Composites Part B 78 (2015) 401–408

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Elastic behaviour and failure mechanism in epoxy syntactic foams: The effect of glass microballoon volume fractions

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A R T I C L E I N F O

Article history:
Received 24 August 2014
Received in revised form
27 December 2014
Accepted 1 April 2015
Available online 10 April 2015

Keywords:
A. Polymer-matrix composites (PMCs)
B. Mechanical properties
B. Fracture
C. Finite element analysis (FEA)

A B S T R A C T

A representative elementary volume (REV) in epoxy syntactic foams was generated to incorporate randomly distributed glass microballoons that followed a log-normal size distribution. Finite element modelling of the REV foam was developed and experimentally validated to investigate the elastic behaviour and failure mechanism in the foams with different microballoon volume fractions (V). The localised stresses concentrate in various zones within the foam, and can cause the vertical splitting fracture of microballoons and the micro-crack formation in the matrix. Dependent on the microballoon volume fraction, micro-cracks can propagate to join adjacent micro-cracks and voids left by fractured microballoons, and finally develop into a macro-crack either in the preferred longitudinal (for low V) or diagonal (for high V) directions. This is consistent with the macroscopic observations of the fracture process in the foam specimens. It was also found that elastic characteristics of the foam vary with microballoon volume fractions.

1. Introduction

The syntactic foam, which is a composite material made of microballoons mechanically embedded in the polymer matrix, possesses the advantageous properties such as low moisture absorption, good chemical stability, high specific strength, excellent damage tolerance and energy dissipation capacity. A combination of these properties results in the increased use of the foam in marine, aerospace, automotive, civil and petrochemical applications. The various applications of syntactic foams especially in a load bearing structure require the full understanding of the mechanical properties and the associated failure mechanism.

A number of research activities have been carried out in the past decades to investigate the bulk mechanical behaviour of syntactic foams and the effect of various factors, such as the properties of microballoons and the matrix, microballoon volume fraction and geometry, and strain rate [1–10]. The microballoon volume fraction (V) is one of the key methods to control the mechanical properties of syntactic foams. It has been reported that the volume fraction of microballoons affects the bulk compressive, tensile and flexural properties as well as the fracture toughness and impact resistance of the foam [7,11–15]. Marur [5] and Nielsen [6] proposed the analytical approaches to calculate the Young's modulus (E), Poisson ratio and shear modulus of syntactic foams based on the known constitutive parameters of the microballoons and matrix, such as the elastic modulus, inner and outer diameters of microballoons. These analytical approaches were validated by the experimental results. However, very few studies have focused on the internal stress evolution during the deformation of syntactic foams, which is important to understand the microscopic mechanism determining the bulk behaviour. Furthermore, the effect of microballoon volume fractions in the microscopic scale was rarely studied.

The failure mechanism in syntactic foams significantly determines the lifespan of a component made of the foam. Three macroscopic failure modes in the syntactic foam subjected to compression have been observed and identified in the literature [4,16–19]: shear fracture in the diagonal, longitudinal splitting failure along the compression direction, and layered crushing mode due to the failure of some weak transverse planes. These reports analysed the damage evolution and the associated mechanism of each failure mode, and indicated that the failure modes vary with the properties of constituents, aspect ratio of the specimen and strain rates. However, the effect of microballoon volume fractions on the failure of syntactic foams is still not well understood especially in the multiple scales, and is rarely related to the internal stress field.

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http://dx.doi.org/10.1016/j.compositesb.2015.04.002
1359-8368/

Finite element (FE) modelling has been the effective tool to investigate the stress field and to characterise the constitutive and failure behaviour of syntactic foams [20–24]. A unit cell model, containing one eighth of a hollow sphere embedded in the matrix, was developed to estimate the elastic behaviour of the syntactic foam [21,23]. The model explained some experimental observations, but may not well characterise the overall behaviour because the syntactic foam is heterogeneous in microscopic scale. Hence, a FE model of syntactic foams should consist of a sufficient amount of hollow spheres to better represent the foam. It was demonstrated that a three-dimensional (3D) FE model consisting of a number of microballoons [20,22] was more accurate in predicting the mechanical properties of syntactic foams compared to the one eighth unit cell model [21,23]. However, these models assumed the simple uniform distribution in both the size (equal outer diameter) and location (array arrangement) of microballoons. A 3D model closer to the real foam needs to include the random location distribution of microballoons and the statistic distribution of their sizes [24].

The aim of this work is to investigate the elastic behaviour and failure mechanism in epoxy syntactic foams as well as the effect of glass microballoon volume fractions. A cubic representative elementary volume (REV) in the foam was generated, in which the microballoons with a statistic outer diameter distribution were randomly distributed. The FE model of the REV foam was then developed to predict the localised stress field in the elastic region during the compression of the foam. Uniaxial compression experiments at quasi-static rates were performed on the syntactic foams with different microballoon volume fractions to validate the FE model and to characterise the stress–strain curves and failure process of the foam. The predicted localised stresses were related to explore the failure mechanism for different microballoon volume fractions. Based on the FE predictions and experimental observations, the failure mechanism within the microballoons and matrix was proposed to understand the bulk failure process.

2. Experimental procedure

2.1. Materials and microstructure

The syntactic foams were fabricated by mechanically mixing the 3M Scotchlite glass microballoons S60 (filler) and Epicote 1006 epoxy resin (matrix). The amount of glass microballoons was controlled to achieve the four foams with the respective glass microballoon volume fractions $V = 0.1$, 0.2, 0.3 and 0.4. The microballoons were added to the epoxy matrix in multiple steps to avoid agglomeration. The stir speed was slow to minimise both the damage of glass microballoons and the occurrence of air bubbles in the epoxy. After the mixture became the uniform slurry, it was left in a vacuum oven for 10 min at room temperature to further reduce the air bubbles. Subsequently, the mixture was again stirred slowly for another 20 min before it started to become the gel, because the glass microballoons (bulk density ~600 kg m^{-3}) have the tendency to float to the surface of the epoxy matrix (density ~1100 kg m^{-3}). Finally, the syntactic foam was cast in an aluminium mould coated with the release agents and was subsequently cured for 24 h at room temperature.

Fig. 1(a) illustrates the microstructure of a syntactic foam with the microballoon volume fraction $V = 0.4$ as characterised by scanning electron microscope (SEM). X-ray microtomography [25–27] at 35 kV and 110 μA was used to examine the morphology and distribution of microballoons in the epoxy syntactic foams with a resolution of ~2.5 μm (Fig. 1(b)). The glass microballoons are randomly distributed in the epoxy matrix, resulting in a homogeneous microstructure in the foam (Fig. 1). Good interfacial contacts were observed between the microballoons and matrix (Fig. 1(a)).

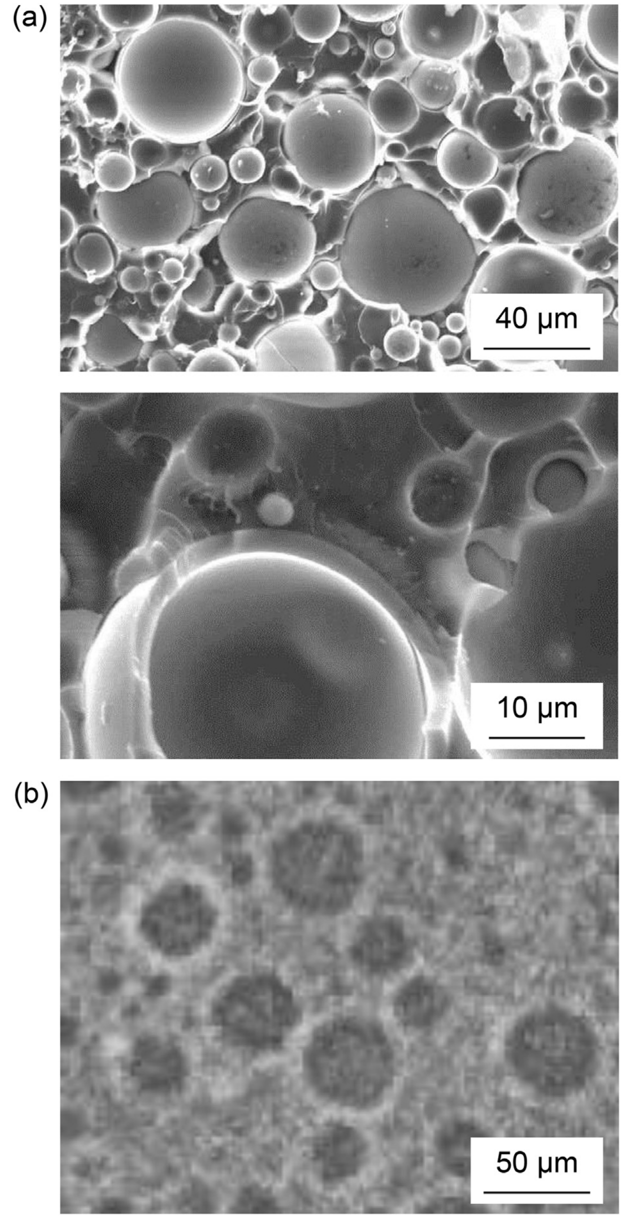

Fig. 1. The syntactic foam with a glass microballoon volume fraction $V = 0.4$: (a) the SEM images at two magnifications and (b) a 2D slice of an x-ray microtomographic image showing the representative cross sections.

The raw glass microballoons S60 were examined in SEM; the outer diameters of individual microballoons were quantified from the SEM images and statistically analysed. It was found that the outer diameter nearly follows a log-normal distribution (Fig. 2). For the majority of microballoons by volume, the outer diameter (D) ranges from 10 to 65 μm. This agrees with the material data provided by the manufacturer (Table 1). The SEM observations on the microballoon debris reveal that the wall thickness of S60 is nearly constant (t = ~2 μm) within the individual microballoons and among them regardless of their outer diameters (Fig. 1(a)).

2.2. Mechanical tests

Cylindrical specimens of $d = 10$ mm diameter and $l = 10$ mm length, thus an aspect ratio of $l/d = 1.0$, were machined from the fabricated syntactic foam rods. The specimen diameter was large