Composites Part B 101 (2016) 53–63

Contents lists available at ScienceDirect

Composites Part B

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

The effect of strain rate and filler volume fraction on the mechanical properties of hollow glass microsphere modified polymer

Xin Zhang [a, b], Pengfei Wang [c], Yihao Zhou [b], Xiaotuo Li [b], En-Hua Yang [d, **], T.X. Yu [e], Jinglei Yang [e, *]

[a] Interdisciplinary Graduate School, Nanyang Technological University, 50 Nanyang Avenue, Singapore, 639798, Singapore
[b] School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore, 639798, Singapore
[c] CAS Key Laboratory of Mechanical Behavior and Design of Materials, Department of Modern Mechanics, University of Science and Technology of China, Hefei, 230026, China
[d] School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore, 639798, Singapore
[e] Department of Mechanical and Aerospace Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

ARTICLE INFO

Article history:
Received 5 January 2016
Received in revised form
25 June 2016
Accepted 29 June 2016
Available online 2 July 2016

Keywords:
Hollow glass microsphere
polymer-matrix composites (PMCs)
Fracture
Mechanical testing

ABSTRACT

Hollow Glass Microspheres (HGM) filled polymers are widely used in marine, aerospace and civil engineering. In this work, the mechanical properties of HGM filled polymers were investigated under low strain rate tests for compressive and tensile behaviors, and high strain rate tests for compressive behaviors. Systematic investigations are carried out to study the mechanical responses, energy absorption and failure modes of HGM filled polymers with different volume fractions of glass microspheres subject to different loading conditions. HGM filled polymers showed strong strain rate effect and the strain rate sensitivity factor increased with the increase of strain rate while decreased with the increase of filler volume fraction. HGM filled polymer absorbed more energy at V_f around 7.5% under low strain rate compression. Different fracture modes were discovered for HGM filled polymers under low and high strain rate loadings by using Computed Tomography (CT) scan and Scanning Electron Microscope (SEM). The numerical results obtained from finite element analysis fitted well with the experimental data. In addition, a convenient generalized model was proposed to depict and predict the compressive strength of HGM filled polymers in the observed range of strain rates.

1. Introduction

Hollow Glass Microspheres (HGM) filled polymer has been developed as buoyancy-aid materials in deep-sea applications as early as 1960s [1]. After the initial development, HGM filled polymer has been widely used in many areas, such as marine [2], aerospace [3], and sports [4], automotive, civil, and petrochemical industries [5]. Especially, it is used as the core material of sandwich composite in the marine panel to protect the structure due to its high specific strength and buoyancy-aid materials due to its light weight. HGM filled polymer is comprised of hollow glass microsphere and polymer matrix. It has been widely investigated due to its high specific strength, relatively high thermal stability, low thermal conductivity, and excellent damage tolerance, which are desirable properties of composites [6–8]. Syntactic foam is one of such HGM filled polymer which has relatively high volume fraction of HGM [9].

The glass microspheres in the matrix can prevent the crack propagation during the loading. As a result, it provides enhancement to the mechanical properties of the epoxy resin. It is well known that the interaction between glass microspheres and epoxy resin plays a critical role in determining the mechanical properties of the glass microsphere modified resin [10]. Otherwise, the microspheres may act as flaws if they are not adequately secured in the matrix [11]. The crack bowing, crack deflection, and debonding are three different failure mechanisms for syntactic foam [12,13]. Studies have indicated that the deformation of syntactic foams is bending dominated, which is to say, the topology of the cells causes the cell edges to bend during the application of force, which may make the HGM filled polymer compliant and slightly weaker, but absorb more compressive energy during static testing [14].

* Corresponding author.
** Corresponding author.
E-mail addresses: EHYANG@ntu.edu.sg (E.-H. Yang), maeyang@ust.hk (J. Yang).

http://dx.doi.org/10.1016/j.compositesb.2016.06.079
1359-8368/

With the aim of obtaining dynamic response of such porous material, Split-Hopkinson Pressure Bar (SHPB) can be used to apply high strain rate loading [15–17]. Li et al. [18] investigated the mechanical response of syntactic foam under different strain rates. Strain rate dependency of compressive properties has been observed. Zhang et al. [13] investigated the hollow carbon microsphere reinforced polymer and reported compressive strength decreases with increasing filler content. Meanwhile, better interfacial adhesion could induce better fracture toughness. Li et al. [19,20] conducted micromechanical analysis of particle-reinforced and fiber-reinforced composites based on unit cell. Unit cell packing has been developed to simulate micromechanical property by using periodically boundary condition.

There is a lack of studies focus on the tensile property of HGM filled polymer. Gupta et al. [21] have processed tensile tests of sixteen types of syntactic foams and adopted four types of HGMs. They observed that both tensile strength and modulus decrease with the increase of volume fraction of HGM.

The absolute strength of HGM filled polymer tends to be very low if the volume fraction of HGM is very high. However the mechanical properties and fracture modes of HGM filled polymer with relatively lower volume fraction of HGM has not been investigated sufficiently. In this paper, the mechanical response of HGM filled polymer with different volume fractions of glass microspheres tests has been investigated systematically subject to both low strain rate loadings and dynamic compressions. Specimens with glass microspheres of 0%, 5%, 7.5%, 10%, 15%, and 20% by volume have been fabricated. The optimized volume fraction of glass microspheres with better energy absorption capacity has been explored. The mechanism of fracture modes and crack propagations of HGM filled polymer under compression has been observed by using CT scan and Field Emission Scanning Electron Microscope (FESEM). Meanwhile tensile properties of HGM filled polymer have also been studied. Finite element method has been applied to study mechanical properties of hexagonal unit cell of HGM filled polymer. Moreover, an empirical model with easy obtained parameters has been established, which can be used to provide reference for the design of HGM filled polymer.

2. Materials and method

2.1. Materials and samples

The epoxy and hardener used were Epolam 5015 resin and hardener, manufactured by Axson Technologies. K1 glass microspheres, supplied by 3M Corporation, were selected and its basic properties can be found in Table 1 [22]. The ratio between epoxy resin and hardener was 100 to 30. As suggested by the manufacture, the pot life for 500 g of mixed epoxy resin was 135 min at 25 °C and the cured density was 1.10 g/cm^3. The debris and broken glass microspheres were filtered out with water sink to guarantee integrity of spheres before usage. The mixture of glass microspheres and resin were stirred continuously but slowly by hand to ensure uniform dispersion of glass microspheres. After which, the suspension was putted into a vacuum oven (MRC, Model: 1410-DIG) and a connected rotary vane vacuum pump (Vacuubrand, Model: RZ-2.5) were used to remove air bubble from the mixture. The mixture was stirred intermittently and slowly to avoid the glass microspheres from floating to the top of the mixture.

Before the well dispersed suspension was poured to silicone gel molds, release agent (Pol-Ease 2300 Release Agent) was applied on the surface of the molds to facilitate removal of solidified specimens. For the molds to fabricate tensile and flexural specimens, silicone cove plates and cover plates were used to guarantee the planeness of the specimens. The specimens were cured for 24 h in atmospheric temperature. After which, the specimens were heated in an oven (Binder, Model: ED-240) under 80 °C for 16 h. Specimens with glass microsphere volume fraction of 0%, 5%, 10%, 15%, and 20% have been fabricated.

2.2. Experiments

2.2.1. Low strain rates testing

The compression specimens had a height of about 22 mm and a diameter of about 9.9 mm which were prepared by using cylindrical mold. The low strain rate specimens were then machined to a height of 15 mm, while the dynamic specimens were machined to 6 mm by using a lathe machine. The tensile specimens were in dog bone shape with a dimension of 4 mm in width, 3 mm in thickness, and 30 mm in length in the center of the specimens. The surfaces of all specimens were polished to guarantee the planeness. Instron 5569 Universal Testing Machine was carried out to process low strain rate compression tests and tensile tests in accordance to the ASTM D695 standard and ASTM D638 standard respectively, as shown in Fig. 1a and b. An extensometer (Instron, Model: 2630-105, Static Extensometer GL) with gage length of 25 mm was used to carry out the tensile tests. Three strain rates at 0.0005 s^{-1}, 0.01 s^{-1}, and 0.2 s^{-1} have been applied for both low strain rate compression tests and tensile tests.

2.2.2. High strain rates testing

For the apparatus to process dynamic compression test, a Split-Hopkinson Pressure Bar (SHPB) was used, as shown in Fig. 1c. Two different lengths of aluminium bullets, 40 mm and 82 mm, were used for the tests. The strain rates that can be obtained from dynamic tests were approximately 1,250 s^{-1} and 2,750 s^{-1}.

Basic mechanical data such as engineering strain, engineering stress, and strain rate can be calculated by using the strain signal collected from the incident and transmitter bars as shown in Eqns (1)–(3). 1-D elastic wave propagation is assumed in the bars.

$$\varepsilon_s(t) = -\frac{2C_0}{l_0}\cdot\int_0^t \varepsilon_R dt \tag{1}$$

$$\sigma_s = E\cdot\frac{A}{A_s}\cdot\varepsilon_T \tag{2}$$

$$\dot{\varepsilon} = -\frac{2C_0}{l_0}\cdot\varepsilon_R \tag{3}$$

where C_0 is the sound wave velocity in the bars, ε_R is the reflect strain and l_0 is the initial length of the specimen. E and A are the modulus and the cross sectional area of bar material respectively, while A_s is the cross sectional area of the specimen, and ε_T represents the transmit strain.

Dynamic equilibrium state [23] has been regarded as an important factor to evaluate the reliability of SHPB testing method. Stress applied to the front end of the sample can be determined by the summation of stresses introduced by the incident and the reflection waves, while stress applied to the rear end of the sample is the stress introduced by the transmitted wave. Fig. 2 shows the rear end and front end stress during the process. As can be seen, force equilibrium is largely achieved which implies the data collected from SHPB is valid.

2.2.3. Numerical study

ABAQUS/Standard was used to simulate the modulus of specimen. In order to simplify the simulation process, unit cell approach