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Analysis of a functionally graded particulate composite under flexural loading conditions

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Abstract

The conventional microstructures of functionally graded particulate composites are based on creating a gradient of either the particle volume fraction or the size along one dimension of the material. However, premature cracking and poor dimensional stability of such composites limit their applications. Hollow particle filled composites, called syntactic foams, present an opportunity to fabricate functionally gradient composites based on a new approach, which relies on creating a gradient of particles as per their wall thickness. The present study is focused on characterizing the functionally graded syntactic foams (FGSFs) based on this kind of structure for flexural properties. In previous studies the FGSFs based on wall thickness variation are found to have considerably higher energy absorption under compressive loading conditions compared to the FGSFs based on volume fraction variation. In this study the experimental results of flexural testing are compared with the theoretical and finite element analysis for both types of FGSFs. Results show that the flexural properties of FGSFs based on wall thickness approach can be controlled more effectively.

Keywords: Particulate reinforced composites; Foams; Fracture; Bending test

1. Introduction

Functionally graded materials (FGMs) are attracting considerable attention due to increasing performance demands in modern engineering applications. Such materials are also used in biomedical [1], sensor and energy applications [2]. FGMs contain either a gradual or a stepwise change in material properties along a given direction. In particulate composites a graded structure can be obtained by either changing (a) the particle volume fraction (V_p) or (b) the particle size along the thickness of the composite [3,4]. In these studies, the FGMs have shown improved mechanical properties compared to their homogeneous counterparts. However, the improvement in mechanical properties is achieved at the expense of dimensional stability at varying temperature and moisture conditions. Gradients in the matrix volume fraction (V_m) and matrix–particle interfacial area can lead to warping, localized swelling, and interfacial fracture when these composites are subjected to high temperature or moisture conditions. Hence, a new approach, which is independent of V_p or size gradient, is required to overcome these limitations.

Hollow particle filled composites, called syntactic foams, are also found studied for functionally graded structure [5,6]. Experimental investigations have revealed that epoxy matrix functionally graded syntactic foams (FGSFs) based on microballoon volume fraction (V_{mb}) variation suffered from early crack initiation under compressive loading conditions. Similar effects were observed under high strain rate deformation. Low fracture strain for the epoxy rich zone causes a constraint on applications and needs further improvement. Hence, the existing two FGM microstructures are not acceptable in several applications. A third possibility exists for creating functionally gradient structure in syntactic foams, which is largely unexplored until recently. The new approach is based on creating a gradient of particle as per their wall thickness [7,8]. Since this approach is independent of volume fractions, the dimensional stability will be better for such composites.

Syntactic foams have been extensively studied for mechanical properties and fracture behavior under compressive [9–11], tensile [12,13], flexural [14–17] and dynamic loading [18–20].

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In these studies it is observed that the compressive fracture of syntactic foams depends on the properties of microballoons, whereas the tensile fracture depends primarily on the properties of the matrix material. The tensile and compressive strength and modulus are found to increase with an increase in the foam density (or decrease in porosity), which can be achieved by either decreasing V_{mb} or increasing the microballoon wall thickness (ω) [7]. The ω is defined as

$$\omega = r_o(1 - \eta) \quad (1)$$

where r_o is the outer radius of microballoons. The parameter η, termed as radius ratio, is defined as [10]:

$$\eta = \frac{r_i}{r_o} \quad (2)$$

where r_i is the inner radius of microballoons. Experimental and finite element studies are available that relate r_o and r_i to the mechanical properties of microballoons [21,22].

Studies on three-point bend tests have been conducted in either flexural [14,23] or short beam shear test configurations [15–17]. In addition, fiber reinforced syntactic foams [24–26] and syntactic foam core sandwich composites have also been studied for bending properties [27]. Several studies on fracture toughness of syntactic foams have tested pre-cracked specimens under three-point bend conditions [28–31]. It was observed that the flexural strength, stiffness and modulus increase with the use of higher wall thickness microballoons in the same volume fraction [14]. The load–displacement curves for plain and particulate reinforced syntactic foams showed considerable variation in the fracture strain in this study. Such an observation was attributed to the presence of matrix porosity, and possibility of having localized compositional variation in the specimens. Crack initiation can be very sensitive to such localized inhomogeneities. The study on the short beam shear strength also showed that the strength of syntactic foams increases as their density increased [16].

The FGSFs based on V_{mb} and η variations, termed as VF- and RR-type, respectively, are fabricated in this study in a layered structure. In the earlier study compressive properties of such FGSFs were characterized and RR-type FGSFs were found to have three to five times higher energy absorption compared to the VF-type FGSFs [7]. The present study is focused on characterizing both types of FGSFs under three-point bend conditions. The FGSFs are analyzed by means of theoretical and finite element analysis and the results are compared with the experimental results.

Syntactic foams are widely used as core materials in sandwich structured composites for structural applications, where flexural properties are important. Hence, characterization of flexural properties and understanding the deformation process under such loading condition is important. Increasing interest of the aerospace industry in lightweight and highly damage tolerant materials is a motivation for developing variations of these materials with enhanced performance levels [32–34].

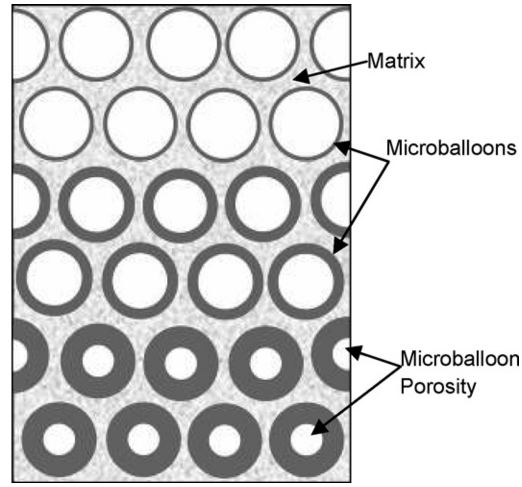

Fig. 1. Schematic microstructure of a functionally graded syntactic foam having a gradient in the microballoon wall thickness.

2. Structure of the FGSFs

A schematic representation of RR-type FGSFs is shown in Fig. 1 . In this microstructure the porosity is enclosed within microballoons, which are embedded in a polymeric matrix. The ω is changing along the material thickness, leading to a graded structure. Since the only parameter that is changing is r_i, the micrographs of any section of the RR-type FGSFs appear to be the same. Hence, the existence of functionally graded structure in RR-type FGSFs can be confirmed only by measuring the density difference at various locations in the material. A typical micrograph of a syntactic foam containing V_{mb} of 0.6 is shown in Fig. 2 .

3. Materials and processes

In the first step 16 compositions of plain syntactic foams are fabricated and cut into thin strips. In the second step these strips are adhesively bonded in specific arrangements to create layered FGSF specimens. The experimental procedure is outlined below.

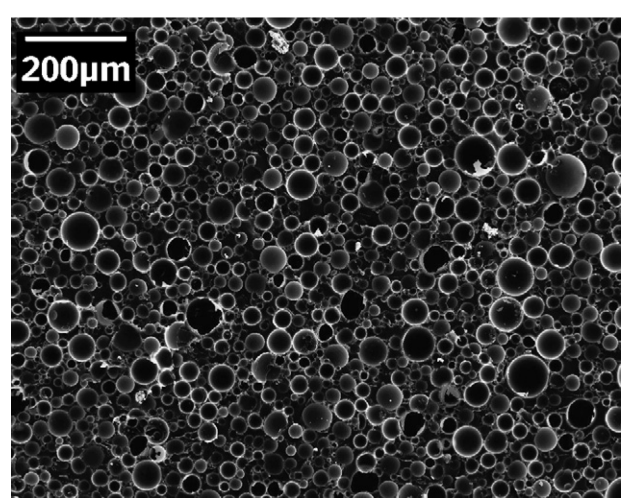

Fig. 2. Scanning electron micrograph of a syntactic foam.