthopaedic implant technology are being driven by rising life expectancy as well as an increase in early-onset osteoarthritis. The first orthopaedic implant was used in 1940 when the life expectancy was 63.6 years, rising to 81.65 years by 2022, with 22% of 4-5 years old children and 33% of children aged 10 to 11. Implants that once outlived their recipients are now failing and needing replacement. Biomaterials must develop an interface with a biological system so that they replace/support the organs in the human body [6, 7]. Materials utilized in the fabrication of implants, generally in load-bearing use, should have the following properties: compatibility with bone cells, body corrosion resistance, low elastic modulus, wear resistance, fatigue resistance, more ductile in nature and non-toxicity in the joint environment [8]. Polymers, metals, ceramics, or composites may be the preferred materials depending on the application. Metals are used in dental implants, joint replacements, and staples because they have a high resistance to wear and impact [9]. Due to their suitable physical and mechanical properties, metallic implants are frequently used in clinical settings as opposed to polymers and ceramics. Metallic biomaterials make up the largest portion of the global biomaterials market, which is currently valued at $35.5 billion and is predicted to reach $47.5 billion by 2025 [10]. These metal-made biomaterials involve Ti and Ti-based alloys, 316L-SS and Co-Cr alloys. These biomaterials have a propensity to fail over time despite their frequent use for several reasons, including having a higher modulus than bone, having insufficient wear and corrosion resistance, and not being biocompatible. There are two main detrimental effects of corrosion and wear on metallic implants. In addition to releasing metallic debris, which frequently results in chronic inflammation, allergic reactions, and the development of granulomas (early wound tissue), the implant's structural integrity is also compromised [11].

Hardness and fatigue resistance are decreased as a result of implant mass loss from corrosion. Because the average person takes about 9000 steps/day, joints like the hip and knee must have more resistance to wear because they are subjected to numerous repeated load cycles each day. Cracks that arise as a result of corrosion mechanisms are what lead to stress concentrations at the tip. Crack growths as well as catastrophic implant failure owing to fatigue are mainly caused by stress concentrations that cause some areas of the implant to fail under applied loads that are smaller than those experienced by the rest of the implant [12, 13]. Another common factor in revision surgery for knee and hip replacement is the biological reaction to corrosion products. The immune system of the body may be activated by particulate and ion debris produced by the corrosion process, resulting in inflammation, pain and swelling [13]. If the inflammation persists, the patient will experience long-term pain. Typically, the implant must be removed. As a result, granulomas form, disrupting the implant-bone interface, which is due to the loosening of devices and pain, necessitating implant replacement [14]. Furthermore, the formation of wear debris can result in osteosis, which causes implant loosening [15]. In that case, a lot of work is being put into creating new alloys and altering the surfaces of biomaterials to increase their mechanical properties as well as their resistance to corrosion and wear. Researchers around the world are investigating various methods that help in the production of favourable surface modification of biomaterials, which will extend the life of the implants. Surface modification techniques continue to be the primary area of study for improving the aforementioned properties. The purpose of this book chapter is to give an overview of the biomaterial properties, the reason for implant failure, and the coating methods that enhance corrosion and biocompatibility.

First Generation Biomaterials

For the suitable combination of physical characteristics that matched those of the replaced tissue with a less toxic response from the host [16], synthetic materials known as first-generation biomaterials were used. By the 1940s, titanium and titanium alloys were examples of the first generation, as shown in Fig. (**1**).

The distinct stainless steel materials called stainless steel SS, 316 low vacuum melt (LVM), and 316 low carbon remelt (LRM) comparison studies in terms of elemental composition such as iron percentage and mechanical properties are given in Table **1a, b**. The properties of distinct metal-made biomaterials for orthopaedic applications are represented in Fig. (**2**).

CHAPTER 9

Overview of Orthopedic Implant Materials and Associated Problems

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Abstract: Orthopedic Implant is a high-risk medical device. Its main function is stabilization and fixation of bone but some are functional devices like hip arthroscopy, knee joint replacement implants, spinal cages, *etc.* Some common materials used to manufacture implants are Titanium, Titanium alloy (Ti_6Al_4V) as per ISO 5832-3, Stainless Steel-316 as per ISO 5832-1, tantalum, bioabsorbable material like PLLA, PGA, PLDLA, *etc.* The implant should have some fundamental properties such as being biocompatible, corrosion resistant, and having good mechanical properties. Though the implants have these properties, some complications like bacterial adhesion cause infection, poor osseointegration, and loosening of the implant. To overcome these complications, one of the effective and simple solutions is coating. The coating can enhance osseointegration, reduce infection, increase bone ingrowth and mechanical strength, *etc.* The coating of a material with desirable properties over the implant is a tough and complex process. The antibacterial coating materials are chitosan, gentamicin, Rifampicin, Titanium oxide, *etc.* Similarly, the coating material for osseointegration is hydroxyapatite (HA), extracellular matrix (ECM), magnesium coating, *etc.* There are different technique for coating materials like the Dip-Coating method, magnetron sputtering, sol-gel technique, electrophoretic deposition, *etc.* Although coating is the most effective way to overcome some above-mentioned complications, most of the implants are sold on the market without coating. Coating is a complicated and costly process. It is still in its niche in research and development, however, it has a lot of potential for the future. Hence, in this chapter, the author mainly focuses on orthopedics implant materials, associated problems, and distinct coating materials techniques, which are discussed in detail.

Keywords: Coatings, Corrosion, Implants, Infection, Issues, Material, Osseointegration, Scope, Wear.

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INTRODUCTION

The use of orthopedic implants is exponentially increasing and so as complications related to it. During the life cycle of an implant, it is affected by many factors like corrosion, wear, infections, foreign body effects, poor osseointegration, *etc.* Corrosion and wear of the implant are very critical, they not only weaken the implant but may cause toxicity that leads to death of patients. Therefore, high corrosion resistant metals or polymers are used in the orthopedic industry like stainless steel 316 as per ISO 5832-1, titanium-5 as per ISO 5832-3, tantalum as per 13782, nitinol, Tritium and Polyether Ether Ketone PEEK as per ASTM F2026-17, *etc.* Similarly, the infection forms around the implant not only prolongs the recovery of fracture but sometimes also leads to the failure of the implant. The infection is generated through a complex bacterial adhesion process which is briefly explained in a later discussion [1].

To avoid the infection, generally, the doctors prescribe an antibiotic medicine, however, it has some serious side effects that should not be violated. In the same way in the case of foreign body effects and poor osseointegration, the body's immune system treats the implant or prosthesis as a pathogen and releases some inflammatory substances like cytokines, chemokines, degenerative enzymes, reactive oxygen, and many others. These substances cause chronic inflammation which may result in osteosis, lead to aseptic loosening, and finally poor osseointegration too [2, 3]. Previously, most of the research was focused on the implant surface design to prevent coating, however, in the past few years, the researchers have concentrated their research on the coating of implants to prevent the above mentioned complication. The coating of other metals on the medical device is one of the simplest and the most effective solutions to get rid of it. The material used for the coating must be biocompatible and bioactive, and to find the materials with these specific properties is so tough. However, there are some materials available such as ceramic-based material-hydroxyapatite, oxide of Al, Si, Ti, *etc.*, titanium nitride, and titanium-aluminium nitride. Among these, hydroxyapatite base coating seems to be very effective in infection, corrosion resistance, osseointegration, *etc.* Similarly, in polymer-based coating-polyethylene oxide, polyethylene glycol hydrophilic polymethylacrylic acid, *etc.* are observed to be as effective as an antimicrobial. Considering bioactive coating materials, bisphosphonate and zoledronic are beneficial for mitigating the foreign body and improving osseointegration [4, 5].

IMPORTANCE OF ORTHOPEDIC IMPLANTS

Materials for the creation of medical devices were just as readily available in the 20th century as they were for other industrial uses. Indeed, early surgeons created their implants from materials that had a proven track record of successful industrial use in fields like energy, mechanical, aerospace, *etc.* The demands on the prosthetic industry are increasing day by day. A recent report states that the number of hip as well as knee implants has increased to US $ 14 billion worldwide in 2011 and it was further expected to reach by about 7% up to now. Among all the prostheses used, hip, knee, and spinal replacements are extremely high and their number has markedly increased worldwide over the last two decades. It is estimated that as the data is collected, approx. 1 million hip replacements and 2,50,000 knee replacements are carried out each year and the number is expected to be twice in 2025 [6 - 8].

BIOMATERIALS

Biomaterials are substances, engineered to take a form that alone is utilized to direct, by control of interactions with parts of the biological system, the course of any therapeutic or diagnostic procedure in humans or veterinary medicine by Williams [9].

Classification of Biomaterials

Biomaterials are classified into four types on the basis of their application in the medical field *viz.* metals and alloys, ceramics, polymers, and composites. The classification of biomaterials is shown in Fig. (**1**) [10, 11].

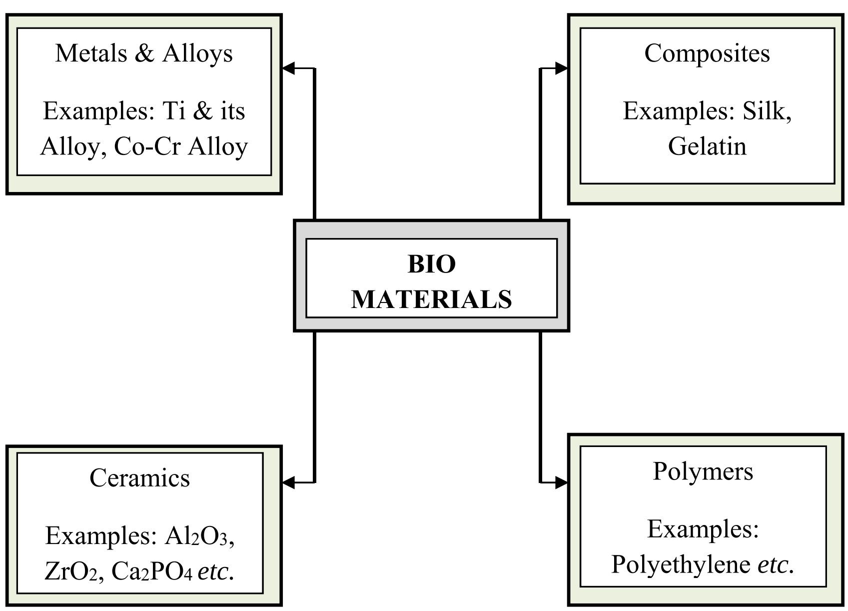

Fig. (1). Biomaterials classification [11].

CHAPTER 10

Cold Spray Coating of Nano Crystallization Material, Method, Properties and Challenges: A Critical Review

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Abstract: In the 1980s, a deposition technique known as cold spray solid-state coating was created. Cold spray technology, unlike conventional thermal spray techniques, can maintain the natural properties of the feedstock, prevent damage to the constituent elements of the substrate and create extremely solid coatings. Nanostructured coatings have the potential to significantly enhance their properties compared to conventional, non-nanostructured coatings. Furthermore, surface coating on metal substrates is a very difficult challenge for the researcher due to the contradictory requirements for various properties. The ability of cold spray to form coatings with nanostructures has also been demonstrated to a great extent. This work aims to provide an in-depth analysis of nanostructured cold-sprayed metal coatings. First, a description of the cold spray technique is given. Next, the issue of Nano crystallization in standard metal coatings is discussed. Then, microstructures and properties of nanomaterial-reinforced metal matrix composite (MMC) coatings and cold-sprayed nanocrystalline metal coatings are discussed. In conclusion, a summary and future prospects for cold spray technology are given. To conclude, the process of developing nanostructured metal coatings has been completed.

Keywords: Coating thickness, Gradient properties, Process parameters.

INTRODUCTION

In the early 20th century, Max Ulrich developed the therapeutic spray technique. Coatings are thermally sprayed on ferrous and non-ferrous metal materials to improve their surface properties. Various states of particles were sprayed onto the substrate to increase the coatings' properties [1]. Cold spray solid-state coating uses a converging divergent nozzle to drive powder against a substrate at a very high velocity. Globally, the industry uses a lot of energy and contributes signifi-

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cantly to environmental pollution [2]. For the last 20 years, traditional thermal spray technology like HVOF has been employed, particularly in the coatings business. This process takes a lot of energy and emits hazardous pollutants into the environment. The coating surface must be made using a clean manufacturing process to address this issue. Powder heating at low temp is used to generate the coating during the spray process, which offers a hygienic production environment. It possesses ultimate applications in the industries [3, 4].

An efficient additive manufacturing technique called cold spray uses a gas flow to excite the alloyed particles before their deposition on a substrate at a particular pressure and temperature. The fact that initially during CS deposition, powder particles remain in the solid state, they may be advantageously used to limit the danger of oxidation, phase change, and increased temp stresses. CS has been used to accelerate the surface functionalization of components used in a range of applications, and it may be utilized to deposit different pure metals and their alloys. Cold spraying, which differs considerably from other techniques in that the process temperature is frequently kept the particle, employs kinetic energy instead of thermal energy to deposit particles [5]. Numerous models have been used to study the mechanics of bonding, but these mechanics are still poorly understood [6]. There is now a link between adiabatic shear instability and the maximum possible bonding contrivance of the cold spray procedure [7]. The thin oxide layers that protect the particles in this mechanism during impact are disrupted, allowing for intensive particle-substrate interaction [8]. The method employs temperatures below 800 °C, in contrast to traditional thermal spraying processes, which use temperatures exceeding 2000 °C. Consequently, the impact speed of the powder elements on the surface is around the opposite side. Cold spray technologies can also be used to create tremendously thick and hefty coatings along a thickness range of 100 µm to 1500 µm [9]. If low oxygen concentration and low porosity coatings could be achieved, the cold spray was used to deposit ductile materials like copper and aluminium. The development of coatings employing less ductile materials, such as titanium and its alloys, is attracting more attention for further study. There are benefits to employing cold spray technology to deposit titanium coatings because it is a method of solid-state powder deposition that produces coatings with less oxide content without a protective setting or vacuum. Cold spray is a solid-state processing method since it is the only thermal deposition method that allows particles to be placed below their melting temperature. The features of coatings formed using CS differ from those of coatings created using other techniques.

Due to the coating advantages of cold spray over other spraying methods as HVOF and APS, its significance has increased [10 - 22]. The features of the numerous metal powders used to create cold-sprayed coatings are briefly covered in this text.

WORKING PRINCIPLE AND NANO CRYSTALLIZATION PHENOMENA

Working Principle

In the 1980s, Anatoly Papain and his associates created cold spray technology in Russia. Powder hopper, gas heating oil, and spraying section are the main parts of the system. For this process, high-pressure helium or nitrogen gas has been used. A supersonic nozzle (De Laval nozzle) is used to inject the powder at a high velocity onto the substrate in the feedstock after heating it below its melting point. The coating's low porosity, high cohesion strength, and strong adhesion as well as plastic deformation during manufacture increase its hardness, resistance to corrosion, and resistance to wear. To fully take use of titanium's potential advantages, the characteristics of cold-sprayed titanium coatings must be enhanced. This study's objective is to look at the link between the characteristics of titanium coatings and process variables such as gas pressure and temperature. Coatings may be applied over bulk materials in a variety of ways at low cost and an effective method for adding new properties to bulk materials, primarily to enhance their functionality and service life.

Nano Crystallization Phenomenon

Between the interfacial regions, particles experience intense plastic distortion. At extremely distorted jetting zones, adiabatic shear instability takes place, thus a hike in temperature rises [23 - 33]. Visibly, these structures presented a clear variation from the particle's top surface to the bottom. The successful creation of nanostructured coatings, which comprise at least one component with a nanometer-scale component, is a result of the special features that nanomaterials provide in comparison to micro-sized materials. Because they offer better surface protection, nanostructured coatings are used in a variety of industries, including electronics, medical, food packaging, and transportation [24]. Numerous parameters affect the development of nanostructured coatings as depicted in Fig. (**1**).

In some situations, nanocoatings might not be effective as protective surfaces. Due to the high density of their grain boundaries, which allow for quick diffusion routes for passivated ions and improved adherence of the protective oxide layer to the substrate's surface, nanocoatings are efficient physical barriers in high-temperature applications [26]. However, because there are more anodic sites because of the greater grain boundary percentage, the surface is more vulnerable

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