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Cellular structures from additive processes: design, homogenization and experimental validation

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Abstract

The importance of lightweight structures in many fields of engineering is well known since long time. The innovations in technological processes based on material addiction allow pushing the design towards challenging geometries and associated structural properties. Engineered materials like lattice structures can be theoretically used to modify the local material properties and strength with minimization of the mass of components; in practice, several issues are still to be solved in stabilization of additive processes and achieving repeatable structures able to pass qualification procedures. At this purpose, dedicated experimental and design methods like those reported in this paper are needed.

Keywords: lattice structures; homogenisation; additive layer manufacturing; characterization; finite element method

1. Introduction

In biomechanics, current solutions for bone, dental and orthopedic implants are based on components made of metal alloys such as titanium alloys. These materials provide excellent resistance to corrosion in a biological reactive environment, biocompatibility, fatigue resistance, and high strength-to-weight ratios compared to other solutions.

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However, clinical experience and simulation results about the failure of this kind of implants shows relevant interface issues; in fact, the contact region between bone and prosthesis is affected by high local gradients of stress, due to the different structural response of the prosthesis and bone tissue. Due to this phenomenon the bone is induced to re-absorption and consequently the prosthesis is subject to collapse.

Lattice structures constitute an excellent solution for this type of applications: if properly designed they can ensure simultaneously the required porosity and mechanical strength of the bone tissue. In fact, they belong to a special class of lightweight structures that can withstand relatively high loads and possessing, at the same time, a regular customizable porosity that can accommodate bone cells and ensure the primary stability of the implant (Gibson and Ashby, 1981).

The lattice is composed of a *modular unit* which, periodically repeated in space, composes the volume of the component. One of the main properties of these structures is the possibility to modify the material relative density by changing the lattice geometry, with the same parent material. Thanks to this preliminary hypothesis, it is possible to scale the mechanical properties of the solid material to those of the entire elementary unit (Dallago and Luchin, 2016; De Pasquale 2107), often referred as representative volume element (RVE). By means of a general homogenization procedure it is possible to replace, at the macroscopic scale (i.e. that of the part), the true geometrical structure of the RVE by a homogeneous anisotropic continuum with equivalent elastic properties. These properties can be computed by means of different (and very general) homogenization schemes: the volume-average stresses method (Catapano and Montemurro 2014), the strain energy-based method (Montemurro et al. 2016).

Several approaches are available in literature for the optimum design of lattice structures. Some methods are based on topology optimization (Nguyen et al. 2012), other approaches include the use of analytical models for evaluating the basic mechanism of the fundamental unit and extend it to the whole component (Deshpande et al. 2001). Further methods are based on numerical models relying on the RVE behavior to describe the mechanical response of the whole lattice (Catapano and Montemurro, 2014; Montemurro et al. 2016; Webb et al. 1994). In (Catapano and Montemurro 2014; Montemurro et al. 2016) the homogenized behavior of the constitutive RVE is integrated in the framework of a multiscale optimization approach which aims at being general and considering all the design variables intervening at different scales. This multiscale optimization procedure, also called multiscale two-level (MS2L) approach, has been firstly introduced in (Montemurro et al. 2012) where it was applied to the least-weight design of a composite wing-box section. The MS2L approach is a very general technique to optimize complex structures at each relevant scale, so it is well suited for lattice structures. The MS2L methodology does not make use of simplifying hypotheses, it properly takes into account all design variables involved at each scale (micro-meso-macro) and it is based on the one hand upon the polar formalism (Montemurro 2015) to rigorously and smartly describe the behavior of anisotropic parts and on the other hand on the utilization of a special genetic algorithm (GA) (Montemurro et al. 2012; Montemurro et al. 2015) able to deal with optimization problems involving a variable number of design variables.

This work gives a brief overview of the application of the *volume average stress-based homogenization method* utilized in the framework of the MS2L methodology for the optimum design of lattice structures (by taking inspiration from previous research works (Catapano and Montemurro 2014; Montemurro et al. 2016)). The results obtained through this homogenization scheme are compared with those provided by simplified analytical methods (De Pasquale 2017). An experimental validation, through published results, of the proposed numerical homogenization approach is also presented. The main benefit of the proposed homogenization method is the prediction of the equivalent elastic properties of the lattice without using any preliminary simplified hypothesis. Moreover, this technique has no restrictions in terms of the RVE topology and materials: RVE of complex geometry composed of several constitutive phases can be easily integrated within the procedure and their equivalent elastic properties can be always computed without modifying the proposed homogenization scheme. Of course, the homogenization provides the connection between the microscopic scale, i.e. that of the RVE, and the macroscopic one represented by the overall lattice structure.

2. Samples fabrication

Samples are fabricated with SLM and EBM processes in Ti6Al4V alloy (De Pasquale et al. 2017). For the SLM process, the EOS M290 machine with 400W Yb-fibre laser is used (Tab. 1) and an Arcam Q10 (Tab. 2) machine is