Transactions on Additive Manufacturing Meets Medicine
Trans. AMMM, Vol 1, No 1, 2019, Article ID S10T01

Infinite Science | Publishing

Fatigue behavior and morphology in selective laser melted Ti-6Al-4V cellular materials

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Abstract: Selective Laser Melting (SLM) has shown great potentialities in the production of lattice materials due to the intrinsic advantages of rapid prototyping technologies. Nevertheless, the low accuracy and precision of this manufacturing process is a well-known issue that is critically important for the fatigue properties of metallic lattices with strut thicknesses of a few hundred microns. In this work, we discuss some aspects regarding the relationship between the as-built morphology of SLM Ti-6Al-4V cubic cell lattice structures and their fatigue properties.

I. Introduction

Motivated by the desire to improve the fatigue resistance of Ti6Al4V SLM cellular structures for biomedical implants, in a previous work [1] the authors explored the possibility to reduce the stress concentration effects in circular strut cross-section cubic cell lattices by connecting the struts at the junctions with fillets of constant radius. Cellular specimens were produced and scanned with a µCT system and the differences with the nominal model were highlighted both regarding the diameter of the struts (t_0) and the fillet radius (R). Moreover, it was observed that such deviations translated into a mismatch between the elastic modulus and the fatigue strength measured experimentally and the values estimated from the nominal geometry [2]. This showed the need for a deeper investigation of the correlation between the as-built and the as-designed morphology. This lead to a subsequent work [3], in which a set of mathematical relationships was obtained experimentally that express the as-built strut diameter as a linear function of the as-designed strut diameter t_0 and the as-built fillet radius as a linear combination of both the as-designed geometric parameters (t_0 and R) for various inclinations of the struts to the printing direction.

In this work, we use these expressions to modify the diameter of the struts of the CAD to compensate for the as-built/as-designed mismatch in regular cubic SLM Ti6Al4V lattices of the type described in [3]. The effectiveness of such procedure in improving the geometry of the lattice is discussed. Moreover, push-pull fatigue tests are carried out on the specimens and the effects of the compensation procedure and of the fillets on the fatigue resistance are discussed.

II. Material and methods

The compensation procedure consist in reversing the formulas derived in [3]. In this way, expressions are obtained that relate the CAD parameter to the as-built parameter. In this work, the fillet radius was not compensated and is left for future work; thus, only the strut thickness will be considered. The section of the struts oriented at 0° to the printing plane have been shown [2,3] to have an elongated cross-section (reasonably assumed elliptical), defined by a major axis (or vertical axis because it is aligned with the printing direction) and a minor axis (or horizontal axis, because it is perpendicular to the printing direction). On the other hand, the struts perpendicular to the printing plane have retained their circular cross section, thus the section is defined by its diameter. In practice, by appropriately modifying the cross-section of the struts (Figure 1a) with the compensation model, a CAD of the unit cell is obtained (Figure 1b) that, input to the manufacturing process, produces a lattice with the desired geometry (circular struts of diameter t_0, as indicated by the dashed lines in Figure 1a). Such approach has been applied to design specimens to be tested under fully reversed fatigue conditions (Figure 1c). Two batches of seven specimens each were printed: batch A, with specimens placed vertically on the baseplate of the SLM machine (that is, the vertical struts are parallel to the loading direction), and batch B, with specimen placed horizontally on the base plate (the horizontal struts are parallel to the loading direction). The aim is therefore to study the influence of the printing direction on the fatigue behavior. Nominally, the fillet radius, the strut diameter and the unit cell side are 600 µm, 670 µm and 4000 µm, respectively.

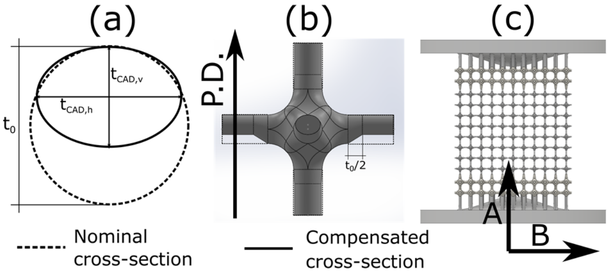

Figure 1. The compensation concept: (a) the CAD strut cross-section (defined by $t_{CAD,v}$ and $t_{CAD,h}$) is designed with the aid of the compensation model to produce the desired (t_0) cross-section after manufacturing (horizontal struts); (b) compensated CAD of the unit cell (note the transition segment of length $t_0/2$); (c) specimen for fatigue testing (the arrows indicate the printing direction for each batch).

DOI: 10.18416/AMMM.2019.1909S10T01

The powder used in the SLM is medical grade Ti-6Al-4V alloy ($O_2 < 0.2\%$) with particles of diameter < 45 µm. The thickness of the discretization slices is 60 µm. A stress-relief heat treatment was applied after printing, while no surface treatments were applied.

The metrological characterization of the as-built lattices was carried out by feeding pictures taken with an optical stereomicroscope to an in-house Matlab® image segmentation routine. The code automatically recognizes the boundaries of the lattice and measures the fillet radii and the strut cross-section parameters and then carries out a statistical analysis. More details of the procedure are provided in [3].

The specimens were fully reversed fatigue cycles (R = -1) on a Rumul 50 kN Testronic resonant testing machine under load control, at 120 Hz.

III. Results and discussion

The results of the metrological assessment show that the compensation procedure was effective in reducing the as-built/as-designed mismatch on the strut diameters compared to the results reported in [3] (Figure 2).

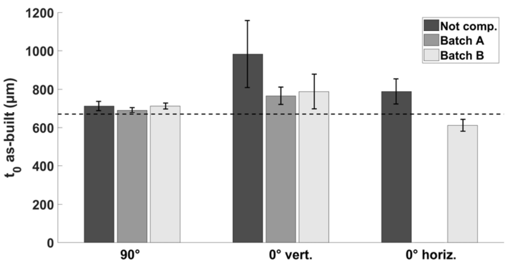

Figure 2. As-built strut section parameters of batch A and B with standard deviation classified according to their angle to the printing plane compared with the non-compensated specimens described in [3]. *The dashed line indicates the as-designed value (670 µm).*

The fillets below the struts oriented at 0° (R-) are sharper than in the other locations of the lattice, suggesting the presence of a systematic weak spot for fatigue resistance. The morphological differences between batches A and B are not statistically significant.

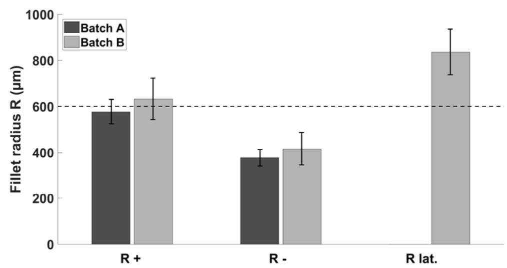

Figure 3. As-built fillet radius measured in batches A and B in the various locations of the lattice. "R+" and "R-" indicate the fillet radii measured in the plane normal to the printing plane, on the upper and on the lower side of the horizontal struts, respectively. "R lat" refers to the fillets measured in the printing plane. The dashed line indicates the as-designed value (600 µm).

Batch A shows better fatigue properties compared to batch B (Figure 4). This was expected considering that in batch A the struts aligned with the load are printed normal to the printing plane and consequently are considerably more regular than those laying in the printing plane. Indeed, it was observed that in batch A fatigue fracture always occurs close to the junctions, at the fillets identified with "R-" and is localized in a specific area of the specimens. On the other hand, in batch B failure always occurs in the middle of the struts and simultaneously in various locations. In the graph, the S-N curve obtained from four specimens of a third batch (identified as "D") is also shown, which was printed as batch A but was designed with sharp (corner) fillets. These data are collocated below and above of those from batch A and B, respectively. The as-built fillet radius of batch D is approximately 150 µm on average and fatigue fracture always occurs at the junctions. It is interesting to observe that the scatter of the fatigue data of batch A is considerably higher. In our view, this can be explained considering that batch A, having a more regular morphology (wide fillets and uniform load bearing struts) is more sensitive to local geometrical defects.

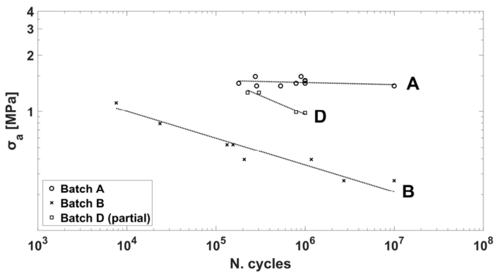

Figure 4. S-N curves measured from the fully reversed fatigue tests, for each batch of specimens. The dotted lines represent the linear regression of the experimental data.

IV. Conclusions

S-N curves of regular cubic Ti-6Al-4V SLM lattices were shown and discussed in relation to the as-built morphology of the lattice and the printing direction. From the observations, it can be concluded that fine-tuning the geometry of cellular lattices, such as adding a fillet radius at the junctions, can have great positive effects on the fatigue resistance. Moreover, the orientation of the struts to the printing direction can significantly alter the fatigue fracture behavior.

AUTHOR'S STATEMENT

Research funding: the study has been partially funded by the Autonomous Province of Trento (Italy) within the FAMAC research project. Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study.

REFERENCES

[1] M. Dallago, V. Fontanari, E. Torresani, M. Leoni, C. Pederzolli, C. Potrich, M. Benedetti, *Fatigue and biological properties of Ti-6Al-4V ELI cellular structures with variously arranged cubic cells made by selective laser melting*, J Mech Behav Biomed Mater 78, pp. 381–394, 2018

[2] M. Dallago, B. Winiarski, F. Zanini, S. Carmignato, M. Benedetti, *On the effect of geometrical imperfections and defects on the fatigue strength of cellular lattice structures additively manufactured via Selective Laser Melting*, Int J Fatigue 124, pp. 348–360, 2019

[3] M. Dallago, S. Raghavendra, V. Luchin, G. Zappini, D. Pasini, M. Benedetti, *Geometric assessment of lattice materials built via Selective Laser Melting*, Mater Today Proc 7, pp. 353–361, 2019