# On counting cells in open pore foams

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PAPER

# On counting cells in open pore foams

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## Abstract

The number of cells in a sample of an open pore foam is usually expressed as ppi (pores per inch), but it is not easy to deduce the total number of cells in a sample from this information. In this paper we derive a linkage between the cell number of a foam sample, the volume fraction of the solid and the mean thickness of its ligaments by means of computer simulations.

## 1. Introduction

Many works deal with geometric properties of open-pore foams, their description and estimation.

In [1], Jang *et al* depict individual ligaments and cells of open-pored polyester urethane open cell foams and aluminium open cell foams using x-Ray tomography. They examine several pores and ligaments and analyse them statistically, identify closed walls and find nodes in which more than three ligaments meet. Then, the authors model open-pored foams using the Kelvin Cells and the identified geometric parameters. They also consider isotropic random foam generated by Surface Evolver. With these models, they simulate the elastic properties of the computer models and find that they depend on geometric parameters of the samples.

Redenbach [2] models foams by means of random Laguerre tessellations using knowledge of the heterogeneity of cell shape and size, which are obtained with the help of the so-called sectional image processing chain. Finally, she examines her models with regard to E-moduli, effective heat conduction and acoustic absorption coefficients.

In [3] various methods of algorithmic foam generation are presented: Voronoi tessellations, Laguerre tessellations, Lattice Based Structures, Poisson Voronoi Tessellation, Hard-Core Voronoi Tessellation, Poisson Laguerre Tessellation, Laguerre Tesselation using random packings of balls, and the Random Pertubation of the Wearie-Phelan Foam. Numerous geometric parameters of the open-pored structures are investigated: shape factors, the number of nodes and the number of ligaments per unite volume, the number of the faces per unite volume, the middle total ligament length per unite volume, the surface area of cells per unit volume, the mean number of faces of a typical cell, the mean area of the faces of a typical cell, the mean surface area of a typical cell, the mean width of a typical cell, the mean volume of a typical cell and the mean ligament thickness.

In [4], de Jaeger *et al* analyse their self-produced metal foams by means of $\mu$CT, extract the classic parameters (porosity (greater than 0.88), surface-to-volume ratio, pore radii (elliptical shape), ligament lengths, ligament cross-sections) and derive further (less obvious) parameters (Heywood circularity factor, axial shape factor, etc.). Using this knowledge the authors build iterative orthotropic Kelvin cell foams and validate them against the actual real foams. The comparison parameters are porosity and surface-to-volume ratio. The agreement is very good.

In [5] Bock *et al* perform x-ray analysis of geometric properties and compare them with existing computer models. They determine the ligaments density (number of the ligaments per square meter), ligament thickness, ligament length, ligament orientation and the pore shape distribution.

In [6] the modeling method has great similarities with our filling algorithm [7]. The authors reproduce actual foams, which they take from the literature and for which there are experimental measurements, and then they perform CFD simulations (pressure drop) to validate their foam models with a very good agreement. They also perform simulations with tomographically reconstructed samples, and compare the results with those of

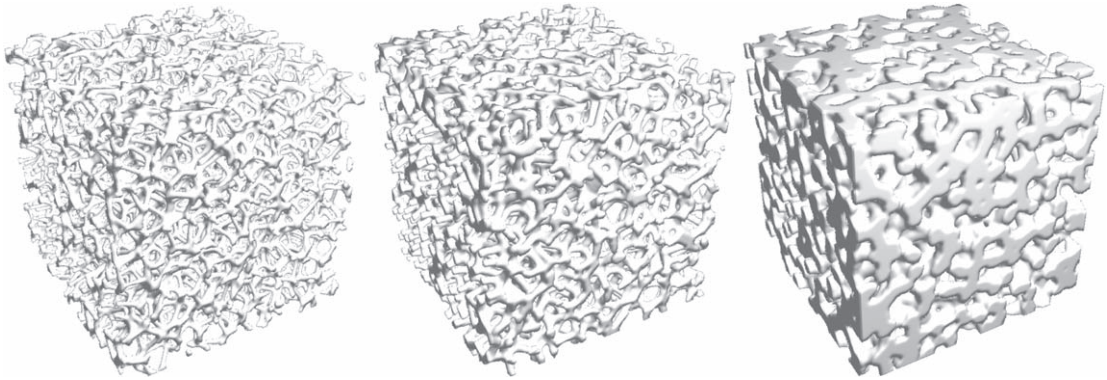

**Figure 1.** Synthetically generated open pore foam samples of the physical size $2 \times 2 \times 2$ cm$^3$, with pore radius and with ligament thickness of (a) 0.9 mm and 0.1 mm, (b) 0.9 mm and 0.2 mm, (c) 0.9 mm and 0.5 mm, respectively. The samples are produced by means of simulation software Pace3D [9] combined with algorithmic filling method described in [7].

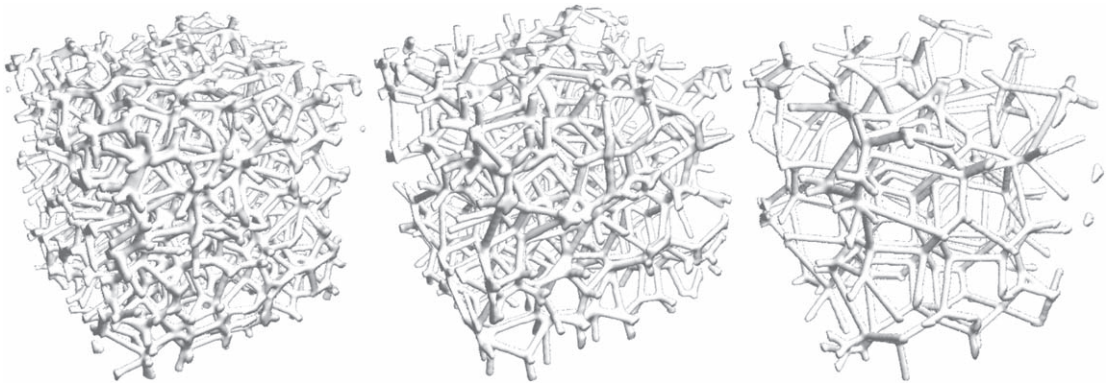

**Figure 2.** Synthetically generated open pore foam samples of the physical size $2 \times 2 \times 2$ cm$^3$, with pore radius and with the ligament thickness of (a) 1.5 mm and 0.2 mm, (b) 2.0 mm and 0.2 mm, (c) 3.0 mm and 0.2 mm, respectively.The samples are produced by means of simulation software Pace3D [9] combined with algorithmic filling method described in [7].

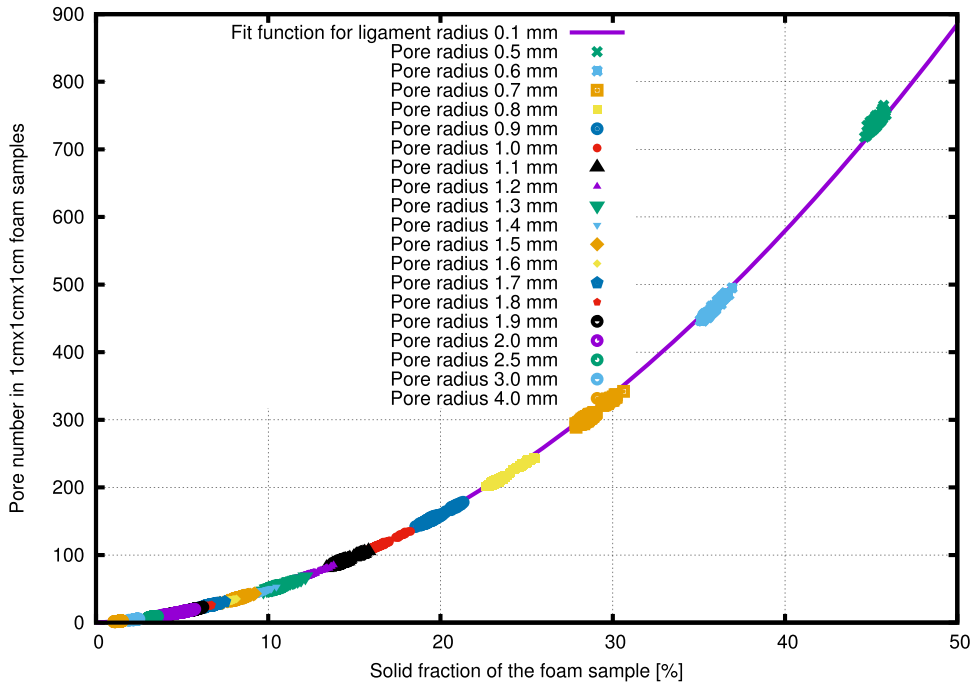


**Figure 3.** Pore number in open foam samples for ligament radius of 0.1 mm. Pore and ligament radii are input parameters and the pore number is an output parameter of our filling method.

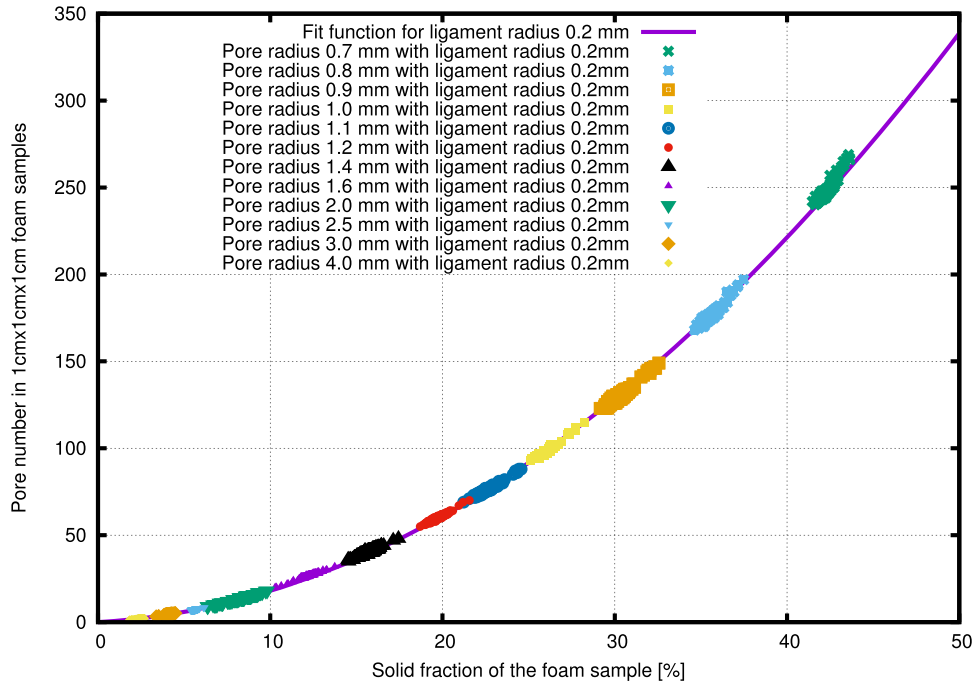


**Figure 4.** Pore number in open foam samples for ligament radius of 0.2 mm. Pore and ligament radii are input parameters and the pore number is an output parameter of our filling method.

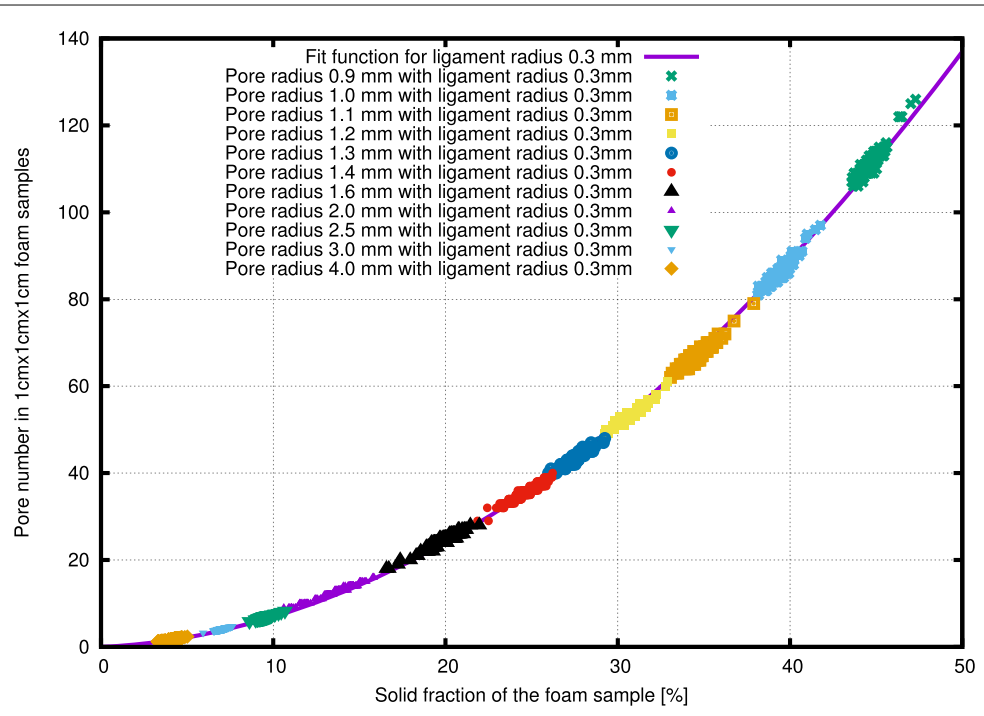


**Figure 5.** Pore number in open foam samples for ligament radius of 0.3 mm. Pore and ligament radii are input parameters and the pore number is an output parameter of our filling method.

algorithmic models, again with a very good agreement. They also compare the specific surface of their own algorithmic and experimental models. They again identify quite a good match.

High resolution x-ray microtomography is used in [8] for the characterization of pore structure and effective thermal conductivity of iron ore sinter.

But no source known to us presents a method for estimating the *number of the cells* in a open pore foam sample.

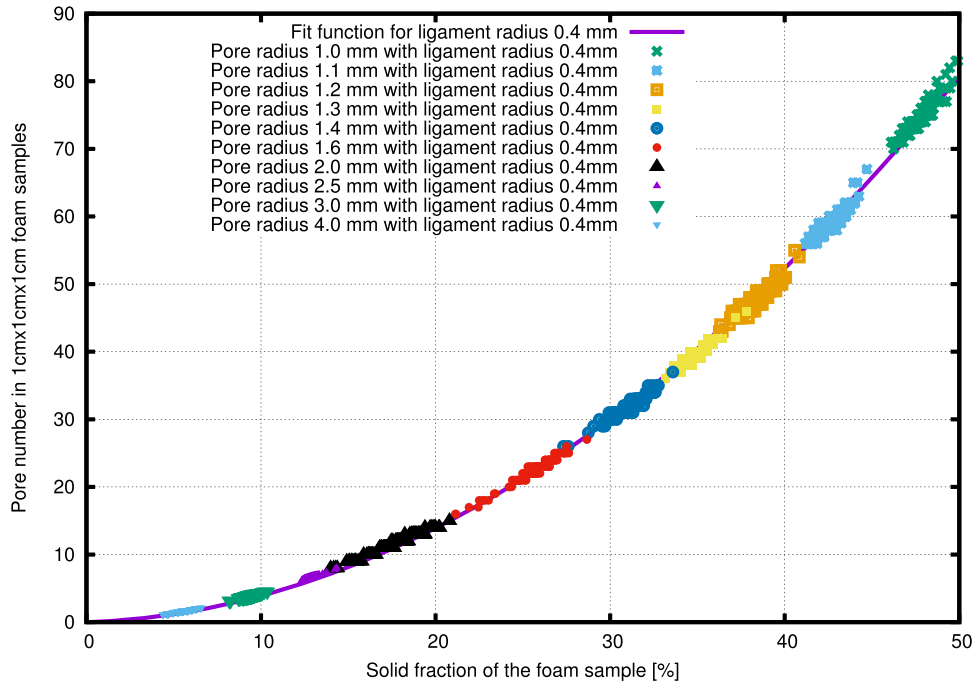


**Figure 6.** Pore number in open foam samples for ligament radius of 0.4 mm. Pore and ligament radii are input parameters and the pore number is an output parameter of our filling method.

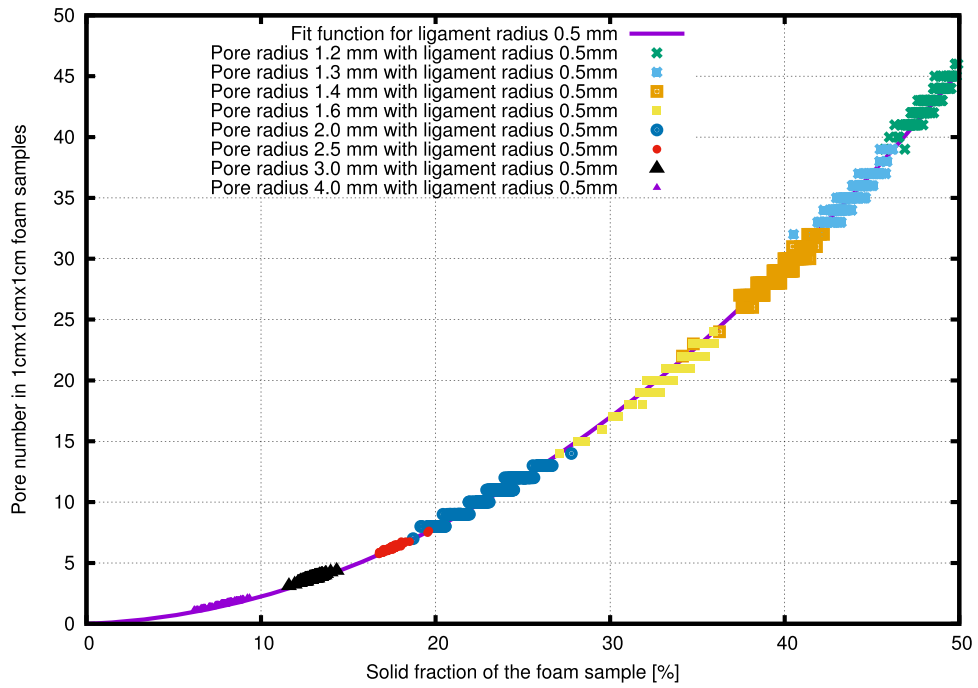


**Figure 7.** Pore number in open foam samples for ligament radius of 0.5 mm. Pore and ligament radii are input parameters and the pore number is an output parameter of our filling method.

Usually, the number of the pores in a volume is a quantity difficult to estimate. Instead, the volume fraction of the solid and the thickness of the ligaments are often experimentally known and measurable parameters of a foam. In our preliminary article [7], a method to create synthetic open porous structures is presented by setting geometrical parameters such as the mean pore radius, the mean ligament radius and by controlling the volume fraction of the solid. This algorithm automatically evaluates, how many pores are randomly set in the domain for

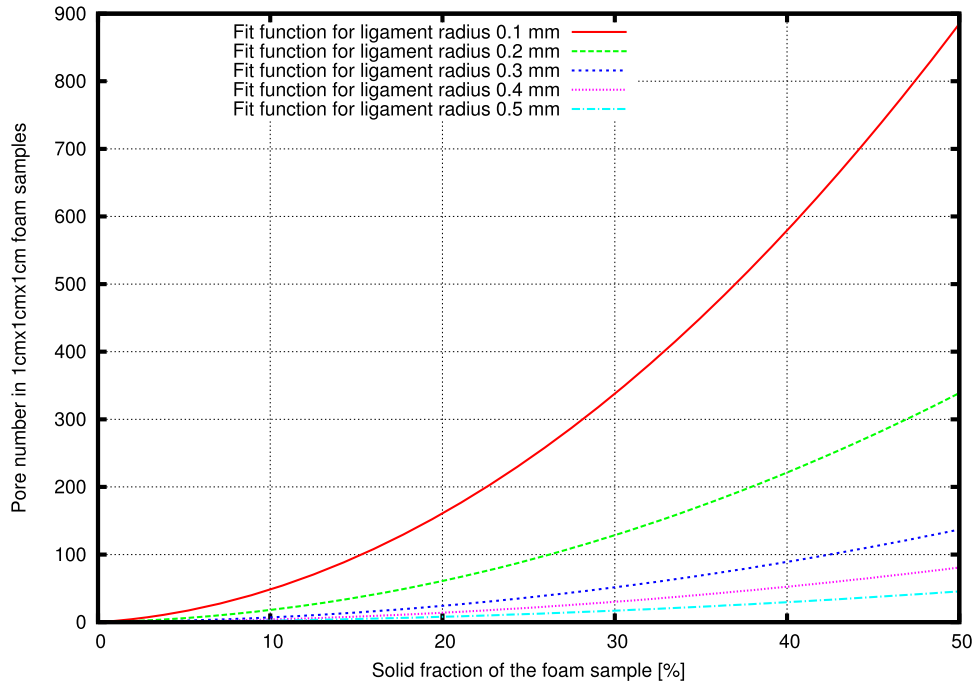


**Figure 8.** Fitting functions for the dependence of pore number in open foam samples on the volume fraction of the solid for five different ligament thicknesses. The fitting function is given in equation (1).

the defined geometric input parameters. Also the volume fraction of solid can be determined by means of a post-processing tool.

Using this filling algorithm we generate several hundreds of open cell structures and investigate the dependence of the number of pores in a fixed volume element on the ligament thickness and on the volume fraction of the foam specimen. This allows the derivation of a mathematical expression for the correlation of these three quantities (equation (1)).

## 2. A method to create synthetic open pore foam structures

Our algorithm to create random synthetic pore structures is described in detail in [7], which is embedded in the simulation software Pace3D [9]. We briefly outline the main steps: first, imaginary pores of a given radius are set in a domain randomly but as compactly to each other as possible. Their imaginary centers are the network of outlets for the Voronoi decomposition of the domain. The edges of the Voronoi polygons are then thickened to the diameter $2l$ modeling the ligaments of the open cell structure. The algorithm automatically establishes the pore number set in the domain.

## 3. Results on pore number determinations

We choose several combinations of the pore radius (0.7 mm ... 4.0 mm) and ligament radius (0.1 mm ... 0.5 mm) and analyse up to 900 computational samples.

Examples of generated structures are shown in figures 1 and 2.

pore foam samples of the physical size $2 \times 2 \times 2$ cm$^3$, with pore radius and with the ligament thickness of (a) 1.5 mm and 0.2 mm,

Figures 3–7 illustrate the dependence of the pore number on the solid fraction in the domain for five ligament radii of respectively 0.1 mm, 0.2 mm, 0.3 mm, 0.4 mm and 0.5 mm. Pore and ligament radii are input parameters for the filling algorithm we use to create the samples. The pore number is an output value of the creation procedure. All five functions for the dependence of the pore number on the solid fraction are comprised in figure 8.

The constructed function in figures 3–7 is based on the fitting function $f(x) = ax^2 + bx$. Figure 9 displays the coefficients $a$ and $b$ for the five values of the ligament radii. They can be fitted by $Ae^{Bx}$. The fitting functions were found using the command line program gnuplot, which in turn uses the nonlinear least-squares (NLLS) Marquardt-Levenberg algorithm [10]. All in one the number of $N$ pores in a 1 cm$^3$ can be calculated by means of:

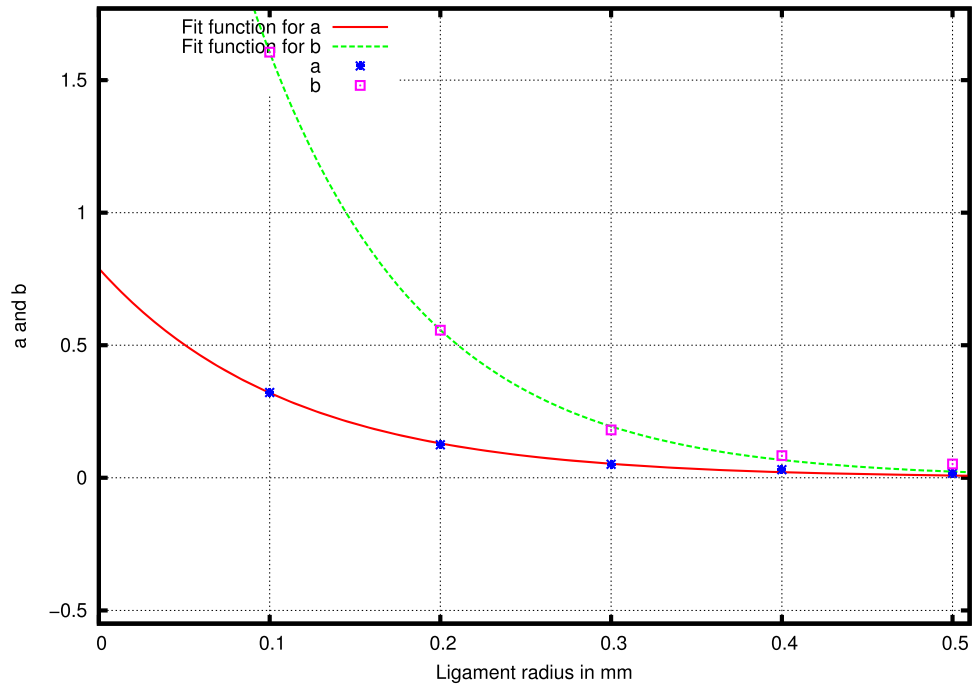


**Figure 9.** Fitting functions for the coefficients a and b in the ansatz function $f(x) = ax^2 + bx = 0.789\exp(-9.021l)x^2 + 4.613\exp(-10.562l)x$ like in equation (1).

$$N = 0.789\exp(-9.021l)s^2 + 4.613\exp(-10.562l)s, \tag{1}$$

where $l$ is the radius of the ligaments and $s$ is the solid fraction (in percent) of the foam sample.

## 4. Conclusions

In the present study, we derive a mathematical formulation to describe the quantitative dependence of the pore number on the two parameters: ligament thickness and the fraction of the solid.

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## Compliance with Ethical Standards

This study was funded by the Helmholtz Gesellschaft (EMR program at Karlsruhe Institute of Technology). The authors declare that they have no conflict of interest. Our research didn't involve human participants or animals.

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