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Analytical study of structural thermal insulating syntactic foams

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ABSTRACT

Syntactic foams composed of a resin matrix and hollow glass spheres represent one viable solution for structures requiring both enhanced structural and thermal insulation properties. Designing syntactic foams with both high strength and thermal insulating properties is difficult since these two properties are inherently in opposition to one another. As a result, it is critical to systematically select matrix and particle materials and volume fractions of each, which will result in acceptable strength and thermal properties. The focus of this research is to investigate the effects of sphere particle packing and size distribution on effective thermal conductivity, strength, and stiffness of syntactic foams. The analysis is performed through finite element thermal and stress analysis of various sphere packing and size distributions under several particle-to-matrix conductivity and stiffness ratios. The results show the effective thermal conductivity predictions to be relatively independent of packing and size distribution while predicted strength and stiffness properties show a greater dependence on packing and size distribution, particularly for high particle-to-matrix stiffness ratios.

1. Introduction

Lightweight structural thermal insulating composites have a number of applications in space and deep sea exploration as well as aerospace, marine, and civil infrastructure. Syntactic foams represent one viable composite solution for structures requiring both enhanced structural and thermal insulation properties.

Syntactic foams consist of filler particles in a continuous matrix to enhance the thermal and/or mechanical properties. These properties include density, stiffness, strength, toughness, coefficient of thermal expansion, and conductivity. In recent years syntactic foams composed of hollow glass spheres in a polymer resin matrix have gained considerable attention due to their high compressive strength [1], high insulation properties [2], and high-energy absorption [3], leading to their use in the aerospace [4] and marine [5] industries. The composite nature of syntactic foams allow for thermal and mechanical properties to be tuned by varying the type and volume fraction of particles [6–9].

Designing syntactic foams with both high strength and thermal insulating properties is challenging since these two properties are inherently in opposition to one another. As such, it is critical to systematically select particle and matrix materials and volume fractions of each, which will result in desired thermal and mechanical properties. To aid in design of syntactic foams a number of "closed form" analytical models have been developed to predict the effective thermal conductivity (ETC) of syntactic foams [2,9–11]. Although these models have shown good results with specific experimental measurements at less than 40% volume fraction of spheres, none of the models relate well over a large range of filler particle-to-matrix thermal conductivity ratios. Most existing analytical models are limited to two dimensions and consider only a single sphere in a unit cell, thus limiting the volume fraction of spheres to 52%. For example, a model which correctly predicts ETC for an aluminum/epoxy syntactic foam cannot accurately predict a glass/epoxy foam due to the large difference in particle-to-matrix thermal conductivity ratios (1833 and 4.3 respectively). Fig. 1 gives the difference in ETC results for five analytical models between the two particle-to-matrix thermal conductivity ratios mentioned. Each of the four literature models [12–15] predict higher ETC values than the series model, with the results widely varying between the two thermal conductivity ratios.

Many analytical models [16–20] have also been developed to predict the strength of syntactic foams based on particle geometry and constituent material properties. Most of these models are either limited to two dimensions or are limited to a 52% volume fraction of spheres. Based on the deficits of these existing models this study investigates three-dimensional finite element (FE) modeling based on RVEs with various sphere size distributions and packing geometries to more fully capture the physical geometry of syntactic foams.

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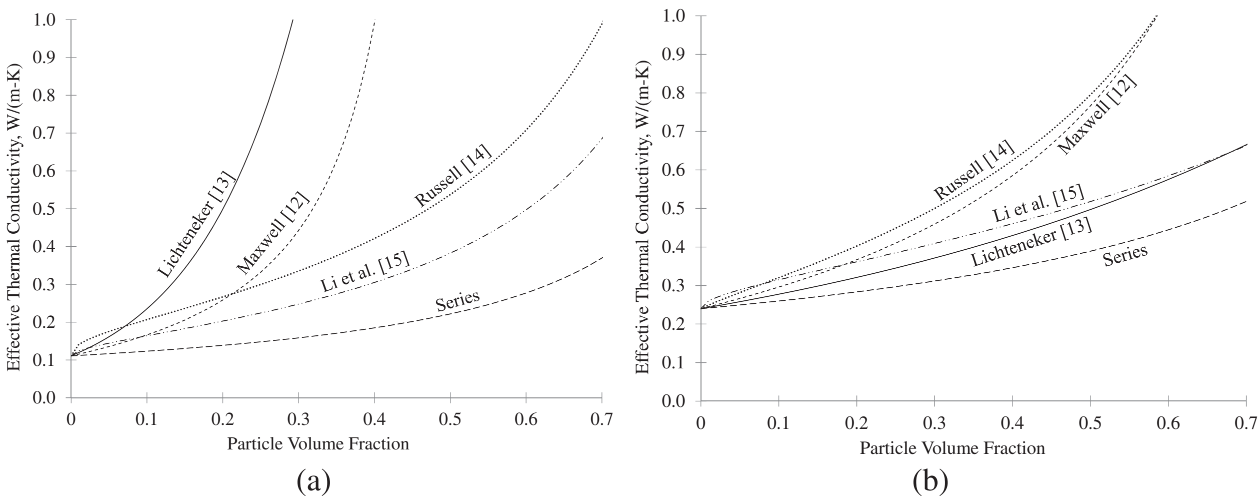

Fig. 1. Plot of ETC as a function of volume fraction for aluminum/epoxy and glass/epoxy foams with particle-to-matrix conductivity ratios (a) 1833 and (b) 4.3.

The primary objective is to investigate the effects of hollow glass sphere particle packing and size distribution on ETC, strength, and stiffness of syntactic foams over a range of sphere loadings from 0% to 70% by volume and various particle-to-matrix conductivity and stiffness ratios. This study is limited to constant material properties and does not consider the dependence of material properties on temperature.

2. Modeling

Based on the limitations of previous models to accurately predict ETC and mechanical properties (strength and stiffness) over a broad range of particle and matrix properties, this study uses full three-dimensional thermal and stress analysis based on the finite element method to predict ETC and mechanical properties. The study considers three different hollow glass sphere packing geometries and size distributions within an RVE. An illustration of the three RVE configurations is given in Fig. 2. The configurations consist of (a) a single sphere in a unit volume having a maximum particle volume fraction of 52%, (b) a single center sphere with smaller spheres in the corners resulting in a maximum particle volume fraction of 72%, and (c) a single center sphere and corner spheres with additional smaller spheres along the edges, leading to a maximum volume fraction of 74%. In order to maintain the RVE symmetry, all three RVEs use square packing arrays.

The RVE finite element models were created in Abaqus/CAE 6.12 with tetrahedral elements where mesh refinement was performed until convergence was reached for both stress and heat flow. The models are based on the following assumptions [21]:

1. The syntactic foam is globally homogenous.
2. The matrix and particle constituent materials are locally isotropic.
3. The matrix is free of voids.
4. The RVE is located in an infinitely symmetric, square packing array (Fig. 2).

The hollow glass spheres considered in this study are 3M™ K11 Glass Bubbles, which consist of a range of sphere diameters from 30 to 110 μm. Based on the effective density information provided by the manufacturer the shell thickness for each sphere diameter was determined. A summary of the sphere geometries for each model configuration is presented in Table 1, where the radius (Rad.) and shell thickness (Th.) of each sphere are given. Referring to Fig. 2d, spheres 1, 2, and 3 are the center, corner, and edge spheres respectively. As seen in Table 1, a total of 22 thermal and mechanical models were created to study each of the configurations over the specified volume fraction range at volume fraction increments of 0.1.

2.1. Thermal Modeling

To determine the effects of sphere size distribution and packing on calculated ETC values, a thermal analysis was completed using three-dimensional heat transfer FE analysis. Heat transfer occurs through conduction, radiation, and convection; however, previous work by Skochdopole [22] as well as Stark and Frick [23] has shown convection to have negligible effects for hollow spheres with diameters less than 4 mm and foams with porosities less than

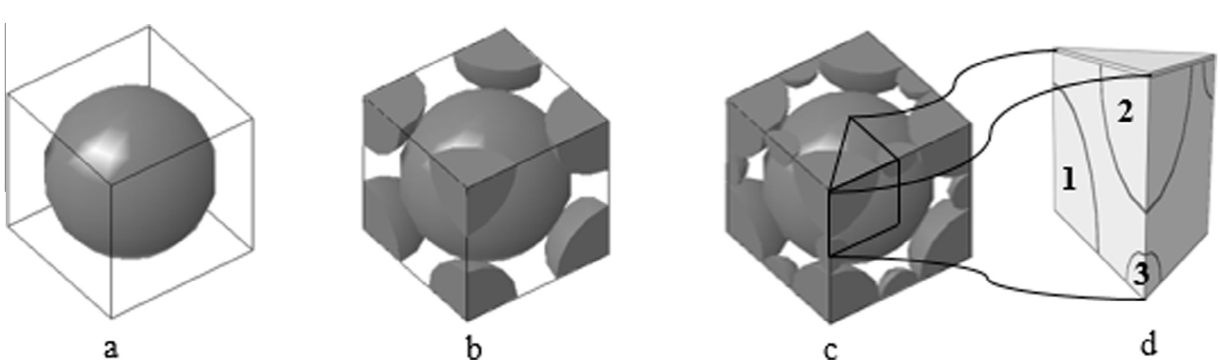

Fig. 2. RVE geometries including: (a) a single sphere, (b) two sizes of spheres, (c) three sizes of spheres, and (d) the 1/16 RVE used in finite element analysis.