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Effects of laser processing parameters on the mechanical properties, topology, and microstructure of additively manufactured porous metallic biomaterials: A vector-based approach

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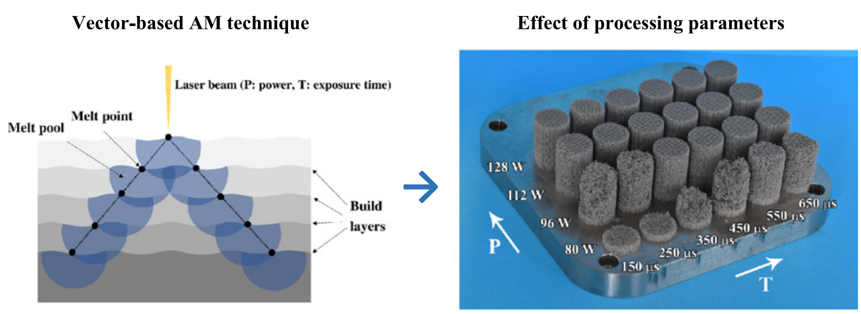
HIGHLIGHTS

- Additive manufacturing of porous materials using a vector technique is introduced.
- Empirical relationships are presented for prediction of topological/mechanical properties.
- Mechanical properties increase with increasing either laser power or scanning time.
- The effects of laser power and exposure time could be decoupled.

GRAPHICAL ABSTRACT



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ABSTRACT

Additively manufactured (AM) porous structures are a new class of biomaterials with many advantages as compared to conventionally produced biomaterials. The goal of this study was to find out how the laser processing parameters including laser power and exposure time affect the mechanical properties, topology, and microstructure of porous biomaterials AM using a novel vector-based approach. Several cylindrical porous specimens were additively manufactured using a wide range of exposure time and laser power. The effects of those parameters on the surface roughness, strut diameter, relative density, hardness, elastic modulus, yield stress, first maximum stress, and plateau stress of the porous structures were studied. The results showed that the rate of change in mechanical and topological properties with respect to exposure time was non-linear while it was linear with respect to the laser power. The results also showed that the effects of laser power and exposure time on the mechanical properties and topology of AM porous structures could be decoupled from each other, enabling derivation of predictive emperical relationships. The emperical and experimental curves showed very good agreement, which further validates the validity of the separation method used for obtaining the emperical relationships. The analytical relationships for elastic modulus and yield stress that we had obtained in a previous study could predict the elastic modulus and yield stress of the porous strucutres when the energy input was high enough (i.e. exposure times ≥ 450 µs), because the local mechanical properties of the matrix material decreased for the lower levels of energy input. The change in the mechanical properties of the bulk material due to change in laser processing parameters should thus be taken into account.

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1. Introduction

Additively manufactured (AM) porous structures are a new class of biomaterials, which have shown many advantages [1–4] over conventional biomaterials. Moreover, it is possible to use AM techniques to fabricate patient-specific implants based on the computed tomography (CT) images of each patient. Titanium and its alloys exhibit properties that make them suitable for biomedical applications including a high degree of biocompatibility, corrosion resistance, and durability [5–7]. Using AM techniques, it is also possible to manufacture interconnected open-cell porous biomaterials with controlled unit cell shape and size. Porous biomaterials have shown several advantages over traditional solid implants. For example, the high degree of porosity in the volume of such structures drastically decreases the stiffness of the metallic implant to the values close to the stiffness of natural bone. The low stiffness of the implant helps in better distributing the mechanical load between implant and natural bone and, thus, assists in avoiding future bone resorption. The hollow space inside porous structures also allows for easy body fluid transport inside the implant [8,9] and consequently stimulates bone ingrowth, thereby improving implant fixation and longevity.

The most well-known AM techniques for making metallic porous biomaterials are selective laser melting (SLM) [10] and selective electron beam melting (SEBM) [11]. In both techniques, the usual workflow starts off with constructing a surface tessellation language (STL) file describing the geometry of the to-be-manufactured part. The CAD file is then virtually cut into several slices with predefined thicknesses (usually in the range of 30–100 μm [12]). The laser or electron beam then follows the contours found in every slice and melts the specified areas within the powder bed, thereby fusing the powder together and creating a solid part in a layer-by-layer fashion. After the laser/electron beam has scanned the contours found in each layer, the powder bed moves down by the slice thickness and a fresh layer of powder is deposited on the build plate. As a rapid melting-solidification process, the microstructure, topology, and mechanical properties of the resulting part are strongly dependent on the laser/electron beam processing parameters [13–17].

In the past, a few groups [12,18–23] have studied the effects of laser beam parameters on the microstructure and the mechanical properties of porous biomaterials. In the previous studies, the 3D constructed CAD files of the porous structure have been used to determine the scanning line of the laser beam. In such techniques (as demonstrated in Fig. 3 of [24]), the 3D model of the structure is constructed in CAD programs. The resulted model is converted into STL file and then sliced by the 3D printer preparation software. Each strut in each layer can consist of several melting paths. In the current study, we use a different, i.e. vector-based, approach to manufacture porous biomaterials. In this approach, the lattice structure is designed by defining the struts as vectors describing its start and end coordinates without any strut diameter data, and thus no STL files are needed to describe the surface of the structure. Slicing to the desired height creates a cloud of intersection points between the vectors and the slice planes. During manufacturing, each intersection point is molten by a single strike of the laser (Fig. 1). In the jumps between the points, the laser is deactivated. The selected power and the exposure time of the laser on each point determines the energy input and, thus, the size of the melt pool and the diameter of the struts constituting the porous structure. This approach has two major advantages over the STL-based technique. First, it removes the intermediates steps required for creating the STL file and slicing the resulting geometry. Those intermediate steps could be computationally expensive and reduce the accuracy of the contours. Second, there is a direct relationship between the processing parameters and the microstructure, topology, and mechanical properties of the resulting porous structure. We studied how the laser processing parameters including laser power and exposure time affect the microstructure, topology, and mechanical properties of the resulting AM porous biomaterials. Porous structures were therefore additively manufactured with a wide range of exposure times and laser powers. The effect of those parameters on the surface roughness, strut diameter, hardness, relative density, elastic modulus, yield stress, first maximum stress, and plateau stress of the porous structures was studied.

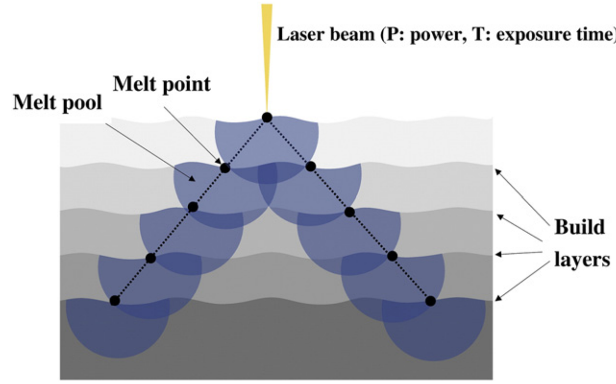

Fig. 1. Schematic view of the vector-based additive manufacturing technique for creation of a porous structure (two oblique struts are shown above).

2. Materials and methods

2.1. Materials and manufacturing

In conventional Powder Bed Fusion processes, the product is built based on a STL-file with all dimensions defined before printing. For lattice structures, the scanning strategy is based on the area of the object on a specific slice plane. Large areas will have a combination of a hatch and a contour while small areas, like struts of several 100 μm will have contours only. In the vector-driven approach, the strut thickness of the lattice structure that is built, is not pre-defined. The vector-driven file simply consists of a cloud of intersection points between vectors and slice planes (Fig. 2a). Every intersection point will be a location for the laser to strike. Therefore the struts are built up, on each slice layer (Fig. 2b), by single weld spots and not the conventional contours and hatches. As a result, the diameter of the strut is a product of the energy that is put in, namely laser power and exposure time. We have used this vector-based technique to make lattice structures with variable cross-sections (Pentamode mechanical meta-material [25]). Cylindrical specimens (∅15 × L20 mm) with a diamond-type cubic lattice structure were built using a commercially available SLM125 machine (Realizer GmbH, Borchen, Germany). The SLM machine was equipped with a YLM-400-AC Ytterbium fiber laser (IPG Photonics Corporation, Oxford, USA) with the ability to emit 400 W of radiation in the wavelength range of 1070 ± 10 nm. As the feedstock, plasma atomized, spherical Ti-6Al-4V-ELI grade 23 powder, according to ASTM B348, with a particle size range of 10 to 40 μm was acquired from AP&C (AP&C Advanced Powders and Coatings Inc., Boisbriand, Canada). Prior to fabrication, the building chamber was flushed with argon gas until an oxygen level of 0.2% was reached. The mild steel building substrate was pre-heated to 100 °C. Table 1 provides an overview of the process parameter settings that were varied during the experiments. At the maximum laser power and exposure time (128 W and 950 μs), severe soot formation was observed, most likely due to local overheating of the powder bed. The lumps of soot, the level of which was higher than that of the powder bed, caused damage to the wiper of the SLM machine. As a result, the parts were printed partially. The minimum printing parameters were chosen based on the energy input's ability to weld the subsequent layers without creating gaps.

On the build plates, 24 coordinates were defined, 4 horizontally and 6 vertically, with an equal distance of 16 mm. On each coordinate, a specimen was printed. The specimens were divided in three groups