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A Systematic Review of Health Informatics and Chemical Methods in Manufacturing Orthopaedic Titanium Plates

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Abstract

In the manufacture of orthopaedic products, extra care is taken to ensure that the plates; including titanium ones, undergo intensive chemical and thermo-chemical treatments to produce products that can tolerate high levels of strength, biocompatibility, wear and corrosion resistance. From all the titanium and its alloys used in medical applications the most widely used material is Ti-6Al-4V since it has excellent mechanical properties and is bio compatible. Comprehensive analysis of the chemical methodologies for orthopedic titanium plate production is presented in this systematic review which is done according to PRISMA guidelines. An extensive search of literature was done electronically from the PubMed, Scopus, Web of Science, and Google Scholar databases with options on subject terms such as titanium and orthopaedic implant. This analysis involved papers authored by scholars and scientific research articles available from 2000 to 2023, focusing on chemical purification techniques Alloying, Surface treatment, and Additive manufacturing. After that, two authors separately extracted data and finally compared them to minimize the risk of bias; the quality of the selected studies was assessed using CASP-checklist. Some of the chemical processes for the production of titanium are briefly reviewed based on category of material processing and purification that involves the Kroll process as well as other methods like the FFC Cambridge process which has better efficacy and effects on the environment. It extends to areas of alloying and melting method as the vacuum arc remelting (VAR), electron beam melting (EBM) methods which are crucial when making homogenous Titanium alloy. The hot working processes such as rolling and forging to analyse their impact on mechanical characteristics of the material. Are reviewed. The various heat treatments such as solution treatment and aging are discussed for the development of the required properties of strength and hardness.

Surface treatments, including anodizing, acid etching and chemical polishing as well as hydroxyapatite coatings are important with regards to biocompatibility as well as wear resistance. Advancements in AM such as SLM and EBM are showcased to synthesise intricate fully densified biomedical titanium implants. Also, a strict *chemical characterization process guarantees quality labour, with higher regulatory compliance. The final points of the review are environmental and economic impacts and it is stressed that green chemistry should be adopted to eliminate the adverse effect on the environment. Possible future research areas are associated with fine-tuning of chemical methods and procedures, optimization of the titanium orthopaedic plates use, and widening of application in the medical field.*

Keywords: *Titanium, Biocompatible Materials, Orthopaedic Procedures, Material Science*

Introduction

Orthopaedic applications have specific demand on the applied materials because the material shall be super strong, biocompatible, and have high wear and corrosion resistances. But it is fascinating to note that today titanium and its alloys particularly Ti-6Al-4V-elbow have found acceptance as superior material for orthopaedic implants like plates, screws and artificial joints. Manufacturing of orthopaedic titanium plates includes several processes like chemical and thermo-chemical so that it can have the required properties and performance. [1,2]This review synthesises the broad chemical processes used to manufacture orthopaedic titanium plates and focuses on recent improvements, issues, and developments.

This systematic review will aim at included all the chemical methods that are used in the synthesis of orthopaedic titanium plates. The study employs systematic review approach in the conduct of the research and is guided by PRISMA checklist.

Methodology:

1. Literature Search
A comprehensive literature search was conducted across multiple databases, including PubMed, Scopus, Web of Science, and Google Scholar. Keywords used in the search included "titanium," "orthopedic plates," "chemical processes," "manufacturing," "biocompatibility," "corrosion resistance," and "surface treatments." The search was limited to articles published in English between 2000 and 2023.

2. Inclusion and Exclusion Criteria : Inclusion criteria:
Peer-reviewed articles focusing on the chemical methodologies in the manufacturing of orthopedic titanium plates.
Research papers, review articles, and case studies that specifically discuss chemical purification, alloying, surface treatments, and additive manufacturing.
Studies addressing the biocompatibility, mechanical properties, and corrosion resistance of titanium plates relevant to orthopedic applications.

Exclusion criteria:
Articles not focused on orthopedic applications.
Papers lacking detailed chemical methodology or experimental data.
Non-peer-reviewed materials such as conference abstracts, editorials, and opinion pieces.

3. Data Extraction
Data extraction was independently carried out by two reviewers using a standardized form to ensure consistency and minimize bias. Extracted information included authors, publication year, study type, chemical processes discussed (e.g., purification, alloying, surface treatments), key findings, and implications for orthopedic applications.

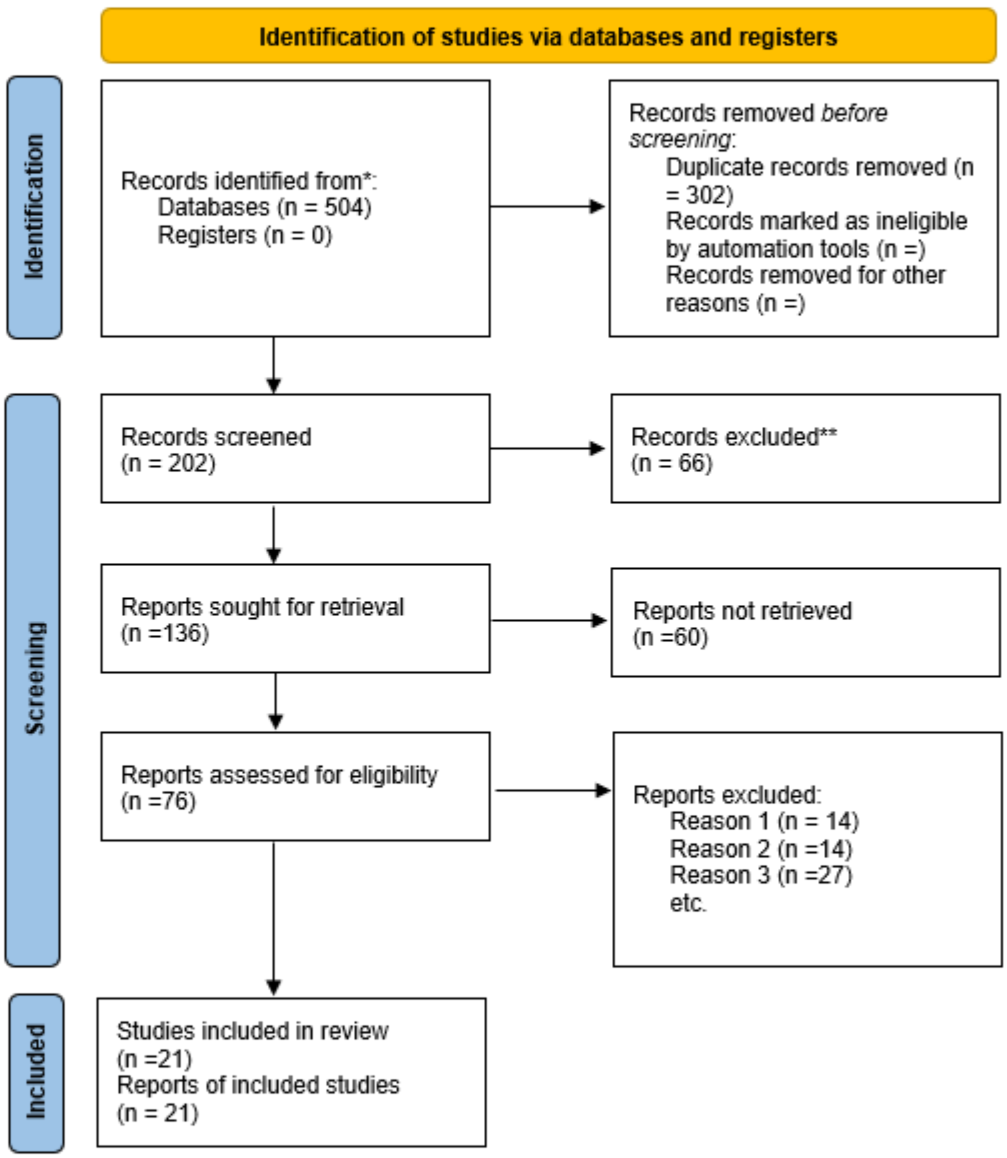
4. Quality Assessment
The quality of included studies was assessed using the Critical Appraisal Skills Programme (CASP) checklist. Each study was evaluated based on its methodological rigor, relevance, validity, and clarity of reporting.

5. Synthesis and Analysis

Extracted data were summarized and analyzed to identify trends, advancements, and gaps in the literature. Both qualitative and quantitative analyses were performed to provide a comprehensive overview of the chemical methodologies in the manufacturing of orthopedic titanium plates. Key findings were synthesized to draw conclusions and identify future research directions. (figure 1)

By adhering to these systematic methodologies, the review ensures a thorough and unbiased examination of the current state of chemical processes in manufacturing orthopedic titanium plates.

Figure 1 showing the PRISMA flow chart



1. This process essentially includes the extraction of raw materials from its natural environment and the subsequent purification.

Manufacturing of orthopaedic titanium plates begins with the extraction of titanium from its ores. The Kroll process [3]remains still now dominating the Titanium production business, this involves the reduction of Titanium tetrachloride ($TiCl_4$) with magnesium to form Titanium sponge. Purity is of significance when it comes to orthopaedic applications as a result of the issues of biocompatibility and mechanical properties. After the Kroll process, the titanium sponge as well is subjected to processes such as vacuum distillation and leaching with the help of acids to help get rid of trace elements including oxygen, nitrogen and carbon. Newer methods such as FFC Cambridge process which uses electrochemical reduction is also being developed for better efficiency and to have less harm to the environment.

2. Alloying and Melting

Usually the titanium impurities such as aluminium and vanadium and other added together to produce Ti-6Al-4V; a variety that is utilized in orthopedic applications. It also improves the properties such as strength, fatigue endurance limit and the ability to resist fractures. The most common practices when involved in formation of alloy is vacuum remelting or arc electrical remelting (VAR) or electron beam remelting (EBM) so as to minimize the impression of oxygen in the metallic melt by evaporation. [4]These techniques help in making a homogenous distribution of the alloying elements. Techniques such as cold hearth melting and plasma arc melting are also used to modify the microstructure in an effort to minimize inclusion and thus upgrade the quality of the alloy being produced.

3. Hot Working Processes

After obtaining the alloyed titanium ingots they go through the rolling and forging procedures which transform the titanium ingots into plates. These processes are mostly done at high temperatures to allow for easy deformation and to also enable the grain size to be minimized in as far as mechanical properties like ductility or toughness are concerned. These processes require protective atmospheres such as argon or should be conducted in vacuum to avoid formation of oxide layer on the surface of the material thus compromising the chemical makeup of the P-N junction. Some progress achieved in these processes includes thermomechanical treatments[5] that enable controlling the microstructure of metals to order to suit the particular orthopaedic application.

4. Heat Treatments

Annealing and other heat treatments are crucial so as to obtain the right mechanical characteristics of orthopaedic titanium plates. In fact, the most widely used heat treatment process in titanium alloys is solution treatment and aging (STA). [6]In solution treatment the plates are heated to labile the alloying elements and then rapidly cooled to freeze in the alloying elements in the matrix. Ageing entails A reheating to enable the formation of narrow intermetallic precipitates that improves the strength and hardness of the metal. Restriction of chemistry during heat heat-treatment entails that protective and reactive gases atmospheres are not permit on the work-piece since they cause oxidation and removal of the required microstructure and mechanical properties.

Benefits Titanium Orthopaedic Plates

Orthopaedic plates are used to fix most bone fractures and they are conducive to the bone healing process. Of all the used materials, titanium and its alloys, especially Ti-6Al-4V has been renowned as the most appropriate material to be used in orthopaedic implants such as plates, screws and replacement joints. Such preference has numerous advantages connected with usage of titanium instead of other materials. The author remarked some major advantages of using titanium orthopaedic plates in this review by discussing about the mechanical properties, biocompatibility, corrosion resistance, flexibility in imaging practices and long-term stability.

1. High Strength-to-Weight Ratio

Another benefit that is going to outweigh the others is the fact that titanium has a very high strength to weight ratio. It is about as strong as a steel, but about 45% lighter to boot. This property is most beneficial for orthopaedic use because lighter implant will lessen discomfort and fatigue of the patient. This is because a lighter implant has less impact on such tissues as the bone and thus, the rate of healing will be faster which then means that the patient can be allowed to move more while recovering.

2. Excellent Biocompatibility

One hears often the term biocompatibility when it comes to any material that is used in the manufacture of implants. Of all biometals, titanium elicits least immune reaction when incorporated in the human body thus possibilities of the implant being rejected are slim. The oxide layer that forms on the surface of titanium is chemically stable and does not leach with body fluids hence its good compatibility with bone and soft tissues. It also fosters osseointegration that is, the bone cells grow onto the implant surface and anchor themselves to it resulting in a strong biological bond that increases the strength and durableness of the orthopaedic plate.

3. Superior Corrosion Resistance

This makes titanium to be unique in that it has ability to withstand the corrosive nature within the physiological conditions while compared to other material like the stainless steel. The external oxide layer is also one cause for biocompatibility and is also responsible for the endurance of titanium against the corrosive signs of bodily fluids. This characteristic makes titanium orthopaedic plates to be long lasting so that there are minimal chances of implanting failure due to degradation. Thanks to the increased resistance to chemicals like chlorides present in the body fluids, titanium implants do not corrode as fast thus the decreased rates of wear and tear.[7-9]

4. The properties discussed above along with other properties such as non-magnetic properties and MRI compatibility.

Titanium is non ferromagnetic, this constitutes the fact that it is not attracted to magnets and in the same way does not hamper magnetic fields. Another aspect which makes this property suitable is the fact that some of the patients will need MRI scans after implantation. Mr image titanium implant does not produce image artifacts so that the diagnostic images are clear and highly accurate. [10]This is a very important factor over other materials such as stainless steel which may alter the image outcome of an MRI scan and hinder the post-operation tests.

5. High Fatigue Resistance

The mechanical properties of titanium are high fatigue resistance which means its capacity to withstand cyclic loading. In orthopaedic uses, screw like implants is placed under constant stress issues due to the cyclical use of body parts. The fatigue behaviour of the titanium material used in the design of the orthopaedic plates makes the plates to remain strong for a very long time thus, minimizing the chances of having an implant that fails and the patient and or doctor requiring a repeated surgery. [11]This property is particularly valued in bones that are responsible for bearing loads such as the femur and the tibia.

6. Young's Modulus of Elasticity comparable to Bone

On this respect, titanium has a value of elastic modulus closer to the natural bone as opposed to stainless steel or cobalt-chrome alloys.[12] This similarity in stiffness reduces the so called stress shielding where the implant has a lower elastic modulus than that of the bone material and therefore results in the diffusion of the implant material and weakening of the bones. Titanium orthopaedic plates duplicate the mechanical properties of bone more effectively than stainless steel, thereby allowing natural load transfer, bone to plate bonding and stimulation of the natural process of bone remodelling around the implant.

7. Customization and Manufacturing Versatility

The current developments in manufacturing technologies like the additive manufacturing or the 3D printing technology enables the production of titanium orthopaedic plates that can fit the bone's anatomical features of a particular patient. [13]It should be noted that such an individually-oriented approach gives better results concerning the fit and purpose of the implant. Also, owing to the versatile properties of titanium in terms of the applicable manufacturing techniques such as machining, forging and casting a multitude of implant designs is possible according to the specific requirements in the clinical field.

8. Over length Of Life And The Requirement For Re-Operation

The properties like high tensile strength, corrosion resistance, biocompatibility and fatigue resistance which has been achieved through the use of titanium material for orthopaedic plates enhances the product's durability. Titanium implant patients have comparatively lesser implant failure and complications which would make less need for revisions. [14,15]It also enhances the health of the patients as well as cuts on the costs of doing more invasive procedures or even costly long term care.

5. Surface Treatments and Coatings

Surface treatments are a very important factor that defines the wear resistance, corrosion resistance, and biocompatibility of titanium plates. [16,17]Several chemical methodologies are employed:

Several chemical methodologies are employed:

• Anodizing: This electrochemical process leads to the formation of passive oxide film on the surface of titanium which increases the corrosion properties of the material and offers foundation for higher bone bonding.
• Acid Etching: Acid treatments which include hydrofluoric and nitric acids work to clean and roughen the surface to enhance bone advancement.
• Chemical Polishing: Contaminants such as acids and other reagents in chemical polishing smoothens the surface and minimizing stress concentrators that may cause early failure.
• Hydroxyapatite Coating: Such calcium phosphate based coating is put by methods such as plasma spraying which increases osteoconductivity and compatibility with the bone.

6. Chemical Milling and Machining

Chemical milling or chemical etching is a method that allows removal of material in order to create small or complex shapes and designs on the plates of titanium, for example, in this process, chemical reagents such as hydrochloric or sulfuric acid is applied in a controlled manner to dissolve away the undesired material but without applying mechanical force. [18]This results to high degree of accuracy which makes chemical milling suitable in manufacturing highly geometric implants that are used in orthopaedic treatments. However, there is need to be cautious when handling chemical substances which are hazardous for use and reliable methods for disposing of these chemicals has to be taken.

7. Additive Manufacturing Innovations
Selective laser melting (SLM) and electron beam melting (EBM) form of AM technologies have brought drastic changes in the design and manufacturing of medical devices such as orthopaedic implants. These processes include the successive coating of a substrate with an aperture of titanium powder, that may be sintered or melted by high energy beams. [19]Chemical strategies in AM address the issues of high purity of the final powders, for instance, via gas atomization and plasma spheroidization. This cements the foundation upon which gelation of the powder is controlled so as to possess a uniform properties and quality.

8. Chemical analysis or characterization and quality control
Therefore, throughout the different manufacturing process stages chemically formulating and monitoring is critical to meet the demanded orthopaedic implant qualities. [20]Microstructural and compositional analyses of the coating are conducted using X ray diffraction (XRD), scanning electron micrography (SEM) and energy disbursal X ray spectroscopy (EDS). Most chemical techniques such as ICP-MS and GD-MS help in getting highly accurate quantities of trace elements and impurities in a sample. These analyses assist in maintaining some level of standardization and quality and since medical devices are regulated, it is vital to achieve quality products.

9. Environmental and Economic Considerations
It was also evident that the chemical methods used from manufacture orthopaedic titanium plates present environmental and economic related concerns. [21]The use of sustainable practices because some chemical processes employ hazardous chemicals and are energy demanding. Researchers and industry have adopted sustainable strategies, for example using recyclable chemical and or energy saving techniques. Also, enhancements in the chemical processes could minimize costs associated with the process due to increased efficiency as well as yield. More attention should be paid to recycling titanium scraps as well as applying the principles of green chemistry.

Conclusion
Orthopaedic titanium plates are made by a complex of procedures involving the usage of highly effective chemical reactions to produce strength, biocompatibility and durability. Pre-processing methods include material purification and composition modification; while post-processing methods include surface treatment and the use of metal part manufacturing technology. These properties make titanium better for orthopaedic use as it has high strength to weight ratio, favourable biocompatibility and high corrosion resistance. The future developments are expected to be aimed at improving chemical processes in terms of productivity, eco-friendliness and cost breakthroughs. Further study and developments on the chemical strategies will therefore be vital to satisfying the dynamic orthopaedic medicine requirements in an effort to increase the patients'

wellbeing besides enhancing the effectiveness of the titanium-based implants in the long run. Therefore, this systematic review provides clear evidence about the significance of chemical techniques to develop orthopaedic implant manufacturing field.

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