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Numerical and experimental assessment of fatigue life of additively manufactured PA12 lightweight materials

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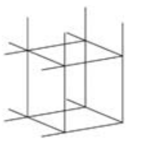
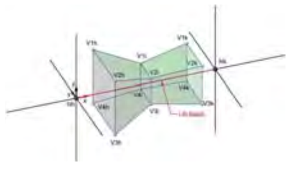
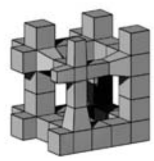
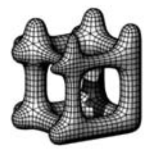
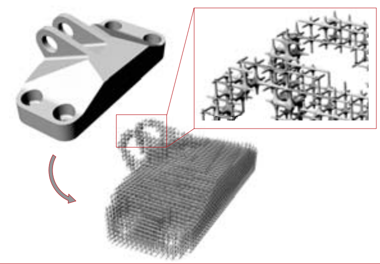
Abstract

Additive Manufacturing (AM) technologies allow for the production of customized and optimized parts. AM is fully exploited by topology optimization at a macroscale level and by cellular solids at a mesoscale level. Commercial CAD software show important limitations in lattice structures modeling methods: lack of scalability, robustness and automation. To overcome these issues, recent researches proposed a new approach based on direct polygonal mesh modeling, exploiting subdivision algorithms to obtain smooth surfaces and to avoid stress concentration at struts nodal points. Nevertheless, mechanical properties and fatigue behavior of lattices modeled with this novel approach are not yet well understood. In this work, numerical and experimental static and fatigue tests were carried out on additively manufactured bulk and lattice specimens; furthermore, stress distribution and surface curvature were numerically studied. Results showed that the modeling method enhances lattice fatigue life.

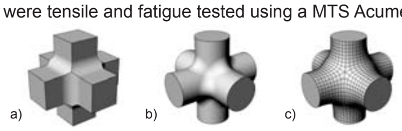
Geometric modeling

To obtain a lattice structure, a solid model is replaced by a wireframe model regularly repeating a simple cubic unit cell along x-, y-, z- axes. A simple and consistent mesh model is defined around the lines of the wireframe: each beam element is modeled with 8 planar mesh faces, assuming a double truncated pyramidal shape. Then, Catmull – Clark subdivision surface algorithm is applied and a smooth mesh is obtained, with no need of further filleting operations at nodes and/or naked edges.

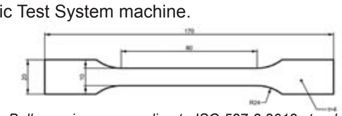
Materials and methods

5 types of specimen were used: 2 types of bulk specimen and 3 types of lattice specimen. A 7.5 mm cell dimension has been chosen. The resistant area of each cell is equal to 6.25 mm². A constant section area allows to concentrate on the mechanical behavior of specimens originating from different modeling approaches. Two sets of specimens were produced in Polyamide 12 (PA12) with two powder bed fusion (PBF) technologies, in order to compare different technologies performances. Specimens were tensile and fatigue tested using a MTS Acumen 3 Electrodynamic Test System machine.

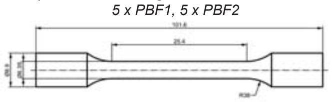


Unit cell types: a) squared section and 1 mm fillet radius (SF); b) circular section and 1 mm fillet radius (CYF); c) subdivided unit cell after 3 iterations of the Catmull-Clark scheme (CC).
d) example of specimen.
(SF, CYF, CC) x (9 x PBF1 + 12 x PBF2)


d)

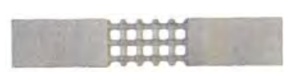


Bulk specimen, according to ISO 527-2:2012 standard.
5 x PBF1, 5 x PBF2



Bulk specimen, according to ASTM E606-12 standard.
12 x PBF1, 12 x PBF2

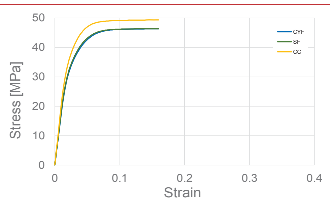
PA12 specimen realized with PBF1.



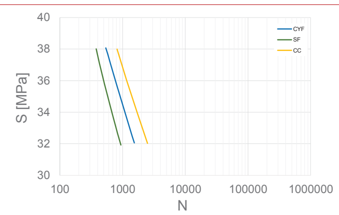
PA12 specimen realized with PBF2.

MTS Acumen 3.

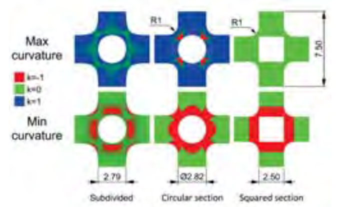
Numerical analyses



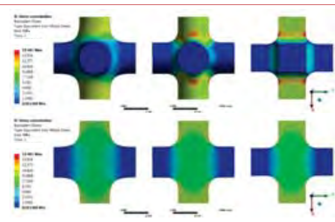
Stress/Strain curves for lattices, PBF2.



Wöhler curves for lattices, PBF2.



Curvature analysis of unit cells.



Stress distribution analysis of unit cells (full cell above, sectional view below).

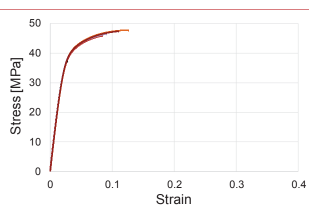
Numerical analyses were conducted to investigate the static behaviour of the lattices made with PBF2. Simulations were performed using *Ansys WB 16.2* and assuming a non linear elastic material model obtained by the experimental static tests on bulk specimens. The results show three curves with a very similar trend. The elastic moduli for SF, CYF, CC are 1814.5 MPa, 1765.7 MPa, 2054.8 MPa, respectively.

The lattices Wöhler curves were computed using the nominal stresses, $K\sigma$ factor, i.e. stress concentration factor, and the experimental fatigue curves on the bulk specimens. It was found that CC has the best fatigue strength as a consequence of the results of the following curvature and stress distribution analyses; the SF showed instead the worst fatigue behaviour.

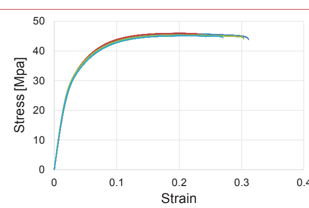
Minimum and maximum surface curvature were analyzed in *Rhinoceros 6* using *AdvMesh* tool from *Rhino Open Projects*. The sharp transition of curvature in SF and CYF cells indicates that fillets realized with software command produce a C^1 surface; Catmull-Clark subdivision scheme, instead, produces C^2 surfaces except at extraordinary vertices, where they are C^1. Thanks to its curvature continuity, CC cells surfaces are smoother than SF and CYF ones.

Further analyses were conducted in Ansys WB 16.2 to obtain stress distribution on SF, CYF and CC unit cells during a tensile test with a load of 10 MPa. In agreement with curvature analysis, smoother surfaces lead to lower stress peaks and smoother stress values transition. As can be seen from the sectional view, the different modelling approaches affect stress distribution inside the unit cell too: CC cell has a lower stress gradient with respect to SF and CYF cells.

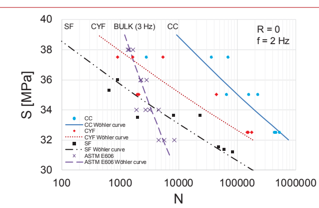
Experimental results



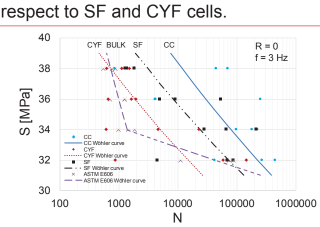
Stress/Strain curves for ISO 527 specimens, PBF1.



Stress/Strain curves for ISO 527 specimens, PBF2.



Wöhler curves for lattice and ASTM E606 specimens, PBF1.



Wöhler curves for lattice and ASTM E606 specimens, PBF2.

	PBF1		PBF2	
	Mean	Std Dev	Mean	Std Dev
E [MPa]	1869.8	43.3	1525.6	61.3
UTS [MPa]	46.93	0.86	45.59	0.38
ε_{max} [mm/mm]	0.1028	0.0192	0.3000	0.0487

Tensile tests results show that PBF1 has a higher Young Modulus than PBF2 but has a smaller elongation at break. Ultimate Tensile Strengths are statistically close.

During fatigue tests, bulk specimens, compared with lattice structures, highlighted a better behavior at high stress but a worst behavior at low stress. Moreover, ASTM E606 specimens realized with PBF2 show the fatigue limit starting at 34 MPa. CC specimens show an improved fatigue life in both PBF1 and PBF2, thanks to a lower stress concentration at nodal points due to wider and continuous surface curvatures, obtained by the proposed geometric modeling approach.

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