euspen's 20th International Conference & Exhibition, Geneva, CH, June 2020
www.euspen.eu

Metal Additive Manufacturing of Multi-Material Dental Strut Implants

M. Kain[1*], V. K. Nadimpalli[1*], A. Miqueo[2], M. C. May[3], J. A. Yagüe-Fabra[2], B. Häfner[3], D. B. Pedersen[1], M. Calaon[1], G. Tosello[1]

[1]*Department of Mechanical Engineering, Technical University of Denmark, Building 427A, Produktionstorvet, 2800 Kgs. Lyngby, Denmark*
[2]*Escuela de Ingeniería y Arquitectura, Universidad de Zaragoza, Calle María de Luna, 50018 Zaragoza, Spain*
[3]*wbk Institute of Production Science, Karlsruhe Institute of Technology, Kaiserstraße 12, 76131 Karlsruhe, Germany*

*mkain@mek.dtu.dk, vkna@mek.dtu.dk

Abstract
The demand for high flexibility and mass customization within medical implants has resulted in the early adoption of additive manufacturing technologies in the medical sector. Apart from offering unique customization opportunities, metal additive manufacturing of implants also enables the generation of functionally structured surfaces showing increased biocompatibility. The need for improving properties like biocompatibility is essential since many patients suffer from dental implant failures such as screw loosening, integration failure or implant breakage. The high requirements for implant materials depending on the specific implant environment and function complicates the implant design and results in multi-component implants. This could be overcome by the use of multi-material metal additive manufacturing that enables functionally graded part production. However, current commercial laser powder-bed fusion systems are limited to a single material at a time. By utilizing an open-architecture laser powder-bed fusion system by Aurora Labs it was possible in a controlled way to mix AISI 316L Stainless Steel with AISI 440C Stainless Steel during the fabrication of a dental strut-like geometry thereby functionally grading the properties of the material to have a low hardness near the gums and a higher hardness around the crown. The material distribution was evaluated by cutting and etching and the hardness was measured at various locations. The current work demonstrates the technical viability of manufacturing functionally graded dental strut implants by leveraging multi-material metal additive manufacturing.

Multi-material, Metal Additive Manufacturing, Dental Implant

1. Introduction

During recent years the development and improvement of metal additive manufacturing (MAM) technologies have expanded the domain of application significantly. Previously, the most common areas of applications where found within the field of complex part geometries at low volume application or for high value customized parts. However, as the technology improves and becomes more economically efficient it becomes feasible to manufacture cheaper highly customized low volume parts. Such parts can be found within the domain of medical implants, where patient specific customization offers an advantage compared to conventionally mass-produced implants [1].

The manufacturing of dental implants is a known area when it comes to integration of additive manufacturing, where additively manufactured dental crowns are already being offered on a wider scale [2]. However the remaining part of the implant, which is assembled from several part components, is currently mass-produced using conventional manufacturing methods. One of the reasons for assembling several components is the different functional requirements in the environment around the implant. Another aspect of AM in implant manufacturing is the possibility to apply functional structuring to a surface or the full implant in order to enhance the biocompatibility, which also acts as the main motivation for the investigation undertaken in this study [3].

Most current MAM systems are limited to the use of a single material in a build which restricts the capability of functionally grading the manufactured parts. Hence, a modified L-PBF system has been utilized in the present work that is capable of controlling the mixing of material powders thereby creating continuous interfaces between two different materials [4]. This preliminary research investigates the potential application of multi-material MAM technology for the manufacturing of functionally graded dental implants.

2. Implant Design for Multi-Material Additive Manufacturing

The environmental change in the mouth significantly influences the functional requirements of the implant components. The implants crown, as shown in figure 1, is exposed and needs a cosmetic finish that matches the patient's teeth.

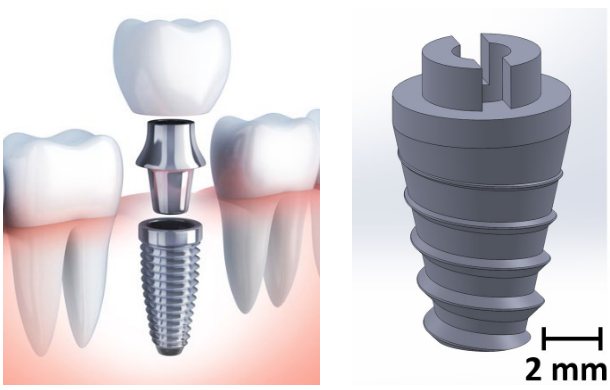

Figure 1. Left: Schematic picture of components in a simple dental implant consisting of (from the top): Crown, Abutment, Strut [5]. Right: CAD drawing of simplified combined strut and abutment.

The crown is frequently made from a ceramic material that can be coloured in custom shades of white, whereas the abutment and the strut, as shown in figure 1, is frequently made from either titanium or stainless steel [2].

2.1. Functional gradation

It is important that the functional requirements of the implant matches the surrounding environment. Whereas the top of the implant must be strong and yet gum compatible, the lower part should have bone-compatible capabilities such that a strong bond between the overall implant and the jaw is ensured. By combining the abutment and the strut, as schematically shown in figure 1, it is possible to reduce the assembly into a single part. Due to the different functional requirements of this part it can be manufactured using multi-material MAM where the lower part, originally the strut, is manufactured in one material while the top part, originally the abutment, is manufactured in a second material. A strong bonding of the two materials is ensured due to the gradual change of the interface material composition during the build. The possibility to introduce geometrical structures on the surface when manufacturing using MAM is of large interest, however in this preliminary study, no functional structuring has been introduced in the design.

2.2. Implant design for additive manufacturing

In order to manufacture the implant component a few design alterations must be considered to optimize manufacturability and minimize the need for post processing. A minimum angle of inclination of 45 degrees has been ensured across the full specimen to avoid the need for support structures.

2.3. Manufacturing

The implant specimen was manufactured on an Aurora Labs S-Titanium Pro laser powder bed fusion (L-PBF) system which simultaneously combines two 150 W CO_2-laser sources. The systems have been adapted to enable specific ratio mixing of two different metal powders for individual layers throughout the build job. The two powder materials used in this work are AISI 316L Stainless steel and AISI 440C Stainless steel with a concentration of 316L of 100 % in the lower part of the specimen and a 50/50 concentration of 316L and 440C in the upper part of the specimen, as shown in figure 2. The operating process parameters are thoroughly described in Nadimpalli *et al*. [4].

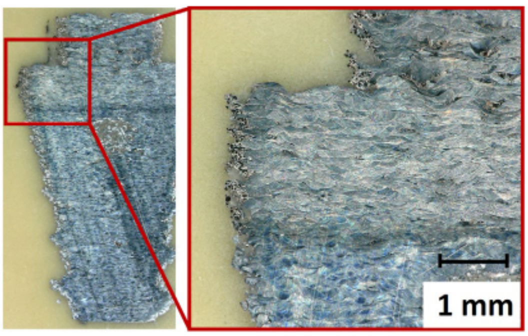

Figure 2. Sample shown as cut, embedded, polished and etched. Different material compositions visible for the lower and top part.

2.4. Specimen analysis methodology

In order to characterize the specimens, the samples were cut and embedded before polishing until 4000 grit SiC paper and subsequent 3 µm and 1 µm diamond pasted polishing. The samples were analysed by light optical microscopy (LOM, Zeiss Axio A1). The hardness of the samples were evaluated using a FutureTech FM-700 Vickers microhardness tester with a 2 N load and 10 s load time. The average and standard deviation of the microhardness were based on five repeated measurements.

The dimensional part deviation has been evaluated using a Nikon 225 X-ray CT system with an acceleration voltage of 200 keV and a power of 15 W to achieve a voxel size of 11.5 µm. The power and acceleration voltage were optimized to obtain a good transmission through the dental strut component.

3. Results and Analysis

3.1. Hardness evaluation

From the hardness measurement a hardness of $HV_{0.2}$ 234 with a STD of 9 was measured for the lower part of the specimen consisting of 100 % concentration of stainless steel 316L. The upper part of the specimen with a concentration of 50 % 316L and 50 % 440C a hardness of $HV_{0.2}$ 280 with a STD of 11 was measured. Both hardness's have been evaluated according to the DIN 50150 standard.

3.2. Part deviation

From figure 3, it can be seen that a part deviation in the range of ±0.5 mm is to be found. This deviation may be present due to the rough surfaces of the as printed part. For this particular study, no surface treatment, such as abrasive blasting, has been applied however; such a process step would significantly alter the surface topography and deviation and would be essential before implanting the dental strut in a patient.

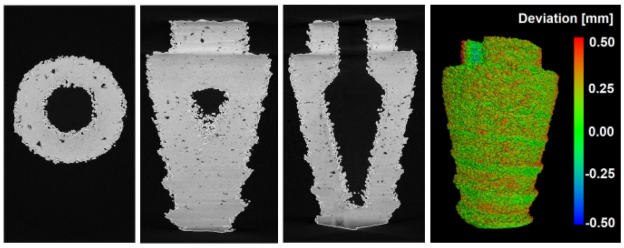

Figure 3. X-Ray CT scan of the implant specimen showing X, Y and Z cross section projections and part deviation plot from the nominal CAD model.

4. Conclusion

A multi-component implant was analysed and combined into a single component before being manufactured using multi-material MAM. Thereafter, an analysis of mechanical properties such as material hardness was evaluated for different areas. The functional gradation of both material and geometry possible through Multi-material MAM shows promise in the manufacturing of specimens that are subject to different functional requirements potentially within the field of patient-specific dental implants.

Acknowledgements

This study was undertaken in the context of DIGIMAN4.0 Project ("Digital Manufacturing Technologies for Zero-defect Industry 4.0 Production", www.digiman4-0.mek.dtu.dk) supported by the European Commission (project no. 814225) and Manufacturing Academy of Denmark (www.made.dk) "MADE Digital" supported by Innovations Fund Denmark (project no. 6151-00006B).

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