Improvement of the fatigue life of lattice structures covered by a thin envelope for biomedical applications

A. T. Sola[1], L. Weiss[1], P. Laheurte[1] and E. Fleury[1]

1 LEM3, Université Lorraine, 7 Rue Félix Savart, Metz, France

Abstract
Additive manufacturing allows the production of parts of a high geometric shape complexity hardly realisable by other manufacturing techniques. Additive manufacturing is particularly suitable for the fabrication of scaffold-type structures, also named lattice structures, that are of interest in various fields. By covering these lattice structures by a thin envelope, the realised parts can be applied in the biomedical sector and more particularly as prostheses.
The application of manufactured parts is still hindered by the presence of microstructural defects reducing considerably the mechanical properties. The objective of this study was thus two-fold: to investigate the fatigue properties of Ti-6Al-4V samples with lattice structures produced by additive manufacturing and to study the effect of SMAT (Surface Mechanical Attrition Treatment) on the improvement of the fatigue life.

Keywords *lattice, SMAT, additive manufacturing, fatigue life*.

Introduction

While conventional manufacturing processes enable the fabrication of engineering components of complex geometries by either moulding and/or material subtractive processes, additive manufacturing (AM) consists in building 3 dimensional components by adding specific thickness layers of material from a CAD and CAO data model. AM technology has been around for more than 20 years for the purpose of prototyping and today is used as a mass production technique with applications in different fields such as aeronautics, medicine, automotive, etc.
In AM, a heat source is applied to melt metal powder or wire that are used as base materials. The manufacturing is carried out layer by layer. The three most common types of technologies are powder bed fusion, material extrusion and material deposition from a concentrated energy source [1].

The most remarkable advantages offered by AM [2], are:

- the simplicity and flexibility to manufacture any complex part,
- the reduction in waste material,
- the reduced manufacturing times thanks to the optimization of the design,
- the reduction in the cost per part.

The interest in maintaining optimal mechanical properties while reducing weight is of great interest in the design of parts. This can be achieved by the introduction of lattice structures, Triply-Periodic-Minimal-Surfaces (TPMS) or topological optimization methods. The first two are based on spatial patterns that are repeated in space. The mechanical properties, such as Young's modulus, thus depend on the lattice and size and also on the strut radius [3]. The most widely investigated lattice structures are based on Bravais lattices or crystal structures, BCC or FCC and modifications of these, z-struts (BCCZ and FCCZ) [4]. These types of structure allow for better mechanical adaptation and osseointegration as well as good fixation of implants [4].

Several investigations have already studied possible post-treatments with the aim of improving the quality of the parts and have particularly addressed the problems of porosities as well as the surface condition that are inherent to the AM processing. Some examples are heat treatment, high isostatic pressure treatment, machining, chemical polishing, etc. The SMAT (Surface Mechanical Attrition Treatment) post-treatment consists in the application of a very severe plastic deformation at the surface of the component that refines the grain size and introduces compression-type residual stresses in the sub-surface. The microstructure modifications result in the enhancement of the fatigue limit by delaying the propagation of cracks owing to the crack-closing effect thus avoiding fast propagation rate. In addition, SMAT provides a good surface condition and increases wear resistance [5], [6].

Experimental Methods

Ti-6Al-4V spherical powder was used for the fabrication of cylindrical dogbone-shape samples (Figure 1a). XRD analyses (not shown here) confirmed the presence of α' martensite in the as-additive manufactured samples. Two geometries of tubular specimens were manufactured by PBF (Powder Bed Fusion), one in the form of a pipe with a variable thickness and the other with a homogeneous envelope of 400 µm thickness along the entire gauge length of the specimen (Figure 1a). The total length of the fatigue test samples was 64 mm, with a gauge length of 20 mm and a minimum diameter of 3,8 mm. The difference in fatigue life between specimens without lattices and specimens filled with cubic lattices (struts radius 0.26 mm and lattice size of 1 mm) has been investigated. In addition, the effect of severe deformation (SMAT) after fabrication was compared for each case. After manufacturing, each sample has been polished with a grid size of 1200, 2400 and 4000 #. For some of the specimens, this surface preparation was followed by a SMAT treatment.

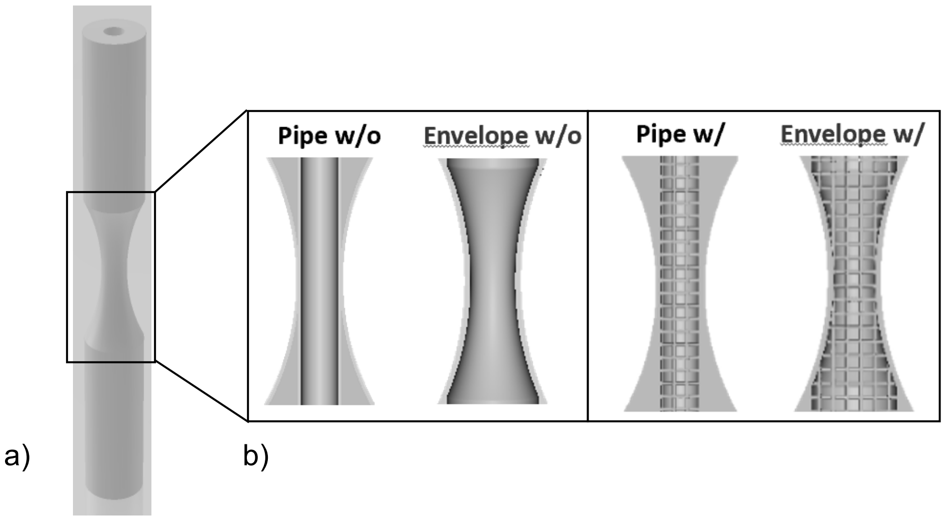

Figure 1. Schematics showing the geometry of the sample; a) an entire sample and b) details of the gauge length samples (w/o: without lattices, w/: with lattices).

The SMAT treatment was carried out by impacting 100C6 balls of 2 mm diameter out at room temperature for 10 min and at a distance of 20 mm from the vibrating part (frequency of 20 kHz for an amplitude of 60 µm). Rotational bending fatigue tests were performed at room temperature and at a frequency of 30 Hz until fracture. This made it possible to stress the material superficially and to observe the effect of the SMAT treatment.

Experimental Results

Figure 2 shows the fatigue resistance (number of cycles to failure) at different stress amplitude. Without SMAT treatment, the fatigue life of the envelope-type and pipe-type samples, with or without lattice structures, can be described by an unique Wohler-type curve. In general, SMAT post-treatment significantly improves the fatigue life. However, a thorough observation indicates that the gain in fatigue life is greater for the samples without lattice than for the sample having lattice structures.

The fatigue behaviour depends essentially on the mechanical properties of the material defined by the thickness of the envelope, the lattice shape and by the relative density, geometry and topology of the unit cell for the lattices on the other hand [4].

Before application of SMAT and, for any geometry, the samples with lattice structures have a considerably superior fatigue life than the samples without inner lattice structures. However, once the SMAT treatment is applied, the fatigue behavior for the samples with lattices tends to become similar to that of the samples of envelope geometry without lattices. One hypothesis that could explain these observations is that several small cracks are formed during the fatigue test within the lattice structure that eventually coalesce to lead to the catastrophic failure of the thin envelope.

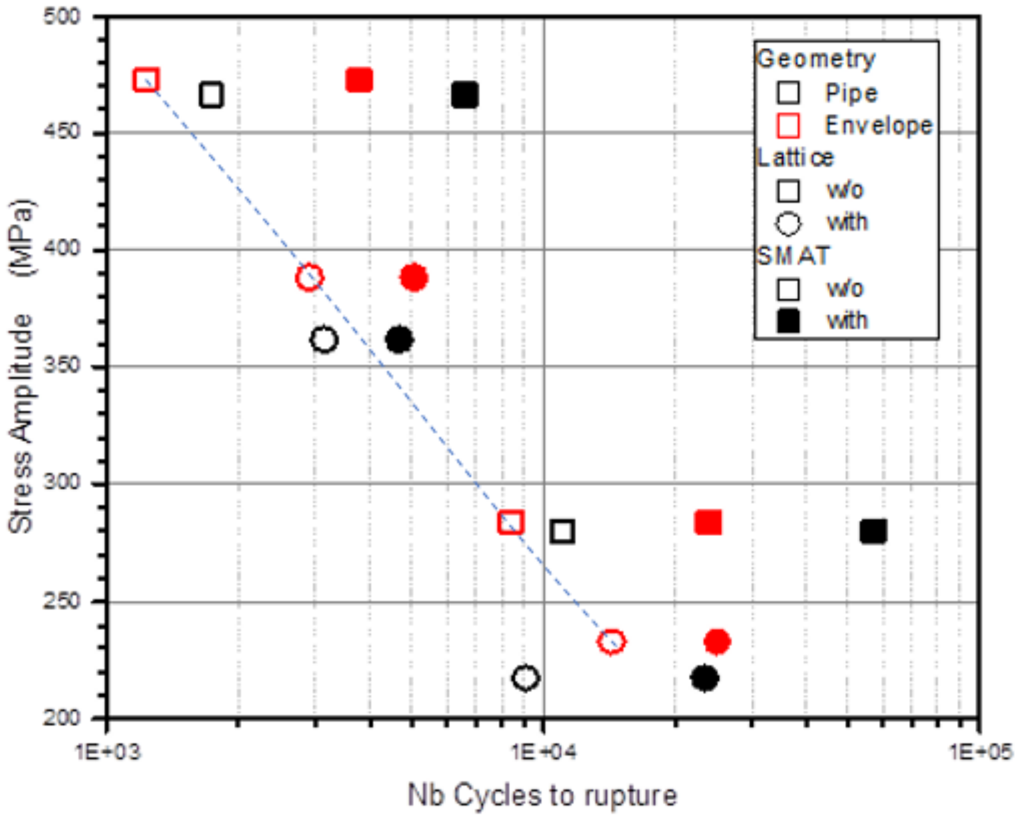

Figure 2. Fatigue performance for different geometries and processing conditions.

Additively manufactured samples contain defects and particularly porosities that are sometimes difficult to control. These defects can result from the lack of powders, lack of energy from the heat source, presence of gas bubbles, oxide, etc. and they affect premature crack formation in sample tested under cyclic loading. However, SMAT helps to close surface defects and to introduce compressive residual stresses slowing down the propagation of possible cracks formed.

The application of SMAT post-treatment improves the number of cycles to failure by 40 to 400% (Table 1), without affecting the integrity of the thin envelope (400 µm). This fact is more remarkable as it can also be observed under the most unfavourable mechanical conditions (part consisting of the envelope only, without the inner lattices). For samples with lattice structure, the theoretical stress amplitude values were obtained from the numerical simulation by Abaqus.

On 2 mm diameter specimens prepared by Electron Beam technique, Persenot et al. have compared the effect of SMAT with the effect of surface machining on the fatigue properties after HIP treatment [8]. Though the application of SMAT surface treatment considerably improved the numbers of cycles to failure of HIPed samples, these authors demonstrated that surface machining was more efficient to enhance the fatigue properties because of the reduction in the surface roughness that appears to be the most critical parameter.

Table 1. Fatigue gain (number of cycles) after SMAT.

Lattice	Stress Amplitude	Envelope geometry gain	Pipe geometry gain
With	Low > 350 MPa	75 %	157 %
Without	Low > 250 MPa	185 %	418 %
With	High > 200 MPa	74 %	49 %
Without	High > 450 MPa	205 %	280 %

SEM observations of the sample after fatigue tests revealed the origin of the fractures. Figure 3 shows the lack-of-fusion defects present on the surface and inside the envelope. Defect size also affects the fatigue resistance, and it is important to note that many of these defects are interconnected or separated by a very thin thickness of material which would lead to premature cracking.

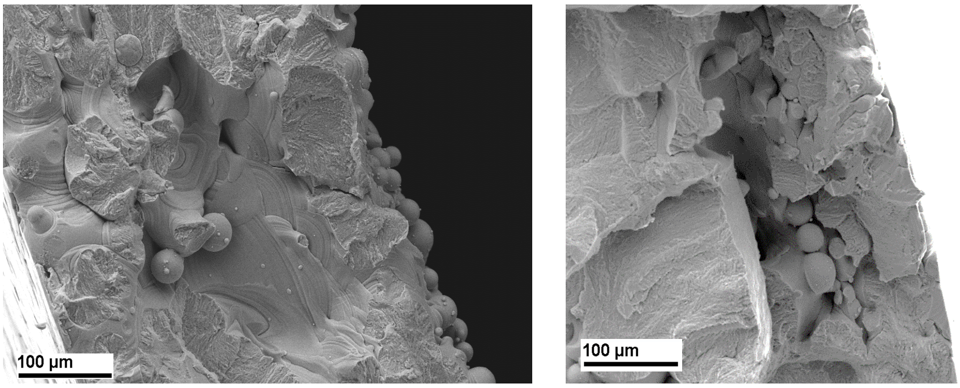

Figure 3. SEM images of the rupture of SMATed envelope sample (left) and SMATed pipe sample.

Figure 4 shows the cross-section of a SMATed sample. The modification in the grain size and morphology (initial needle shape) of α'Ti-martensite can be clearly observed in this figure. The thickness of the modified region is about 52 µm and it is composed of nanograins of α'Ti-martensite. Similar thickness size of the SMATed zone has been reported in Kumar et al.'s work [7].

The EBSD map shows black areas whose Kikuchi patterns are blurred or overlapped because of poor indexing. Poor indexing is due to highly strained regions or highly deformed microstructure that has formed nanograins. Indexing becomes more favourable deeper from the surface [9].

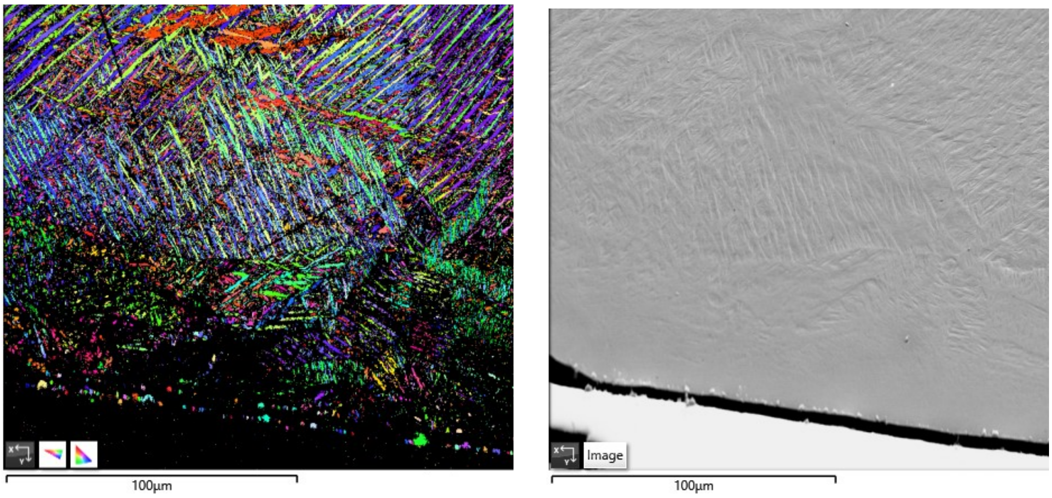

Figure 4. EBSD (left) and SEM (right) cross-section image of a SMATed sample.

The results presented in this article will be confirmed with additional tests in order to improve the data statistic.

Conclusions

The final goal of this study is to improve the quality of the new generation prostheses by lightening their weight while improving the mechanical resistance and the condition of the external surface in contact with the biological tissues (SMAT avoids machining the raw parts by homogenising the roughness).

In this work, two specimen geometries were tested and the effect of inner filling with lattice structures was examined under cyclic solicitation. The thin envelope surrounding these structures have been SMATed to compare the effect of post-treatment on the fatigue life via rotary bending tests performed at room temperature and high frequency.
By taking into account of the reinforcement resulting from the lattice on the stress calculation, the fatigue life of the specimens with and without inner lattice structures, if expressed in the Stress amplitude versus Number of cycles to failure, can be described by a unique Wohler curve. In general, the SMAT post-treatment enhances considerably the fatigue properties. The fatigue life enhancement was found to be more pronounced for pipe-life specimens in comparison to envelope-type samples.

A quantitative investigation is currently undertaken to optimize the SMAT conditions and to correlate the size and position of the defects with the fatigue life.

Acknowledgements

The authors would like to thank the Ministry of Higher Education, Research and Innovation for the grant obtained for this project. We would also like to thank Paul Lohmuller to produce the samples.

References

[1] F. Laverne, F. Segonds, and P. Dubois, ‘*Additive Manufacturing - General Principles*’, Techniques de l'ingénieur, 2016. (in french)
[2] M. Srivastava, S. Rathee, S. Maheshwari, and T. K. Kundra, *Additive Manufacturing: Fundamentals and Advancements*. Boca Raton: CRC Press, 2019.
[3] P. Didier, G. L. Coz, G. Robin, P. Lohmuller, A. Moufki, and P. Laheurte, ‘*Consideration of additive manufacturing media for machining completion*’, 24ème Congrès Français de Mécanique, 2019. (in french)
[4] T. Maconachie *et al.*, ‘SLM lattice structures: Properties, performance, applications and challenges’, *Mater. Des.*, vol. 183, p. 108137, Dec. 2019.

[5] P. Maurel, L. Weiss, P. Bocher, and T. Grosdidier, '*Effects of SMAT at cryogenic and room temperatures on the kink band and martensite formations with associated fatigue resistance in a β-metastable titanium alloy*', *Mater. Sci. Eng. A*, vol. 803, p. 140618, Jan. 2021.

[6] C. Dureau *et al.*, '*On the Influence of Ultrasonic Surface Mechanical Attrition Treatment (SMAT) on the Fatigue Behavior of the 304L Austenitic Stainless Steel*', *Metals*, vol. 10, no. 1, p. 100, Jan. 2020.

[7] S. Kumar, K. Chattopadhyay, and V. Singh, '*Effect of ultrasonic shot peening on LCF behavior of the Ti–6Al–4V alloy*', *J. Alloys Compd.*, vol. 724, pp. 187–197, Nov. 2017.

[8] T. Persenot, A. Burr, E. Plancher, J.-Y. Buffière, R. Dendievel, and G. Martin, '*Effect of ultrasonic shot peening on the surface defects of thin struts built by electron beam melting: Consequences on fatigue resistance*', *Addit. Manuf.*, vol. 28, pp. 821–830, Aug. 2019.

[9] Y. Samih, B. Beausir, B. Bolle and T. Grosdidier, *'In-depth quantitative analysis of the microstructures produced by Surface Mechanical Attrition Treatment (SMAT)'*, *Materials Characterizatoin.*, vol. 83, pp. 129–138, Jun. 2013.