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Enhancing the tensile properties of EBM as-built thin parts: Effect of HIP and chemical etching

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ABSTRACT

As-built Ti-6Al-4 V thin parts were manufactured using Electron Beam Melting (EBM) and characterized by optical microscopy and laboratory X-ray tomography in order to observe their microstructure, pore distribution and surface aspect. Chemical etching and HIP post-treatments were applied to as-built samples and their effect on the material and static mechanical properties were studied. Tensile tests were performed on both as-built and post-treated samples and their results compared to the ones reported in the literature for machined EBM samples. Because of the significant variations of the cross section observed along the gauge length, the calculation of the tensile stresses is not straightforward. Three simple sections were measured from the tomography scans. The average section along the gauge length was considered as the most suitable. The tensile mechanical properties of the as-built samples were studied and a detrimental effect of the surface state on the yield strength, ultimate tensile strength and elongation to failure was observed. Smoothing of the surface irregularities induced by chemical etching provoked an increase of those mechanical properties whereas the change of the microstructure generated by the HIP treatment leads to a decrease of the material strength that goes along with an increase of the ductility. Down scaling factors were proposed in order to take into account the sample state, as-built or post-treated.

1. Introduction

Architectured materials and in particular lattice structures exhibit an outstanding combination of mechanical, thermal and acoustic properties and are therefore good candidates to replace monolithic materials especially when weight saving is involved like in the aeronautics industry, see e.g. [1–8]. Until recently however, manufacturing such metallic lattice structures was very challenging with conventional techniques requiring multiple processing steps, see e.g. [9,10]. With the emergence of powder-bed based additive manufacturing techniques such as selective laser melting (SLM) and electron beam melting (EBM), the production of lattice structures is becoming easier. However, if one aims at popularizing such materials in different industrial applications, it is necessary (i) to assess if the as-built geometry is conform to the ideal CAD geometry and (ii) to control the mechanical properties of the built parts, see e.g. [11–14]. It has been demonstrated that Ti-6Al-4 V EBM parts exhibit tensile properties as good as wrought materials, see e.g. [15–20], but this was assessed on bulk tensile specimens that were previously hot isostatically pressed (HIP) and subsequently machined so as to respectively reduce internal porosity and remove the surface irregularities inherited from the EBM process. Nevertheless, when dealing with complex geometries with thin parts or struts assemblies like in lattice structures, machining techniques that would be conventionally used to reduce surface roughness are prohibited. This can partly explain why the development of lattice structures in the industry is still limited. As a result, one has to keep in mind that for such geometries, the mechanical properties can be strongly affected by the presence of defects in as-built parts, in particular residual porosity and surface irregularities, see e.g. [21–24]. Therefore, appropriate post-treatments ([24–29]) have to be applied and their impact investigated to determine how this defect issue could be overcome or at least limited in such complex geometries.

The objective of the present paper is to characterize the tensile behaviour of as-built Ti-6Al-4 V thin parts produced by EBM and to investigate the effect of different post-treatments applicable for complex geometries. To mimic the behaviour of thin parts or struts, a specific geometry was used for producing tensile specimens with a nominal diameter of 2 mm. Nevertheless, one has to keep in mind that the situation in lattice structures is expected to be much more complicated. Indeed, complex loading conditions are suspected in lattice

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structures. Two cases have to be distinguished: the case of bending dominated structures and the case of stretching dominated ones. In a stretching dominated lattice structure such as the octet-truss geometry, the predominant loading modes are uniaxial tension and compression. As a consequence, the results of the present investigation provide insights into the mechanical behaviour of individual struts in a stretching dominated lattice structure. However, this cannot be directly used to infer the properties of structures where bending is predominant. In addition, it has to be specified that the local loading conditions in the vicinity of nodes, even in stretching dominated structure, might be complex. Investigating the local loading conditions at nodes is currently a topic under investigation but turns out to be out of the scope of the present paper.

A thermomechanical (HIP) and a chemical (etching) post-treatment as well as a combination of both were applied to the as built samples. X-ray microtomography was used to identify the critical defects and to try to quantify the effect of post-treatments on the static mechanical behaviour. Several simple approaches are finally proposed to take into account the presence of the identified defects and thus rationalize the results.

2. Experimental Procedures

2.1. Samples Manufacturing

Cylindrical tensile specimens with a gauge length of 10 mm and a nominal diameter of 2 mm were produced vertically, i.e. with their tensile axis aligned with the building direction, using an ARCAM A1 EBM machine and Ti-6Al-4 V ELI powder, see Fig. 1. The unusual geometry of the tensile specimens, i.e. with a relatively small nominal diameter (2 mm) was deliberately chosen so as to be representative of a single strut of a lattice structure (large surface to volume ratio). The chemical composition of the initial powder batch is given in Table 1. The standard "Melt" build theme recommended by ARCAM for a layer thickness of 50 μm was chosen to define the set of melting parameters and scanning strategy used during the EBM process.

2.2. Post-treatments: HIP, Etching and HIP + Etching

Several types of post-treatment were applied to the as-built tensile specimens: Hot Isostatic Pressing (HIP) and chemical etching as well as a combination of both in order to investigate their effect on the tensile mechanical properties. Conventional machining was not investigated because they cannot be used for lattice structures or thin parts.

Table 1
Chemical composition of the initial Ti-6Al-4 V powder batch used for this investigation.

Elements	Al	V	C	Fe	O	N	H	Ti
wt.%	6.47	3.93	0.01	0.22	0.09	0.01	0.001	Bal.

HIP was used to reduce the amount of internal defects, i.e. lack of fusion-type porosity or gas porosity inherited from the initial powders (entrapped gas during the atomization process). The HIP thermomechanical process consisted of a temperature rise of 300 °C/h followed by an annealing of 2 h at 920 °C under a pressure of 100 MPa immediately followed by a natural furnace cooling (the temperature decreases to below 150 °C after 3 h).

Chemical etching was used to decrease the surface defects of the as-built tensile specimens. Each specimen was dipped at room temperature in a fresh solution consisting of 12 mL HF (48%), 40 mL HNO_3 and 300 mL of distilled water (no stirring of the solution). Two different etching times were investigated: 30 and 60 min. The specimens were extensively rinsed under water immediately after being removed from the etchant in order to eliminate any trace of acid.

2.3. X-ray Tomography

Laboratory X-ray tomography was used in order to obtain a full 3D characterization of the gauge length of the tensile samples. Every single tensile specimen was scanned by X-ray microtomography in the as-built condition as well as after different post-treatments (HIP, chemical etching or both) so as to evaluate their impact on porosity and surface quality. The scans were performed with a phoenix|x-ray V| tome| x laboratory tomograph using a 2.5 μm voxel size, i.e. a spatial resolution of ~ 4 μm. In order to visualize the whole gauge length, 5 scans were required at different heights along the sample axis. The following scanning parameters were used: U = 90 kV, I = 240 μA, exposure time = 333 ms, 720 projections per scan. As a result, the scanning time per sample (over its entire length) was roughly 1 h. A standard filtered back projection method was used to reconstruct the 3D images (phoenix

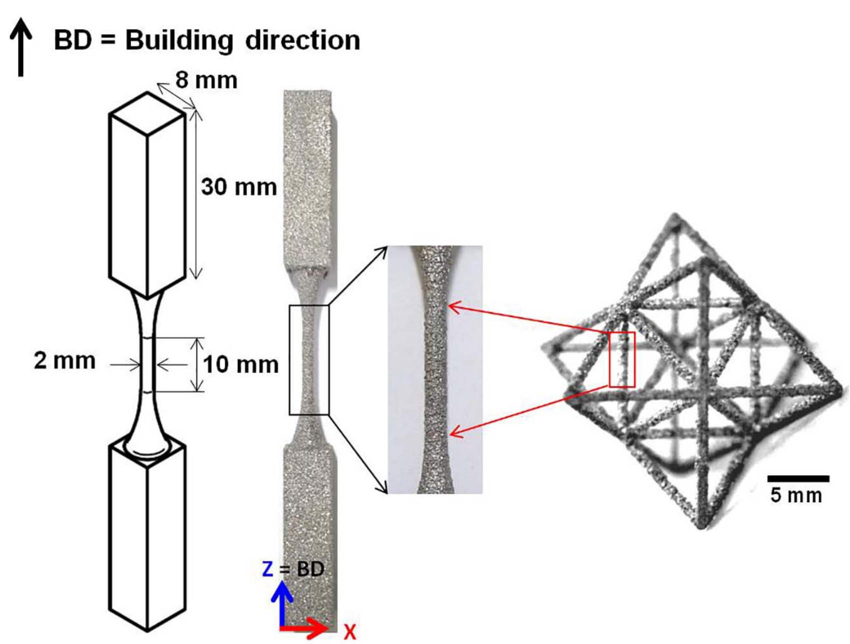

Fig. 1. Geometry of the tensile specimens with dimensions given in mm and designed so as to be representative of a single strut of a lattice structure.