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Application of a hybrid additive manufacturing methodology to produce a metal/polymer customized dental implant

M. Silva[a], R. Felismina[a], A. Mateus[a], P. Parreira[c], C. Malça[a,b]*

[a]Centre for Rapid and Sustainable Product Development, Polytechnic Institute of Leiria, Rua de Portugal, 2430-028 Marinha Grande, Portugal
[b]Department of Mechanical Engineering, Polytechnic Institute of Coimbra, Rua Pedro Nunes,3030-199 Coimbra, Portugal
[c]Entrepreneurship Department, Coimbra Nursing School, Rua 5 de Outubro, 3046-851 Coimbra, Portugal

Abstract

In this paper an integrated methodology for implants personalized manufacturing is presented. This methodology materializes the hybrid material implants manufacturing through the integration of two or more advanced Additive Manufacturing (AM) technologies. Furthermore, high strength biomechanical implants with optimized geometry and mass can be manufactured by biomimetic concepts application. The combination of polymers and ceramics or polymers and metal materials (or metal alloys) allows a significant leap in the development and production of a great diversity of components and applications. The combination of advanced additive manufacturing processes, e.g. the Selective Laser Melting (SLM) or Selective Laser Sintering (SLS) and the StereoLithography (SL), make possible the production of parts with almost unlimited geometric freedom and custom multimaterial. The manufacturing flexibility and the processing capacity of the different combinations of materials - metal/polymer - obtained from hybrid additive manufacturing systems - SLM/SL - are demonstrated here by the manufacture of a dental bridge implant.

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Keywords: Edentulism; Hybrid material customized implants; Metal/Polymer implants; Hybrid additive manufacturing process, SLM/ SL.

* Corresponding author. Tel.: +0-000-000-0000 ; fax: +0-000-000-0000 .
E-mail address: author@institute.xxx

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1. Introduction

The prevalence of edentulism is considered an index that, although coarse, indicates the quality of oral health of a significant segment of the population [1]. Fixed prosthesis has been a commonly adopted solution to solve this problem. However, the oral rehabilitation of edentulous patients, through the use of fixed total prostheses, involves previous reconstructive procedures, which may include soft tissue problems, instability of the removable prosthesis, papillary hyperplasia - "denture callus", poor tissue tolerance and functional, aesthetic and psychological problems [2]. These limitations have led to a growing demand for alternative approaches such as implant prostheses or the placement of bone integrated implants, which has made dental implantation a widely accepted and widespread therapeutic approach in dentistry. However, a significant number of patients, whether due to single or multiple tooth loss, a process of osteolysis, or genetic factors, presents mandibular or maxillary bone atrophy, that is, it does not present a sufficient bone thickness for implant placement [3].

The combination of additive manufacturing technologies and new designs inspired in algorithms that mimic patterns, e.g. Voronoi patterns, provides new ways of thinking about form, material behavior, structure performance, geometry optimization, etc [4-7]. Furthermore, new hybrid material components, e.g. metal/polymer, besides size and mass component decrease, allow for enhanced mechanical properties, improved application reliability and multifunctional features. Due to their high performance, hybrid material parts are increasingly sought in several markets such as electronics, aeronautics, automotive, among others. However, the current supply of these types of components is low since a hybrid additive manufacturing approach is required.

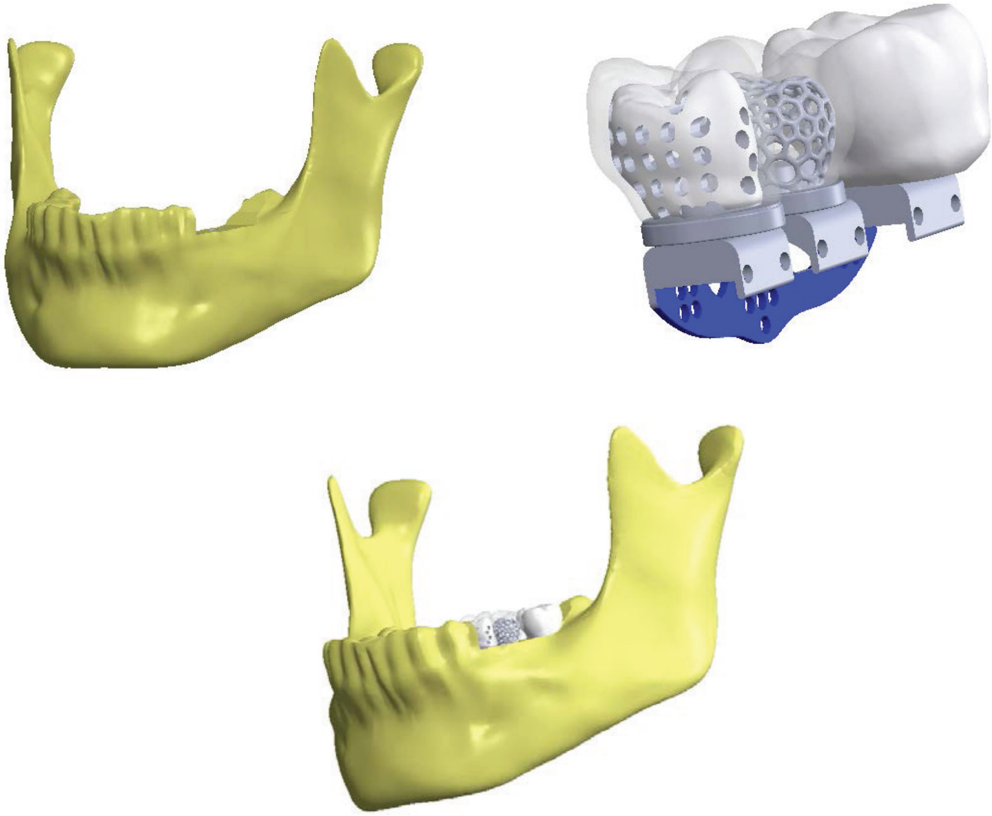
Concerning the health area, bone replacement customized implants is a very important application, where hybrid material manufacturing parts have had a high demand growth, in particular, permanent and/or temporary medical implants with mechanical properties identical to bone. The development of both new hybrid materials and hybrid manufacturing processes, which lead to implants that satisfy biocompatibility, mechanical, and structural behaviors, customized geometry, comfort and aesthetic needs, appears as an innovation. This integrated strategy will contribute to reduce recovery times, reduce symptoms and improve functional capacity, which translates into a significant impact on the quality of life of medical interventions. With these purposes and in order to find an alternative solution for edentulism problems, a procedure to develop and manufacture customized, less costly and suitable dental implants, avoiding an initial surgery and allowing immediate intervention, is presented in this paper. This procedure, apart from 3D direct digital design modelling of customized implant [7], uses a combination between the two advanced additive manufacturing technologies, the SLM and the SL [4,5]. This combination enables the photopolymerization of a polymer in the voids of a 3D core metal mesh previously produced by SLM. This biocompatible metal mesh, which has the required mechanical strength, was optimized based on Voronoi patterns to promote rigid and soft tissue regeneration and growth [6]. The core mesh is then placed on the SL platform and the additive process starts with the first daylight resin layer polymerization until the complete manufacture of the crown teeth.

2. Application of a AM hybrid strategy to the manufacturing of customized dental implants

Recent developments in CAD/CAM tools, where machining is done from a block of material, have allowed the replacement of conventional orthoses, prosthesis and implant techniques [8]. However, these subtractive techniques present serious limitations in the manufacture of structures with complex geometric shapes, which limits the range of products that can be manufactured by this technology. The use of the SL technique, for example, eliminates the molding process to obtain the positive mold, allowing its production directly from the CAD file. It has been demonstrated that, by SL, orthoses can be produced with variable thickness, with better fit, greater comfort and dimensional accuracy [9]. Faustini et al. And Pallari et al. [11, 12] have demonstrated the feasibility of SLS in the manufacture of custom orthotics in particular with respect to the development of a mass customization system that, with the exploitation of the freedom of design offered by the SLS, offers a holistic approach with significant clinical potential. Using the combination of two or more AM techniques, e.g. SLM / SL or SLM / SLS, it is possible to produce biomechanical devices with high mechanical strength and optimized mass/volume ratios of material thanks to the use of two or more kinds of materials. However, the manufacturing of parts with functional gradients - multimaterial components - is a huge challenge due to the different processing parameters associated with each type of material. A strategy to achieve this is presented in this paper applied to a customized dental implant manufacturing.

2.1. Image acquisition of jaw and virtual development of customized dental implant

The maxilla geometry was captured using a computed tomography (CT) equipment. In this case the CT dataset were derived from a female with an edentulism problem (absence of three teeth) in the left side of the jaw. A sequence of several parallel images of the 2D cross-sectional slice was obtained. The slice spacing was 0.5 mm and the pixel size was 0.334 mm/dot. Each image acquired was sequentially numbered and converted into Non-Uniform Rational B-Splines (NURBS) representations of the surfaces in order to achieve the subsequent 3D model. The NURBS on each cross-sectional slice were imported into commercially available 3D CAD software, aligned using a fixed reference frame and joined together by means of several surface/solid reconstruction strategies. The 3D CAD solid model of the jaw obtained is shown in Fig. 1.a), where the accurate location and extent of the edentulism problem can be observed.



a) b)

c)

Fig. 1. 3D CAD model of the: a) patient's maxilla with edentulism problem; b) generation from a Voronoi pattern and a topological optimization procedure of the core geometry of the dental bridge; c) resulting from the assemblage between the jaw and the bio-inspired customized dental implant.

A customized implant was designed in a virtual environment, using a conventional CAD software package, with a view to maintaining optimal aesthetics and function of the jaw. The implant geometry is generated to fit the edentulism defect from geometric and biomechanical points of view. Therefore, and based on biomimetic principles, with the application of 3D modeling methodologies and topological optimization tools, in this case using Voronoi standards [6], the metallic inner meshes shown in Fig. 1.b) of the teeth core of the dental bridge were built. After defining the geometry of the biomechanical teeth core, the remaining body of dental bridge, i.e. the teeth crowns were constructed based on the anthropometric data of the patient. Fig. 1.c) shows the full virtual model - the 3D CAD model resulting from the assemblage between the jaw and the customized implant - of the bio-inspired dental implant whose core is fabricated from a material of high mechanical strength, e.g. metal or ceramic, and a coating (teeth crowns) produced with a polymeric material or ceramics in order to confer to the dental bridge the required biomechanical features.

2.2. Hybrid processing

The physical models of the dental bridge was fabricated using a hybrid AM process that resulted from the combination of the SLM and SL techniques are schematically represented in Fig. 2. The process begins with the production of a metal mesh through the SLM process as shown in Fig. 3. The mesh is then placed on the SL platform and the additive process begins with the polymerization of the first layer of the photosensitive resin. Fig. 4. shows the custom dental bridge developed and manufactured using two types of materials, one for the core and another - coating - for the teeth crowns, by the combination of two AM processes. The combination of manufacturing processes now described allows the production of components of high mechanical strength and/or gradients of physical and mechanical properties, thanks to the combination of two or more types of materials and the application of topological optimization tools.

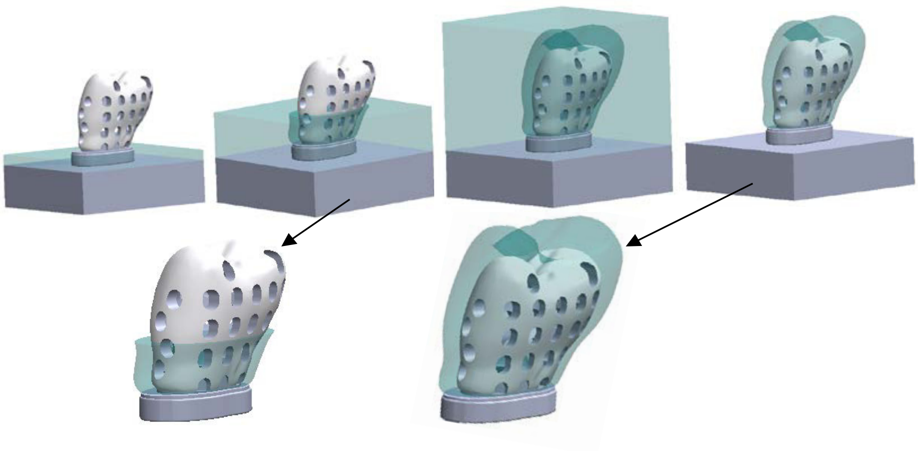


Fig. 2. Steps of the AM hybrid process: Combination of SLM and SL techniques

Fig. 3. Production, by SLM, of the tooth and dental bridge cores

Fig. 4. Multimaterial and personalized physical model of the dental bridge.

The flexibility of construction, geometric freedom and processability of the different materials from the combination of AM techniques allows for extension of the field of application of the integrated methodology proposed here. For example, in the case of an implant submitted to a force variation throughout its compliance, it would be an advantage to produce this implant with a variation of rigidity throughout its compliance since this parameter is determinant for the tissue stimulation, bone integration and reduction of possible bone fracture in the region adjacent to the implant.

4. Conclusions

The purpose of this work was to generate a customized multimaterial dental implant for a specific patient with edentulism. For this, the maxilla 3D geometry was constructed and the edentulism problem dimensionally characterized. Afterwards, and in order to restore the proper anatomical form and functional relationship of the maxilla, the geometry of implant was constructed and optimized to fit the edentulism defect. Voronoi standards were therefore applied as topological optimization tools. Concerning dental bridge manufacturing, the SLM and SL AM techniques were combined to produce teeth with functional gradients. The production possibility of parts with functional gradients increases the production range of high strength parts with optimized mass/volume ratio and superior quality. Furthermore, this work shows that the partnership between clinicians, designers, engineers, manufacturing specialists and the user results in optimized, differentiated and high added value products, in particular, for medical applications as exemplified here.

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