Title:
3D Mesoscale Modeling of Aluminum Foams for FEA of Scattering Effects due to Cell Distribution

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Introduction:
Mechanical behavior of metallic foams is strictly related to relative density calculated in relation to the bulk material [4,7]. Under compression, void distribution (stochastic or regular) and cell morphology (open or closed cell, aspect ratio, …) also affect the progressive local behavior, inducing scattering on the load-displacement curves [8,10]

Finite Element Analysis (FEA) may support the analysis of cell effects and may help to quantify the scattering related to the characteristics of cell morphology. In [10], a modeling strategy based on Voronoi cell distribution and a sensitivity analysis to the computational parameters have been discussed. More in detail, the effects of cell thickness are treated according to the sensitivity to numerical parameters necessary in explicit FEA set-up (mass scaling, element size). In [6], mesoscopic models investigate the effect of impact velocity, material strength and porosity distribution on energy absorption capability of metallic foams.

In [2], examples of how mesoscale modeling may describe the effective behavior of foams in mechanical tests are provided, together with two approaches for achieving FEA models from experimental morphological data. One approach is based on Voronoi cell, the other on Reverse Engineering based on reconstruction of cut sections or tomography, that now is becoming more widespread [11]

Geometrical modeling of mesoscale porosity needs to reproduce patterns, according to Voronoi diagram, or unit cell replication (e.g. Kelvin cell structure) through proper space filling strategies [1,9]. Voronoi diagrams are preferred for cells with stochastic distributions like those present in metallic foams. Shared library like Voro++ or commercial add-ons like Voronoi Sketch generator may help to model mesoscale structures with different complexity.

The aim of this paper is to discuss a foam modeling approach based on a surface tessellation provided by a Voronoi diagram, investigating the sources of approximation errors on the final model in the respect of the assigned relative density and cell morphology.

Main Idea
To define a design tool able to support scattering evaluation of foam behavior, the workflow to model specific cell morphology and distribution through FEA must be consolidated, so that different cell

conditions may be planned and simulated. According to this general purpose, in this paper, we present the pursuance of the Voronoi diagram approach that is presented in [2], discussing how the steps in the modeling workflow may introduce geometrical approximation errors. The development of the foam model generation has been carried out in Matlab2018, meanwhile the FEA model optimization has been provided through Hypermesh, from the Altair Hyperworks suite.

Workflow input is represented by the relative density and the statistical distribution of cells, defined in terms of areas (thus averaged radius), circularity, and presence or not of a bulk outer wall, mainly due to the alloy solidification in the die.

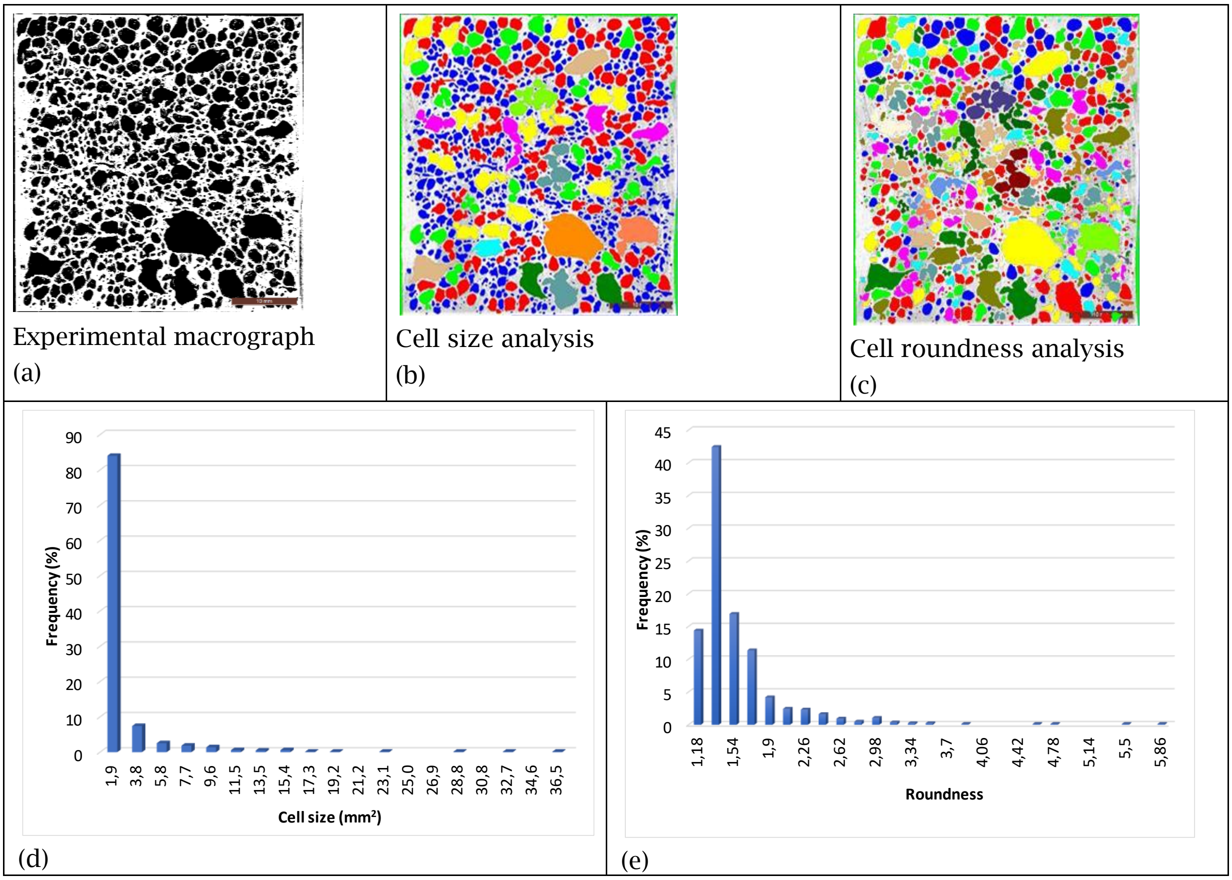


Fig. 1: Foam cell morphology evaluation through transversal cuts.

Fig.1 provides an example referred to a single slice cut from a specimen. Fig 1(a) shows a photo of a foam specimen transversal section; 1(b) and 1(c) show the image segmentations regarding the cell size and roundness analysis, respectively; in 1(d) and 1(e) histograms of the distributions of cell size and roundness; *R*. According to the experimental conditions and resources, statistical distributions of the cell morphology may be evaluated through cuts on assigned slices of the specimens or through non-destructive tests like tomography.

Starting from an assigned relative density and assuming shape and lengths of the specimen (rectangular or cylindrical section), the workflow for modeling the foam starts, providing a set of seeds able to partition the volume, according to a Voronoi diagram.

The number of seeds are computed according to the formulas:

$$num\_seed = floor\left(VVF \cdot \frac{V}{V_{sphere}}\right) \quad (1)$$

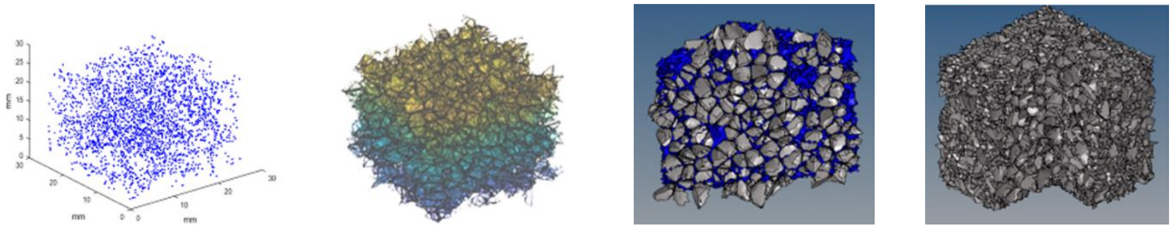
$$V_{sphere} = \frac{4}{3} \cdot \pi \cdot r^3 \quad (2)$$

where *VVF* stands for the Void Volume Fraction in the respect of the specimen volume, *V*, and *r* stands for the cell mean radius derived from foam cell morphology.

Cell radius and roundness values outside the experimented distribution are taken into account as a post-process of the Voronoi diagram, through a threshold on the elaboration of the mesh related to each cell. Cells outside the threshold are then recomputed iteratively so that the difference between the actual VVF and the initial one is minimized.

The Voronoi Diagram provides an "STL" convex tessellation of the outer surfaces of the voids (that represent the boundaries of the cell) but, unfortunately it cannot be directly applied as FEA model, since a proper solid mesh must be created and optimized.

Fig.2 shows with an example the evolution of the model from the seed generation (a) up to the final tetramesh suitable for the FEA, passing through the tessellation of the outer surfaces of voids (b), the volume definition among cells (c) and solid mesh creation of the volume (d).



(a) (b) (c) (d)

Fig. 2: FEA modeling steps. (a) cell seed; (b) cell convex tessellation; (c) volume definition; (d) FEA solid model.

The solid mesh may be built in two ways:

1. as a tetramesh starting from regular surface meshes of the cells and of the external edges of the specimen;
2. as a tetramesh of the overall volume defined from the boundary surfaces of the cells and the specimen.

The first way may be carried out starting from an optimized re-meshing of the tessellation of the outer surfaces of the cells; the second way asks for a surface fitting of the outer surfaces of the cells and for their selection to define the overall volume to be meshed.

To avoid time consuming FEA pre-processing activities, and mesh errors at possible critical areas (non-manifold local meshes or missing elements, for example), the first approach is here selected and discussed.

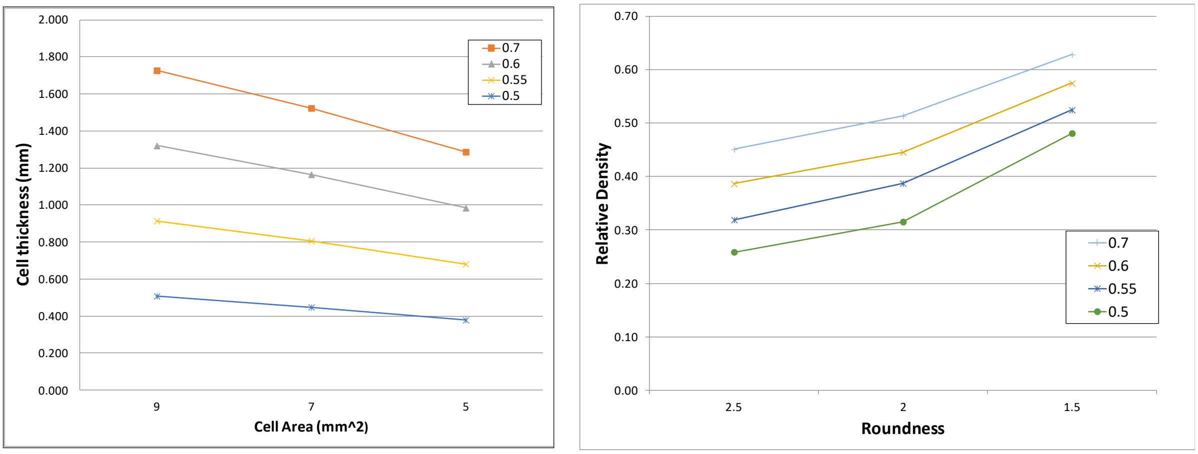
More in detail, after the Voronoi diagram, each cell is meshed through Delaunay tessellation. This tessellation should be optimized for FEA, so that shape approximations are induced, affecting cell shape and volume. This introduces errors in the final morphological values (aspect ratio, cell radius, VVF). These errors must be correctly evaluated if the model is applied for simulating specific geometrical mesoscale conditions.

According to these problems, two sensitivity analyses have been conducted. The first one investigates how the Voronoi diagram and its Delaunay tessellation can mimic the desiderated cell morphology distribution. The second one studies the final relative density applying different levels of mesh length to the tessellation of the outer surfaces of the cells.

In the sensitivity analysis about cell morphology distribution the Delaunay tessellation of the cells is analyzed to evaluate:

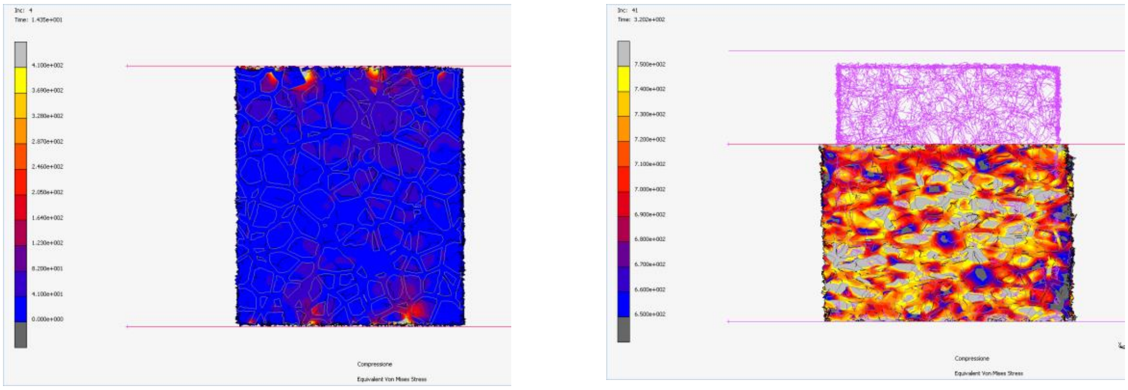
- the averaged normal distance between cells (it is strictly related to the cell thickness of the foam structure);
- the effective final relative density.

As shown in Fig.3 the nominal relative density is not achieved due to the necessity of deleting or reshaping cells provided by the Voronoi diagram with roundness or radius greater than the ones present in the experimental distribution. These effects are always present with the same trends so that a proper compensation factor may be found.



(a) (b)

Fig. 3: Sensitivity analysis on final foam geometrical characteristics related to Cell Area and Roundness with different assigned nominal relative densities [0.5;0.7].



a b

Fig. 4: FEA of the 3D mesoscale model: equivalent Von Mises stress state (MPa) at yielding (a) and at maximum compression load (b).

The second sensitivity analysis investigates the effects of the optimization made on the tessellation of the cells. In this case the effects have been investigated through distance analyses from the original STL, which is directly generated from the Voronoi diagram, and through shape errors taken along some test sections of the foam models. The comparison of the morphological errors induced by the optimization of the mesh length is then correlated to the initial geometrical input of the foam model, so that also in this case a quantification of the percentage modeling error may be provided together with a discussion of a provisional compensation factor suitable for reducing this error.

Examples and proofs of the validity of this approach are provided through the discussion of two FEA test cases, made according to this approach and experimentally validated through compression tests. Fig. 4 shows one of them in the respect of a split Hopkinson bar compression test, for strain rate effect evaluation.

Conclusions

The final aim of the paper is to demonstrate the robustness of the proposed 3D mesoscale modeling approach that considers the cell morphological shape distribution provided as input. Approximation errors due to the FEA solid mesh are discussed and minimized. Doing so a systematic approach based on FEA can be applied on many 3D mesoscale geometries to evaluate the scatter in the mechanical response of aluminum foams.

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