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Exploring the Potential of 3D Printed High Nitrogen Nickel-Free Stainless Steel for Use in Dental Applications

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Abstract

The innovative medical-grade high-nitrogen nickel-free stainless steel material presents a promising avenue for applications in biomedical engineering, owing to its exceptional biocompatibility, remarkable resistance to corrosion, superior mechanical properties, and significant cost-effectiveness. By replacing nickel with nitrogen, this material effectively addresses potential concerns related to nickel allergies, thereby ensuring safer medical alternatives for patients compared to conventional stainless steel. This paper provides an exhaustive examination of the material's performance attributes and its current research status, both domestically and internationally, offering a comprehensive overview of its potential applications in the biomedical field. Through detailed comparative analyses with traditional alloys, it elucidates the material's advantages and highlights its potential for widespread adoption in medical settings. Moreover, the parper conducts a thorough evaluation of the material's current applications, identifying pertinent challenges that need to be addressed for its optimal utilization. Finally, the paper delves into the prospective advancement of 3D-printed high-nitrogen nickel-free stainless steel in oral medicine, offering valuable insights into its anticipated applications and its potential to drive innovation and expand possibilities in the realm of oral healthcare.

Keywords

High-nitrogen Nickel-free Stainless Steel; 3D-printed; Stomatology.

1. Introduction

Currently, the materials commonly used in oral cavity treatments are nickel-chromium alloy and titanium alloy. However, nickel-chromium alloy has a high specific gravity, poor elasticity, and weak corrosion resistance. Additionally, it contains elements such as nickel and chromium that are harmful to the human body. On the other hand, the casting process for titanium and titanium alloy is demanding and expensive [1]. Meanwhile, as digital technology continues to advance, 3D printing is rapidly emerging in the dental field, offering the potential for personalized and precise production. Additionally, the increasing demands of orthodontics, prosthetics, and other related technologies are driving the need for advanced materials suitable for 3D printing. Therefore, in order to meet the needs of dental clinical applications, it is necessary to develop materials that are easy to process and have good biocompatibility. The new medical biomaterial, high-nitrogen nickel-free stainless steel, replaces nickel with nitrogen. This not only avoids the toxic effects that may be induced by the dissolution of nickel ions, but also provides excellent mechanical properties, corrosion resistance, and biocompatibility. Menzel[2] et al. analyzed the feasibility of using high-nitrogen nickel-free austenitic

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steels in biomedical applications. The study suggests that high-nitrogen nickel-free stainless steel has great potential for development in the dental field. This paper outlines the current research and clinical applications of new high-nitrogen nickel-free stainless steel materials in the biomedical field. The aim is to explore the feasibility and development direction of 3D printing high-nitrogen nickel-free stainless steel in the oral field and provide a reference for its application. The language used is clear, concise, and objective, with a formal register and precise word choice.

2. Biocompatibility Study of High Nitrogen Nickel-free Stainless Steel

Many countries have already issued application standards for medical high-nitrogen nickel-free stainless steel. The biocompatibility of high-nitrogen nickel-free stainless steel, as a novel biomedical material, has become a major research focus. Liu Meixia et al. from the Chinese Academy of Sciences conducted comparative studies on the biocompatibility of high-nitrogen nickel-free stainless steel with L605 alloy and 316L stainless steel, demonstrating that high-nitrogen nickel-free stainless steel exhibits significantly better hemolytic resistance than L605 alloy and 316L stainless steel[3]. Ma Tianchi et al. concluded, through cell adhesion experiments, MTT assays, and alkaline phosphatase activity analysis, that the biocompatibility of high-nitrogen stainless steel with rat bone marrow stromal cells increases with increasing cold deformation [4]. However, processing cold deformation may affect the mechanical properties of high-nitrogen nickel-free stainless steel, and further research is needed to balance biocompatibility and mechanical properties. Lu Hua et al. conducted in vitro experiments on cytotoxicity, hemolysis, carcinogenicity, etc., of high-nitrogen nickel-free stainless steel materials; compared with 316L medical stainless steel materials, they evaluated their subcutaneous reactions, sensitivities, and acute/subchronic systemic toxicities through different animal evaluations[5]. They demonstrated that high-nitrogen nickel-free stainless steel bone implant materials pose no potential harm to the body's tissues and organs, and have a more pronounced effect on promoting new bone formation than 316L medical stainless steel. They have significant clinical prospects in applications such as dental implants and gap retainers.

The aforementioned studies indicate that the novel high-nitrogen nickel-free stainless steel exhibits remarkable biocompatibility both in vitro and in vivo, surpassing traditional 316L medical stainless steel in hemolytic resistance and promotion of bone growth. Furthermore, compared to conventional stainless steel, high-nitrogen nickel-free stainless steel, devoid of nickel elements, possesses superior physical, chemical, and biocompatible properties. Consequently, future research endeavors are likely to focus on the utilization of personalized 3D-printed high-nitrogen nickel-free stainless steel in areas such as the fabrication of dental frameworks and gap retainers.

3. 3D Printing High Nitrogen Nickel-free Stainless Steel Application Investigation

High-nitrogen nickel-free stainless steel is a single-phase microstructure where nitrogen partially or entirely replaces nickel. The production of austenitic stainless steel by "nitrogen substitution for nickel" not only enhances the mechanical properties and corrosion resistance of stainless steel, reduces costs, but also improves the stability of the austenitic phase and reduces magnetic permeability. [6].

Compared to traditional machining processes, 3D printing can produce parts with high dimensional accuracy and low surface roughness directly. It is a precise and efficient method of manufacturing. The Selective Laser Melting (SLM) process is a 3D metal printing technology that uses a laser or an electron beam as a heat source to melt and solidify powdered materials layer by layer in a confined space and under the protection of an inert gas to construct products. This process does not require a binder, which reduces assembly time, improves material utilization, and saves production costs. Ni Guolong [7] and Ren Jianbiao [8] explored the process parameters for selective laser melting (SLM) molding to obtain high-quality, high-nitrogen, nickel-free stainless steel. SLM's high cooling rate and rapid solidification of the alloy were utilized to inhibit nitrogen escape. The results indicate that SLMformed specimens exhibit superior tensile strength, yield strength, and elongation compared to castings. Wang Shuhuan and other scholars [9] conducted experiments on the preparation of high-nitrogen stainless steel technology using the atmospheric pressure overmatching powder laser selective zone melting method. The aim was to address the high cost and complexity associated with the high-pressure preparation of high-nitrogen nickel-free stainless steel equipment. The results provide theoretical support for improving the mechanical properties and corrosion resistance of high-nitrogen nickel-free stainless steel at a lower cost, and have broad application prospects.

The defects in SLM production differ from those in conventional casting and forging. The main defects in SLM parts are porosity, cracks, and internal stresses. Porosity patterns can be round or irregular. Round porosity is mainly caused by gas trapped in the melt pool, while irregular porosity is due to the unstable shape of the melt pool. During SLM, the large temperature gradient in both vertical and horizontal directions causes uneven deformation during cooling, resulting in internal stresses within the print. Internal stress can cause micro-defects that lead to slight cracks. 3D printing of high nitrogen nickel-free stainless steel is a cost-effective, efficient, and flexible alternative to medical 316L austenitic stainless steel. High nitrogen nickel-free stainless steel meets medical standards for corrosion resistance and biocompatibility, and its comprehensive performance is even better. This material is important for dental materials as it helps to balance the current problems and improve the future. The future improvement of SLM technology to optimize finished dental materials is worth further exploration.

4. 3D Printing of High-nitrogen Nickel-free Stainless Steel for Clinical Applications

The field of healthcare is witnessing rapid development in personalized 3D printing technology, which has great potential for clinical dentistry. Currently, there are several full denture systems available for clinical oral restoration, including SUN's digitized full denture system and full denture 3D printing system, among others [10]. 3D printing technology is achieved through Selective Laser Melting (SLM). SLM is characterized by the direct melting and solidification of metal powders to produce metallurgical bonding. It is essentially a transient metallurgical process in which a micron-sized molten pool of microgold is solidified at high speed [11]. Compared to other metal fabrication processes, Selective Laser Melting (SLM) offers several advantages, including high efficiency, waste elimination, design flexibility, reduced assembly, increased productivity, and cost savings. Previous studies have shown that high-nitrogen stainless steels are utilized in cardiovascular surgery due to their excellent biocompatibility as cardiovascular scaffolds [12]. Additionally, the new surgical implant, Biodur® 108, which is made of high-nitrogen, nickel-free stainless steel and was developed by Jetmax in the United States, has already been introduced to the market, demonstrating that the performance of high-nitrogen steel meets practical requirements.

In summary, 3D printing of high-nitrogen nickel-free stainless steel has been used in clinical cardiovascular and other fields. The future application of high-nitrogen nickel-free stainless steel as a 3D printing material to oral restorations, orthodontics, maxillofacial plastic surgery, and other areas has great potential.

5. Summary

In recent years, China has exhibited synchronous growth in the field of 3D printing technology, demonstrating sustained attention to this technology. However, it has also exposed some issues that need to be addressed. Currently, the core technologies of 3D printing software and equipment in China are mainly monopolized by foreign countries, resulting in our heavy reliance on imports, which are often expensive. This limitation impedes the development of 3D printing technology in the field of oral medicine in China. Additionally, the promotion of 3D printing technology using high-nitrogen nickel-free stainless steel faces several challenges:

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(1) There are ethical concerns regarding the safety of 3D printed high-nitrogen nickel-free stainless steel implants. When conducting human trials, in addition to standard regulatory approval processes, more consideration needs to be given to the uncertainty of long-term effects of implants and liability issues in case of complications. (2) Specific application parameters and standards for the use of high-nitrogen nickel-free stainless steel in various aspects of the oral field are lacking and require further exploration to fully exploit its potential in dental medicine.(3)During the 3D printing and post-processing stages, metal powder with particle sizes smaller than 100 micrometers poses a risk of inhalation and mucosal damage. Workers need to wear protective gear such as respirators and protective clothing, and inert gases are used to prevent asphyxiation caused by their leakage.

In summary, the application of 3D printing technology with high-nitrogen nickel-free stainless steel has shown promising results in fields such as the cardiovascular system and surgical implants. With medical-grade high-nitrogen nickel-free stainless steel being a material characterized by its simple manufacturing process, low cost, excellent mechanical properties, corrosion resistance, and good biocompatibility, it is expected to find widespread use in dental metal materials. The advent of 3D printing with high-nitrogen nickel-free stainless steel is poised to usher in a new era in the field of oral medicine.

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