Spacecraft bracket design using additive manufacturing

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ABSTRACT

The major efforts in the space industry have the aim of finding ways to reduce the overall costs of building and launching a spacecraft (S/C). A combination of structural optimization and additive layer manufacturing (ALM) can be the answer for respecting the most decisive elements like mass reduction and minimum lead time, which translates into cost saving. This paper presents two different concepts of design and structural optimization for thruster support brackets. One approach was to use an in-house tool of optimization which resulted into a stiff and reliable structure. The second design was obtained using commercial of the shelf (COTS) tools of structural optimization. Both approaches significantly decreased the number of design iterations and the time needed to obtain the final solution. In order to take full advantage of the design flexibility given by ALM and reduce the mass furthermore, internal cavities were considered in both design concepts. This raised a contamination problem of the S/C's components which was avoided by designing closely with the manufacturer, a powder removal procedure. The combination of ALM, structural optimization and joint effort with the manufacturer, lead the team to high-quality and efficient structures with fewer points of potential failure and a lower production cost.

KEYWORDS: spacecraft design, structural optimization, additive manufacturing, internal cavities, powder removal.

NOMENCLATURE

S/C – Spacecraft

ALM – Additive Layer Manufacturing

COTS – Commercial Of The Shelf
TO – Topology Optimisation
ESO – Evolutionary Structural Optimization
SIMP – Solid Isotropic Material with Penalisation
CAD – Computer Aided Design
CT – Computed Tomography scan
NDT – Non-Destructive Testing

1 INTRODUCTION

The aerospace industry has a long history in supporting and utilizing cutting edge technologies and being a trendsetter in manufacturing. Innovative materials, state-of-the-art manufacturing processes and more and more capable software were produced by this industry decades ago and are now common for other industries.

The environmental restrictions and competitive market conditions pushes the industry to identify new approaches and breakthrough solutions. A manufacturing process that was thought to revolutionise the aerospace industry from the beginning was additive layer manufacturing (ALM) due to its great advantages like shorter development process, freedom to design complex geometries with the aim of improving reliability and performance, on-demand and on-site manufacturing and in-process quality assurance.

Topology optimisation (TO) is a method inspired by nature that produces organic structures with an optimal distribution of material. Conventional manufacturing processes often struggle or even fail to produce the designs that result from the use of TO [1], but the freedom of shape given by building a structure layer by layer instead of extracting it from a block of material, smooths the path to more lightweight and load adapted structures.

The aim of this paper is to present two different approaches on structural optimisation of two similar structures that are intended to be produced using ALM.

2 DESIGN APPROACH

This paper explores the potential of TO as a design process for creating organic structures feasible for manufacturing using ALM techniques. Topology Optimization for ALM as part of an industrially focused project called Atkins, Brackett et al. wrote an overview of the issues and opportunities for the application of topology optimization methods for additive manufacturing with the main conclusion that: "it is no longer the manufacturing stage that is the limiting factor in the realisation of optimal designs; it is the design stage" [2].

The process of creating and manufacturing topology optimised structures is presented in Figure 1. It's structured in two main parts that are strongly correlated. The topology optimization and reconstruction must be performed considering the constraints imposed by the ALM process, i.e. minimum thickness, minimum radius, no internal supports. The manufacturing process must comply with the material properties used in the optimisation process and the small details provided by TO.

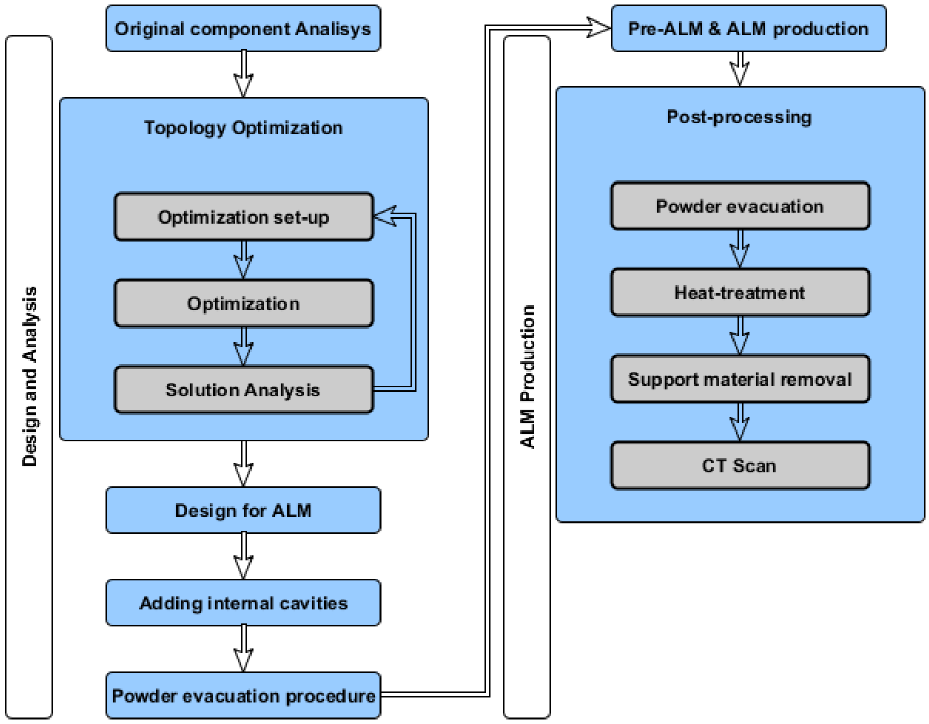


Figure 1 Design for ALM methodology

Topology optimization methods provide the material distribution within a design domain such that an optimal structure is obtained with respect to a set of loading cases. The two most practical methods of topology optimization are Solid Isotropic Material with Penalisation (SIMP) and Evolutionary Structural Optimization (ESO). SIMP is a "soft-kill" method, the design volume being divided into a grid of N elements (isotropic solid microstructures), each element *e* having a fractional material density ρ_e. The objective function is the strain energy SE, under a constraint of target volume V*, meaning the algorithm searches the material density distribution inside the design domain that minimizes strain energy for a pre-set structure volume. The densities of the microstructures are gathered in the vector P and represent the optimization parameters. [3]. An alternative to SIMP is ESO, introduced by Xie and Stephen in 1993 [4]. This method involves repeatedly removing small amounts of structurally unloaded material to evolve the topology towards an optimal shape.
Starting from the input presented in Figure 2 and the requirements presented in two main approaches were considered: one using an in-house tool of optimization, Optruss [5] and the second using a COTS tool, Optistruct.

Table 1 Requirements

Analysis type	**Modal analysis**	**Static analysis**
Requirements	first frequency >100 Hz	± 30g in all directions

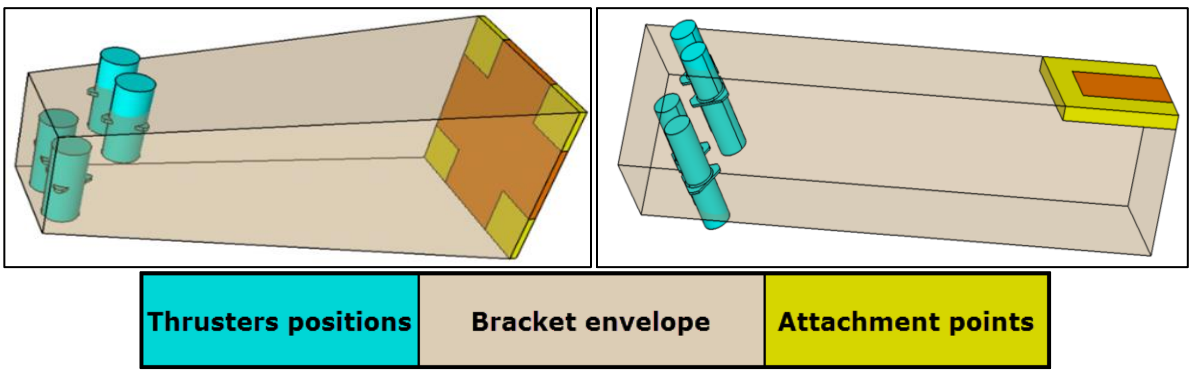


Figure 2 Input design space

2.1 Approach A

The first approach was a size optimization performed using the in-house tool Optruss, under the formalism of Topology Optimization of multiple truss beam structures from which the most suitable structure was chosen. The code is written in FORTRAN 95, and is structured as a typical FEM code. Although SIMP/OC is the driver in our code, the process could be seen as size optimization, specific to truss/beam problems [5]. The density variation from the attachment points to the top of the structure is as expected and the number of trusses is greatly reduced in a very short time. During a SIMP optimization, every element is an independent design variable and is determined to either be present (1) or void (0) in the final topology.
The truss structure provided by the optimizer was reconstructed in order to fit the attachments and to provide maneuvering space in specific areas.

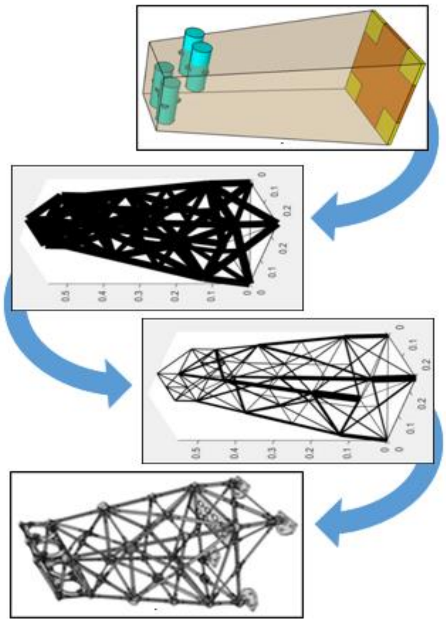


Figure 3 Approach A – Design process

2.2 Approach B

In the second approach a COTS optimization software was used, Optistruct which is is an industry proven, modern structural analysis solver for linear and nonlinear problems under static and dynamic loadings [6]. If in the first approach a discrete structure was considered, in this step it was considered a continuum structure. Two optimization iterations were necessary in order to achieve a convincing material distribution. The most important input in this approach was the design space which may have a great influence on the output structure. During the optimization process there was a significant trial and error effort involving the non-design areas of the attachments. A specific application of the non-design area at the bolted zone (yellow) had been implemented in order to make the interpretation much easier and to obtain better results.
The optimised structure was redesigned by including the necessary connections and by providing access inside the structure.

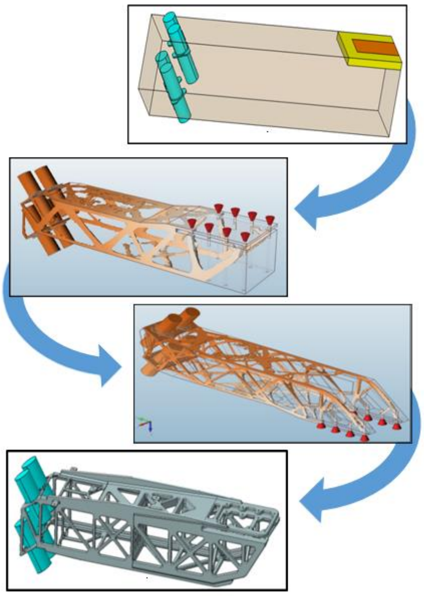
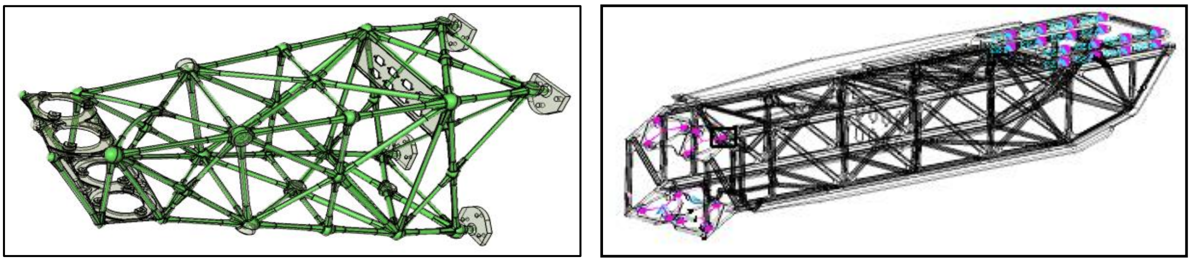


Figure 4 Approach B- Design process

As mentioned before, an important criteria is the mass, therefore in order to improve the stiffness furthermore and reduce the mass as much as possible, hollow structures were considered. In the process of hollowing the entire structure, special attention to the constraints of the manufacturing process must be given. Even if ALM gives a freedom of shape difficult to reproduce using subtracting procedures (i.e. milling), it still has few limitations regarding minimum thickness, minimum internal radius or the avoidance of internal supports. The structures were re-interpreted and re-analysed in order to proper evaluate the proposed designs (Figure 5).



b) Approach A- internal cavities a) Approach B- Internal cavities

Figure 5 Final designs

3 MANUFACTURING

Although the manufacturing technique was established from the beginning, the next step is to find a manufacturer which possesses a 3D printer with the appropriate build volume in accordance with the needed part. As mentioned before, before actually printing the part, there are still relevant manufacturing limitations that depend on a specific ALM machine or setting (printing regime) which have impact on our designs.

Taking into account that both structures, although different in principle, are designed to be hollow, the first manufacturing limitation was regarding the minimum thickness which was applied accordingly. Together with the minimum thickness constraint, also minimum internal diameter has to be considered and applied to the design.

A powder evacuation procedure was needed to be developed for both designs in order to safely eliminate all the powder potentially trapped inside the structure. The powder evacuation is critical, in parts that are intended to be used in space applications, because of the contamination issue. In order to have a better judgment in developing the procedure, the understanding of the steps right after printing the part are discussed in detail with the manufacturer. Each manufacturer may have a different set of steps, but in our case, which are presented in Figure 6.

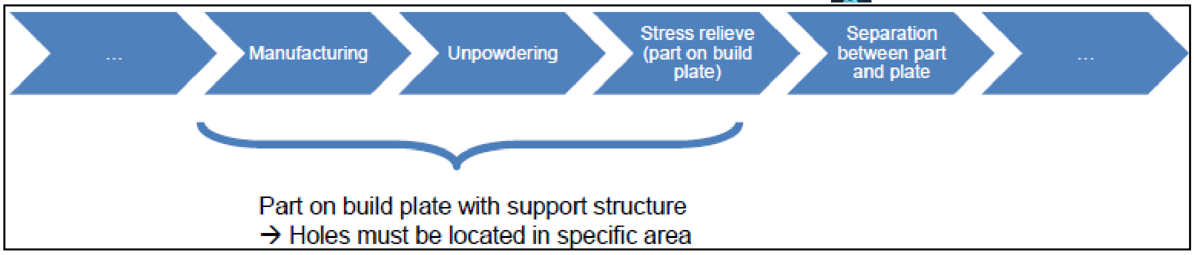


Figure 6 Manufacturing process in case of hollow structures [7]

The order presented is critical because the powder has to be efficiently eliminated before removing the supports. A heat treatment is needed to remove the internal stresses induced by the printing process, otherwise the structure will deform. If the heat treatment is made before removing the powder, it will weld to the structure. [7]

With the steps clarified, the part orientation on the build plate (Figure 7) of the ALM machine becomes relevant, because there is a need to create evacuation orifices. The positioning of the orifices has to be iterated between the design team and the manufacturing entity in order to have a complete evacuation, but no critical weak areas. Taking into account that the structures are built with internal cavities, all of them have to be interconnected, where possible, where not, additional evacuation orifices need to be placed.

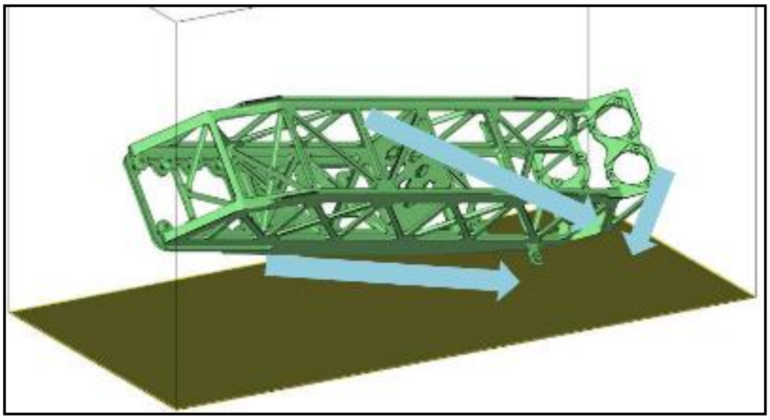


Figure 7 Evacuation orifices placement indications [7]

An information loop between the manufacturer and the design team facilitates the settlement of all the presented problems.

After the fine tuning of the design regarding the adaptation for ALM powder evacuation, both structures have to be fully checked in order to verify if any internal support material is needed. The internal support material had to be avoided in our structures because of the impossibility of removing them afterwards. Another reason is that any internal support may trap powder inside the bracket. After a thorough check, the models needed to have the geometry slightly modified. The solutions implemented for model A by the team are presented in Figure 8.

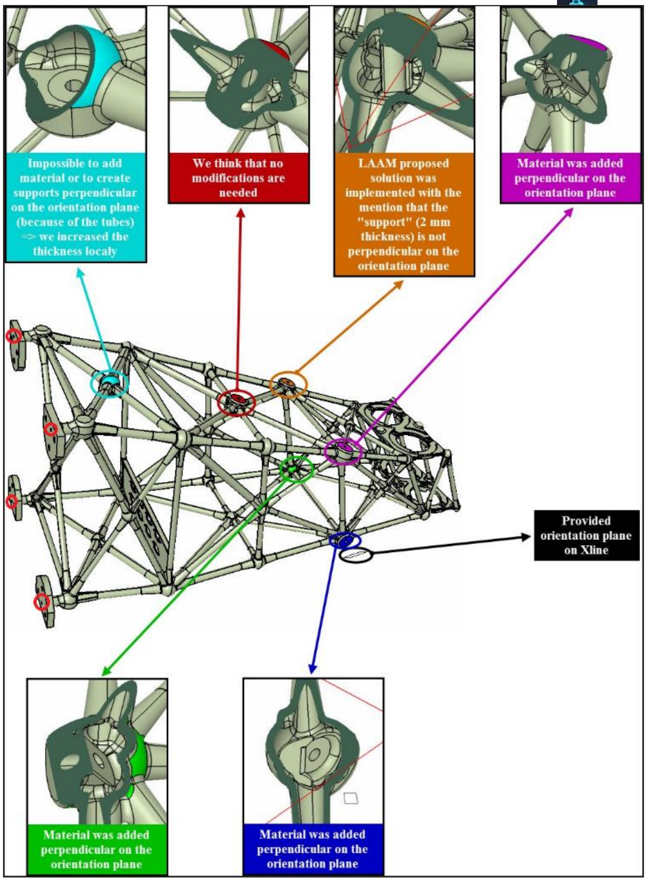
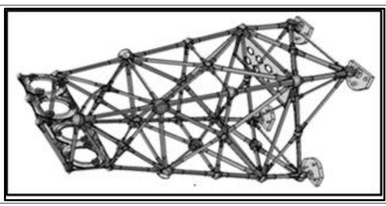
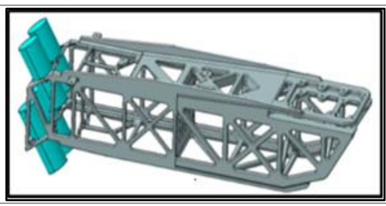


Figure 8 INCAS proposal in eliminating internal supports

After the implementation of detailed design tuning a final structural analysis is performed and then the CAD files are sent to the manufacturer to prepare them for the ALM printing process. As a first step, a final estimation is made in order to determine the material volume used for each model along with the support volume, together with a build time estimation. The brackets are to be manufactured on an Xline 1000R ALM machine from Concept Laser by virtue of the large overall dimensions of the brackets. As seen in Table 2, the material chosen right after the given input was AlSi7Mg0.6. This was chosen from the usual ALM powder materials because it appears to be the best compromise between structural properties, density and price.

Table 2 Model A and Model B estimations

	Model A	**Model B**
Machine	Xline 1000r	
Material	AlSi7Mg0.6	
Volume [cm³]	407	672
Support volume [cm³]	1200	1100
Build time [days]	9 days	10 days
		

Although Xline 1000R has many live monitoring systems, a qualification procedure is needed in order to have the approval for a spacecraft component to be manufactured using this process. From the qualification procedure, we can mention the CT scan check which was made, firstly, to identify the presence of remaining powder inside. Secondly, the structural integrity of the brackets is intended to be checked in order to identify their defects that would jeopardize the S/C. The second objective was also needed for qualification reasons.
A CT scan was made by the manufacturer, in order to verify the structure. The main objectives of the CT scan were:

- Material filling;
- Porosities and cracks;
- Lack of fusion;
- Trapped powder;
- Powder residues;
- Unmolten powder. [7]

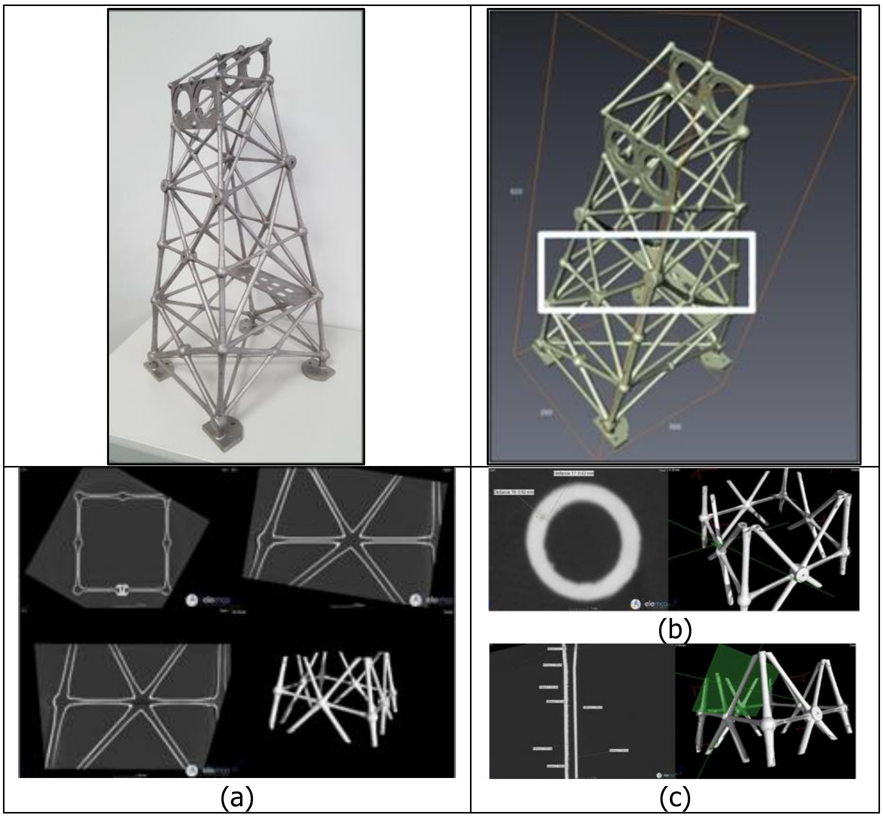


Figure 9 CT scan results [7]

The CT scan conclusions are:

- No problem identified regarding material filling and molten powder;
- Very few porosities and no cracks, as in Figure 9 (b);
- No problem identified regarding the lack of fusion;
- No trapped powder identified;
- No powder residues identified;
- No areas of unmolten powder identified;
- Internal roughness depends on structure orientation during manufacturing, Figure 9 (c);

4 CONCLUSIONS

Two different design approaches where implemented, with the discrete material TO using Optruss and continuous material TO using Optistruct. Taking into account that one of the methods needs an

approximated input in order to find the optimum solution, two similar structures were considered to be objective.
The computation time needed for model A was significantly shorter than the one for model B, but more time is needed to define the input geometry to be optimized.
The part intended to be 3D printed hollow, is to be designed in accordance with the limitation imposed by the machine and the manufacturer. In our case minimum thickness, minimum internal diameter where the decisive details which had impact on our designs.
For hollow space structures, they need to be adapted to the appropriate powder evacuation procedure. This is needed because of high-risk contamination issues. The evacuation orifices need to be placed accordingly with the part orientation on the build plate.
To obtain an optimal design from the manufacturing point of view, the manufacturer needs to be in the loop from the beginning.
Internal supports are to be avoided in all hollow structures because they are unnecessary mass and because they could block the pathway intended for the powder evacuation. Where internal supports appear, the best way to mitigate the indicated risk, is to locally fine tune the geometry.
CT scan was selected as an NDT method to check if there is any trapped powder and also to check the structural integrity of the 3D printed part.
Although ALM does not provide fully dense components, as seen from the CT scan, no major manufacturing issues where found apart from few porosities.

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