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Corrosion resistance and mechanical characterization of ankle prostheses fabricated via selective laser melting

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Abstract

This paper reports the results obtained in the evaluation of the corrosion resistance and mechanical characterization for SLM fabrication of endoprosthetic ankle devices. The corrosion behavior was monitored by recording the EIS spectra and polarization curves during 15 days of immersion in phosphate buffer saline (PBS) solution at pH 7.4 and pH 4, simulating the compositions of the body fluids under normal and inflammatory conditions, respectively. The surface of the samples was characterized with a scanning electron microscope coupled with an energy dispersive microanalysis (SEM/EDS). Finally, by considering mechanical resistance, corrosion resistance and manufacturing time, a differentiated process parameter strategy was proposed for bulk and surface fabrication.

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Keywords: SLM; corrosion; CoCr powders; endoprosthetic

1. Introduction

Cobalt-Chromium-Molybdenum (CoCrMo) alloys are biomaterials widely used also in orthopaedic implants because of their excellent mechanical properties, high corrosion and wear resistance. The main drawback is their low workability by conventional processes due to the high melting point, high hardness and limited ductility [1].

The potential of using Selective Laser Melting (SLM) for manufacturing customized CoCr implants was recently investigated in-vitro, though for dental applications [2-4]. SLM is an Additive Manufacturing (AM) technique enabling the fabrication of 3D components by joining material layer-by-layer via melting and re-solidification of fine metallic powders [5]. Fabrication of full-density, porous-graded, customized implants can be performed by personalized 3D modelling, i.e. avoiding typical geometrical limitations of traditional manufacturing and the constraints to a very limited number of sizes. SLM also offers a high level of control over the architecture of the manufactured component, ensuring reproducibility and enabling scaling-up and standardization [5].

To date, SLM has been used only for the production of CoCr components for the dental industry [2-4], and not applied yet for other prostheses [6].

Aiming to address these issue, all the necessary instruments to design and fabricate custom and biomechanically sound endoprostheses (from total joint replacements, to partial replacements of focal osteocartilaginous defects) are now available. State-of-the-art tools include medical imaging, subject-specific joint modeling, and computer-based surgical techniques. Moreover, SLM is a very promising technique to manufacture such prostheses: complex and personalized shapes can be obtained, different and controlled porosity levels can be attained and innovative materials could be used in order to facilitate osteointegration and bone adaptation, and therefore strong biological fixation of the prosthesis component into the bone.

For a successful implementation of SLM based production of these prostheses, however, several challenges need to be

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overcome. Components manufactured by SLM are characterized by non-equilibrium physical, metallurgical and chemical properties and a careful control of the process parameters is necessary to ensure proper microstructure, dimensional accuracy, and high mechanical properties. The corrosion behavior is another important issue, since metal release and formation of corrosion products cause adverse health effects during long exposure to metal ions. The presence of dissolved oxygen, chloride ions, biological macromolecules and, low pH value during inflammatory conditions, make the bio-fluids very aggressive [10]. The CoCr alloys exposed to the body fluids can be subject to corrosion processes because of the local dissolution of passive film, particularly in the presence of wear of the metal component [11]. In this regard, the recently developed CoCr based SLM alloys seem to be promising materials in view of the non–equilibrium microstructure [2].

In a previous work [9] a suitable double strategy for prosthesis manufacturing was proposed. In particular, by a proper selection of different laser process parameters, bulk and surface fabrication was optimized in terms of mechanical properties. In this work, the same strategy was applied to prepare 2 different types of samples and their corrosion behavior was studied in solutions simulating biological fluids both in the presence and in absence of inflammatory conditions.

2. SLM process

CoCr samples were produced using LPW powders whose chemical composition is reported in Table 1, in accordance to ASTM F1537. These were spherical in shape, with dimensions in the range 15-45 µm.

C	Cr	Co	Mn	Mo
⩽ 0.04	27-30	Balance	⩽ 1	5-7
Ni	Si	W	Al, Ti, O	Fe
⩽ 0.5	⩽ 1	⩽ 0.2	⩽ 0.10	0.75

Table 1: CoCr powder chemical composition.

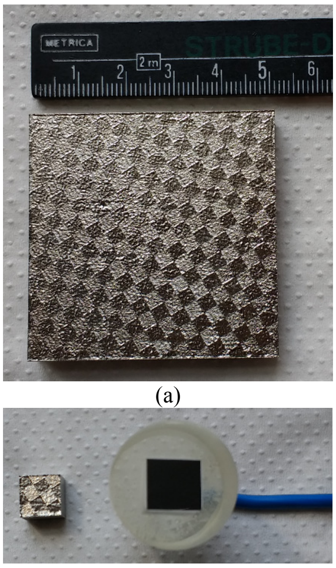
All specimens were fabricated using a SISMA MYSINT100 system equipped with an Yb-Fiber laser with a maximum power of 150 W and a focused spot diameter of 50 µm. The samples were built in a chamber filled with nitrogen and a residual oxygen content of 0.4 % in volume.

Firstly, in order to define the optimum parameters from a strength point of view, tensile specimens were built with a 7 mm circular cross-section, 25 mm gauge length and a 5 mm transition radius between the gripped ends and the parallel length. The parameters are reported in Table 2 and three samples for each set were built for the tensile tests. The hatch distance (space between two adjacent laser tracks) was constant and equal to 0.06 mm. A chessboard laser scan strategy approach was selected and a full description is reported in [9].

Power (W)	150	150	150
Scan speed (mm/s)	700	900	1200

Table 2: SLM parameters used for the tensile tests.

Finally, combining the results of the tensile tests obtained with parameters in Table 2 with those presented in [9], two different sets of SLM process parameters were selected for the fabrication of corrosion test samples with geometrical shape as in Figure 1a and parameters as in Table 3.



(a)

(b)

Figure 1. a) Sample obtained through the SLM process: 50 mm in width, 50 mm in length and 10 mm in height; b) Samples cut and embedded in an epoxy resin to be used in electrochemical tests.

Test	Power (W)	Scan speed (mm/s)	Fluence (J/mm^3)
B1	150	900	138.8
B2	90	1200	53.6

Table 3: Process parameters used for corrosion resistance tests.

In order to make more evident the influence of the process parameters presented in Table 3 on surface quality and structural density, Figures 2 and 3 are reported. Usually, fluence facilitates powder melting instead of sintering, so promoting higher density.