Available online at https://www.gyanvihar.org/researchjournals/ctm_journals.php
SGVU International Journal of Convergence of Technology and Management
E-ISSN: 2455-7528
Vol.10 Issue 2 Page No 28-42

Development of Composite Coating of PEEK and AgNP on 316L Stainless Steel Substrate for Biomedical Implants

[1]Hemant Parashram Pathade, [2]Dr. Neeraj Kumar, [3]Dr. A. Haldar
[1, 2, 3] Department of Mechanical Engineering, Suresh Gyan Vihar University,
Jaipur, Rajasthan, India
[1]hemantpathade@gmail.com

Abstract— Biomedical implants are advanced devices crafted to either replace or support biological structures in the human body, aiming to enhance functionality, improve quality of life, and even save lives. These implants are constructed from diverse materials chosen for their ability to integrate seamlessly with biological tissues, exhibit biocompatibility, and possess appropriate mechanical properties. The development of biomedical implants has advanced over decades, propelled by advancements in materials science, engineering, and medical technology. Key materials include metals like titanium, stainless steel such as 316L, and Cobalt-Chromium alloys like CorNiCe, along with polymers like Polyether-ether-ketone (PEEK) and bioceramics such as hydroxyapatite. Each material offers distinct advantages suited to various types and applications of implants. Biomedical implants fulfill a wide range of medical needs across different disciplines. Orthopedic implants, for example, replace damaged joints or bones, restoring mobility and alleviating pain. Cardiovascular implants like stents support blood flow in arteries affected by conditions like atherosclerosis. Dental implants replace missing teeth, supporting prosthetic teeth or bridges. Neurological implants can restore hearing or help manage symptoms of Parkinson's disease. The success of biomedical implants hinges on their biocompatibility, ensuring they do not provoke immune responses or tissue rejection. Advances in surface modifications and coatings enhance biocompatibility and promote integration with surrounding tissues, ensuring long-term stability and functionality. Designing and fabricating biomedical implants involves rigorous testing to ensure safety and efficacy. This includes mechanical testing for durability, biocompatibility assessments, and often, clinical trials to validate performance in real-world conditions. Regulatory bodies like the FDA in the US oversee the approval process, ensuring implants meet stringent standards before entering the market. Future research aims to enhance implant materials, reduce infection rates, extend longevity, and develop smart implants capable of monitoring physiological parameters or delivering therapeutic substances. As technology progresses, biomedical implants continue to evolve, offering new possibilities and improved patient outcomes worldwide. The development of a composite coating using Polyether-ether-ketone (PEEK) and silver nanoparticles (AGNP) on a 316L stainless steel (SS) substrate aims to enhance biocompatibility and antibacterial effectiveness. PEEK contributes mechanical strength, biocompatibility, and resistance to biofilm formation, while AGNP provides antimicrobial properties against pathogens. This approach integrates the corrosion resistance and mechanical strength of 316L SS with the advantageous characteristics of PEEK and AGNP, potentially improving the durability and infection resistance of biomedical implants, especially in vascular stents and orthopedic devices.

Keywords— 304 Stainless Steel, 316 L stainless steel, PEEK and AGNP CoCrNiFe (Cobalt-Nickel-Chromium-Molybdenum alloy), Ti6Al4V (Titanium-6 Aluminum-4 Vanadium alloy), CoCrSS (Cobalt-Chromium Superalloys (CoCrSS), CoCrMo (Cobalt-Chromium-Molybdenum), Mercury from gold**.**

I. INTRODUCTION

Biomedical implants are innovative devices created to either restore or improve the functionality of human tissues and organs [1]-[4]. They have transformed medical treatments by providing solutions to diverse conditions, from injuries to chronic diseases. These implants aim to replace, support, or improve biological structures affected by injury, disease, or congenital issues [5]-[7].

Correspondence to: Hemant Parashram Pathade, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
Corresponding author. E-mail addresses: hemantpathade@gmail.com

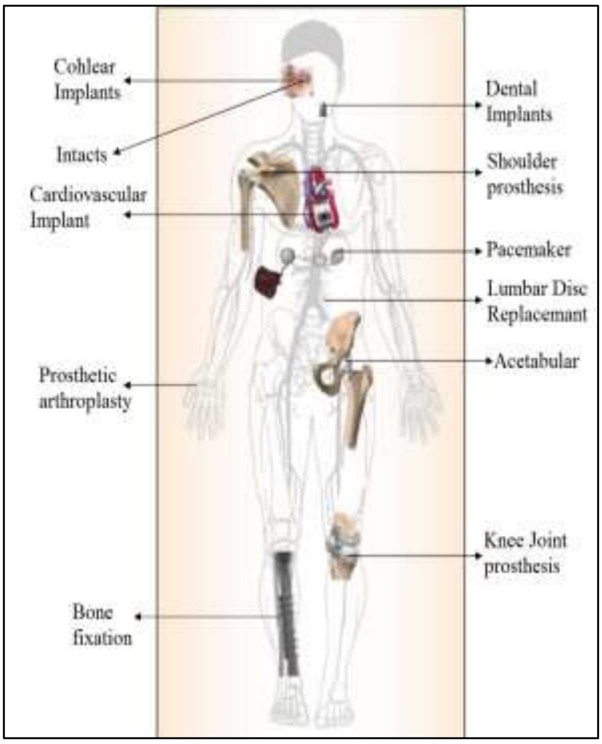

Fig. 1 Biomaterials used for implant [1]

Their development involves advanced materials science, engineering, and medical innovation, ensuring they meet biological, mechanical, and physiological needs for compatibility and durability within the human body. Critical to their success is the careful selection of materials with essential properties tailored to their specific applications [2]. Biomedical materials, similar metals (such as alloys made of titanium and stainless steel), polymers (such as polyethylene and silicone), ceramics (including alumina and zirconia), and composites (like carbon fiber-reinforced polymers), are chosen for their biocompatibility, mechanical robustness, corrosion resistance, and capacity to fuse with biological tissues [1]. Each material offers distinct advantages tailored to specific medical needs, ensuring optimal performance and long-term viability. For example, stainless steel alloys such as 316L are valued for their corrosion resistance and mechanical properties, adapting them for use in orthopedic implants, surgical instruments, and cardiovascular devices. Titanium alloys like Ti6Al4V are known for their lightweight nature, excellent biocompatibility, and high strength-to-weight ratio, making them ideal for applications such as joint replacements and dental implants [6].

TABLE 1

MECHANICAL PROPERTIES OF METAL-BASED BIOMATERIALS USED INTENSIVELY IN ORTHOPEDICS

Material	Elastic Modulus (Gpa)	Tensile Strength (Mpa)	Compression Strength (Mpa)	Yield Strength (Mpa)	Elongation at Break (%)	Vickers hardness (Hv)
316 L steel	193-200	579-1351	480-620	290	40	190
Ti-6Al-4V	110	760–970	896-1172	850–900	14	349
Co-Cr & Ni-Mo alloy	220–230	450–1896	980-1450	240–450	50	450
Human bone	30	137.3		51-66	1.49	26.3

Polymer materials such as polyethylene and silicone offer flexibility, ease of fabrication, and compatibility with soft tissues, making them valuable For applications like breast implants, catheters, and drug delivery systems. Ceramics like alumina and zirconia provide excellent wear resistance, biocompatibility, and durability, suitable for load-bearing roles in hip and knee replacements [7].

TABLE 6

BIOCOMPATIBILITY, CORROSION RESISTANCE, APPLICATIONS, ADVANTAGES AND DISADVANTAGES OF POLYMERIC BIOMATERIALS UTILIZED IN ORTHOPAEDICS

Material	Properties	Biocompatibility	Corrosion Resistance	Applications	Advantages	Disadvantages
Ultra-High Molecular Weight Polyethylene (UHMWPE)	Melting point is low, Chemical stability is Poor, Electrical conductivity is very	Good	Excellent	surgical orthopaedics, medical tubing, implants for the spine, bone	High strength-to-weight ratio, Chemical resistance	Low melting point, Processing difficulty

Polymethylmethacrylate (PMMA)	low, Thermal conductivity is very low to intermediate, Mechanical deformation is very high, plastic (can be easily shaped and processed), Thermally unstable; low strength			screws, Replacement of Joints, rebuilding the face, stents, heart valves, dental implants	Sturdy and non-biodegradable design with good flexibility	Shrink during polymerization
Polyetheretherketone (PEEK)					Good mechanical properties, Chemical resistance	Inadequate surface qualities and aesthetic function

Composite materials like carbon fiber-reinforced polymers offer a blend of strength, lightweight properties, and corrosion resistance, making them valuable for applications in orthopedic implants and prosthetic limbs. Advances in computer-aided design (CAD), 3D printing, additive manufacturing, and biomaterials engineering guide the design and fabrication of biomedical implants, enabling precise customization to match individual patient anatomical and physiological characteristics, thereby improving surgical outcomes and patient recovery. Biomedical implants undergo extensive testing and regulatory scrutiny to ensure they are safe, reliable, and effective [5]-[8]. Preclinical studies assess biocompatibility, mechanical performance, and long-term durability, while clinical trials evaluate how implants perform in humans under controlled conditions. The field is rapidly evolving due to ongoing research and innovation aimed at overcoming challenges like implant rejection and infections and improving long-term outcomes. Future trends include smart implants with sensors to monitor health metrics and adjust treatment in real-time, as well as bioactive coatings and biomimetic materials to enhance tissue integration and reduce complications. Biomedical implants are crucial in modern medicine, offering transformative solutions that restore health, mobility, and quality of life to millions worldwide. Continued advancements in technology and understanding of materials and biology promise further innovation and improved patient care [9]-[13].

II. LITERATURE REVIEW

Biomaterials are utilized in fabricating devices designed to interface with biological systems, aiming for durable performance and minimal risk of failure [1]-[4]. Biomaterials are "nonviable materials used in medical devices, intended to interact with biological systems," according to Williams (1981).' These materials find extensive application in repairing, replacing, or augmenting damaged or diseased components of the skeletal system, including the teeth, joints, and bones, with various applications delineated by Hench (1985). An indispensable criterion for biomaterials is their capacity to interact harmoniously with bodily tissues, avoiding adverse effects [1]. Biocompatibility, crucial for any biomaterial, denotes its ability should execute well and evoke a suitable response from the host for its intended purpose [2]. For orthopedic implants aimed at bone fractures and replacements, materials must exhibit chemical stability, mechanical strength, and compatibility with bodily fluids and tissues. Corrosion represents a substantial hurdle to the durability and functionality of metallic and alloy orthopedic devices [5]-[7]. Cobalt-chromium (Co-Cr) alloys, titanium and its alloys, and stainless steel (SS) are among the metals and alloys frequently found in biomedical implants. Stainless steel implants are susceptible to localized corrosion such as pitting and rusting in cracks. Titanium creates a stable coating of TiO_2, yet wear can still lead to the release of particles into the body [8]. To address these challenges and improve biocompatibility, various strategies are employed. These include adding titanium and nitrogen to stainless steel to change their surface qualities, covering stainless steel surfaces with bioceramic coatings, and ion implantation. These approaches are aimed at enhancing the performance and longevity of orthopedic devices [9]-[12].

The human body poses significant challenges to implanted metal alloys due to its saline, oxygenated atmosphere with a pH of approximately 7.4 and a temperature of 98.6°F (37°C). Chloride solutions, found in the body, are particularly corrosive to metals. Biomedical corrosion is further complicated by the body's specific ionic composition and protein concentration. While changing the composition of an alloy can have an impact on its mechanical, physical, or electrochemical properties, these modifications pale in comparison to the diversity brought about by utilizing various manufacturing processes. Therefore, it is crucial for biomedical applications of major metals and alloys to carefully consider these factors. Medical applications include cranial plates, orthopedic fracture plates, dental implants, spinal rods, joint replacement prostheses, stents, and catheters, among other applications where 316L stainless steel is widely used. Applications for cobalt-chromium and titanium alloys include maxillofacial reconstruction, orthopedic fracture plates, heart valves, spinal rods, joint replacements, orbit reconstruction, dental implants, stents, and ablation catheters. These alloys include Nitinol, Ti-6Al-4V, Ti-5Al-2.5Fe, and Ti-6Al-7Nb. Processes like heat treatment, cold working, and surface finishing are essential to maximize the performance of these metals, particularly when it comes to strengthening their resistance to wear and corrosion. Because metals are naturally prone to corrosion, pre-passivation is usually performed on implants before final packaging. Methods such as electrochemical anodizing or acid baths for titanium alloys, and electropolishing for cobalt and stainless steel alloys, are used. The choice of alloy for implants hinges on whether they will bear loads and necessitate resistance to

Correspondence to: Hemant Parashram Pathade, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
Corresponding author. E-mail addresses: hemantpathade@gmail.com

wear and fretting. In situations without movement, like static scenarios, galvanic couples can still form, although the difference in potential between the metals is less critical compared to the necessary strength-to-weight ratio and yield strength. To fasten a titanium alloy bone fracture repair plate, for example, stainless steel screws may be used [13]-[15].

Biomaterials are essential for humanity, significantly benefiting individuals with congenital heart disease and elderly patients who rely on biomedical implants to prolong their lives. Older adults often need geriatric physicians' assistance due to various ailments stemming from their long-used and worn-out body systems. Arthritis is a common condition affecting many elderly and sometimes younger individuals, causing immobility and severe pain. Despite significant scientific progress, the exact cause of arthritis remains unknown. Bioimplants are increasingly essential not only for individuals with diseases but also for young, active people like athletes who frequently require replacements as a result of fractures and extreme strain. The significance of biomaterials became apparent post-world wars and has grown more critical amid global terrorism. Today, bioimplants are widely employed across various medical fields including Veterinary medicine, dentistry, orthopedics, cardiology, plastic and reconstructive surgery, ophthalmology, neurology, immunology, histopathology, and experimental surgery. A variety of materials, including metals, alloys, polymers, ceramics, and composites, are used to create these implants. Bioimplants encounter complex biological environments involving tissues and bones. Early in human history, scientific understanding was limited, but credit for modern bioimplants goes to pioneers like Paul Winchell, Otto Wichterle, John Charnley, Per-Ingvar Branemark, Harold Ridley, and others. Their experimental innovations, initially tested on animals, laid the groundwork for biomaterials compatible with the human body. Ancient Egyptians and Romans utilized materials like wood for furniture, gold and iron for dentistry, and linen for sutures and prosthetics, despite facing challenges due to limited knowledge of corrosion. Following World War II, materials including silicone, nylon, Teflon, stainless steel, and titanium significantly expanded the range of biomaterials available [1]-[4].

Biomaterials include materials, both natural and synthetic, designed to replace or repair bodily parts to mimic natural living tissues or organs thereby enhancing human health. They must exhibit biocompatibility and, depending on their purpose, may require biodegradability or bioabsorbability. Biomaterials fall into categories such as metals, polymers, ceramics, or combinations thereof. This overview focuses particularly on metallic biomaterials, emphasizing their wide-ranging applications. Commonly employed Alloys made of titanium, cobalt-chromium, and stainless steel are examples of metallic materials [1]-[5].

The weld metal of stainless steel 316, which contains 0.07% nitrogen, underwent manual metal arc welding (MMA). Pitting corrosion susceptibility was evaluated in welding and aging scenarios. After aging at temperatures of 1023 K and 1123 K for durations ranging from 0.5 to 100 hours, microstructural studies were conducted. Electrochemical potentiokinetic analysis indicated no reaction peak, suggesting no chromium-depleted zone, and indicating resistance to pitting corrosion against Laser melting deposition (LMD) was used to examine the microstructure and corrosion performance of stainless steel 316, focusing on the weld metal's sigma, carbide, and Cr2N phases after being aged for 100 hours at 1123 K. The use of a ring-shaped beam in LMD aimed to minimize residual stress, prevent sintering, control heat accumulation, and enhance surface coating quality. The research explored how different processing parameters affect the electrochemical corrosion resistance of stainless steel 316 coatings. It was observed that stainless steel 316 demonstrates enhanced corrosion resistance, with a 30% improvement compared to stainless steel 304 substrates. Stress corrosion cracking tests identified intergranular cracks and a network of grain boundaries within stainless steel 316. It has been discovered that substantial grain clusters are essential for enhancing grain boundary engineering. Moreover, a thioacetate-functionalized monolayer was formed on SiO2-coated SS316 using a thioacetate hexadecyltrimethoxysilane [13], [21], [23].

In modern healthcare, advancing patient survival rates and quality of life hinges on developing implantable materials that closely mimic natural body functions. These materials need to fulfill certain requirements: they need to be dependable, secure, able to withstand the environment inside the body, non-carcinogenic, inert to living tissues and possess a significant amount of mechanical strength. These days, a vast range of materials are employed, including ceramics (bioinert, bioglass, and bioresorbable types), metals and alloys (such as Ti, stainless steel, Co–Cr, Ta, Nb, Zr, Mg, and Fe alloys), carbon nanostructured implants, and polymers (such as meshes and composites). These materials are indispensable in orthopedics, traumatology, cancer, and reconstructive surgery because of their excellent biological compatibility, flexible mechanical and physical capabilities, resistance to corrosion, and other beneficial attributes. Biomaterials, despite their wide range, don't universally address all medical challenges due to limitations in strength, integration properties, fixation complexity, and biointegration. For instance, metal implants with a high elasticity may eventually lead to metallosis, or bone resorption, when metal ions permeate the surrounding tissues. Despite their corrosion resistance, ceramic implants are delicate and have a high modulus of elasticity, which prevents them from being used in mechanically stressed locations. Large ceramic implants also lack sufficient mechanical strength. Additionally, polymers can release low-molecular-weight substances as they age, posing toxic and carcinogenic risks to the human body [5], [9], [12].

Polyether-ether-ketone (PEEK) has become a promising alternative to conventional materials like titanium and zirconia in the field of implant dentistry. Although pure PEEK has limited antimicrobial activity,

Correspondence to: Hemant Parashram Pathade, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
Corresponding author. E-mail addresses: hemantpathade@gmail.com

Various approaches have been studied to lessen the development of biofilms and bacterial colonization on its surface. These approaches include sulfonation of PEEK, incorporation of therapeutic agents, application of bioactive coatings, and development of nanocomposites. The research underscores the significance of surface characteristics like contact angle and roughness in influencing biofilm formation, with studies focusing on germs like Staphylococcus aureus and Escherichia coli are initially vulnerable to biofilm formation, innovative methods have shown encouraging outcomes in enhancing PEEK's antibiofilm and antimicrobial properties [43]-[39].

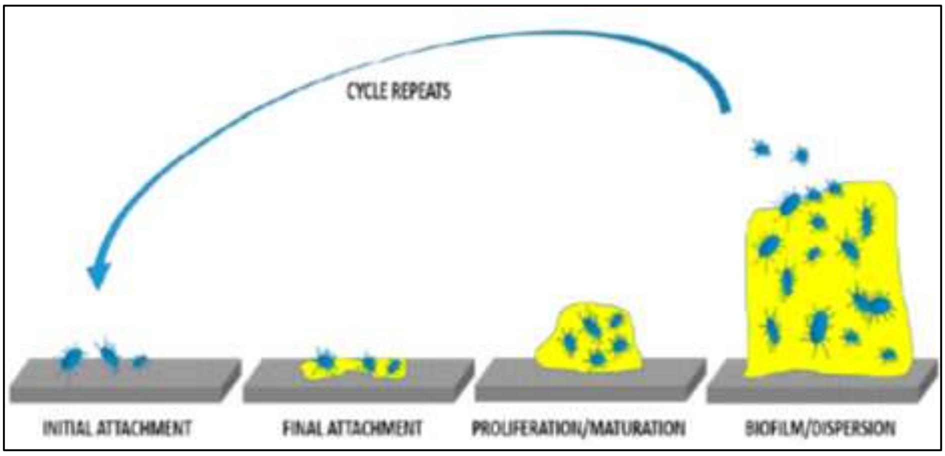

Fig. 4 The biofilm development on implants surfaces [6].

In orthopedic surgery, infections often cause implant failures. Silver nanoparticles (AgNPs) are effective antibacterial agents used in modifying orthopedic implants to prevent infections. It's vital to understand their precise antibacterial mechanism to optimize implant designs. AgNPs can impact osteogenic cells by affecting their adhesion, proliferation, and differentiation. Enhancing AgNPs' biocompatibility and utilizing advanced implant modification technologies are critical. Despite routine antibiotic use, challenges like antibiotic resistance and bacterial biofilm formation on implant surfaces reduce antibiotic efficacy. Thus, there is an urgent requirement to identify a potent antibacterial agent to combat drug-resistant bacteria and to alter prostheses to prevent biofilm formation. Silver (Ag) is known for its robust antibacterial properties and is extensively used in medical applications. Silver nanoparticles (AgNPs), created via nanotechnology, offer improved physical, chemical, and biological characteristics. Recent interest has grown in employing AgNPs to modify orthopedic implants for infection prevention. Research indicates that AgNP-coated external fixation pins, mega-prostheses for large bones like the femur or tibia, and bone cement incorporating AgNPs effectively inhibit infections. Despite their promising potential, further investigation is required to elucidate the AgNPs' unique antibacterial actions and how they affect osteogenic cells [39]-[45].

Silver is widely available and known for its antimicrobial effects, primarily owing to silver ions having a broad range of properties against bacteria. Unlike antibiotics, silver is less poised to contribute to the progress of multidrug-resistant bacteria. But when applied directly, halide ions, like chloride, can bond with silver ions, reducing their effectiveness over time. To address this, silver nanoparticles (AgNPs) have been synthesized and are used extensively. These nanoparticles release silver ions more effectively due to their high specific surface area. AgNPs, particularly those smaller than 10 nm, also show antiviral properties, although their overall antimicrobial effect is weaker than bulk silver. Given these characteristics, AgNPs are valuable in combating infectious diseases, prompting the development of medical tools coated with them [40].

Coated silver nanoparticles (AgNPs) have garnered significant attention for their diverse applications across electronics, antimicrobial treatments, industrial uses, optics, and medical expertise including biosensing and drug delivery systems. But still, their adoption in medical applications remains constrained by potential cytotoxicity concerns. Researchers have addressed this by coating AgNPs with various substances, effectively mitigating their toxicity. The kind of coating material and its thickness have an impact on the characteristics of coated AgNPs, impacting their performance. This review explores current advancements in (a) synthesizing coated AgNPs, encompassing methods and materials used for coating, (b) assessing the cytotoxic effects of the coating of AgNPs; and (c) evaluating these nanoparticles' optical properties [40].

Silver (Ag) is a versatile chemical element with applications in medicine, electronics, and household products. For instance, silver sulfadiazine is commonly used to treat burn wounds by preventing biofilm formation and promoting wound healing. Despite its valuable properties, silver is classified as a precious metal due to its limited availability. One drawback is its susceptibility to oxidation when exposed to oxygen, which limits its use in certain applications. Recent advancements in nanoscience and nanotechnology have enabled the production of Compared to other nanoparticles, silver displays distinct physical, chemical, and biological characteristics of larger-scale silver materials. These nanoparticles are extensively

Correspondence to: Hemant Parashram Pathade, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
Corresponding author. E-mail addresses: hemantpathade@gmail.com

studied using various analytical techniques to explore their potential applications [42], [43].

Bone is a multifunctional tissue in vertebrates, serving roles like mechanical support, organ protection, and calcium storage. The demand for bone recovery due to various factors like tumors, infections, osteoporosis, and aging is increasing annually. Orthopedic surgeries worldwide perform over four million bone-related operations yearly. Implants and scaffolds in orthopedics typically use materials that promote bone regeneration. Addressing diverse patient needs involves customizing implants and scaffolds for biological and mechanical compatibility, posing clinical challenges related to anatomical locations, sizes of defects, mechanical characteristics, and patient circumstances. developments in tissue engineering, nanotechnology, biomanufacturing, and biomaterials sciences have significantly benefited bone-related research by addressing complications and failures associated with conventional materials. Among the metallic and metallic oxide nanoparticles that have been the focus of many studies are zirconia, silver, gold, and magnesium. These nanoparticles are mainly used in orthopedic implants and scaffolds for cell labeling, bioactive molecule transport, and improving the characteristics of the implant and scaffold [9]-[17]. This review focuses on recent advancements, functions, and applications of these nanoparticles in orthopedic contexts, highlighting current challenges and future research directions.

Silver has a long history of use as an antimicrobial agent, often in conjunction with other technologies. It has been applied in various forms, such as silver sulfadiazine or silver nitrate, in burn and ulcer treatment creams and dressings. Silver has also been used in home equipment like refrigerators and washing machines, as well as in food packaging to avoid contamination for its antimicrobial properties. With the rise of nanotechnology, there has been a dedicated investigation into the antibacterial properties of silver nanoparticles (AgNPs). The greater surface area-to-volume ratio of these nanoparticles which range in size from 1 to 100 nm makes them more efficient against bacteria than bulk silver. At the nanoscale, AgNPs exhibit distinct electrical, optical, and catalytic characteristics, making them valuable for uses for specific medication delivery, diagnostics, detection, and imaging. The exceptional antibacterial properties of silver nanoparticles (AgNPs) have garnered significant interest from researchers and industries alike. AgNPs exhibit strong antimicrobial effects against a wide range of pathogenic and infectious microorganisms, including those with multidrug resistance. Their increased antibacterial effectiveness at the nanoscale is especially advantageous in settings related to health and medicine, where AgNPs are being explored for integration into various products. Silver nanoparticles (AgNPs) are utilized in a range of applications, such as apparel, cosmetics, dental goods, catheters, dressings, and equipment for handling food and surgery. Their effectiveness as antibiotics is attributed to their ability to target multiple structures within microorganisms, allowing them to combat different types of bacteria simultaneously [43].

In recent research, hydroxyapatite (HA) has gained significant attention as a coating on 316L stainless steel implants. This approach aims to enhance biological stabilization, promote bone growth around implants, and optimize recovery times. HA, a bioceramic, is valued for its in-vitro bioactivity, osteoinductive, and osteoconductive properties. Previous studies have shown that implants coated with HA can successfully achieve low corrosion current density, increase bone development and renewal, and achieve good corrosion resistance. In this paper, the researchers evaluated previous investigations on hydroxyapatite (HA) and its composite coatings' application process, mechanical and physical properties, in vitro bioactivity, and biocompatibility on substrates made of 316L stainless steel. Their findings indicate that HA and its composites can synergistically enhance corrosion resistance, promote biocompatibility, facilitate direct tissue bonding, expedite treatment, and potentially reduce healthcare costs [10], [25], [27], [30].

Surface coating technology plays a crucial role in enhancing orthodontic appliances by improving properties including improved corrosion resistance, less friction, and antibacterial properties This technology not only boosts treatment efficiency and safety but also mitigates side effects while prolonging appliance durability. Commonly used materials for functional coatings include metals, metallic compounds, polymers, bioactive materials, and carbon-based materials substances. These coatings are often applied in layers onto substrates using methods like chemical deposition, sol-gel dip coating, and physical vapor deposition (PVD). While studies show diverse coatings effectively enhance appliance performance, achieving optimal combinations of these properties remains a challenge, requiring further safety and durability validation [9]-[16].

The primary emphasis lies in detailing contemporary approaches to surface modification of stainless steel (SS), aimed at altering surface properties like chemistry, topography, and wettability/surface charge while preserving its bulk characteristics. For medical applications, stainless steel (SS) is still a popular choice because of its good biocompatibility and outstanding mechanical qualities. It finds extensive use in manufacturing orthopedic prostheses, cardiovascular stents/valves, and more recently, in the additive manufacturing of personalized implants using three-dimensional (3D) printing. Despite its strong mechanical characteristics, stainless steel (SS) lacks optimal functionality, leading to susceptibility to bacterial adhesion and biofilm formation. Given the rising antibiotic resistance among bacteria, there is a critical need to develop implants with antibacterial properties. Various strategies have been proposed and are explored here. Particularly noteworthy are innovative approaches involving treatment with highly reactive plasma, which can potentially modify the topography, chemistry, and

Correspondence to: Hemant Parashram Pathade, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
Corresponding author. E-mail addresses: hemantpathade@gmail.com

wettability of SS under specific treatment conditions [18]-[22].

Polyether ether ketone (PEEK) is widely used in orthopedic implants due to its exceptional mechanical and biocompatibility properties. However, bacterial infections and aseptic loosening can lead to implant failure. Researchers have created a biocompatible and antibacterial coating for PEEK implants using a surface modification technique with polydopamine (PDA). This is followed by the deposition of silver (Ag) nanoparticles, resulting in the PEEKPDAAg coating. This approach aims to enhance the integration of implants with bone tissue and improve overall implant success rates. The formation of silver nanoparticles on PEEKPDAAg surfaces was observed via scanning electron microscopy. PEEKPDAAg showed significant antibacterial activity against both S and MRSA while also demonstrating minimal toxicity to MC3T3E1 cells. aureus and E. coli in vitro, with effective antibacterial performance also observed in vivo. Furthermore, in vivo, studies indicated favorable osseointegration of PEEKPDAAg implants, supported by micro CT evaluation and pushout tests. Overall, these findings suggest that PEEKPDAAg substrates, easily prepared, offer significant biocompatibility and antibacterial capabilities, making them a promising material for orthopedic implants [34]-[39].

Electrophoretic deposition (EPD) of PEEK-Al2O composite coatings on 316L stainless steel substrates employing ethanolic solutions comprising micrometer-sized PEEK particles and nanoscale alumina. Zeta potential and transmission electron microscopy studies verified that the homogeneously produced composite coatings, including 20 to 70 weight percent PEEK, demonstrated interparticle electrostatic interactions. With increasing deposition time and applied potential difference, the EPD yield grew logarithmically. To increase substrate-coating adherence, reproducible PEEK-alumina coatings needed to be heat treated for 30 minutes at 343°C at a rate of 10°C per minute. One economical method for producing PEEK-Al2O3 composite films on metallic substrates is electrophoretic deposition or EPD. Hardness assessments and scratch tests showed that the coatings had high alumina content, suggesting that even a lower amount of alumina could still significantly improve mechanical properties. When assessing corrosion resistance in a chlorine environment, When compared to uncoated stainless steel substrates, PEEK-alumina composite coatings demonstrated a significant increase in pitting potential, outperforming pure PEEK films [16], [24], [35], [36].

Silver nitrate is reduced with sodium borohydride in a polyvinyl pyrrolidone (PVP) solution to produce silver nanoparticles (AgNPs). The creation of metallic nanoparticles with an average size of 32 nm was confirmed by dynamic light scattering and transmission electron microscopy. They then used an epoxy glue at room temperature to cover a PEKK polymer substrate with 0.5% AgNPs. By giving the PEKK framework antibacterial qualities, this coating technique hopes to lower the risk of periodontal disease in people wearing removable partial dentures. FTIR (Fourier transform infrared) spectroscopy to verify the AgNP-in-resin coating's successful transfer to a polymeric surface. AgNPs were consistently deposited on PEKK samples, as validated by atomic force microscopy (AFM) and scanning electron microscopy (SEM). In comparison to untreated PEEK, evaluation against Porphyromonas gingivalis showed a 22.5 mm inhibitory zone and an 83.47% antibacterial efficacy rate for 0.5% Ag-PEKK, suggesting a great potential for antibacterial uses in implants [12].

Metal nanostructure-treated polymers are well-known for their ability to induce antibacterial effects in medical applications. However, achieving an optimal balance between bactericidal effectiveness and acceptable cytotoxicity levels, typical of metal nanostructures, has hindered their widespread adoption. This study investigates the integration of silver nanoparticles (AgNPs) onto polyetheretherketone (PEEK) surfaces using periodic surface structures produced by lasers (LIPSS). The research highlights laser-induced forward transfer technology as a viable method for uniformly decorating PEEK surfaces with AgNPs, whether the surface is smooth or LIPSS-patterned. The antibacterial study demonstrated that nanostructured PEEK containing AgNPs, when compared to flat surfaces with similar particle concentrations, exhibited superior bactericidal efficacy. This innovation suggests the potential for creating templates that enhance the production of antibacterial biopolymers through replication processes, or for direct application in tissue engineering [39-42].

Polyetheretherketone (PEEK) is recognized for its outstanding mechanical chemical characteristics. It exhibits high thermal stability, The material exhibits a glass transition temperature at 143°C and melts at 343°C, making it highly suitable for structural and insulation purposes. PEEK is also biocompatible, making it ideal for medical device applications. Research has expanded significantly into developing PEEK coatings through various methods, including printing, electrophoretic deposition, thermal spraying, plasma spraying, and flame spraying [38].

A method involving electrophoretic deposition (EPD) was used to successfully apply PEEK-Al2O3 composite coatings onto 316L stainless steel substrates. The coatings, made from ethanolic suspensions containing nanoscale alumina and micrometer-sized PEEK particles, were recognized for their consistent and even application. PEEK concentrations in the coatings varied between 20 to 70 wt.%. electrostatic interactions between the two types of particles were identified through zeta potential and transmission electron microscopy (TEM) analyses. Electrophoretic deposition (EPD) efficiency demonstrated a logarithmic growth with deposition duration and applied potential difference. The successful application of PEEK-alumina coatings was achieved through heat treatment at 343 °C for 30 minutes, with a heating rate of 10 °C/min to enhance substrate-coating adhesion. Electrophoretic deposition (EPD) proved cost-effective for creating PEEK-Al2O3 composite films on metal substrates. Research employing scratch tests and hardness measurements revealed that these coatings exhibited higher alumina content than required, suggesting the potential for significant mechanical improvements with reduced alumina levels. In chlorine environments, PEEK-alumina composite coatings demonstrated superior corrosion resistance compared to pure PEEK films, significantly enhancing the pitting potential when compared to uncoated stainless steel substrates [35].

The effectiveness of a silver nanoparticle-coated stainless steel alloy embedded in poly(DL-lactic-co-glycolic acid) (PLGA) as a material for antimicrobial implants. It demonstrated strong antibacterial properties in both laboratory and living tissue models. Additionally, SNPSA supported the proliferation and maturation of MC3T3-E1 pre-osteoblasts in vitro. In contaminated rat femoral canals, SNPSA implants promoted bone formation while effectively reducing bacterial presence. These findings suggest SNPSA has the potential to mitigate implant-associated infections and improve clinical outcomes in orthopedic surgeries [34].

Developing orthopedic coatings with antibacterial capabilities involves integrating chitosan, Bioglass particles (9.8 µm), and silver nanoparticles (Ag-np) using a one-step electrophoretic deposition (EPD) process. It investigated their structural characteristics, initial bactericidal effects, and cellular interactions in vitro, utilizing stainless steel 316 as the benchmark metallic substrate for orthopedic applications. electrophoretic deposition (EPD) containing either chitosan alone or combinations of chitosan with Bioglass. Chitosan serves a dual purpose as an agent that complexes and stabilizes, ensuring the consistent deposition of silver nanoparticles (Ag-np). The incorporation of Bioglass particles into the coatings led to bioactivity, promoting the formation of carbonated hydroxyapatite when exposed to simulated body fluid (SBF). A minimal amount (less than 7 wt.%) of the silver incorporated in the coatings was released over 28 days in SBF, with the release rate being adjustable by varying the sequence of coating layer deposition. The minimal release of Ag ions (less than 2.5 ppm) effectively suppressed the growth of Staphylococcus aureus over 10 days. Chitosan and chitosan/Bioglass coatings supported MG-63 osteoblast-like cell growth over 7 days. However, coatings with chitosan/Bioglass/Ag-np, containing 342 µg of Ag-np, showed cytotoxic effects, possibly due to the increased silver nanoparticle concentration in the coatings [15], [24], [35].

To prevent bacterial invasion on biomedical implants and improve their long-term fixation, preventing initial bacterial adherence is crucial. Surface coatings like zirconia (ZrO_2), known for their smoothness, are increasingly used to enhance implant durability. pulsed laser deposition (PLD) to apply ZrO_2 and silver (Ag) ZrO_2 composite coatings onto 316L stainless steel (316L SS) to reduce bacterial biofilm formation and enhance resistance to antibacterial agents. They examined phase purity, surface characteristics, coating thickness, and elemental compositions using techniques like X-ray diffraction (XRD), atomic force microscopy (AFM), and scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDS). The antimicrobial efficacy of these coatings against Escherichia coli (E.coli) and Staphylococcus aureus (S.aureus) was evaluated using total viable count (TVC) and epifluorescence microscopy. The study found that ZrO2 coatings showed antibacterial properties against E.coli, while Ag–ZrO_2 composite coatings were more effective against both E.coli and S.aureus strains [38].

Temperatures ranging from 200 to 550°C were used to implant heavy helium ions at 10 keV into thin 316L austenitic stainless steel foils in situ. This process generated nanometric bubbles that were overpressurized, their density and size varying significantly based on the fluence and temperature of implantation. A detailed investigation, including rigorous statistical analysis and consideration of free surface effects, explored the beginning and development of these bubbles. The results indicate that higher fluence levels promote both nucleation and growth of bubbles, while higher temperatures primarily enhance bubble growth over nucleation. By contrasting activation energies with current bubble nucleation models, insights into the underlying mechanisms were obtained [39].

Because noble metal ions like silver, cobalt, or copper are efficient against germs and fungi, the creation of novel materials infused with these ions is becoming more and more relevant in both commercial and medical applications. While many such products are primarily used in medical bandages to prevent infections or in sportswear to combat odors, advances in Thanks to sol-gel technology, hybrid materials can now be created. These hybrids can include a variety of ingredients, including organic additions and inorganic salts, opening avenues for developing functional materials tailored for diverse purposes. antimicrobial coating for metal surfaces using a silver-infused hybrid organic-inorganic sol-gel substance. The study explores how heat treatments impact the hybrid matrix structure, the clustering of silver ions, and their effectiveness in killing bacteria. The synthesis of sol-gel materials involved the hydrolytic condensation of methyl-triethoxysilane (MTES) and tetraethoxysilane (TEOS) in an acidic environment. For mechanical strengthening, silica nanoparticles were added, and Ag^+ ions were supplied via silver nitrate. The glass slides and 316L stainless steel underwent dip coating, followed by densification at temperatures of 50°C, 150°C, and 450°C. The effects of thermal treatment on silver aggregation and the matrix structure were examined using characterization methods such as electrochemical impedance spectroscopy, small-angle X-ray spectroscopy, and X-ray photoelectron spectroscopy. Agar diffusion experiments were utilized to measure inhibitory halos on Escherichia coli cultures to evaluate the effectiveness of biocidal treatments and determine how thermal treatment, particle size, and silver status affect antimicrobial characteristics [40-44].

III.PEEK AND AGNP

Polyether ether ketone (PEEK) and silver nanoparticles (AgNPs) represent significant advancements in biomedical implant materials. PEEK, a semi-crystalline

Correspondence to: Hemant Parashram Pathade, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
Corresponding author. E-mail addresses: hemantpathade@gmail.com

thermoplastic polymer, is highly valued for its exceptional mechanical properties, biocompatibility, and radiolucency in medical implants. Its high strength-to-weight ratio, elasticity similar to bone, and resistance to fatigue and wear make it ideal for load-bearing applications such as spinal and orthopedic implants. PEEK's biocompatibility minimizes tissue reactions, and its radiolucency allows for clear imaging during postoperative evaluations. Furthermore, PEEK is highly machinable, allowing for intricate implant designs customized to individual patient requirements. Recent studies have concentrated on improving PEEK's ability to resist bacterial contamination, aiming to reduce infection risks linked with implants. Silver nanoparticles (AgNPs) are also being explored for biomedical implants due to their strong antimicrobial properties. AgNPs demonstrate broad effectiveness against bacteria, fungi, and viruses by disrupting cell membranes and crucial enzymatic functions necessary for survival. This feature is highly beneficial for mitigating implant-related infections, a significant issue in orthopedic, dental, and cardiovascular procedures. Integrating silver nanoparticles (AgNPs) into implant materials such as PEEK improves their resistance to bacterial colonization while maintaining biocompatibility and mechanical strength. Scientists are investigating different approaches to enhance the dispersion and stability of AgNPs within implant matrices, aiming to ensure prolonged antimicrobial effectiveness [36]-[39].

IV. 304 STAINLESS STEEL

Biomedical implants have relied heavily on stainless steel, particularly 304 stainless steel, Due to its excellent mechanical properties and resistance to corrosion, biocompatibility, and ease of manufacture. This alloy, which is mostly made of iron, chromium, and nickel, has been widely employed in implants and medical devices for everything from cardiovascular to orthopedic purposes. Its adoption in medicine represents a significant advancement in biomaterials. Stainless steel became prominent in biomedical implants in the mid-20th century, driven by the need for materials capable of withstanding physiological conditions and mechanical stresses. 304 stainless steel emerged due to its corrosion resistance, primarily due to chromium content, and offered superior performance compared to earlier materials like cobalt-chromium alloys and titanium alloys. An austenitic alloy of 8–10.5% nickel and 18–20% chromium makes up 304 stainless steel. These components provide a protective oxide layer that aids in the material's resistance to corrosion. It also boasts high tensile strength, good ductility, and toughness, making it suitable for uses in the human body that require load bearing. The body usually tolerates the alloy well, resulting in little irritation and showing good tissue compatibility over long periods. Its biocompatibility has been validated through extensive clinical use in various implants, ensuring stability and integration with surrounding tissues. In orthopedic surgery, 304 stainless steel is used for fracture fixation devices, bone plates, and screws because of its Resistance to corrosion and the ratio of strength to weight. It withstands sterilization processes like autoclaving, meeting surgical requirements effectively. In cardiovascular medicine, 304 stainless steel is employed in stents, pacemaker components, and surgical instruments. Its ability to be shaped precisely and resist blood corrosion is advantageous in these critical applications. Despite its benefits, challenges include potential ion release and surface film formation affecting long-term biocompatibility. Innovations like surface modifications and coatings aim to enhance biocompatibility while maintaining mechanical integrity. Ongoing research focuses on improving stainless steel implants through alloy modifications, surface treatments, and integrating technologies like additive manufacturing. These advancements aim to customize implants for better patient outcomes and satisfaction [2]-[20].

V. 316 L STAINLESS STEEL

316L stainless steel is highly valued in biomedical implants due to its exceptional corrosion resistance, biocompatibility, robust mechanical properties, and versatility across a wide range of medical devices. This variant of austenitic stainless steel has played a pivotal role in advancing biomaterials, offering robust solutions to meet rigorous requirements for implantable medical devices. The development of 316L stainless steel for biomedical implants evolved alongside its adoption in broader medical applications during the mid-20th century. It was primarily driven by the necessity for materials capable of enduring extended exposure to physiological conditions without compromising mechanical strength. 316L stainless steel became favored for its heightened resistance to corrosion and ability to maintain stability in diverse biological environments. Biocompatibility is a crucial consideration when choosing materials for biomedical implants, and 316L stainless steel stands out in this aspect. It is generally well-tolerated by the human body, causing minimal inflammation and showing good tissue compatibility even during long-term implantation. Its safety and reliability in various medical devices have been affirmed through extensive clinical use, highlighting its suitability for medical applications. In orthopedic surgery, 316L stainless steel is extensively used to create joint replacements, bone plates, screws, and fixation devices. Its robust mechanical strength Its corrosion resistance makes it perfect for implants that endure physiological stresses while aiding bone healing and integration. The alloy's capacity to retain structural integrity and functionality over extended periods ensures favorable patient outcomes in orthopedic procedures. In cardiovascular medicine, 316L stainless steel finds extensive use in vascular stents, cardiac pacemaker components, and surgical equipment due to its corrosion resistance and biocompatibility. These properties are crucial for ensuring the longevity and performance of implants. Additionally, its ability to be shaped into complex forms and compatibility with sterilization methods further enhance its suitability for cardiovascular implants. Despite its many advantages, 316L stainless steel implants face challenges such as potential metal ion release and the formation of surface films that could affect long-

Correspondence to: Hemant Parashram Pathade, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
Corresponding author. E-mail addresses: hemantpathade@gmail.com

term biocompatibility. Current research is concentrating on overcoming these obstacles through advanced surface modification techniques like plasma spraying, coatings with bioactive materials, and nanotechnology. These innovations aim to enhance the alloy's surface properties without compromising its mechanical strength or corrosion resistance, thereby improving implant performance and patient outcomes. Future developments are expected to focus on optimizing biocompatibility, enhancing antibacterial properties, and customizing implant designs to better mimic natural tissues. Additive manufacturing (3D printing) holds promise for personalized implant production, offering tailored solutions based on individual patient anatomy and medical requirements, potentially transforming biomedical implants and enhancing global patient care [18]-[22].

VI. COCRNIFE (COBALT-NICKEL-CHROMIUM-MOLYBDENUM ALLOY)

CoCrNiFe, also known as Cobalt-Nickel-Chromium-Molybdenum alloy, is highly valued due to its exceptional mechanical properties and corrosion resistance, and biocompatibility, in biomedical implants, specifically tailored for orthopedic and dental surgical applications. This specialized alloy typically includes cobalt, nickel, chromium, and molybdenum as its primary constituents, with additional elements like tungsten and carbon added in varying amounts to enhance specific characteristics. Its composition is meticulously designed to ensure optimal mechanical strength, wear resistance, and protection against corrosion, crucial for implants enduring physiological conditions. Chromium and molybdenum play key roles in providing outstanding resistance to various forms of corrosion, including those prevalent in chloride-rich environments within the human body. Biocompatibility is a critical requirement for biomedical implants, and CoCrNiFe alloys are engineered to meet rigorous standards in this regard. Extensive research and clinical use have shown they integrate well with human tissues, minimizing adverse reactions and inflammation during long-term implantation. This compatibility supports tissue integration, reduces post-surgery complications, and ensures patient safety and implant durability. In orthopedic surgery, CoCrNiFe alloys are widely used for joint replacements like hip and knee prostheses, as well as in bone plates, screws, and intramedullary nails. These implants benefit from the alloy's high strength, fatigue resistance, and wear resistance, crucial for supporting weight-bearing joints and enabling natural movement. Their ability to withstand mechanical stresses over extended periods enhances patient mobility and post-surgical quality of life, making CoCrNiFe a preferred choice in orthopedics. CoCrNiFe alloys are indeed crucial in dental surgery, especially for dental implants and prosthetic components. Their biocompatibility and resistance to corrosion are vital for ensuring the durability and functionality of implants in the oral environment, where they must withstand significant mechanical stresses. The alloy's ability to integrate with bone tissue supports successful implantation, facilitating both functional and aesthetic dental restoration. However, challenges such as wear debris, potential metal ion release, and long-term biocompatibility issues are areas of concern. Ongoing research aims to mitigate these challenges through advanced surface treatments like plasma spraying, bioactive coatings, and nanotechnology-based modifications. These innovations aim to improve the alloy's surface properties while preserving its mechanical strength and biocompatibility, thereby enhancing overall implant performance and patient outcomes. Future advancements in CoCrNiFe alloys are expected to focus on optimizing mechanical properties further, enhancing antibacterial features, and exploring new applications in regenerative and personalized medicine. Technologies used in additive manufacturing, such as electron beam melting (EBM) and selective laser melting (SLM), offer promise for producing implants with precise geometries tailored to individual patient needs, potentially revolutionizing biomedical implantology with customized solutions that improve treatment effectiveness and patient satisfaction [21].

VII. TI6AL4V (TITANIUM-6 ALUMINUM-4 VANADIUM ALLOY)

Titanium-6 Aluminum-4 Vanadium alloy, or Ti6Al4V as it is technically named, is highly prized in biomedical implants because of its remarkable mechanical qualities, biocompatibility, and corrosion resistance. This titanium-based alloy has significantly advanced medical device technology, serving diverse applications from orthopedics to dental prosthetics. Composed primarily of titanium (Ti), aluminum (Al), and vanadium (V), typically in proportions of approximately 90%, 6%, and 4% respectively, along with trace elements like oxygen and iron, Ti6Al4V offers a unique combination of strength, lightweight nature, and biocompatibility crucial for implants. Its surface's capacity to form a persistent oxide layer improves biocompatibility, aiding in osseointegration and reducing unfavorable tissue reactions. Biocompatibility is essential for biomedical implants, ensuring they interact well with biological tissues without causing immune responses. Ti6Al4V alloy is highly biocompatible, and extensively researched over years of clinical use. Its inertness and ability to integrate with bone tissue support osseointegration, are crucial for the stability and success of orthopedic and dental implants. In orthopedic surgery, Ti6Al4V alloy is extensively used for joint replacements like hip and knee prostheses, spinal implants, bone plates, and screws. Its strength and fatigue resistance allows it to endure mechanical stresses in weight-bearing joints, ensuring long-term durability. Its elastic modulus is similar to that of bone in humans, which reduces stress shielding and encourages natural load transmission, improving patient mobility and quality of life after surgery. Ti6Al4V alloy is extensively utilized in dental implants and prosthetics because of its corrosion resistance and biocompatibility, crucial for long-term success in oral environments. Dental implants made from Ti6Al4V provide stable support for crowns, bridges, and dentures, resembling natural tooth roots and enhancing

Correspondence to: Hemant Parashram Pathade, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
Corresponding author. E-mail addresses: hemantpathade@gmail.com

dental aesthetics and chewing efficiency. The alloy's ability to maintain structural integrity and resist bacterial colonization further supports its suitability for dental applications, leading to positive clinical outcomes and patient satisfaction. Despite its advantages, challenges with Ti6Al4V implants include concerns about wear debris, potential metal ion release, and allergic reactions in some individuals. Ongoing research aims to address these challenges through advanced surface modifications, such as coatings with bioactive materials and textured surfaces that improve bone integration. Innovations in additive manufacturing techniques allow for customized implants with complex geometries tailored to individual anatomy, optimizing implant performance and patient outcomes. Future developments in Ti6Al4V alloys are expected to focus on enhancing mechanical properties, optimizing surface characteristics to improve biological responses, and exploring new applications in regenerative and personalized medicine. Continued advancements in material science will drive innovation in titanium-based alloys, potentially revolutionizing biomedical implants with superior performance, reliability, and biocompatibility, thereby improving patient care globally [23]-[26].

VIII. COCRSS (COBALT-CHROMIUM SUPERALLOYS (COCRSS)

Cobalt-chromium superalloys (CoCrSS) are highly specialized materials widely used due to their remarkable mechanical properties, corrosion resistance, and biocompatibility, in biomedical implants, particularly in orthopedics and cardiovascular surgery. These alloys primarily consist of cobalt (Co) and chromium (Cr), often with additions of molybdenum (Mo), nickel (Ni), and other elements like tungsten (W) and carbon (C). Each element contributes uniquely to the alloy's characteristics, like mechanical strength, hardness, and corrosion resistance. Chromium, for example, enhances resistance to corrosion by covering the surface with a layer of protective oxide, crucial for durability in biological environments. Molybdenum further boosts corrosion resistance, particularly in chloride-rich bodily fluids, ensuring the longevity and reliability of implants. Biocompatibility is crucial for biomedical implants, ensuring they integrate well with biological tissues and minimize adverse reactions. Cobalt-chromium superalloys are recognized for their excellent biocompatibility, supported by extensive clinical research and experience. These alloys are inert, corrosion-resistant, and promote osseointegration, making them ideal for orthopedic and cardiovascular applications. In orthopedics, Cobalt-Chromium Superalloys are used in joint replacements like hips and knees, as well as bone plates and screws. Their high strength, wear resistance, and fatigue resistance support natural movement and durability, crucial for patient mobility and quality of life. The alloys' ability to withstand sterilization and maintain stability over time ensures reliable performance in orthopedic surgeries. These alloys are used in surgical equipment, pacemaker components, and vascular stents in cardiovascular treatment. The longevity and effectiveness of implants depend heavily on their outstanding mechanical properties, such as their remarkable tensile strength and resistance to corrosion. Their versatility in shaping intricate designs further enhances their utility in cardiovascular implants, ensuring optimal functionality and compatibility with vascular structures. While Cobalt-Chromium Superalloys offer numerous advantages, challenges such as wear debris, potential metal ion release, and long-term biocompatibility remain. Current research focuses on overcoming these issues through advanced surface treatments like bioactive coatings and textured surfaces for better tissue integration. developments in selective laser melting and electron beam additive manufacturing, allow for the creation of customized implants tailored to patient anatomy, enhancing implant performance and outcomes. Future developments in Cobalt-Chromium Superalloys aim to improve mechanical properties, refine surface characteristics for better biological responses, and explore applications in regenerative and personalized medicine. Advances in materials science and manufacturing are poised to drive innovation, creating next-generation medical devices that offer superior performance, reliability, and biocompatibility. These advancements hold the potential to significantly impact biomedical implants, addressing current clinical challenges and enhancing global patient care [2], [27]-[29].

IX. COCRMO (COBALT-CHROMIUM-MOLYBDENUM)

Cobalt-chromium-molybdenum (CoCrMo) alloys are crucial in biomedical implants because of their exceptional mechanical qualities, resilience to corrosion, and biocompatibility, particularly in orthopedic and dental surgery. These alloys have advanced medical device technology by offering durable solutions for implants needing high strength and wear resistance in challenging physiological conditions. CoCrMo alloys typically contain cobalt, chromium, and molybdenum as main components, with additional elements like nickel, iron, and carbon adjusted to achieve specific operties. Chromium forms a protective oxide layer, enhancing corrosion resistance, while molybdenum boosts resistance to pitting and crevice corrosion, crucial in chloride-rich bodily environments. Biocompatibility is crucial for biomedical implants to ensure they integrate well with biological tissues and cause minimal post-implantation reactions. CoCrMo alloys demonstrate excellent biocompatibility, supported by extensive clinical research showing their ability to integrate with bone tissue and promote osseointegration. Their inert nature and corrosion resistance ensure long-term stability within the body, contributing to successful outcomes in orthopedic and dental surgeries. In orthopedic surgery, CoCrMo alloys are widely used for joint replacements like hip and knee prostheses, as well as bone plates, screws, and intramedullary nails. These implants benefit from the alloy's high strength, wear resistance, and fatigue resistance, crucial for enduring mechanical stresses and supporting natural movement. Their compatibility with sterilization processes and ability to maintain dimensional stability over time ensure reliability and longevity in orthopedic procedures, enhancing patient mobility and quality of life. CoCrMo Because of their corrosion resistance, alloys are widely employed in dental implants and prosthetics resistance and biocompatibility, crucial for long-term success in the oral environment. These implants provide stable support for crowns, bridges, and dentures, resembling natural tooth roots and enhancing dental aesthetics and chewing function. The alloy's ability to maintain structural integrity and resist bacterial colonization further enhances its suitability for dental applications, contributing to positive clinical outcomes and patient satisfaction. Despite their advantages, challenges associated with CoCrMo implants include concerns about wear debris, potential release of metal ions, and long-term biocompatibility. The goal of ongoing research is to address these issues by developing alloys with improved wear and corrosion resistance, coatings containing bioactive ingredients, and textured surfaces that promote better tissue integration. Technological developments in additive manufacturing, including selective laser melting (SLM) and electron beam melting (EBM), allow for the creation of implants that are specifically shaped to fit the anatomy of each patient, improving results and performance. Future advancements in CoCrMo alloys are expected to focus on enhancing mechanical properties, refining surface characteristics to improve biological responses, and exploring new applications in regenerative and personalized medicine. Continued progress in material science and manufacturing technologies will drive innovation in CoCrMo alloys, paving the way for next-generation medical devices that offer superior performance, reliability, and biocompatibility. These developments promise to transform biomedical implant technology, addressing current clinical challenges and improving patient care worldwide [2], [30]-[33].

X. MERCURY FROM GOLD

Mercury in gold alloys for biomedical implants, particularly in dental restorations, highlights a significant chapter in biomaterials evolution. It underscores the intricate relationship between materials science, biocompatibility, and clinical effectiveness. The incorporation of mercury into gold alloys for dental applications has a long history, evolving from early metallurgical experiments to standardized dental amalgams by the 19th century. This amalgam, typically comprising gold, silver, tin, and copper, aimed to overcome the limitations of pure gold in dental restorations by enhancing durability, workability, and affordability. Mercury was crucial in forming a plastic mass that could fill cavities effectively. Gold amalgams generally contain around 50% gold, along with varying amounts of silver, tin, and copper, and a small proportion of mercury to aid in mixing and setting. The process involves blending powdered metals with liquid mercury, initiating a chemical reaction that creates a malleable mass capable of fitting into tooth cavities. Once hardened, the amalgam becomes a robust, corrosion-resistant material able to endure the mechanical strains that come with biting and chewing. Gold amalgams, including those containing mercury, have demonstrated favorable biocompatibility over decades of clinical use. The inert nature of gold, combined with the stable oxide layer that forms on its surface, helps minimize irritation and inflammation in surrounding tissues, promoting long-term oral health and the integrity of restorations. In dentistry, gold amalgams with mercury have been widely employed for dental fillings, crowns, and bridges due to their durability, longevity, and ease of manipulation during placement. The alloy's ability to withstand wear and corrosion in the moist, acidic environment of the mouth makes it particularly suitable for posterior restorations where strength and longevity are critical. Additionally, its thermal conductivity properties closely resemble those of natural tooth structure, reducing sensitivity and enhancing patient comfort. Despite its extensive use, concerns have arisen regarding the safety of mercury-containing dental amalgams, particularly regarding potential mercury exposure and toxicity. While mercury in dental amalgams becomes bound within the solid matrix after setting, trace amounts of mercury vapor may still be released during placement, removal, or chewing. Regulatory bodies and health organizations have introduced guidelines to mitigate these risks, emphasizing proper handling, disposal, and patient education on the benefits and risks associated with dental amalgam restorations. Advancements in dental materials science have led to alternatives like resin-based composites and ceramic restorations, which offer aesthetic benefits and address concerns related to mercury exposure. These materials, favored for their tooth-colored appearance and adhesive bonding properties, may not always match the durability and longevity of gold amalgams in certain clinical situations. The choice of restorative material often depends on factors such as patient preferences, oral health needs, and the skills of the dental practitioner. Future developments in dental biomaterials will likely explore new alloys, composites, and ceramics that balance aesthetic appeal, mechanical strength, and biocompatibility. Research efforts will focus on refining material formulations and manufacturing techniques to meet evolving clinical demands for durable, visually pleasing restorations that enhance patient comfort and oral health outcomes. Furthermore, as research continues, a greater knowledge of the long-term consequences of mercury exposure from dental amalgams will be gained, which will inform legislative decisions and patient care procedures [2], [43]-[45].

XI. CONCLUSIONS

A major advancement in biomedical implant technology involves creating a composite coating using Polyether-ether-ketone (PEEK) and silver nanoparticles (AGNP) on a 316L stainless steel (SS) base. This novel method aims to capitalize on the distinctive attributes of each material to prolong the useful life and performance of biomedical implants, particularly in the dental and orthopedic domains. Strong mechanical qualities are a well-known characteristic of 316L stainless steel, resistance to corrosion, and compatibility with biological tissues, making it a staple in various medical implants such as orthopedic devices and vascular stents. Despite these advantages, challenges like bacterial adhesion and

Correspondence to: Hemant Parashram Pathade, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
Corresponding author. E-mail addresses: hemantpathade@gmail.com

subsequent infections remain, potentially compromising implant success. PEEK is a high-performance polymer that is selected due to its mechanical robustness, wear and fatigue resistance, and biocompatibility. The composite's antibacterial qualities are enhanced by the incorporation of silver nanoparticles into the PEEK layer. Well-known for their strong antibacterial properties, silver nanoparticles efficiently prevent the growth of a wide range of bacteria. This antimicrobial feature is particularly critical in medical implants where preventing bacterial colonization is essential for minimizing implant-related infections. The process of applying the composite coating involves several crucial steps, including preparing the surface of the 316L SS substrate to ensure robust adhesion and longevity of the PEEK-AGNP coating. Techniques such as plasma treatment or chemical etching may be employed to enhance surface roughness and promote bonding between the substrate and the composite layer. Deposition methods like electrophoretic deposition or spray coating are utilized to ensure even coverage and precise thickness control across the implant surface. Once implanted, the PEEK-AGNP composite coating serves multiple purposes. It acts as a barrier against corrosion, safeguarding the underlying 316L SS substrate from degradation in the challenging physiological surroundings of the human body. Additionally, the presence of silver nanoparticles actively combats bacterial colonization on the surface of the implant, lowering the possibility of biofilm growth and associated infections. This dual functionality not only enhances the biocompatibility of the implant but also extends its operational lifespan, potentially reducing the necessity for costly and invasive revision surgeries. A significant advancement in biomedical implant technology has been made with the integration of a composite covering on a 316L stainless steel basis that mixes PEEK and silver nanoparticles. This invention efficiently makes use of the antibacterial power of silver nanoparticles, the biocompatibility of PEEK, and the mechanical strength of stainless steel. By this kind of integration, major implantology difficulties are intended to be addressed in a synergistic manner. Future research endeavors may concentrate on refining the composite's composition, refining deposition techniques, and conducting extensive in studies both in vivo and in vitro to prepare the ground for safer, more durable biomedical implants in clinical settings.

REFERENCES

[1] Noam Eliaz, “Corrosion of Metallic Biomaterials: A Review”, Materials 2019, 12, 407, 2019. (https://doi.org/10.3390/ma12030407)

[2] Niyou Wang, Jerry Ying Hsi Fuh, S Thameem Dheen, A Senthil Kumar, “Functions and applications of metallic and metallic oxide nanoparticles in orthopedic implants and scaffolds”, Journal of Biomedical Materials Research Part B: Applied Biomaterials, pp. 1–20, 2020. (https://doi.org/10.1002/jbm.b.34688)

[3] Geetha Manivasagam, Durgalakshmi Dhinasekaran and Asokamani Rajamanickam, “Biomedical Implants: Corrosion and its Prevention - A Review”, Recent Patents on Corrosion Science, Vol. 2, pp. 40-54, 2010. (https://dx.doi.org/10.2174/1877610801002010040)

[4] Douglas C. Hansen, “Metal Corrosion in the Human Body: The Ultimate Bio-Corrosion Scenario”, The Electrochemical Society Interface, Summer 2008, pp. 31-34, 2008.

[5] U. Kamachimudali, T. M. Sridhar And Baldev Raj, “Corrosion of bio implants”, Sadhana Vol. 28, Parts 3 & 4, June/August 2003, pp. 601–637, 2003. (https://doi.org/10.1007/BF02706450)

[6] Matic Resnik, Metka Benˇcina, Eva Leviˇcnik, Niharika Rawat, Aleš Igliˇc and Ita Junkar, “Strategies for Improving Antimicrobial Properties of Stainless Steel”, Materials, 13, 2944, 2020. (https://doi.org/10.3390/ma13132944)

[7] Xiuju Liu, Kang Gan, Hong Liu, Xiaoqing Song, Tianjie Chen,Chenchen Liu, “Antibacterial properties of nano-silver coated PEEK prepared through magnetron sputtering”, dental materials, 33, 2017. (http://dx.doi.org/10.1016/j.dental.2017.06.014)

[8] Wei-Fang Lee, Lu-Ying Wang, Ting-Yi Renn, Jen-Chang Yang , Lih-Sheng Fang, Yi-Huan Lee and Pei-Wen Peng, “Characterization and Antibacterial Properties of Polyetherketoneketone Coated with a Silver Nanoparticle-in-Epoxy Lining”, Polymers, 14, 2906, 2022. (https://doi.org/10.3390/polym14142906)

[9] Tamara V. Basova, Evgeniia S. Vikulova, Svetlana I. Dorovskikh, Aseel Hassan, Natalya B. Morozova, “The use of noble metal coatings and nanoparticles for the modification of medical implant materials”, Materials & Design 204, 109672, 2021. (https://doi.org/10.1016/j.matdes.2021.109672)

[10] Joalen P. Monte, Adriana Fontes, Beate S. Santos, Giovannia A.L. Pereira, Goreti Pereira, “Recent advances in hydroxyapatite/polymer/silver nanoparticles scaffolds with antimicrobial activity for bone regeneration”, Materials Letters 338, 134027, 2023. (https://doi.org/10.1016/j.matlet.2023.134027)

[11] Ruichu Zhang, Bing Han and Xiaomo Liu, “Functional Surface Coatings on Orthodontic Appliances: Reviews of Friction Reduction, Antibacterial Properties, and Corrosion Resistance”, International Journal of Molecular Sciences, 24, 6919, 2023. (https://doi.org/10.3390/ijms24086919)

[12] F. Pishbin, V. Mouriño, J.B. Gilchrist, D.W. McComb, S. Kreppel, V. Salih, M.P. Ryan, A.R. Boccaccini, “Single-step electrochemical deposition of antimicrobial orthopaedic coatings based on a bioactive glass/chitosan/nano-silver composite system”, Acta Biomaterialia 9, pp. 7469–7479, 2013. (http://dx.doi.org/10.1016/j.actbio.2013.03.006)

[13] G. Pradhaban, Gobi Saravanan Kaliaraj, Vinita Vishwakarma, “Antibacterial effects of silver–zirconia composite coatings using pulsed laser deposition onto 316L SS for bio implants”, Progress in Biomaterials, 3, pp. 123–130, 2014. (http://dx.doi.org/10.1007/s40204-014-0028-5)

Correspondence to: Hemant Parashram Pathade, Department of Mechanical Engineering, Suresh Gyan Vihar University, Jaipur
Corresponding author. E-mail addresses: hemantpathade@gmail.com

[14] Nicole Ciacotich, Rameez Ud Din, Jens J. Sloth, Per Møller, Lone Gram, “An electroplated copper–silver alloy as antibacterial coating on stainless steel”, Surface & Coatings Technology, 2018. (https://doi.org/10.1016/j.surfcoat.2018.04.007)

[15] S. Thirumalai Kumaran, K. Baranidharan, M. Uthayakumar, P. Parameswaran, “Corrosion Studies on Stainless Steel 316 and their Prevention – A Review”, INCAS BULLETIN, Volume 13, Issue 3/ 2021, pp. 245 – 251, 2021. (https://doi.org/10.13111/2066-8201.2021.13.3.21)

[16] E. Tabesh, H.R. Salimijazi, M. Kharaziha, M. Mahmoudi, M. Hejazi, “Development of an in-situ chitosan'copper nanoparticle coating by electrophoretic deposition”, Surface & Coatings Technology, 2019. (https://doi.org/10.1016/j.surfcoat.2019.02.040)

[17] Aneeqa Nawaz, Shaher Bano, Muhammad Yasir, Abdul Wadood and Muhammad Atiq Ur Rehman, “Ag and Mn-doped mesoporous bioactive glass nanoparticles incorporated into the chitosan/gelatin coatings deposited on PEEK/bioactive glass layers for favorable osteogenic differentiation and antibacterial activity”, Materials Advances, 2020. (https://doi.org/10.1039/d0ma00325e)

[18] Chintan Morsiya, “A review on parameters affecting properties of biomaterial SS 316L”, Australian Journal of Mechanical Engineering, 2020 (https://doi.org/10.1080/14484846.2020.1752975)

[19] S. Jublot-Leclerc, M.-L. Lescoat, F. Fortuna, L. Legras, X. Li, A. Gentils, “TEM study of the nucleation of bubbles induced by He implantation in 316L industrial austenitic stainless steel”, Journal of Nuclear Materials 466, pp. 646-652, 2015. (http://dx.doi.org/10.1016/j.jnucmat.2015.09.013)

[20] Cong Peng, Takayuki Izawa, Liwei Zhu, Kensuke Kuroda, and Masazumi Okido, “Tailoring surface hydrophilicity property for biomedical 316 L and 304 stainless steels: a special perspective on studying osteoconductivity and biocompatibility”, ACS Applied Materials & Interfaces, 2019. (https://doi.org/10.1021/acsami.9b17312)

[21] Jingfeng Quan, Kaijie Lin, Dongdong Gu, “Selective laser melting of silver submicron powder modified 316L stainless steel: Influence of silver addition on microstructures and performances”, Powder Technology, 2020. (https://doi.org/10.1016/j.powtec

[22] Yu-Sung Kim, Dae-Wook Kim, In-Sik Lee, Sungook Yoon, Daeil Kim, Shinhee Jun and Byung-Chul Cha, “Effect of N+ Implantation on Surface Characteristics of 316L Stainless Steels for Bipolar Plate in PEMFC”, Coatings, 10, 604, 2020. (https://doi.org/10.3390/coatings10070604)

[23] Mahmoud Z. Ibrahim, Ahmed A.D. Sarhan, T.Y. Kuo, Farazila Yusof, M. Hamdi, “Characterization and hardness enhancement of amorphous Fe-based metallic glass laser cladded on nickel-free stainless steel for biomedical implant application”, Materials Chemistry and Physics, 2019.(https://doi.org/10.1016/j.matchemphys.2019.121745)

[24] Fatemeh Khosravi, Saied Nouri Khorasani, Shahla Khalili, Rasoul Esmaeely Neisiany, Erfan Rezvani Ghomi, Fatemeh Ejeian, Oisik Das and Mohammad Hossein Nasr-Esfahani, “Development of a Highly Proliferated Bilayer Coating on 316L Stainless Steel Implants”, Polymers, 12, 1022, 2020. (https://doi.org/10.3390/polym12051022)

[25] Martinus Kriswanto, Muhammad Khairurrijal, Dave Leonard Junior Wajong, Tofan Maliki Kadarismanto and Yusril Yusuf, “Stainless Steel 316 L Metal Coating with Capiz Shell Hydroxyapatite Using Electrophoretic Deposition Method as Bone Implant Candidate”, Key Engineering Materials, Symposium of Materials Science and Chemistry II, ISSN: 1662-9795, Vol. 840, pp 336-344, 2020. (https://doi.org/10.4028/www.scientific.net/KEM.840.336)

[26] Madhan Kumar, Muhammad Ali Ehsan, Rami K. Suleiman, And Abbas Saeed Hakeem, “Fabrication and Characterization of Nanostructured AACVD Thin Films on 316L SS as Surface Protective Layers in Simulated Body Fluid”, Metallurgical and Materials Transactions a Volume 51A, pp. 4301-4312, August 2020. (https://doi.org/10.1007/s11661-020-05843-9)

[27] Behnam Doudkanlouy Milan, Hurieh Mohammadzadeh, Robabeh Jafari, Mohammad Soltani, “A review on hydroxyapatite and its composite coatings on 316L stainless steel substrate for tissue engineering applications”, The 13th Congress of Iranian Ceramic Society & 3rd International Conference of Ceramics, Sharif University of Technology, Tehran, Iran, 24th & 25th May 2022.

[28] Sehrish Mukhtar, Waqas Asghar, Zubair Butt, Zaheer Abbas, Mudaser Ullah, Rana Atta-Ur-Rehman, “Development and characterization of hot dip aluminide coated stainless steel 316L”, Journal of Central South University, 25(11), pp. 2578–2588, 2018. (https://doi.org/10.1007/s11771-018-3937-y)

[29] Rodianah Alias, Reza Mahmoodian, Mohd Hamdi Abd Shukor, Been Seok Yew, and Martini Muhamad, “Enhancement of as-sputtered silver-tantalum oxide thin film coating on biomaterial stainless steel by surface thermal treatment”, (ANEMS) International Conference, 2018. (https://doi.org/10.1063/1.5030882)

[30] Karuppasamy Prem Ananth, Jinxing Sun and Jiaming Bai, “An Innovative Approach to Manganese-Substituted Hydroxyapatite Coating on Zinc Oxide–Coated 316L SS for Implant Application”, International Journal of Molecular Sciences. 19, 2340, 2018. (https://doi.org/10.3390/ijms19082340)

[31] Mengqi Zhang, Xiaomo Liu, Hongfei Shang, Jiuxiang Lin, “Comparison of TiN and CNx coatings on orthodontic stainless steel: Tribological and biological evaluation”, Surface & Coatings

Technology, 2019. (https://doi.org/10.1016/j.surfcoat.2019.01.072)

[32] D. Sivaraj, K. Vijayalakshmi, “Enhanced antibacterial and corrosion resistance properties of Ag substituted hydroxyapatite/functionalized multiwall carbon nanotube nanocomposite coating on 316L stainless steel for biomedical application”, Ultrasonics - Sonochemistry 59, 104730, 2019. (https://doi.org/10.1016/j.ultsonch.2019.104730)

[33] Dr S Hima Bindu, Dr S V Kala Vani, Dr G Nirisha, Dr N Madhuri, Dr B Sai Deepa, Dr. S Hemadri, "Evaluation of Antibacterial Effect of Silver Nanoparticle Coated Stainless Steel Band Material – An In vitro Study", Orthodontic Journal of Nepal, Vol. 9 No. 2, July-December 2019. (http://dx.doi.org/10.3126/ojn.v9i2.28404)

[34] Renata Scheeren Brum, Luiza Gomes Labes, Cláudia Ângela Maziero Volpato, César Augusto Magalhães Benfatti and Andrea de Lima Pimenta, “Strategies to Reduce Biofilm Formation in PEEK Materials Applied to Implant Dentistry—A Comprehensive Review”, Antibiotics, 9, 609; 2020. (https://doi.org/10.3390/antibiotics9090609)

[35] Xin Yang, Qiang Wang, Yinchang Zhang, Huazheng He, Shouliang Xiong, Pingbo Chen, Congming Li, Lei Wang, Guohai Lu, Yaozeng Xu, “A dual-functional PEEK implant coating for anti-bacterial and accelerated osseointegration”, Colloids and Surfaces B: Biointerfaces 224,113196, 2023. (https://doi.org/10.1016/j.colsurfb.2023.113196)

[36] Ilaria Corni, Nico Neumann, Dietmar Eifler and Aldo R. Boccaccini, “Polyetheretherketone (PEEK) Coatings on Stainless Steel by Electrophoretic Deposition”, Advanced Engineering Materials, 10, No. 6, 2008. (https://doi.org/10.1002/adem.200800010)

[37] Ilaria Corni, Nico Neumann, Saša Novak, Katja König, Paolo Veronesi, Qizhi Chen, Mary P. Ryan, Aldo R. Boccaccini, “Electrophoretic deposition of PEEK-nano alumina composite coatings on stainless steel”, Surface & Coatings Technology 203, pp. 1349–1359, 2009. (https://doi.org/10.1016/j.surfcoat.2008.11.005)

[38] Sigrid Seuss, Marion Heinloth, Aldo R. Boccaccini, “Development of bioactive composite coatings based on combination of PEEK, bioactive glass and Ag nanoparticles with antimicrobial properties”, Surface & Coatings Technology, 2016. (https://doi.org/10.1016/j.surfcoat.2016.03.057)

[39] Andrés Felipe Cruz-Pacheco, Deysi Tatiana Muñoz-Castiblanco, Jairo Alberto Gómez Cuaspud, Leonel Paredes-Madrid, Carlos Arturo Parra Vargas, José Jobanny Martínez Zambrano and Carlos Andrés Palacio Gómez, “Coating of Polyetheretherketone Films with Silver Nanoparticles by a Simple Chemical Reduction Method and Their Antibacterial Activity”, Coatings, 9, 91, 2019. (https://doi.org/10.3390/coatings9020091)

[40] Yunan Qing, Lin Cheng, Ruiyan Li, Guancong Liu, Yanbo Zhang, Xiongfeng Tang, Jincheng Wang, He Liu, Yanguo Qin, “Potential antibacterial mechanism of silver nanoparticles and the optimization of orthopedic implants by advanced modification technologies”, International Journal of Nanomedicine, 13, pp. 3311–3327, 2018. (https://dx.doi.org/10.2147/IJN.S165125)

[41] Shingo Nakamura, Masahiro Sato, Yoko Sato, Naoko Ando, Tomohiro Takayama, Masanori Fujita and Masayuki Ishihara, “Synthesis and Application of Silver Nanoparticles (Ag NPs) for the Prevention of Infection in Healthcare Workers”, International Journal of Molecular Science 20, 3620; 2019. (https://doi.org/10.3390/ijms20153620)

[42] Heba Mohamed Fahmy, Ayaat Mahmoud Mosleh, Aya Abd Elghany, Engy Shams-Eldin, Esraa Samy Abu Serea, Somaia Ashour Ali and Ahmed Esmail Shalan, “Coated silver nanoparticles: synthesis, cytotoxicity, and optical properties”, The Royal Society of Chemistry Advance, 9, 20118, 2019. (https://doi.org/10.1039/c9ra02907a)

[43] Atiqah Salleh, Ruth Naomi, Nike Dewi Utami, Abdul Wahab Mohammad, Ebrahim Mahmoudi, Norlaila Mustafa and Mh Busra Fauzi, “The Potential of Silver Nanoparticles for Antiviral and Antibacterial Applications: A Mechanism of Action”, Nanomaterials, 10, 1566, 2020. (https://doi.org/10.3390/nano10081566)

[44] Tamara Bruna, Francisca Maldonado-Bravo, Paul Jara and Nelson Caro, “Silver Nanoparticles and Their Antibacterial Applications”, International Journal of Molecular Sciences, 22, 7202, 2021. (https://doi.org/10.3390/ijms2.2137202)

[45] Yi Liu, Zhong Zheng, Janette N. Zara, Chingyun Hsu, Donnalisa E. Soofer, Kevin S. Lee, Ronald K. Siu, Lloyd S. Miller, Xinli Zhang, Doug Carpenter, Chunling Wang, Kang Ting, Chia Soo, “The antimicrobial and osteoinductive properties of silver nanoparticle/poly (DL-lactic-co-glycolic acid)-coated stainless steel”, Biomaterials 33 pp. 8745-8756, 2012. (http://dx.doi.org/10.1016/j.biomaterials.2012.08.010)