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Influence of the cell geometry on the tensile strength of open-cell ceramic foams

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Abstract

Nowadays used open cell foam ceramic materials are mostly of irregular structure which means that the shape of particular foam cells does not exhibit any regular pattern. On one hand, such foam structures lead to only very slight anisotropic or even isotropic behavior upon the mechanical loading, but on the other hand they do not have an optimal resistance to failure upon given loading conditions and level of porosity. The strength of the ceramic foam structure can be thus further improved by design of cells having various regular shapes. Such foams can finally exhibit an orthotropic behavior from both the elastic and strength point of view. To understand how different types of cells influence the foam characteristics in various directions, foam structures with various cell shapes were thus studied and investigated in terms of their tensile strength within this contribution. The structures were modelled by means of beam element based FE models and by utilization of the stress criterion defining failure of particular struts. Totally six different cell types were analyzed under consideration of the same porosity of the final foam structure and amount of the strength anisotropy was quantified. Relation between orientation of struts with respect to a loading direction and the foam strength was discussed in more details. Recommendations for an employment of particular cell types for specific loading conditions were given.

Keywords: ceramic foam; Kelvin cell; Voronoi tesselation; tensile strength; FE model

1. Introduction

Open cell foam ceramic materials are nowadays widely used in various lightweight, high temperature or filtering applications but still not very often in mechanically loaded applications due their relatively low resistance to failure.

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Nomenclature

a	dimensions of the FE model
D_C	cell size (diameter of the sphere inscribed in the cell)
D_S	strut diameter
E_{bulk}	Young´s modulus of the bulk ceramic
F_{fr}	applied force upon the foam failure
u_i	displacement in the direction of the coordinate system axes (i=x,y,z)
x, y, z	Cartesian coordinate system axes
φ_i	rotational degree of freedom on the nodes of the beam elements (i=x,y,z)
ν_{bulk}	Poisson´s ratio of the bulk ceramic
σ_c	tensile strength of the bulk ceramic material
σ_{fr}	apparent failure stress of the foam structure

Most of these structures are composed of cells having irregular shapes coming mostly from the processing technology (e.g. the replica method). Thanks to a significant development in the field of additive manufacturing it is however possible to prepare ceramic foam structures also by 3D printing technology where arbitrary shape of particular cells can be prepared. Such technology enables thus to design foams with significantly better mechanical properties (including tensile strength) than the currently used irregular foam structures. An example of possible designs of open cell foam structures is shown in Fig. 1. These designs will be also further investigated within this work.

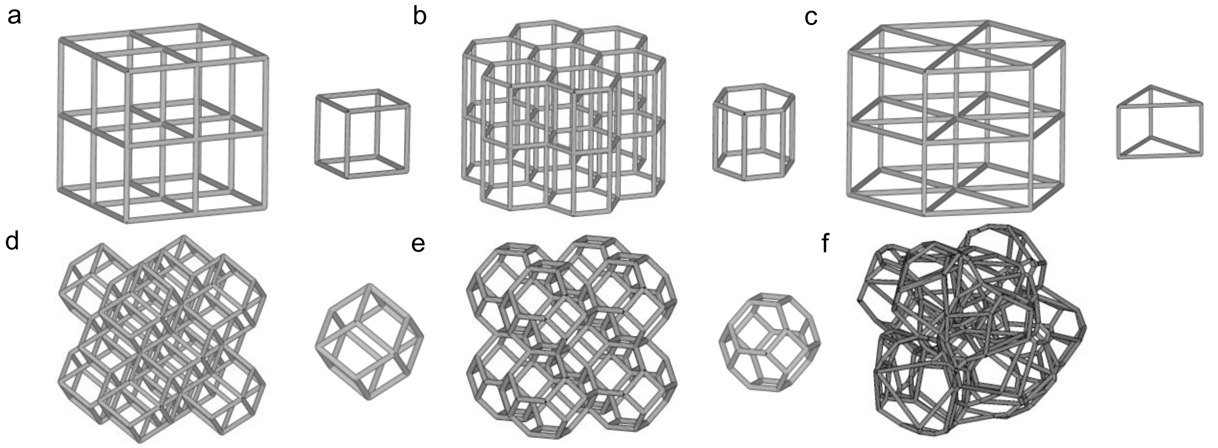

Fig. 1. Analysed shapes of cells within the open-cell foam structures: (a) cubic, (b) hexagonal prism, (c) triangular prism, (d) rhombododecahedral, (e) tetrakaidecahedral (Kelvin cell), (f) irregular.

Understanding and prediction of fracture of such foams under various loading conditions is thus essential to enable their employment in mechanically loaded applications. In the first approximation, the mechanical strength of these structures can be roughly estimated using relations presented e.g. by Gibson and Ashby (1999), Fleck and Qiu (2007), Romijn and Fleck (2007), Quintana Alonso and Fleck (2007) which were mainly derived for simple 2D or 3D foam structures with regular cell pattern. Another potential and more precise way how to estimate the strength of the open cell foam structures is to use their 3D Finite Element (FE) models based on the beam elements (representing particular struts) which can take into account the real size of the specimen, real average cell size or strut thickness, eventually also shape of the strut cross-section. Such an approach can be found e.g. in Ševeček et al. (2019), Jin and Wang (2012), Ševeček et al. (2017) or Ševeček et al. (2018). Its main advantage lays in still relatively low computational costs when also bigger foam volumes are assessed (since each strut is represented usually just by one or few beam elements). The simplest condition for the definition of the strut failure is the stress condition defining failure of the corresponding strut when the maximum tensile stress on it exceeds the tensile strength σ_c of the material. It was shown that even this simple method provides relatively good approximations of the foam tensile strength predictions in comparison with experimental observations Ševeček et al. (2019).

Main aim of this paper is to utilize the above mentioned modelling method to analyze the influence of geometry of cells shown in Fig. 1 on the mechanical strength of open cell foam structures composed of these cells. The foam strength will be studied in various directions in order to characterize the level of anisotropic response of particular cells. Obtained results will help to find a design of the most suitable foam structure for a given mechanically loaded component having a desired reliability.

2. Numerical simulations

2.1. FE model

Foam structures with various shapes of cells shown in Fig. 1 were created using the Voronoi tessellation technique in mathematical software MATLAB and then exported into the FE system ANSYS. Here, particular struts were meshed using beam elements. An approach for modelling of foam structures based on beam elements (already presented in previous work of authors - Ševeček et al. (2019)) was employed. Namely, each strut was modelled using three beam elements. At the ends of each strut rigid beam elements MPC184 of length $0.3D_s$ (strut diameter) were used in order to correctly capture the stiffness of the connection of multiple struts in one node. The central part of the strut was modelled using standard quadratic beam elements BEAM183 with 6 degrees of freedom in each node. More details about this modelling approach can be found in the above mentioned reference. To investigate the tensile strength, a cubic model of size 10x10x10mm (Fig. 2a) with inner foam structure shown in Fig. 2(b)-(g) was employed. Dimensions of each cell within this model were defined by a sphere of a unit diameter D_c=1mm inscribed in this cell. Diameter of struts D_s was set so as to obtain total porosity of the foam structure of 85% in all cases depicted in Fig. 1. The porosity of 85% corresponds to the porosity of available (irregular cell) ceramic foam specimens prepared by the replica method from VUCOPOR®A material. The whole model was always clamped on one side and on the opposite side displacement load in z (eventually x and y) direction was applied – see defined boundary conditions in Fig. 2(a).

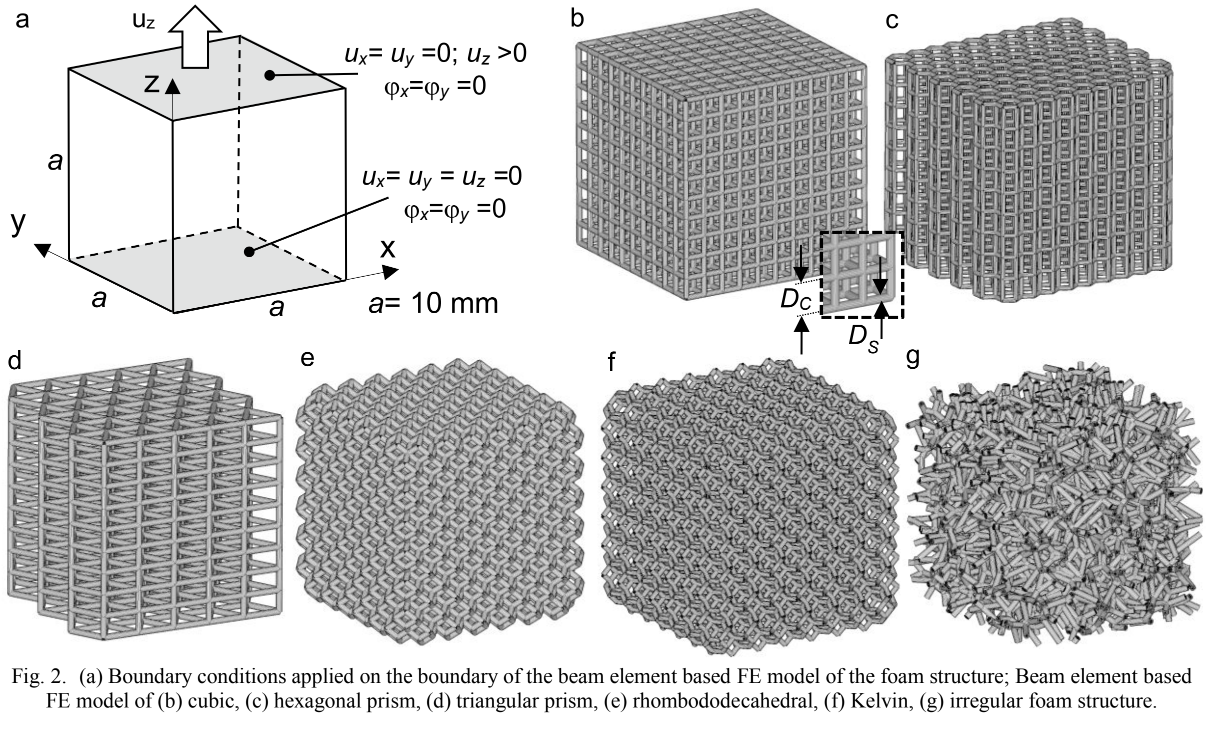

Fig. 2. (a) Boundary conditions applied on the boundary of the beam element based FE model of the foam structure; Beam element based FE model of (b) cubic, (c) hexagonal prism, (d) triangular prism, (e) rhombododecahedral, (f) Kelvin, (g) irregular foam structure.

The Young's modulus of the ceramic material was considered to be E_{bulk}=90 000 MPa, Poisson´s ratio ν_{bulk}=0.25 and tensile strength of the bulk material σ_c=60MPa (which all corresponds to a "VUCOPOR®A" - Al_2O_3 based ceramic foam) – see Ševeček et al. (2019). The created models were formed of 2k-14k struts (depending on the type of the structure shown in Fig. 2(b)-(g).

2.2. Simulation of the tensile test – determination of the tensile strength

In order to determine a tensile strength or, in other words, the critical applied force leading to breakage of the specimen, a stress criterion, deciding about failure of particular struts, was employed. The model was subjected to stepwise displacement load (in *z, x* and *y* direction) and in each loading sub-step the stress conditions in all struts were monitored. In case when the tensile stress on the strut surface exceeded its critical value (in our case corresponding to the strength of the bulk ceramic σ_c=60MPa) the corresponding element of the strut was removed and a new FE solution with the same applied load was performed. If there were, within the next simulation step, no struts with stresses higher than σ_c, the applied displacement was increased and the whole procedure repeated. Such a simulation process was iterated until the whole foam structure was divided into 2 pieces or at least until that moment when the reaction force at top nodes of the model started to drop (which indicated that the tensile strength of the foam structure was attained) – for more information see Ševeček et al. (2019). An example of the final fracture surface obtained on the beam element based model of the rhombododecahedral and irregular foam structure is shown in Fig. 3(a)-(b). The amount of broken struts was around 490 in case of the irregular foam structure and around 540 in case of the Kelvin cell structure. These numbers correspond also approximately to the amount of simulation steps which had to be performed to receive final fracture surface and whole loading curve shown in Fig. 3(c). The graph in Fig. 3(c) shows typical loading curves obtained from the tensile test simulation (again for the case of rhombododecahedral and irregular foam mesh). Namely, it is the total reaction force in top nodes calculated for a given displacement load. One can also observe in this graph that the irregular foam structure is almost 3 times stiffer than the rhombododecahedral upon consideration of the same level of porosity of both meshes (85%). This can be explained by a presence of large amount of short struts which makes the nodal points of the foam structure stiffer and also by presence of struts oriented in various direction (in case of the rhombododecahedral mesh all struts are inclined by 45° with respect to the loading direction).

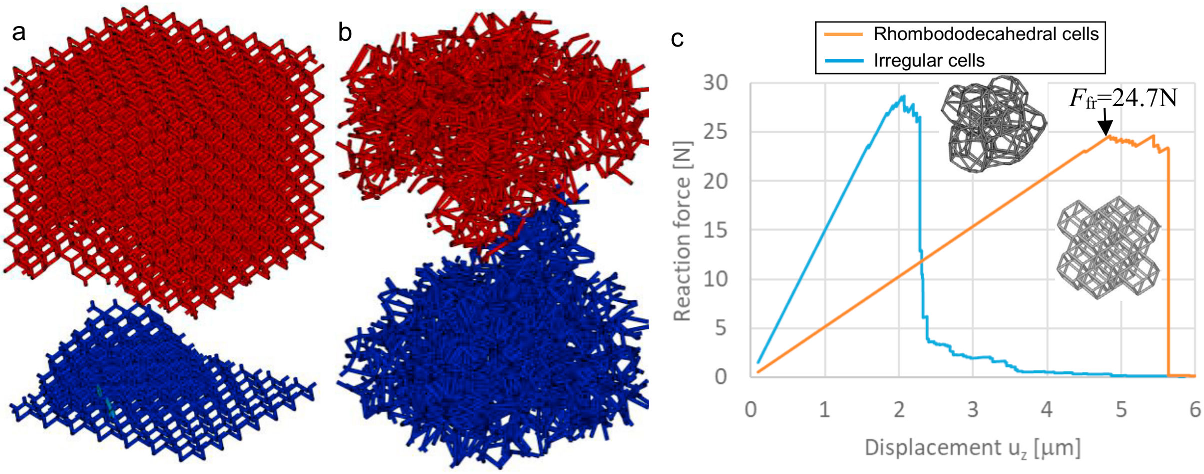

Fig. 3. Examples of the final foam fracture after the whole iterative simulation process for the case of (a) rhombododecahedral foam structure and (b) irregular foam structure; (c) example of the *F*(u) loading curves for rhombododecahedral and irregular foam structure obtained from the FE simulation.

3. Results and discussion

The graph in Fig. 4 shows results of the normalized tensile strengths calculated for all investigated foam structures shown in Fig. 2 by means of the uniaxial tensile test simulation described in the previous section (and performed for an uniaxial loading of the foam structure in *x*, *y* and *z* axis). For easier comparison of strengths of particular cell shapes, all tensile strengths were divided by the minimal tensile strength determined on the rhombododecahedral mesh which was, for the geometry shown in Fig. 1(d) or Fig. 3(a), determined to be $F_{fr}= F_{fr,min}$=24.7N (see Fig. 3(c)). In terms of stress (related to the model cross-sectional area) has the tensile strength of rhombododecahedral mesh value of $\sigma_{fr}=\sigma_{fr,min}=F_{fr,min}/S$=0.247 MPa (for specimen cross-sectional area $S=a \cdot a=10 \cdot 10=100\text{mm}^2$ – see Fig. 2(a)).

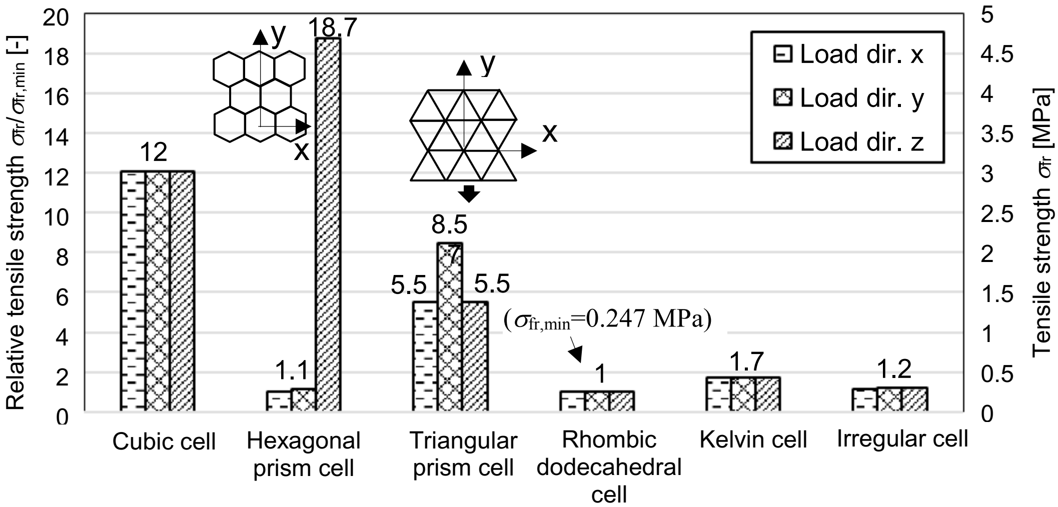

Fig. 4. Comparison of the relative tensile strength of all investigated foam structures in directions of the Cartesian coordinate system axes. The values of tensile strengths are normalized by the minimal tensile strength determined on the rhombododecahedral cell foam structure.

By qualitative comparison of all investigated structures (having always the same porosity 85%) it was found that the highest resistance to uniaxial mechanical load is obtained in case of foams having most of struts oriented in the loading direction so that primarily pure tensile mode is induced on them (which is a case of cubic and hexagonal cells in the *z*-direction). The cubic mesh exhibited the same mechanical strength in all 3 principal axes while the hexagonal mesh had significantly lower fracture resistance in *x* and *y* direction (due to presence of inclined struts in *x* and *y* direction). On the inclined struts of the foam structure bending loading is induced which leads to significantly higher surface stresses (responsible for a strut failure upon lower applied load) in comparison with struts loaded by pure tension upon the same external load. The only exception is the triangular prism cell which exhibits higher strength even when it is loaded in the (*y*) direction where inclined cells are present – as shown in Fig. 4. The reason for such behaviour is the fact that the inclined cells lays only in the plane *xy* and form a truss structure on whose struts just pure tensile or compressive loading occurs (in other words, no bending component on struts due their special formation in the *xy* plane is present).

One has to note yet that all the investigated foam structures were loaded and analysed always in the direction of main principal axes *x*, *y* and *z* (see Fig. 2). Nevertheless, some of the structures (such as the cubic cell mesh) can exhibit significantly lower strength when they are loaded in other direction than the principal one (since the struts will become subjected to bending and not only to a pure tension). The cubic structure is thus suitable only for cases where the loading is oriented always in the direction of principal axes. In that case the strength of the cubic structure is approximately 12 times higher than of the rhombododecahedral cell mesh (upon the same foam porosity) which is a significant difference. If just a uniaxial loading is expected within the designed component, the most fracture resistant foam upon the given porosity is the hexagonal prism foam (in the direction *z* - perpendicular to a hexagon plane). On the other hand, the triangular prism cell mesh is the best option for structures where loading direction may vary during operation. The strength of the rhombododecahedral, Kelvin and irregular cell mesh is the lowest (due to absence of struts oriented in the direction of loading and due to a presence of inclined struts), but their strength can be considered to be more or less isotropic (not directionally dependent).

4. Conclusions

Based upon the 3D FE beam element based model the tensile strength of open cell foam structures was investigated for various shapes of cells. The tensile strength was evaluated in different directions since some of the cell shapes exhibit anisotropic behavior. The size of all studied shapes of cells was designed so that the inscribed sphere in each cell had a unit diameter and the cross-sectional area of struts was set so that the final foam structure had always the same porosity. Failure of struts upon the mechanical test simulation was modelled by employment of the stress criterion. Namely, the strut was considered to fail when the maximal tensile principal stress on it exceeded the tensile strength of the material. Using the iterative simulation procedure, the complete force displacement curve of the tensile test was obtained. The maximal peak of this curve determines the strength of the foam structure. By qualitative comparison of all investigated structures it was found that the highest resistance to uniaxial mechanical load is obtained in case of foams having most of the struts oriented in the direction of the loading so that primarily the tensile loading is induced on them. The foam structures with inclined struts are less resistant to fracture since bending components and thus higher tensile stresses on their surface are induced. The only exception was the triangular prism cell which exhibit relatively high strength also in a direction where inclined struts are present. For the purely unidirectional loading the foam with highest fracture resistance is the hexagonal prism foam, nevertheless its strength in other two directions is significantly lower and is thus not suitable for multiaxial loading. The best option for the orthotropic tri-axial loading is the cubic foam mesh where the strength in all three principal directions is the same and approximately twelve times higher in comparison with the weakest rhombododecahedral mesh. More or less isotropic, but significantly lower strength has the Kelvin, irregular and rhombododecahedral mesh.

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