Mechanics Research Communications 83 (2017) 1–5

Contents lists available at ScienceDirect

Mechanics Research Communications

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

Behavior of syntactic foam under plate impact

Carl-Ernst Rousseau *, Gifford Plume, Miguel Goñi, Bhaskar Ale

Mechanical Engineering, Wales Hall, Univ. of Rhode Island, Kingston, RI 02881, USA

ARTICLE INFO

Article history:
Received 28 December 2015
Received in revised form 10 January 2017
Accepted 6 February 2017
Available online 28 February 2017

Keywords:
Attenuation
Syntactic foam
Ultrasonic
Impact

ABSTRACT

Hollow particulates were cast in an epoxy matrix and subjected to plate impact, at a speed of 300 m/s. Three different microballoon sizes were used, in turn, in the fabrication process, with particulate volume fractions of 5, 10, 20, and 30%. Both particulate size and volume fraction are shown to play a crucial role in the mitigative response of these syntactic foams. Composites with large diameter inclusions mitigate the effects of the imparted stresses to the largest extent, while those made from the smaller inclusions have the nefarious effect of causing a lessening of attenuation to a level below that which is provided by the virgin matrix. Increases in volume fraction tend to enhance the primary response associated with respective particulate sizes. It is also noted that the stress response to dynamic loading emulates the behavior of those same materials when ultrasonic waves are launched through them. The latter could therefore be used as a non-destructive guide to predict the behavior of syntactic foams.

1. Introduction

Syntactic foams are particulate composites with inclusions consisting of hollow spheres. They must be differentiated from open cell structured foams in that the included particulates are complete entrapped and the voids can find no path to the external environment. Their applications are numerous, particularly in the aerospace and marine industries, where light weight materials are essential to aid in buoyancy or lift. In industry, they are characterized by low density, reduced manufacturing costs, customizable and desirable magnetic and electrical properties, high damage tolerance, and increased impact strength [1]. In this paper, the focus will be placed on the dynamic event of impact.

Damage behavior of particulate composites has traditionally focussed on quasi-static loading [2]. Early dynamic research includes a description of the Hugoniot curve in a ductile powder composite of porous aluminum and iron [3]. This was followed by the formulation of a stress wave propagation model in composite materials [4], where the particulate composite was idealized as consisting of a system of periodically alternating materials. The interaction between the successive layers of the resulting complex laminate would represent the scattering effect thought to be present within more general composites. This model has been preserved as an experimentally ideal set up by several researchers, who, with the aid of embedded gauges, have tracked propagating shock wave at interfaces located between alternating material layers [5,6]. Beyond these attempts, experimental work has focussed primarily on the fracture properties of these materials [7], with few attempts at quantifying the amplitude of compressive wave propagation.

In existing particulate wave propagation works, the phenomenon of geometric dispersion of elastic waves has received limited attention. The idea of geometric dispersion has guided this study into investigating the basic physical principles governing the propagation of elastic longitudinal stress waves in epoxy-based syntactic foams. In particular, this paper investigates practical means of lowering the amplitude of the imparted stress as it travels through the material. The current work, based on projectile impact, follows well-established techniques used to assess homogeneous materials [8,9].

2. Theoretical considerations

Consider a material subjected to symmetric planar impact. The ensuing stresses arisen within the specimen will ramp from zero to a maximum value commensurate with the speed of the impactor. With a severe enough impulse, the ramp will steepen to a shock, wherein the physical conditions of the material are dictated by requisite conservations of mass, momentum, and energy:

$$V = V_0 \frac{U_s - (u_p - u_0)}{U_s}, \tag{1}$$

$$\sigma = \sigma_0 + \rho_0 U_s (u_p - u_0), \tag{2}$$

* Corresponding author.
E-mail address: rousseau@uri.edu (C.-E. Rousseau).

http://dx.doi.org/10.1016/j.mechrescom.2017.02.006
0093-6413/

$$E = E_0 + \frac{1}{2}(\sigma + \sigma_0)(V_0 - V), \tag{3}$$

where V, σ, E, and u_p are respectively the end states of specific volume, pressure stress, specific internal energy, and particle velocity achieved from the passage of a shock wave. U_s is the shock front velocity relative to the initial material states of specific volume (V_0), density (ρ_0), pressure (σ_0), particle velocity (u_0), and energy (E_0). As a precursor to the shock, the Hugoniot Elastic Limit, a transition to the plastic regime, is often attained. It is identified in the stress profile as a very narrow plateau, a brief latency preceding the swift resumption of the ascent of the stress to its ultimate peak.

A mild loading environment, as with the conditions pertaining to this work, will belong to a regime where quasi-isentropy can be confidently asserted. Indeed, stresses in the materials tested are limited to 300 MPa, two orders of magnitudes below the 10 GPa quoted by Rosenberg as the threshold where Hugoniot and isentropic definitions of epoxy materials no longer coincide [10].

Strain rate in the burdened material can be estimated directly from stress records [11]:

$$\dot{\varepsilon} = \frac{du}{dx} = \frac{1}{\rho_0 c}\frac{d\sigma}{dx} = \frac{1}{\rho_0 c^2}\frac{d\sigma}{dt}, \tag{4}$$

where ρ_0 is the initial density, c is an appropriate wave speed, and the variation of stress with time is associated with either the rise or fall portions of a recorded stress signal.

Finally, the presence of radial release waves cannot be ignored, as they may potentially corrupt the experimental data. Fortunately, a simple geometric analysis provides a solution to this dilemma. Defining as r, the radial distance from the location of the gage to the edge of the specimen, and D, its distance from the impact face, then the time of arrival of the radial release waves can be defined as $t_{rr} = \sqrt{D^2 + r^2}/c$.

3. Experimental design

3.1. Materials studied

The specimens used in this study were fabricated from an epoxy thermoset matrix mixture. Several variations of these materials were produced, ranging from an indigenous material (no added particulates) to mixtures that included hollow soda-lime-borosilicate micro-balloons. Three types of these glass particles, each featuring different outer and inner diameters, were selected. Details provided by the manufacturer (3M), relating to their respective dimensions and mechanical properties, are listed in Table 1.

The epoxy used in all the castings is an Epo-Thin resin and hardener, manufactured by Buehler, Ltd. It is a low-viscosity thermoset with a nominal curing time of 18 hours at room temperature. The resin is a Bisphenol-A type epoxy resin. The hardener's primary ingredient is a Polyoxyalkylamine blend. The density of the mixed epoxy is given by the manufacturer as 1077 kg/m^3 which was also confirmed experimentally.

The procedure used for producing castings containing the micro-scale glass particles was identical to that used for the virgin epoxy specimens. The nature of this study called for various concentrations of these particles to be mixed with the epoxy prior to casting. Volume fractions of glass beads in the matrix of 5, 10, 20, and 30%, respectively, were used in the experiments.

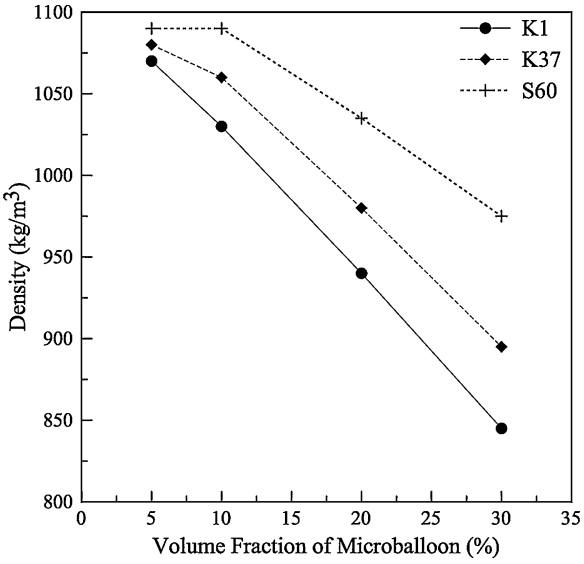

Fig. 1. Density of syntactic foams as a function of volume fraction.

The theoretical density of each glass-epoxy composite specimen was evaluated using the rule of mixtures, which can be formulated as:

$$\rho_{\text{composite}} = \rho_{\text{glass}} \cdot V_{f-\text{glass}} + \rho_{\text{epoxy}} \cdot (1 - V_{f-\text{glass}}), \tag{5}$$

where $V_{f-\text{glass}}$ is the volume fraction of glass, and $\rho_{\text{composite}}$, ρ_{glass}, and ρ_{epoxy} are the densities of the corresponding subscripts, respectively. For each volume fraction, individual specimens were also weighed, their volume measured, and the associated density was derived. Differences between theoretical and measured densities increased with increasing volume fractions of the glass particles in the matrix, as the presence of air voids exacerbated this variance. The weight and density of the constituents, and the measured and theoretical volumes of the composites were used to approximate the volume of air in each specimen. This volume of air was then divided by the measured volume to calculate the percentage of air by volume in each specimen. The maximum air volume fraction is 2.2% for the specimens measured. Density variations are shown in Fig. 1. As radius ratio, defined as (r_i/r_o) for a particle, and particle size increase, density of syntactic foam for a particular volume fraction decreases. The radius ratio is also a measure of the hollowness of the sphere. Finally, any syntactic foam composite fabricated from a specific glass particle type experiences a monotonic decrease in density with increasing volume fraction due to the increasing void content of the matrix.

To further characterize the syntactic foams, the techniques laid out in ASTM Standard D695–10 were used. Specimens with height to diameter slenderness ratios of 2 were compressed using an Instron testing machine at a cross-head rate of 1.3 mm/min. Six specimens of each type were tested. Stress-Strain curves, Compression Moduli, and Yield Strengths were obtained. Composite volume fractions of 5, 10, 20, and 30% were evaluated in compression. A synopsis of these results is presented in Fig. 2 and shows a direct correlation between syntactic foam strength and stiffness, and the crush strength of the particles used as building blocks for

Table 1
Microballoon properties.

Designation	Particle size (μm)	Wall thickness (μm)	Radius ratio (r_i/r_o)	Density (kg/m^3)	Crush strength (MPa)
S60	30	1.49	0.950	600	68.94
K37	45	1.04	0.977	370	20.68
K1	65	0.55	0.992	125	1.72