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Micro-CT-based improvement of geometrical and mechanical controllability of selective laser melted Ti6Al4V porous structures

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ABSTRACT

Despite the fact that additive manufacturing (AM) techniques allow to manufacture complex porous parts with a controlled architecture, differences can occur between designed and as-produced morphological properties. Therefore this study aimed at optimizing the robustness and controllability of the production of porous Ti6Al4V structures using selective laser melting (SLM) by reducing the mismatch between designed and as-produced morphological and mechanical properties in two runs. In the first run, porous Ti6Al4V structures with different pore sizes were designed, manufactured by SLM, analyzed by microfocus X-ray computed tomography (micro-CT) image analysis and compared to the original design. The comparison was based on the following morphological parameters: pore size, strut thickness, porosity, surface area and structure volume. Integration of the mismatch between designed and measured properties into a second run enabled a decrease of the mismatch. For example, for the average pore size the mismatch decreased from 45% to 5%. The demonstrated protocol is furthermore applicable to other 3D structures, properties and production techniques, powder metallurgy, titanium alloys, porous materials, mechanical characterization, tomography.

1. Introduction

Among the ubiquitous applications of porous metals (flame arresters, filters, shock absorbers) [1–9], certain applications impose stringent constraints on their porous morphology. For aerospace lightweight structures and tissue engineering (TE) scaffolds, the internal porous geometry is tailored to obtain desired geometrical, mechanical or fluid transport properties [10,11]. Because the obtained properties can still be highly sensitive to local or systematic variations in e.g. volume fraction or feature size and shape, their production requires a robust technique with high controllability and repeatability in terms of those parameters.

Production techniques like foaming and powder metallurgy are limited in their ability to control the internal shape of porous structures, causing the repeatability of morphology and physical properties to be low [12,13]. Additive manufacturing (AM) techniques provide, due to the layer-wise building method and their direct link with a computed aided design (CAD) model, the ability to produce porous structures with controlled pore and strut dimensions. For example, Li et al. [14] investigated indirect production of porous implants with 3D fibre deposition, and produced structures with controlled and repeatable pore shape and pore size distribution. However, shrinkage after sintering caused the morphological parameters after production to significantly differ from the designed ones. Selective laser melting (SLM) and electron beam melting (EBM), both direct AM techniques, have been used to produce porous Ti6Al4V structures with repeatable morphological properties [4,5,15–22]. However, also for these production techniques significant differences between designed and as-produced pore morphologies were noticed. It is thus inherently difficult to produce customized porous structures matching closely the envisioned morphological and physical requirements.

The aim of this study is to optimize the robustness and controllability of the production of porous Ti6Al4V structures using

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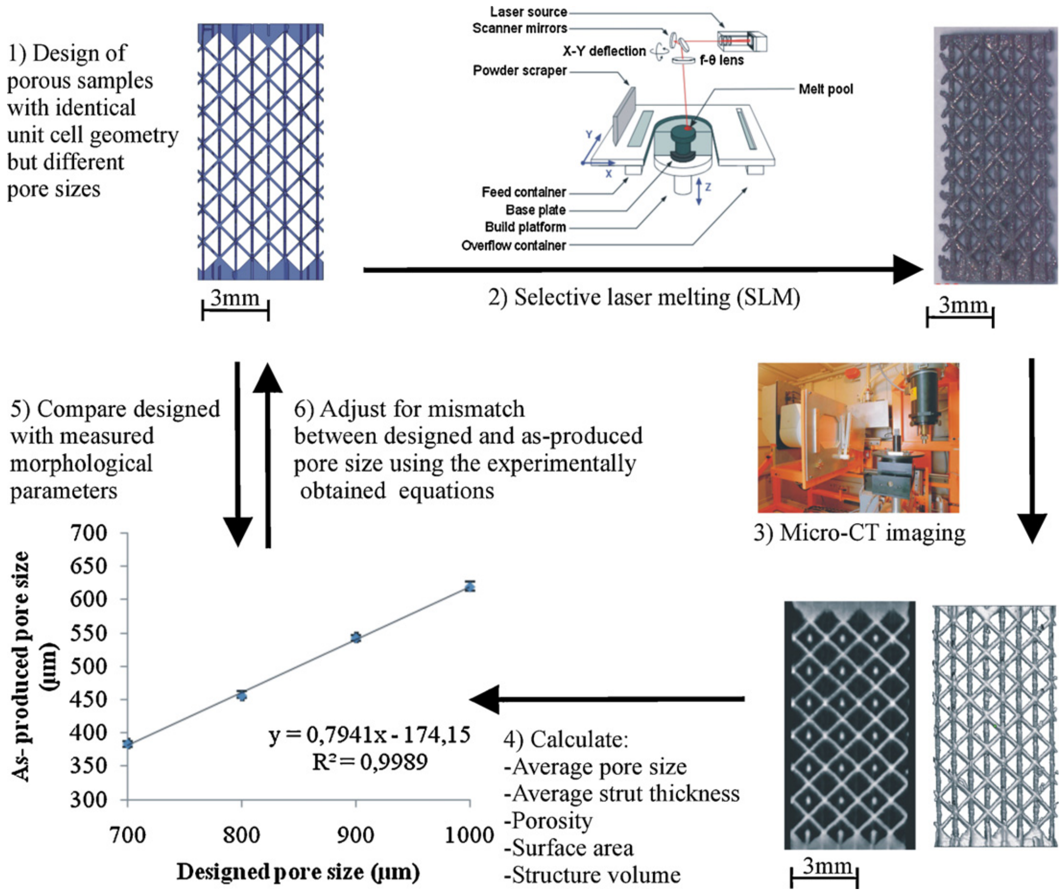

Fig. 1. Schematic overview of the feedback loop between the design and the production including in-depth morphological characterization of the as-produced samples.

SLM by iteratively reducing the mismatch between designed and as-produced morphological and mechanical properties. For this purpose a feedback loop approach was performed two times, consisting of a design, production and in-depth morphological characterization step (Fig. 1). The first run, entitled the 'experimental' run, was needed to evaluate the initial controllability of the SLM process. After this experimental run, the mismatch between designed and as-produced morphology was used as input for the second run, named the 'production' run. The effectiveness of this compensation was verified at the end of the production run. For both runs the morphological properties were characterized by means of microfocus X-ray computed tomography (micro-CT), which for 3D and porous structures is a common measuring technique [1,23–26].

2. Materials and methods

2.1. Design and production of porous Ti6Al4V structures

For the purpose of this study, 6 types of cylindrical samples (height 12 mm, Ø 6 mm) consisting of a truss (i.e. framework of beams) were created using Magics software [Materialise NV, Haasrode, Belgium] based on the same unit cell (Fig. 2A) [22,27], but having different pore sizes. The designed pore size was the distance between two struts as given in Fig. 2C, ranging from 500 to 1000 µm (Table 1). All 6 design geometries had a designed strut thickness (Fig. 2C) of 100 µm. Fig. 2B and D shows a typical STL-file of the design and a typical image of a produced sample with pore size 1000 µm.

Table 1 gives an overview of the 6 design geometries that were produced by SLM for 4 different assessments described in this study, namely (i) micro-CT image analysis, (ii) a repeatability study, (iii) compression testing and (iv) a specific design constraint.

In the experimental run, micro-CT image analysis and compression testing were performed on 5 randomly selected replicates of the 4 design geometries (Table 1).

The repeatability of the SLM process was evaluated using one particular design geometry (po 1000) that was manufactured on 5 different time points spread over 4 months.

In the production run, design geometries po 850 and po 500 were manufactured for validating the increased controllability. Note that the porosity of the former is within the range of the analyzed designs geometries in the experimental run, while the latter is outside this range.

All designs geometries were fabricated by a non-commercial, in-house developed SLM machine [28] using Ti6Al4V powder [Raymor Industries inc., Canada]. SLM is a layer-wise material addition technique that allows generating complex 3D parts by selectively melting successive layers of metal powder on top of each other, using the thermal energy supplied by a focused and computer controlled laser beam. The powder particles were spherical with a size distribution between 25 and 45 µm.

The SLM machine was equipped with a Yb:YAG fibre laser with beam spot size 80 µm and a maximum power of 300 W on the powder bed. Because of high reactivity of Ti6Al4V to interstitial elements such as oxygen, nitrogen, carbon and hydrogen, the SLM process was carried out in a closed chamber flushed with argon gas to reduce the oxygen level below 0.1%. SLM processing of the Ti6Al4V powder was conducted on a titanium base plate with a