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Effective conductivities and elastic moduli of novel foams with triply periodic minimal surfaces

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ABSTRACT

Triply periodic minimal surfaces (TPMS) are employed to create novel cellular materials. They include Schwarz Primitive, Schoen IWP, Neovius, Schoen Gyroid, Fischer-Koch S, and Schwarz CLP geometries. Unit cells are studied using a finite element method with periodic boundary conditions in order to predict effective electrical/thermal conductivities and elastic moduli of these TPMS-based foams. The conductivities vary linearly with relative density. The conductivities of the Primitive-, IWP-, Neovius-, Gyroid-, and S-foams are very close to each other. The conductivity of the CLP-foam needs to be described by two values because of its geometrical asymmetry while the other foams are found to be isotropic when their conductivities are studied. The uniaxial, shear and bulk moduli, Poisson ratio and elastic anisotropy of these TPMS-foams are also computed and compared. When the mechanical properties are investigated, the CLP-foam is found to have highest anisotropy among the considered TPMS-foams. In addition, the Primitive-foam possesses highest shear modulus while the Neovius, IWP-, and Primitive-foams possess highest bulk moduli among the TPMS-foams.

1. Introduction

The architecture of cellular materials affects their overall performance. Cellular materials are a class of materials that is characterized by low density and high specific properties (acoustic, electrical, thermal, and mechanical) (Torrents et al., 2012; Wadley, 2002; Gibson and Ashby, 1997). For example, architectures of cellular materials determine whether they deform in a stretching-dominated mode or a bending-dominated mode (Khaderi et al., 2014; Bauer et al., 2014). A stretching-dominated foam has a higher strength and stiffness compared to a bending-dominated foam with the same relative density (ρ) (Gibson and Ashby, 1997; Ashby, 2006).

In this paper, electrical/thermal conductivities and elastic properties (uniaxial, shear and bulk moduli, Poisson ratio and elastic anisotropy) of novel type of architectured foams are studied. The architectures of these foams are based on the mathematically-known triply periodic minimal surfaces (TPMS) (Al-Rub et al., 2015; Abueidda et al., 2015c; Yang et al., 2010; Chen et al., 2009; Jung and Torquato, 2005; Torquato and Donev, 2004; Dalaq et al., 2016). The TPMS possess a zero mean curvature; in other words, the sum of principal curvatures at each point on the surface is zero (Chen et al., 2009; Jung and Torquato, 2005; Torquato and Donev, 2004). The TPMS have potential of

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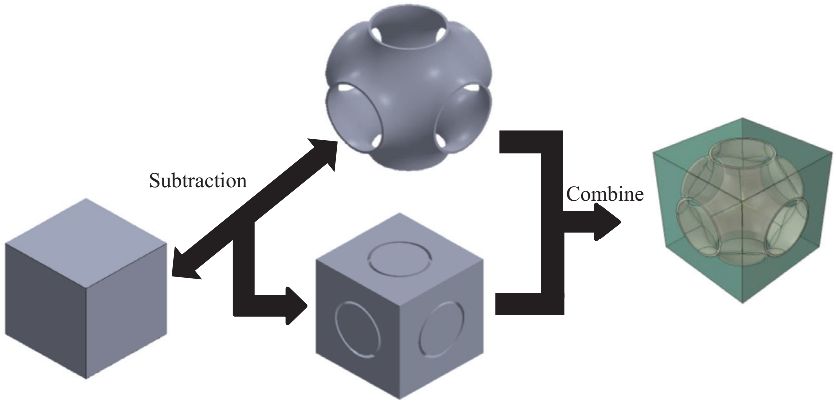

Fig. 1. Summary of method to create TPMS-IPCs.

being employed as lightweight materials for high end technological applications (Schoen, 1970). One common example of the TPMS in nature is a soap film in which the surface tension minimizes the energy of the film. That results in minimization of the surface area of the film and formation of the TPMS morphologies (Torquato and Donev, 2004). Furthermore, TPMS are found in biological systems such as weevils, butterfly and beetle shells (Schröder-Turk et al., 2011; Kapfer et al., 2011; Melchels et al., 2010; Galusha et al., 2008).

Researchers employed TPMS to create materials with enhanced and optimized properties (Torquato and Donev, 2004; Torquato et al., 2002; Kassner et al., 2005; Challis et al., 2008). More specifically, they used the TPMS to create multifunctional two-phase composites with 50% volume fraction of each phase. Moreover, several investigators utilized the TPMS to design and create biomaterials with enhanced properties (Kapfer et al., 2011; Melchels et al., 2010; Yoo, 2012, Yoo, 2011). Wang et al. (2011) studied the macroscopic stiffness, strength and energy dissipation of three bi-continuous composite structures that are based on three TPMS. Composites in literature that are based on TPMS are composites in which TPMS were used as surfaces that separate two phases of the composites (Torquato and Donev, 2004; Torquato et al., 2002; Kassner et al., 2005; Challis et al., 2008; Wang et al., 2011). The work of Jung and Torquato (2005), Torquato and Donev (2004) and Torquato et al. (2002) has focused on IPCs where the interface between two solid phases takes the geometry of TPMS. In another work by Torquato, the effectiveness of few TPMS architectures; namely, primitive, diamond, and gyroid surfaces, in enhancing transport properties has been investigated, but without changing the volume fraction of the solid phase. In this paper, the effects of several types of thickened TPMS architectures with various solid volume fractions (or equivalently various relative densities) on conductivity and elastic properties have been studied. Abu Al-Rub and co-workers utilized the TPMS in a different manner; the reinforcing phases are TPMS-sheets produced from thickening the TPMS while the reinforced phases are generated by subtracting the created TPMS-sheets from their bounding cubic box (Al-Rub et al., 2015; Abueidda et al., 2015c). Combining the reinforcing and reinforced phases forms the so-called interpenetrating phase composites (IPCs) whose periodic phases are interconnected and smoothly continuous. Fig. 1 summarizes the adopted methodology of creating the TPMS-IPCs. Abueidda et al. studied the electrical/thermal conductivities and coefficient of thermal expansion of the TPMS-IPCs and showed their superiority over other reported designs (Abueidda et al., 2015c; Abueidda et al., 2015b). Moreover, Abueidda et al. (2015a) studied the electrical conductivity of the TPMS-IPCs experimentally and investigated the effect of imperfect interface between the phases using a finite element method (FEM). In the present work, only the TPMS-sheets are generated in order to produce foams, and their thermal/electrical conductivities and elastic properties are studied using a finite element method. In this paper, the words sheet and foam are interchangeably used to describe the foams that are made of sheets with TPMS shaped surfaces. Most of the literature on periodic foams is based on lattice-type foams and not shell or sheet type foams which is the focus of the current study. In fact, one can only find in literature the works of the current authors on using thickened TPMS representing a continuous phase in a matrix material to make interpenetrating phase composites, which is different than the current work. This study focuses on creating foams through thickening different TPMS architectures. As emphasized, the previous work by the authors was revolving about the use of TPMS as interpenetrating phase composites whilst this manuscript studies them as foams. Finally, to the best knowledge of the authors, no previous studies are available in literature on quantification of the anisotropy (for both conductivity and elasticity) of TPMS-foams.

2. Architectures

In the present work, the TPMS are utilized as architectured sheets to create novel cellular materials as depicted in Fig. 2. The methodology used to create these foams is described in Abueidda et al. (2015c). By inspecting Fig. 2, one can observe that there are no joints and struts in the