*Proceedings of the IMProVe 2011*
*International conference on Innovative Methods in Product Design*
*June 15th – 17th, 2011, Venice, Italy*

# Geometric modelling of metallic foams

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## Article Information

Keywords:
*Aluminium foam,*
*Microstructural model,*
*CAD modelling,*
*OBB overlapping,*
*X-ray tomography*

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## Abstract

Purpose:
*The aim of this work is the development of a procedure able to model the highly irregular cellular structure of metallic foams on the basis of information obtained by X-ray tomographic analysis.*

Method:
*The geometric modelling is based on the feature "pore" characterized by an ellipsoidal shape. The data for the geometric parameters of the instances are obtained with a methodology which is driven by the pore volume distribution curve. This curve shows how much the cells, whose diameter belongs to a given dimensional range, contribute to the reduction of the total volume.*

Result.
*The presented methodology has been implemented into a CAD tool consisting of a Matlab routine identifying the instances of the feature "pore" and a CATIA's macro modelling the closed cells foam.*

Discussion & Conclusion:
*The CAD model developed for two types of closed cells foams approximates by considerable accuracy both the density and the volume distribution of the real foams.*

## 1 Introduction

Metallic foams are a new class of materials; they are characterized by a cellular structure consisting of a solid metal, frequently aluminium, containing a large volume fraction of gas-filled cells. Several manufacturing processes are currently used and other innovative methods are being developed in order to obtain a more reliable and uniform production. Technological process determines also if the cellular material is made of open or closed cells.

In the last few years interest about metallic foams has significantly increased. These materials, in fact, show an interesting combination of physical and mechanical properties that make them particularly versatile: the low apparent density, for example, allows obtaining a high stiffness/specific weight ratio, the presence of cavities and the essential in-homogeneity provide them acoustic and thermal insulation properties, besides the possibility to absorb impact loads and to damp vibrations. However, the industrial applications of metal foams are yet restricted since there is not a complete characterization of these materials.

Nowadays the design of high-performance materials requires a deep insight into the material microstructure as well as into its influence on properties. Geometric models are important tools for studying these complex structure-property relations. In particular the modelling approach proposed in this paper has as final aim the evaluation of the macroscopic mechanical behaviour of some aluminium alloy foams starting from micro-structural measurements.

The mechanical behaviour of metallic foam is certainly affected by the cell morphology, which represents, therefore, a crucial characteristic for this class of materials. The fundamental work by Gibson and Ashby [1] showed that density is another key parameter influencing the foam behaviour. However, a modelling approach taking into account only these properties can not explain the high scatter in both physical and mechanical properties. Additional micro-structural properties, such as for example the cell volume distribution, the wall thickness and curvature, the internal surface area should be considered in order to better characterize the behaviour of these materials.

The tomographic technique allows a 3D reconstruction of the metallic foam: a voxel model of the foam with a given resolution can be easily obtained. In [2] this model is directly translated into a mesh of cubic elements, having the same dimension of the tomographic resolution, in order to evaluate the behaviour of the cellular material. However, this method is extremely time-consuming because, the specimen, in order to be representative, must be sufficiently large in comparison with the average cell size and consequently this involves a very large number of finite elements and excessive calculation time.

Another approach, based on tetrahedral finite elements, can be more suitably used. In [3] the authors pointed out that, the same accuracy can be reached using the tetrahedral meshes coarser than those produced by the voxel/element method, as the triangles, composing the tetrahedrons, can be larger than the resolution of the tomographic analysis while preserving the actual shape to model. Clearly this approach requires as input the geometric model of the foam microstructure.

In a previous work [4] the authors proposed a comparative study between two different modelling approaches in order to simulate the behaviour of the cellular material during a compressive test. Both the

approaches aimed at modelling a foam characterized by a density value and an average cell size corresponding to real values. The two different approaches differed for the cell morphology. The easiest model was based on the regular repetition of a Kelvin cell [5, 6]. This cell has been largely used because it corresponds to the minimum surface energy for a constant volume. The Kelvin cell model resulted inadequate to describe the foam structure. In particular, Young's modulus of the foam was overestimated. The difference in the elastic module value respect to the experimental value was originated by the regular disposition of Kelvin cell into the model, which was far from the real aspect of the metallic foam. For this reason, the authors focalised their efforts to obtain a second model able to conjugate the geometrical simplicity of an elementary cell and the possibility to build a random assembly. In order to define a schematization with highly random cell morphology, authors' attention focused on an ellipsoidal *surface* having random dimensions, orientation and position. Even if the elastic modulus was yet overestimated, the agreement between experimental and numerical stress-strain curves was better. However, this model presented some problems at higher strains. In these physical conditions, in fact, the proposed model was not able to reproduce the behaviour of the real foam because of some limitations intrinsic to the same model [4].

In the present paper a new methodology aiming at modelling the highly irregular cellular structure of metallic foams is proposed. For each metallic foam under examination a geometric model is obtained approximating very well both the density and the volume distribution of the real foam. In particular, attention is focused on the closed cell foams made of aluminium alloy, since their high relevance in several industrial fields. The model here proposed is yet based on an ellipsoid-shaped feature *"pore"*, but it differs from the surface model proposed in [4] since it is a solid model. In order to reproduce the high irregularity of the foam structure the values of size, location and orientation parameters of the feature "pore" are randomly generated within well-defined ranges which are identified based on the results of the image processing of tomographical scans.

## 2 The modelling approach

The base cell of the foam used in this approach is modelled by the feature "pore". It is an ellipsoid of revolution (or spheroid) whose two distinct semi-axis lengths are denoted a and c. The spheroid is oriented so that its symmetric rotational axis is along the z'-axis (fig. 1). If all the three semi-axes are equal, the feature pore is a sphere; otherwise, depending on whether c<a or c>a, an oblate spheroid (lentil-shaped) or prolate spheroid (rugby ball-shaped) is obtained. In fig. 1 the geometric parameters of this feature are shown. They are:

- semi-axis lengths: a, c;
- center coordinates: $x_c$, $y_c$, $z_c$;
- ellipsoid orientation: azimuth angle ($\theta$) and zenith angle ($\phi$).

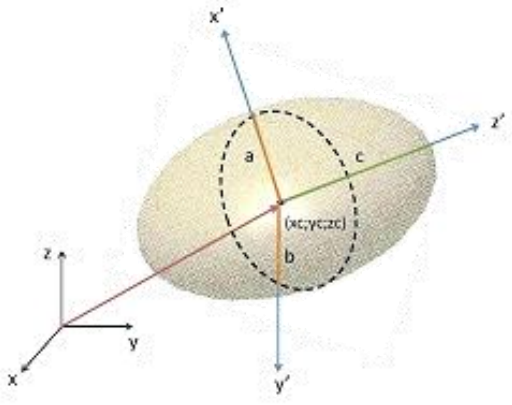


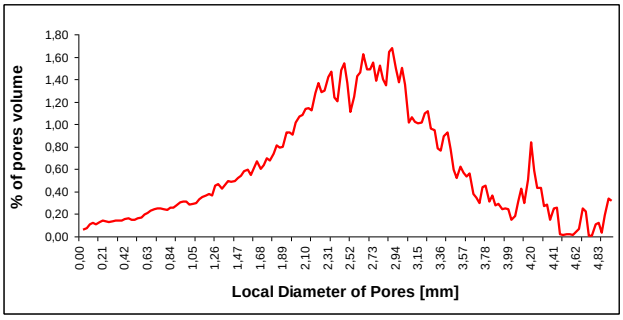

***Fig. 1 The feature "pore".***

In order to describe the high irregularity of the foam architecture, the values to be assigned to the geometric parameters of the feature pore are generated by a uniform random distribution. In particular, the values for the intrinsic parameters (i.e. semi-axes lengths) are obtained by a methodology (described in section 2.1) which is driven from the pore volume distribution curve for the foam under examination. This curve is derived from a tomographical analysis performed on two specimens, one made of Aluligth foam and the other made of Alporas foam. This analysis has been carried out at the Scanco Medical (www.scanco.ch) by the AGμCT40 system; it is based on the same physical principles and mathematical algorithms as the classical medical CT scanner. The analysed object is rotated, and at each position a shadow image is taken. After image acquisition, the internal microstructure of the foam is constructed using a tomography back projection algorithm. The volume was stored in a 3D-image array. After the measurement and reconstruction were completed, a constrained Gaussian filter was used to suppress noise in the original volume data. A thresholding procedure was then used to separate the material from the surrounding. 3D Morphometric analysis was performed as described in [7]. The Foam Volume (FV) can be calculated by counting the foam voxel within a Volume Of Interest (VOI). The ratio of the foam voxel (FV) to the total volume (TV) within the VOI gives the foam volume density (FV/TV).

Furthermore, a distance transformation (DT) method is employed for the determination of the cell size, $d_s$, by fixing spheres into the voids of the structure. The average maximum diameter of the sphere that fits the cell void space gives the corresponding $d_s$-value for cell size. The pores volume distribution can be obtained on the basis of the cell size distribution and it is shown in fig. 2a for Alporas and in fig. 2b for Aluligth.

The center coordinates $x_c$, $y_c$, $z_c$ are generated by a uniform random distribution within the selected reference volume (for example a cube of side length 10 mm). While, $\theta$ and $\phi$ are randomly generated within the interval $[0,\pi]$.

In fig. 3 a picture of the Alporas foam is shown as example.

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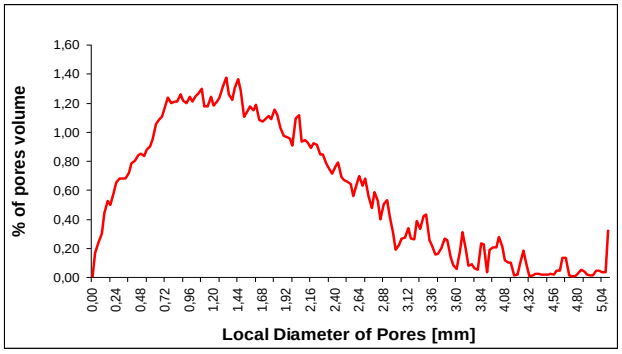



*b)*

***Fig. 2 Pores volume distribution obtained by X-ray tomography for Alporas a) and Aluligth b).***

The final model is obtained by a Boolean subtraction between the reference volume and the aforementioned ellipsoids. This methodology has been implemented into a CAD tool consisting of a Matlab routine identifying the instances of the feature "pore" and a CATIA's macro modelling the closed cells foam.

## 2.1 Data generation of the pore feature parameters

Data needed to define the intrinsic geometry of the pore feature are obtained by a methodology driven from the volume distribution curve for the foam under examination. This curve shows how much the cells, whose characteristic diameter $d_S$ belongs to the range $]d_i; d_{i+1}]$, contribute to the empting of the total volume. For the foams under examination the range amplitude $]d_i; d_{i+1}]$ is chosen as equal to 0.09 mm. This value allows to exclude the pore sizes that not contribute significantly to the volume reduction.

The methodology here proposed begins taking into account the largest cell-sizes, within the range $]d_N; d_{N+1}]$. This range is identified removing all those intervals characterised by higher values for which only fractions of one cell are involved. One or more instances of the feature pore are randomly generated till the related volume fraction is higher than the corresponding value derived from the distribution curve. Then, the instances with $d_S$-values belonging to $]d_{N-1}; d_N]$ are considered and so on.

Not all the instances belonging to the generic range $]d_i; d_{i+1}]$ can be accepted into the model. In fig. 4 the flowchart for the acceptance of a generic ellipsoid $E_i$ and for the evaluation of the related volume is shown. Firstly the procedure verifies if $E_i$ overlaps with another ellipsoid or not. In order to carry out quickly this step, the interference test is applied to the oriented bounding boxes (OBBs). For each ellipsoid, in fact, a rectangular bounding box, having an arbitrary orientation in 3D-space, can be identified. If the OBB containing the ellipsoid $E_i$ does not intersect any other, then $E_i$ cannot collide with anyone of the accepted ellipsoids. In this case, therefore, $E_i$ can be accepted as an instance for the feature pore and the corresponding volume is evaluated. A fast overlap test for two OBBs is based on the *Separating Axis Theorem* [8, 9]. This algorithm projects the boxes onto some axis in space, so that each box forms an interval on the axis. If the intervals do not overlap, then the boxes are disjoint and the axis is called "separating axis". If a separating axis exists, then the OBBs are disjoint. There are 15 potential separating axes for two OBB; they are normal to a face or to an edge for each box. The verification consists in computing the radii of the intervals; if the distance between the box centers projection on axis is greater than the sum of the radii, the intervals are disjoint and the boxes too (fig 5).

***Fig. 3 Alporas foam.***

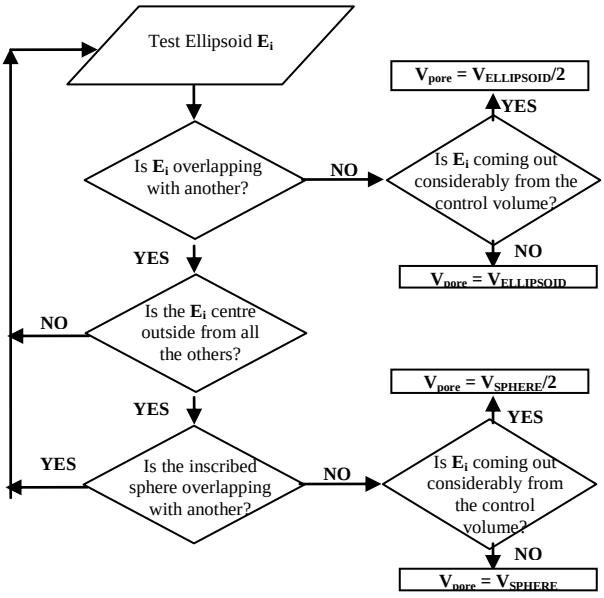



***Fig. 4 Flowchart for the acceptance of a generic ellipsoid Ei and for the evaluation of the corresponding volume.***

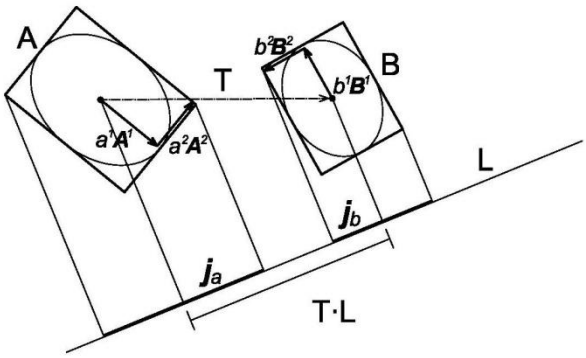



***Fig. 5 L is a separating axis for OBBs A and B because A and B give disjoint intervals under projection onto L.***

When a collision between the OBBs is detected then the procedure verifies if the centre of $E_i$ is outside from all the other accepted ellipsoids. This test aims at discarding ellipsoids, like that shown in fig. 6 and denoted as $E_i$. The condition here presented, besides being not realistic, makes the volume evaluation unreliable and gives several problems during the following CAD modelling.

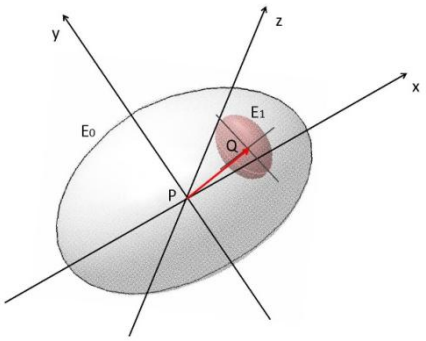



***Fig. 6 The case of an ellipsoid Ei with centre inside another ellipsoid.***

In order to carry out this test the following condition must be satisfied:

$$\frac{\left\|\overrightarrow{PQ}\right\|^2 \cos^2\alpha}{a^2} + \frac{\left\|\overrightarrow{PQ}\right\|^2 \cos^2\beta}{b^2} + \frac{\left\|\overrightarrow{PQ}\right\|^2 \cos^2\gamma}{c^2} > 1 \qquad (1)$$

In (1) P is the centre of an accepted ellipsoidal pore $E_0$. Q and a, b, c are respectively the center and the semi-axes of the ellipsoid $E_i$ to be tested. Finally $\alpha$, $\beta$, and $\gamma$ are the direction cosines of the vector $\overrightarrow{PQ}$ within a reference system with origin in P and coordinate axes coincident with the axes of symmetry of $E_0$.

In order to associate a single $d_s$-value to each cell of the modelled foam, the procedure verifies that a complete sphere can be identified for each pore. The pores, whose internal sphere overlaps with another, are discarded.

To establish if the volume fraction, related to a given $d_s$-range, is higher than the reference value derived from the experimental curve, the volume of the accepted ellipsoid $E_i$ must be estimated. For ellipsoids overlapping each other the volume of the internal sphere is taken into account underestimating the actual pore volume. Moreover, the algorithm also considers if the accepted ellipsoid $E_i$ intersects the faces of the control volume (i.e. the volume of the sample) or not. Also in this case an approximate evaluation of the pore volume is proposed in order to take in account this possibility.

## 2.2 Foam CAD model

Starting from the parameters set obtained by the aforementioned procedure, a CAD model of the metal foam is developed. The CAD modelling follows three steps:

- generation of a cube (the reference volume);
- generation of ellipsoids;
- execution of a Boolean subtraction between the cube and the ellipsoids.

This procedure has been automatized by a CATIA's macro (Visual Basic script), whose steps are detailed in the flowchart in fig 7.

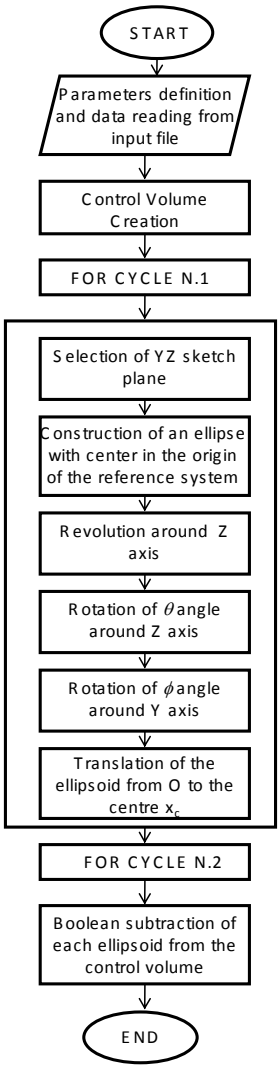



***Fig. 7 Flowchart of the Catia's macro.***

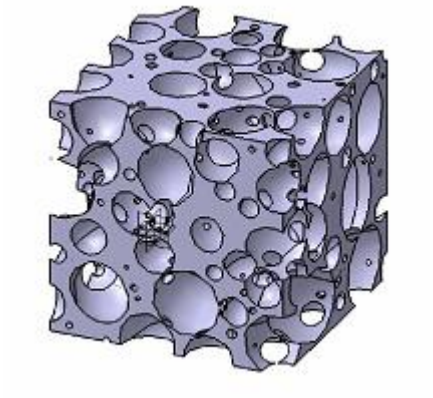
Each ellipsoid is created as revolution solid of a 2D ellipse around the z-axis. After the creation, each ellipsoid is rotated around two axes (fig. 2) and finally translated on its center point. When the ellipsoids are created and positioned, they are subtracted by the cube (the reference volume). It is possible to subtract progressively the ellipsoids, whose diameter belongs to a given cell size

range $]d_i; d_{i+1}]$, and calculate the corresponding volume fraction.

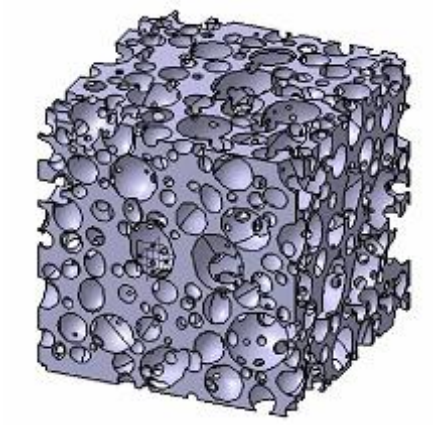
## 3 Results and discussions

The CAD model obtained by the aforementioned procedure is shown in fig 8 a) e b) respectively for Alporas and Aluligth foams.

Firstly, the reliability of the model is verified comparing its relative density to that measured on a real specimen. The pores volume distribution of the CAD model and that resulting from the µCT analysis are also compared and shown respectively in fig 9a for Alporas and in fig. 9b for Aluligth. In these figures, the distribution curve, as approximately estimated by the algorithm here proposed, is shown too. The curve, labelled as microCT, is the pore volume distribution obtained by tomography and used as input in the procedure for data generation of intrinsic parameters a and c. This curve is derived from that shown in fig. 2, resulting from a scan on a 40x40x20 mm specimen. In the case under examination a cube of side length 10 mm is considered as reference volume. Moreover, the range amplitude $]d_i; d_{i+1}]$ is selected equal to 0.09 mm. The curves, labelled as Algorithm and CAD, are the pore volume distribution obtained from the procedure illustrated in section 2.1 and from CAD modelling respectively.

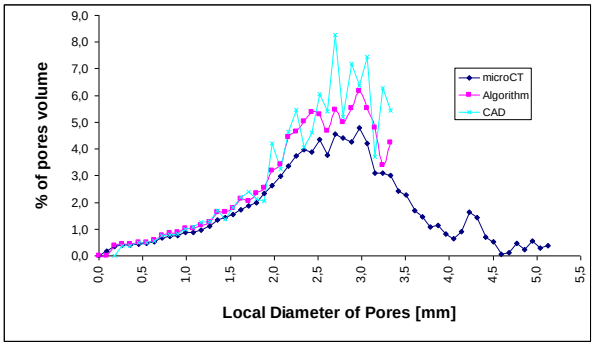


***a)***



***b)***

***Fig. 8 Foam CAD model: Alporas a) and Aluligth b).***

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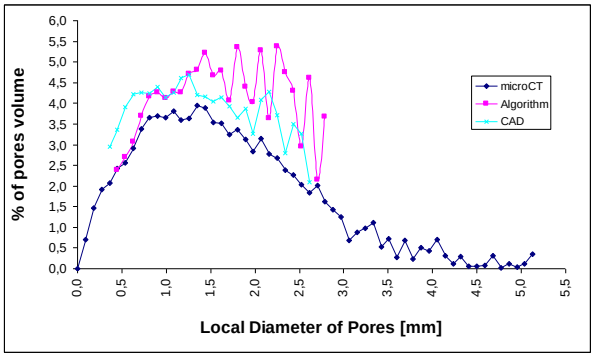


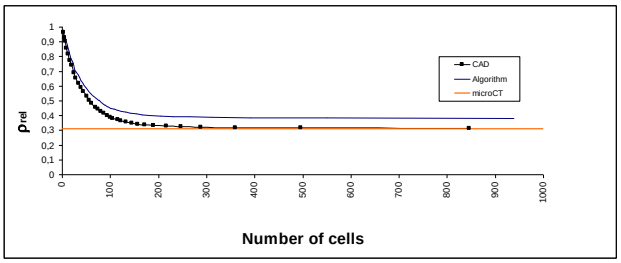

***b)***

***Fig. 9 Comparison of pores volume distribution between the CAD model and those resulting from the µCT analysis and the implemented algorithm. Alporas a) and Aluligth b).***

As shown in fig. 9, the good agreement between the pores volume distributions in input (microCT curves) and in output (CAD curves) shows the validity of the presented methodology for the modelling of both closed cells foams under examination. The higher values of percentage of pore volume deriving from the algorithm and the CAD modelling are due to the fact that, during the generation of cells, the pores with higher $d_s$-values are discarded if at least one cell can not be inserted. The consequently loss of volume is recovered by inserting a higher number of smaller pores. This causes the raising of the output curves. Moreover, the volume calculated during the CAD modelling by CATIA is the highest since the algorithm underestimates the volume of the accepted voids. The contribution to the pore volume due to the smaller pores ($d_s < 0.25$ mm) is neglected in order to limit the number of cells and to reduce the calculation time. The evident oscillation of the CAD curve for higher pore diameters is due to the very low number of cells inserted for these size ranges.

In fig. 10, the trend of the density value versus the number of cells is reported for both foams. As shown, the density decreases quickly up to an almost constant value. This means that few larger pores give a greater contribution to the reduction of the volume; on the contrary a large number of smaller pores gives a very limited or zero contribution. The real density is achieved introducing about 300 cells in the model for Alporas and about 900 cells in the model for Aluligth. Further smaller cells do not change significantly the relative density of the models. In the case of the Aluligth the number of cells is greater since the mean pore diameter is smaller than that

derived from Alporas, as shown from the relative distribution curve.

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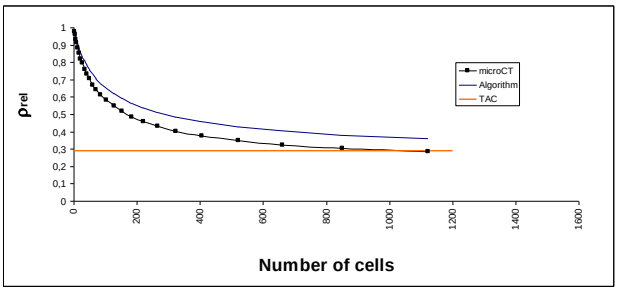


*b)*

***Fig. 10 Relative density of Alporas a) and Aluligth b) foams models versus the number of cells.***

## 4 Conclusion

In this work a new methodology, aiming at modelling the highly irregular cellular structure of metallic foams, has been developed. The model here proposed to reproduce the cellular microstructure of closed cell foams is a solid model based on an ellipsoid-shaped feature *"pore"*. In order to model the high irregularity of the foam structure the data for size, location and orientation parameters of the feature "pore" are randomly generated within well-defined ranges based on tomographic data. In particular, the values for the intrinsic parameters are generated by a methodology driven from the volume distribution curve for the foams under examination. This curve shows how much the cells, whose diameter is within a given range, contribute to the empting of the total volume. On the basis of experimental data deriving from tomographic analysis, two types of closed cells foam are modelled approximating very well both the density and the volume distribution of the real foams.

The presented methodology has been implemented into a CAD tool consisting of a Matlab routine identifying the acceptable instances of the feature "pore" and a CATIA's macro modelling the closed cells foam.

A future work aims at analysing more deeply the CAD foam models here proposed. In particular, a comparison between the geometric parameters obtained by an image processing methodology on one slice of the tomographic scan and one slice of the CAD model will be performed. Moreover, a FEM analysis will be carried out on the CAD model in order to characterise the mechanical behaviour of the considered foams.

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