CHAPTER-1

INTRODUCTION

This chapter introduces biomaterials used in orthopedic implants, including their types and the increasing focus on metallic implants with surface modifications. Addressing bone-related diseases and replacements reflects the commitment to advancing medical technology and improving patient outcomes in developed countries. The goal is to develop materials that can provide long-lasting and effective solutions for implants in wear, corrosion, and biocompatibility behavior for individuals with bone-related conditions, ultimately enhancing their quality of life.

1.1 Background and Motivation

Every year, the number of cases of human bone-related diseases such as osteonecrosis, osteoarthritis, and rheumatoid arthritis has increased. These diseases originate from human complex tissue injuries, tumours, infections, and osteoporosis. Effective medical treatment is required to address orthopedic disease. Joint replacement surgery is a medical technique to relieve pain and disability in people suffering from these disorders. The number of joint replacement surgeries performed each year is escalating. In 2010, the total number of hip and knee replacements in the United States was anticipated to be 2.5 million and 4.7 million, respectively **[1].** Biomaterials are naturally extracted or artificial materials that fabricate structures or implants to replace missing or diseased biological structures, restoring shape and function. Today, three major metal classes are used in the development of orthopedic implants: titanium (as an alloy and commercially pure), stainless steel (316L SS), and cobalt-chromium (Co-Cr) alloys **[2-3].**

Every year, there is an immense demand for orthopedic surgeries for new patients and individuals who require revision surgery. Implant failure occurs due to various causes, including aseptic loosening, instability, wear/corrosion, infection, fibrous encapsulation, osteolysis, periprosthetic fracture, and ingrowth failure **[4].** Although these surgeries are unpleasant, expensive, and sometimes more involved than primary joint replacement surgery, it would be great if the implant's lifespan exceeded the patient's. Unfortunately, these implants frequently become loose over time, causing revision surgery to re-secure or introduce new hardware. Total knee replacements have an anticipated in-service life of 10 to 15 years before this revision is required **[5-6].** The successful completion of these procedures largely depends on many factors, including the surgeon's expertise, the interaction of the implant with the surrounding tissue, and postoperative infections. Because nothing can be done to improve the surgeon's expertise, the focus of implant design must be primarily on materials optimization to encourage natural tissue integration.

Furthermore, implant loosening accounts for 70% of revision surgery instances. As a result, considerable effort has been expended in developing acceptable implant materials with zero-rate revision surgery **[7].** Insufficient stress transfer to bone due to the biomechanical mismatch results in bone resorption (i.e., stress shielding) and may induce aseptic implant loosening after a few years of implantation, prompting revision surgery **[8].** Because of the strain, the implant material must protect the surrounding skeleton from normal stress levels **[9].** Once the metal ions are released from the implant areas, there may be adverse consequences on the surrounding tissues. The biocompatibility of commonly employed bare 316L stainless steel is also a significant problem in these applications **[10].** The only way to overcome this medical condition is through rapid bone development, which can help to fill in any gaps in the bone and firmly anchor the implant to the nearby bone. To accomplish this, the surface of the implant material must be able to attract osteoblast, or bone-forming cells, to colonize, hence starting bone production. Active research on implants made of long-lasting biomaterials is exploding due to these constantly growing human needs. The surface chemistry can be altered by coating the 316l SS with a bioactive material, or the surface roughness can be changed by surface texturing. Because it provides exceptional adherence and a consistent, homogenous coating, direct current magnetron sputtering (DCMS) is a versatile deposition technique.

Additionally, due to its ability to modify the surface area and topography of the implant and improve biocompatibility, surface texturing has also been attracting interest as a surface modification approach on 316L SS. The implant's wettability and biocompatibility were anticipated to increase due to surface texturing and Ta coating working together. This study achieved tantalum coating on the surface of 316L stainless steel using DC magnetron sputtering.

1.1.1 Introduction to Biomaterials

Biomaterials are employed as a component of devices meant to cure abnormally shaped human body parts by strengthening or replacing the missing bones, cartilage, ligaments, or tendons. Biomaterials also include biological substances like bone allografts. Orthopedic biomaterial devices are commonly called implants or prostheses **[11].** The term "biomaterial" refers to a substance (other than a food or medicine) or combination of substances, synthetic or natural in origin, that has been engineered to take a form that can be used alone or as a component of a complex system to control interactions with biological system components and direct the course of any therapeutic or diagnostic procedure in human or veterinary medicine by Williams **[12].** Biomaterials have continued to play an essential role for humanity as humans are born with illnesses such as congenital heart disease and suffer from illness until death. Arthritis is a chronic disease that typically affects the elderly but can sometimes affect younger individuals; despite its prevalence and enormous scientific progress, the aetiology of this disease remains unknown. Because this disease hampers people's lives, they seek substitutes to alleviate immobility and unbearable agony. Aside from the sick, young and vigorous people such as athletes, people who operate heavy machinery, and people who drive automobiles frequently require implants because of the significant increase in accidents. "Non-viable material used in a medical device, intended to interact with biological systems" is known as "biomaterial" **[13].**

1.1.2 Biomaterials market

According to the ageing population in developed nations and patients' desire to maintain the same activity and quality of life, implants have quickly expanded in recent years. The global biomaterials market is anticipated to increase at a compound annual growth rate (CAGR) of 11.8% from 2016 to 2022, reaching $139 billion. Until 2022, the metallic biomaterials category has the potential to contribute significantly to global market revenue **[14].** Since they have received approval from the US Food and Drug Administration (FDA), metallic biomaterials are frequently employed in orthopedic procedures. The growing ageing population, which is vulnerable to problems including cardiovascular, dental, orthopedic, and neurological issues, is one factor driving the worldwide biomaterials market's size. Biomaterials are widely used in load-bearing applications like joint replacement surgery for the hip and knee. The market has grown due to the increased demand for implanted devices. These implanted devices are common in chronic degenerative diseases like orthopedic and cardiovascular conditions. The market is growing due to technological developments in medical technology, such as the creation of intelligent biomaterials and the expansion of the healthcare system. Government and commercial initiatives have enhanced awareness of biomaterials and increased the frequency of neurological illnesses, boosting the market growth in the Asia-Pacific region. However, the high cost of biomaterial manufacture, abrasive wear of implantable products, and product biocompatibility issues restrict market growth **[15].**

This area currently governs the global market for metallic biomaterials, shown in **Fig.1.1**. Metallic biomaterials, which are robust and resistant to fatigue degradation, are commonly employed in orthopedic bone support and replacement treatments. They are widely utilized in dentistry, cardiovascular, and aesthetic procedures. Furthermore, metals are used in neuromuscular stimulation devices due to their high electrical conductivity. Because of the increase in the number of orthopedic procedures utilizing implants, the orthopedic problem is the largest application area of the biomaterial market. Biomaterials create orthopedic implants in various treatments, including joint replacements, Orthobiologics, bioresorbable tissue fixation products, spine implants, viscose-supplementation, and nonconventional modular tumour implants **[16].**

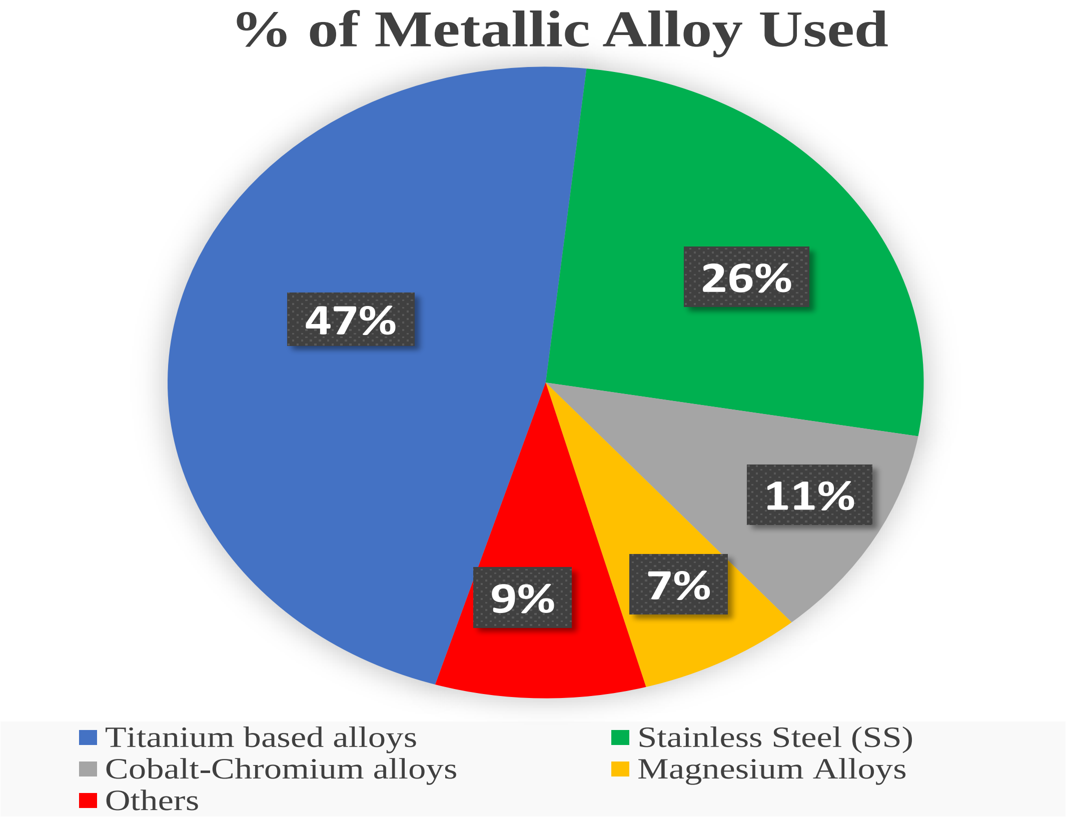

Fig.1.1 Metallic Alloy Used

1.1.3 Evaluation of Biomaterials:

First-generation biomaterials, developed in the 1960s-70s, focused on creating reliable skeletal prostheses. Professor Bonefield stressed the importance of understanding tissue mechanics for prostheses. By 1980, over 50 prostheses made of 40 materials were in trials, with 3 million placed annually. Common traits: biological inertness and high purity to minimize corrosion **[17]. Second-generation** biomaterials, developed by Professor Bonefield in the 1980s, matched host bone mechanics, reducing stress shielding. They introduced bioactivity and design tailoring for a closer fit with live composite bone. The groundbreaking composite included Hydroxyapatite particles and a polyethylene matrix. Resorbable biomaterials degrade as tissue regenerates. Second-gen bioactivity enhances biological response and tissue bonding **[18]. Third-generation** biomaterials combine bioactive and resorbable materials, using transient 3D porous structures for specific molecular-level biological responses. They involve bioactive systems directing cell functions and ECM creation. Molecularly tailored, they're used in tissue engineering for growing cells on modified resorbable scaffolds and for implantation to replace damaged tissues in patients **[19-20].** In the **20th century**, improved diagnostics, biomaterials, and surgeries boosted implantology. Biomaterials play vital roles in various medical fields, enhancing patients' quality of life with devices like dental implants, prosthetic joints, and vascular stents. Pioneers like Ridley, Winchell, Branemark, Wichterle, and Charnley laid the foundation for today's bioimplants, tested on animals before becoming accepted biomaterials for humans **[21].**

Fig. 1.2 shows the evaluation of the biomaterials. It has been found that the assessment concerning the development of bio-implants (further changes in existing material) has been widely increasing in the last decade.

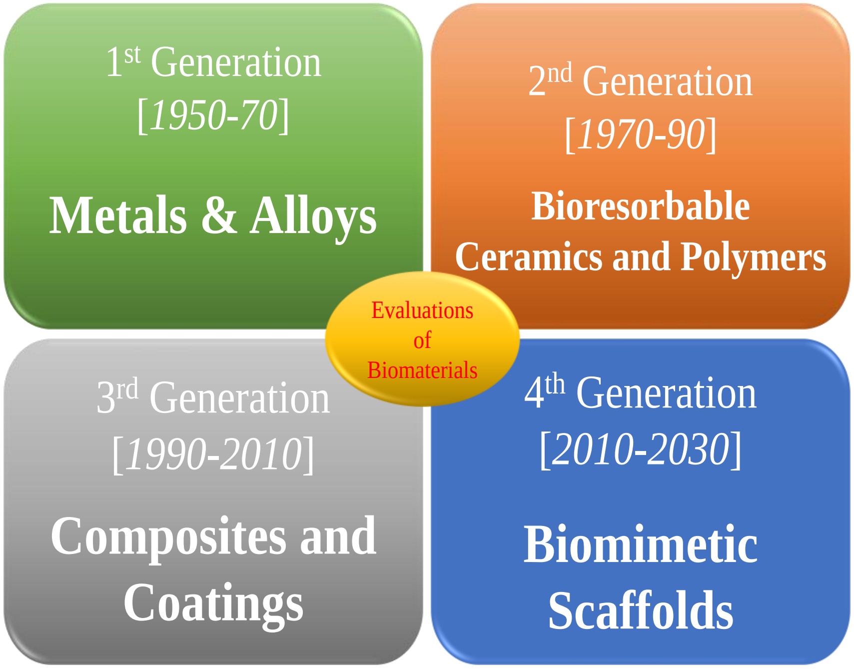

Fig. 1.2 Evaluations of Biomaterials

1.1.4 Classification of Biomaterials

The choice of biomaterial depends on the specific requirements of the intended application, considering factors such as biocompatibility, mechanical properties, degradation rate, desired biological responses and other relevant factors. They are crucial in various medical applications, from implants to drug delivery systems. Biomaterials can be classified based on their composition, origin, and function. Metals and alloys, ceramics, composites, and polymers are the four major biomaterials used in the medical profession **[22].** A schematic representation of the classification of biomaterials is shown in **Fig. 1.3.**

Metals and alloys are used as biomaterials due to their outstanding thermal and electrical conductivity and mechanical properties. Metals and alloys have the following advantages: high strength, high fatigue resistance, relatively excellent wear resistance, easy sterilization, easy fabrication, and shape memory (Ni-Ti). Most metals, including iron (Fe), cobalt (Co), nickel (Ni), chromium (Cr), niobium (Nb), titanium (Ti), molybdenum (Mo), tantalum (Ta), and tungsten (W), were utilized to create alloys for implant manufacture and can only be tolerated in trace amounts by the body. Vanadium steel was the first metal alloy to produce bone plates (Sherman plates) and screws specifically for human usage. Stainless steel is the most common implant alloy utilized in orthopedic applications. Shape memory Ni-Ti alloy is utilized in dental arch wire, microsurgical instruments, blood clot filters, and other applications **[23].**

Ceramics are used in fabricating biomaterials due to their excellent biocompatibility properties and high mechanical strength. Ceramics for implants have high compression strength, wear, and corrosion resistance. The femoral head of the hip prosthesis is made of bio-inert ceramics Al_2O_3 and SiO_2. Tri-calcium phosphate ceramics are utilized for bone repairs, and apatite ceramics are used for synthetic bone. Porous alumina is utilized for tooth roots, and alumina ceramics are used for orthopedics. Carbon has excellent biocompatibility and is commonly employed in manufacturing heart valves. Percutaneous carbon stimulation was used in artificial hearing and visual cortex stimulation for people who are blind. Ceramics for implants have a high elastic modulus (stress shielding) and a low fracture toughness (brittle in nature).

Composites are used as biomaterials obtained by combining two or more materials or phases to attain the best features of each component in one material. Compared to the characteristics of a homogenous material, the properties of composites, such as the elastic modulus, are significantly distinct.

Polymers are macromolecules (proteins, nuclei, acids, and polysaccharides) acquired during the growth cycle of all organisms. Polymeric materials are frequently employed in disposable medical supplies, dental implant materials, prosthetic materials, encapsulation, dressings, extracorporeal devices, drug delivery systems, and tissue-engineered goods in diverse forms such as fibres, rods, fabrics, and viscous liquids. Polymers are classed as non-degradable or bio-degradable based on their chemical stability in the body. Non-degradable polymers that are often used in hip socket replacements include polyurethanes (PU), silicone rubber, acrylic resins, polypropylene (PP), polyethene (PE), and polymethylmethacrylate (PMMA). The prosthesis is fixed to the surrounding bone using acrylic resins as bone cement. In total hip arthroplasties, PE is used as acetabular cups **[24].**

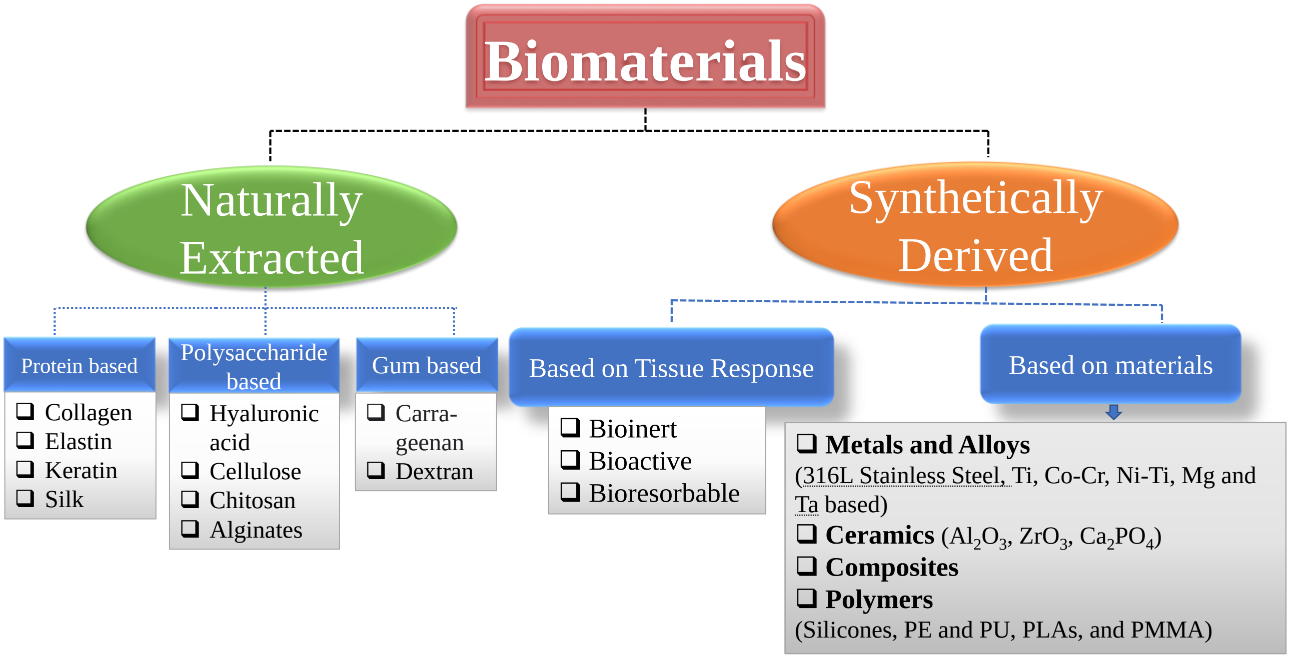

Fig. 1.3 Classifications of Biomaterials

1.1.5 The fundamental requirement of implant materials

Treating diseased or injured living tissue components with biomaterials includes their repair, replacement, or enhancement. First and foremost, a material must be accepted by the human body before it can be considered for implantation. When implanted or postoperative, the substance cannot exhibit adverse effects on the body, including allergy, inflammation, or toxicity. The second need is that materials have the necessary mechanical strength to withstand the forces applied to them. A biomaterial must have good corrosion and wear resistance in a highly corrosive bodily environment and under different loading situations. A biomaterial must stay in contact with the human body's tissues longer and is unlikely to cease functioning. The implant material requires a service duration of 15 to 20 years in older and younger patients over 20 years **[25].** A material must satisfy the following conditions before it can be considered a biomaterial: mechanical qualities, corrosion resistance, osteointegration, and toxicity. An ideal biomaterial would neither be poisonous nor carcinogenic nor impede cellular functioning or create chronic inflammation. Good physical and mechanical properties are vital to satisfy the body's requirements.

Loading or stress causes the bone to regenerate, but insufficient loading causes atrophy. A significantly harder implant minimizes bone loading; stress transmission to surrounding bone is inadequate, resulting in the stress shielding effect **[26].** It could also be demonstrated that the degree of stress protection is directly proportional to the difference in stiffness between the bone and the implanted material **[27].** The deterioration of the stress-shielded bone interface results in a deteriorating interface to the implant, which can result in the implant loosening and fracture of the bone, the interface, or even the implant itself. A substance injected into the human body can affect the organism in a variety of ways, including cytotoxicity (cell death), carcinogenicity (cancer formation), mutagenicity (genetic damage), and pyrogenicity (immune responses). Alternatively, thrombogenicity (blood clotting) **[9, 24, 27].** The term "biocompatibility" was coined to describe the biological behavior of synthetic materials based on two primary factors: the host reaction caused by the implanted material and its breakdown in the physiological environment **[3].**

1.2 Stainless Steel for Orthopedic Applications

Interestingly, 316L stainless steel is widely used in medical and other industries due to its desirable properties, such as corrosion resistance, biocompatibility, mechanical strength, ease of fabrication and processability, and low cost. Adding alloying elements such as nickel, chromium, and molybdenum to the steel composition enhances its properties, particularly in corrosion resistance and mechanical strength. It is important to note that the presence of nickel in stainless steel, while improving its mechanical properties, may also be toxic to the human body. Therefore, minimizing the amount of nickel in the implant material is crucial to reduce potential adverse effects on the patient. The presence of other alloying elements, such as molybdenum, can also improve the resistance of the implant material to pitting corrosion caused by chromium carbide formation.

1.2.1 Clinical Studies of 316L stainless steel

316L stainless steel is a desirable implant material due to its many advantages. It is widely used in developing countries like India, where the affordability of healthcare is a significant consideration. However, considering other factors, such as the patient's specific needs and medical history, is essential when selecting an appropriate implant material. **Table 1.1** depicts the Clinical applications of the 316L SS. The initial success of THA was mainly due to Sir John Charnley's pioneering work and the use of 316L stainless steel in the implants **[18].** However, the long-term use of 316L stainless steel in hip joint implants has been associated with several issues, such as toxicity, poor corrosion and wear resistance, and carcinogenicity of released nickel and chromium. These issues have led to the replacement of 316L stainless steel with more corrosion-resistant and fatigue-resistant alloys as permanent implants. **Fig. 1.4** represents the 316L SS clinical application in implants. Despite the challenges associated with the long-term use of 316L stainless steel, it is still employed in many temporary devices such as internal fracture fixation and traction of the spine, bone plates and screws, intramedullary nails, rods, etc.

Table 1.1 Clinical applications of the 316L SS

Device	**Applications**	**Ref.**
Pins and bone screws	Internal fixation of cortical bone diaphyseal fractures, metaphyseal fractures, and cancellous bone epiphyseal fractures with screws with a self-tapping or non-self-tapping tip and a hexagonal driving head.	**[7]**
Bone plates only	Mandibular and shaft fractures can be internally fixed with a thin, narrow plate with holes for holding screws.	**[11]**
Nail bone plates and blades	Internal fixation of a weight-bearing bone fracture: a single-unit or multiple-component plate and nail.	**[19]**
Cardiac pacemaker housing	Electronics and power source packaging that is hermetically sealed: welded capsule	**[22]**
Dental amalgam retention pins	Significant dental amalgam restoration retention: friction lock, self-threading, and cemented pins were put into the dentin with a 2 mm (0.08 in) exposed region.	**[23]**
Endodontic post and core fabrication	They used endodontic tooth restoration post-fixed during root canal preparation, with the exposed core as a foundation for the crown.	**[23-24]**
Intramodular nail bones	Tube or solid nail for long bone internal fixing	**[28]**
Total joint prostheses	Shoulder, hip, knee, and excellent toe replacement with metal and plastic components: femoral (hip and knee), humeral, talus, and metatarsal components.	**[9]**
Wires	Circumferential cerclage or internal tension band wiring of bone fragments is used to treat comminuted or unstable shaft fractures.	**[29]**

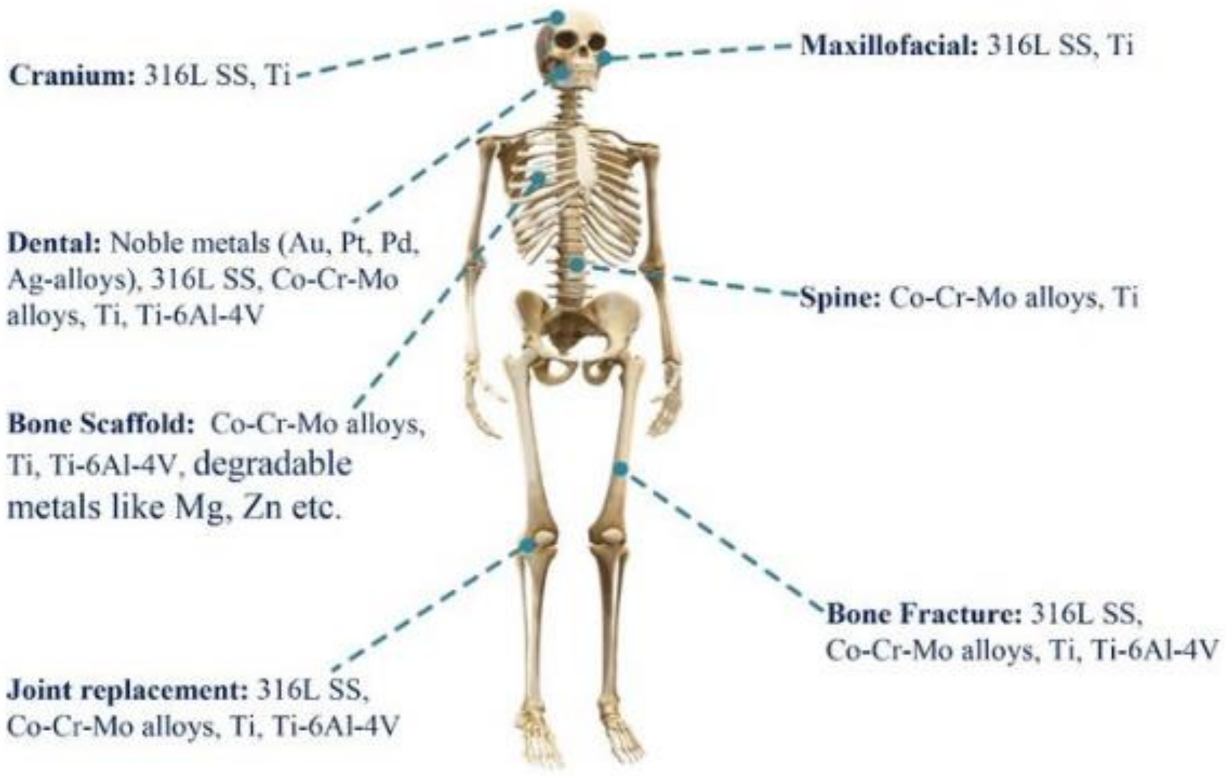

Fig. 1.4 316L SS clinical application in implants **[28]**

This is likely due to the low cost of 316L stainless steel compared to other materials. It is also noteworthy that the top two stem brands made from Orthinox (stainless steel) occupy approximately 60 and 10 % of the UK market, according to the 8th Annual Report of the UK National Joint Registration **[14].** The health and welfare of the human race have significantly benefited from stainless steel over time. In addition to being appropriate for high hygiene and sanitation requirements, stainless steel today allows medical science to combat various infectious diseases directly. Additionally, stainless steel has a low life cycle cost and doesn't require routine maintenance. These characteristics further demonstrate stainless steel's capacity to deliver healthcare services that are both effective and affordable in the future **[7-9].**

1.2.2 Drawback of 316L SS

Stainless steel 316L has been used as a popular surgical implant material due to its corrosion resistance, mechanical properties, and cost-effectiveness. However, as research continues, concerns have been raised regarding using SS316L as an ideal biomaterial. Some of the concerns associated with SS316L as an implant material include its high density, which can make patients feel heavy and uncomfortable. It also contains nickel, which can be dangerous for patients with nickel allergies. Additionally, the wear resistance of SS316L is relatively low, which can cause joints to loosen over time due to the wearing of the metal. SS316L implants are also prone to crevice corrosion and premature failure. Exposure to physiological environments can lead to electrochemical dissolution, releasing iron, chromium, and nickel particles over time, which are believed to have carcinogenic properties. Wearing SS316L can also remove microscopic particles that can become trapped in tissue, leading to body reactions and tissue damage **[29-31].**

Furthermore, SS316L is highly susceptible to cracking and crevice corrosion, and the proliferation of fabric layers has been observed over SS316L implants. Finally, alloys with an iron base can have a galvanic potential that can lead to issues with galvanic coupling if connected with titanium, cobalt, or zirconium implants. It is essential to continue research in this field to develop better biomaterials for implants that can address these concerns and provide patients with more effective and safe options.

- The high density of SS316L compared to bone can make the implant feel heavy and uncomfortable for the patient.
- SS316L is known for its corrosion resistance and relies heavily on the passive oxide layer formed on its surface for protection against corrosion. This oxide layer can be damaged by

mechanical wear and tear, creating pits that can cause localized corrosion. In the case of implant materials, this can lead to loosening of the implant and potentially require revision surgery. Additionally, the low wear resistance of SS316L can result in debris generation, which can cause inflammation and tissue damage in the surrounding area.

- It is known to be susceptible to crevice corrosion, which can lead to the premature failure of implants. This type of corrosion can occur in areas that are difficult to clean, such as under the head of a screw or in a tight-fitting joint. The accumulation of fluids in these areas can create a low-oxygen environment that promotes the formation of corrosive substances, leading to the corrosion of the implant. The resulting corrosion products can cause further tissue damage and inflammation, leading to implant failure.
- SS316L implants have been reported to fail before the prescribed period in some cases, which could be due to various factors such as corrosion, wear, fatigue, and stress corrosion cracking. The failure of the implant before the prescribed period can result in a need for revision surgery, which is associated with additional risks and costs.
- When SS316L implants are exposed to the physiological environment, they undergo electrochemical dissolution, which can release iron, chromium, and nickel particles over time. These particles can potentially have carcinogenic properties and lead to tissue damage and inflammatory reactions. However, it is essential to note that the release of these particles is generally minimal and occurs over a long period.
- Pitting and crevice corrosion can significantly concern 316L stainless steel (SS) implants. Pitting corrosion occurs when small pits or holes form on the implant's surface, leading to cracking and fracture of the material over time. Crevice corrosion occurs when the implant is

placed in a tight space or a crevice between the implant and surrounding tissue or bone, creating an environment with low oxygen levels and high levels of corrosive substances.

- ➢ SS316L locking plates have been reported to fail prematurely due to fatigue loading. Fatigue failure can occur when a material is subjected to cyclic loading, leading to progressive and localized damage accumulation, ultimately resulting in crack initiation and propagation.
- ➢ In some cases, 316L SS implants may need to be revised or removed due to complications such as infection, implant loosening, or other issues, which can be costly and invasive for patients and a potential source of additional complications and risks.

1.3 Surface Modification Techniques

1.3.1 General Overview

Due to its structural stability and inertness, 316L stainless steel is used in biomaterial applications; it lacks dual capabilities, including bone conductivity, blood biocompatibility, and bioactivity. Therefore, 316L SS has to have its surface modified. Additionally, by altering the surface of implants, corrosion resistance can be increased. Comparatively speaking, it is more advantageous than creating extremely corrosion-resistant alloys. The usable features of a bulk material can be preserved while modifying the surface to produce desired surface properties, which can also lower the material's cost. **Table 1.2** shows the different surface modification techniques. Surface modification is done to adjust or control the surface characteristics because implant materials' surface properties directly impact the initial protein adsorption from the biological fluid and activate favourable cell functions and selective recruitment **[32].** Good biocompatibility, improved bone binding capacity, high corrosion resistance, wear resistance, and aesthetic qualities for a biomaterial are desirable properties that can be attained through surface modification **[33].**

Table 1.2 Different Surface Modification Techniques

Techniques	Thickness	Merits	Demerits	References
Sputter coating	0.5–3 µm	Coating thickness uniformity on flat substrates, dense coating	The line of sight technique results in amorphous, costly, and time-consuming layers.	**[34]**
Thermal Spraying	30–200 µm	Low cost, High deposition rates	High temperatures promote breakdown and rapid cooling using the line of sight technique.	**[35]**
Dip coating	0.05-0.5 mm	Complex substrates can be coated with cheap coatings, which are applied rapidly.	High sintering temperature and incompatible thermal expansion	**[36]**
Sol-gel coating	<1 µm	It can coat complex shapes, and low processing temperatures are relatively cheap as coatings are brittle.	The process requires expensive raw materials and controlled atmosphere processing.	**[37]**
Electrophoretic deposition	0.1-2.0 mm	Complex substrates can be coated with quick deposition rates and uniform coating thickness.	Creating coatings without cracks is challenging and needs high sintering temperatures.	**[38]**
Pulsed laser Deposition	0.05–5 µm	crystalline and amorphous coating, and dense and porous coating	Line of sight technique	**[39]**
Biomimetic coating	<30µm	Low processing temperatures can produce bone-like apatite, coat complicated structures, and include bone development hormones.	Requires restoring as well as maintaining a consistent pH of simulated body fluids.	**[40]**

Laser Cladding	2–200 µm	High coating efficiency	The usage of lasers raises safety concerns. Cracks arise due to high residual stresses—the layer of porous covering. Ceramic phases lower toughness and ductility.	**[41]**
Thermal Spraying	75–475 µm	High coating efficiency	High porosity levels in coating layer. Inherent high-temperature causes oxide inclusions, affecting the hardness and abrasion resistance of the coating.	**[41]**
Thermal Oxidation	0.40–6.01 µm	High coating efficiency	The procedure is time-consuming; compared to other treatments, it has little influence on corrosion resistance. High temperatures and extended treatment times result in more visible stratification within the oxide scale, while low temperatures and short treatment times result in discontinuous oxides.	**[41]**
Friction Stir Processing	>150 µm	High coating efficiency	Residual stresses reduce fatigue resistance. Surface roughness is high.	**[41]**
Thermochemical Salt Bath	>40 µm	Low coating efficiency	Prolonged exposure to high temperatures affects production expenses.	**[41]**
Electric Discharge Machining/Coating	3–112 µm	High coating efficiency	Higher sparking energies have the potential to cause implant material surface fractures. The thickness of layers is difficult to control.	**[41]**

1.3.2 Importance of metallic coating

Metal coatings include electroplating, metalizing, hot-dipping, anodic coatings, vapour deposition, galvanizing, and mechanical alloying—different techniques for applying metallic coatings to various substrates. These methods offer additional advantages and are suitable for other applications. Here's a brief description of each process:

1. **Electroplating/electrodeposition** involves using an electric current to deposit a metal coating onto a substrate. The metal to be plated is dissolved at the anode and then deposited onto the cathode (the substrate) through an electrolyte solution. Electroplating is commonly used for decorative purposes, corrosion protection, and improving wear resistance.
2. **Metalizing** is when a metal coating is applied by spraying molten metal onto a surface. The molten metal is typically atomized and propelled onto the substrate using compressed air or a similar method. Metalizing is known for producing thick and durable coatings and can be used for various metals.
3. **Hot-dipping** involves immersing a clean metal substrate into a molten metal bath. The substrate is coated with molten metal, forming a protective layer upon solidification. Hot-dipping is commonly used for galvanizing, where steel or iron is coated with a layer of zinc to protect against corrosion.
4. **Anodic coatings** are created by coating metal anodic to the underlying metal substrate. It allows the coating to provide galvanic protection to the base metal while acting as a physical barrier against the environment. Anodic coatings can be dense, non-porous, and adhesive, providing effective corrosion resistance.
5. **Vapour deposition** forms a metal coating by vaporizing the coating material in a high vacuum chamber. The vaporized metal condenses onto the substrate, forming a thin film coating. This technique allows precise control over the coating thickness and can be used for various metals.

6. **Galvanizing** applies a zinc coating to steel or iron through hot-dipping or electroplating methods. The zinc coating provides excellent corrosion protection to the underlying metal, making it widely used in construction, automotive, and other industries.

7. **Mechanical alloying** involves ball-milling alloy powders onto a metal substrate, resulting in a cold-welded dry coating. This method creates a diffused alloy phase between the substrate and the coating material, enhancing the adhesion and providing unique properties to the coating.

Each of these methods has its advantages and is selected based on the specific requirements of the application, the desired properties of the coating, and the type of substrate being coated.

1.4 Role of Tantalum in Orthopedics Implants

Tantalum (Ta) plays a significant role in human implants due to its unique properties that make it suitable for biomedical applications **[42].** Tantalum has been used extensively in medical applications for over 50 years, including treating cranial defects, dental implants, permanent implantations, radiographic makers for diagnostics, and permanent implantations **[43].** However, it is commonly utilized in various human implants, including orthopedic implants (hip and knee replacements), spinal implants (cages and fusion devices), and other surgical implants. It contributes to the success and longevity of these implants by providing strength, biocompatibility, and imaging compatibility, ultimately improving patients' quality of life and mobility **[44].**

Here are some of the keys that tantalum is essential in human implants **[45-48]**:

a) Biocompatibility: Tantalum is biocompatible, meaning it does not elicit harmful reactions or toxicity when implanted into the human body. It has low reactivity with body tissues and fluids, reducing the risk of adverse reactions or inflammation.

b) **Corrosion resistance:** Tantalum exhibits exceptional corrosion resistance, even in harsh bodily environments. This property is crucial for long-term implant durability and stability, ensuring the material does not degrade over time.

c) **Strength and stability:** Tantalum is a strong and rigid material, allowing it to withstand the mechanical stresses and loads that implants may experience within the body. Its high melting point and deformation resistance contribute to the implant's structural integrity.

d) **Imaging compatibility:** Tantalum is highly radiopaque, meaning it can be easily visualized on medical imaging techniques such as X-rays, CT scans, and MRIs. This characteristic facilitates post-implantation monitoring, assessment of implant placement, and identification of potential issues or complications.

e) **Versatility:** Tantalum can be fabricated into various forms, such as screws, plates, rods, and porous structures, to suit different implant needs. Its malleability and compatibility with advanced manufacturing techniques allow for the production of customized implants that conform to patient-specific anatomical requirements.

f) **Bone integration:** Tantalum has been found to have favourable interactions with bone tissue. Its surface properties promote osseointegration, bone growth, and attachment to the implant, enhancing its stability and helping prevent loosening or failure. Tantalum produces bone plates and screws for fracture fixation and stabilization.

Tantalum's high strength-to-weight ratio allows for lightweight yet strong implants that provide stability and support for bone healing. These components provide stable fixation and support for artificial joints. Tantalum's mechanical strength and corrosion resistance make it ideal for load-bearing applications, where it can withstand the forces and stresses experienced during joint movement. Tantalum exhibits exceptional mechanical strength, which can withstand substantial mechanical loads without deformation or failure. Simultaneously, Tantalum is relatively lightweight. This combination of high strength and low weight is the essence of its impressive strength-to-weight ratio. The high strength-to-weight ratio of Tantalum allows for the creation of lightweight implants. This is crucial in medical applications to minimize the burden on the patient and the skeletal system. Despite being lightweight, Tantalum implants maintain significant strength. This is vital for providing structural integrity and support during the healing process. The strength of Tantalum ensures that the implant remains stable within the body, preventing any undesirable movement that could impede the healing of bones and offering robust support to the surrounding bone tissue, creating an environment conducive to effective healing. Tantalum is generally well-tolerated by the human body, and its biocompatibility contributes to successful integration with the surrounding tissues during the bone healing process.