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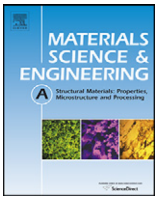

Quasi-static and dynamic compression response of a lightweight interpenetrating phase composite foam

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ABSTRACT

Quasi-static and dynamic compression response of syntactic foam (SF)–aluminum foam interpenetrating phase composites (IPC) is examined. Infusion of uncured syntactic foam (epoxy filled with hollow microballoons) into an open-cell aluminum network results in a 3D interpenetrating structure upon curing. The compression responses are measured at strain rates of ~0.001/s and 1500/s. The dynamic experiments are performed using a split Hopkinson pressure bar set up. The role of volume fraction of microballoons on the response of IPC is examined in terms of yield stress, plateau stress and energy absorption under quasi-static and dynamic conditions. The response of IPC samples are also compared with those made using syntactic foam alone. The results show that the energy absorbed by the IPC foams under dynamic loading is consistently higher than that measured under quasi-static loading conditions. For all volume fractions of microballoons, the IPC samples have better compression characteristics when compared to the corresponding syntactic foam samples. The failure modes and mechanisms of SF and IPC foams are examined both optically (using high-speed photography) and microscopically and the underlying differences are discussed.

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1. Introduction

Multifunctional materials that are lightweight, stiff, strong and tough are of interest to many engineering disciplines for civil and military applications. In this context, a new class of materials called interpenetrating phase composites (IPC) has received attention in recent years [1]. IPCs are multiphase materials in which each constituent forms a continuous 3D network within the material volume. Thus, each phase in its stand alone state has an open-cell microstructure. Furthermore, even though IPCs are heterogeneous on a micro/meso scale, the macroscale response is often isotropic. This co-existence of desirable properties without significant directional dependency or distinct weak planes makes an IPC attractive for structural applications. For example, one phase might offer good toughness and thermal conductivity, while the other phase might enhance stiffness and dielectric properties. Thus, each phase of an IPC contributes its unique property to the overall structural response synergistically.

Among the existing works on IPCs, Prielipp et al. [2] studied the mechanical properties of aluminum/alumina interpenetrating composite and measured fracture strength and fracture toughness of the composite as a function of ligament diameter and volume fraction of the metal reinforcement. The metal reinforced interpenetrating composites consistently had higher fracture strength. Breslin et al. [3] characterized an aluminum/alumina IPC using the method of liquid phase displacement reaction method. The resulting IPC had enhanced density, thermal conductivity and CTE characteristics, without compromising stiffness or fracture toughness. Travitzky et al. [4] showed that the residual stresses developed in silicon during solidification of molten Si within an Al_2O_3 matrix results in better strength and fracture toughness of the resulting Al_2O_3/Si interpenetrating system. Wegner and Gibson [5] developed finite element models to predict the elastic, flow and thermal expansion properties of two phase IPCs. They attributed the enhancement in the thermo-mechanical properties to the contiguity of the phase with the most desirable property. In a later work [6], Wegner and Gibson studied the mechanical behavior of resin-impregnated porous stainless steel. The yield strength, ultimate strength, elongation at failure and the elastic modulus were all found to increase with an increasing volume fraction of steel. Skirl et al. [7] examined the thermal expansion behavior of alumina/aluminum IPC. A pressure infiltration technique was used to introduce aluminum into slip cast and then sintered alumina. The tensile and compressive residual stresses in alumina and aluminum phases were found to enhance the overall thermal coefficient of expansion. An increase in failure strain with increase in the metal content was also reported. Mayer and Papakyriacou [8] studied the fatigue behavior of graphite/aluminum IPC. The lightweight metals such as aluminum were infiltrated into polycrystalline graphite

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to improve the fracture toughness of polycrystalline graphite. A 30% increase in the cyclic strength and a 10% increase in the endurance limit were reported. Tilbrook et al. [9] measured the effective mechanical properties of alumina-epoxy interpenetrating composites and reported strong dependence of properties on the composition and the processing of the material itself. The flexural strength and fracture toughness of graphite/aluminum IPC at room temperature and at 300 °C were examined by Etter et al. [10]. A 200% improvement in both these characteristics for IPC over un-infiltrated material at room temperature was reported. Also, no significant drop in properties was seen at elevated temperatures. Jhaver and Tippur [11] demonstrated the feasibility of a lightweight IPC foam by infiltrating a syntactic foam (SF) [12–14] into an open-cell aluminum network and examined quasi-static uniaxial compression response experimentally and numerically.

As noted in the above reports, the enhancements in the effective mechanical properties of IPC are dictated by the contiguity of the phase with the most desirable properties. Based on this, and pinning on the necessity to enhance the compression characteristics of structural foams, in this paper a lightweight IPC formed by infiltrating syntactic foam[1] (SF) into open-cell aluminum network is proposed for static as well as dynamic applications. An IPC foam formed by continuous interpenetrating 3D network of syntactic and aluminum foams has the potential for improving the structural integrity with good energy absorption characteristics, thus making it a worthwhile material system to study further. The present work builds on the feasibility study of the IPC foam first reported in Ref. [11]. In the current work, the performance of the material system and its mechanical behaviors are studied under both static and dynamic compression. The quasi-static mechanical responses are compared with the dynamic ones obtained using a split Hopkinson pressure bar measurements. High-speed photography and microstructural observations are used to distinguish failure mechanisms of SF and IPC materials. In the next section of this paper, the SF and IPC material preparation details are discussed. In Section 3, the experimental methods used are elaborated. Sections 4 and 5 present the effect of microballoon volume fraction on the quasi-static and dynamic compressive responses of SF and IPC, respectively. Section 6 of this paper discusses and compares the energy absorption characteristics under quasi-static and dynamic loading conditions. The progression of failure is analyzed photographically in Section 7. The results of the study are summarized in Section 8.

2. Material and specimen preparation

The constituents used for preparing the IPC foam were a low viscosity epoxy (Epo-Thin$^{\text{TM}}$ from Beuhler, Inc. USA, mass density of resin ∼1100 kg/m^3), hollow glass microballoons (K-1$^{\text{TM}}$ microballoons from 3M Corp., bulk density 125 kg/m^3) of average diameter of ∼60 μm and wall thickness of ∼0.6 μm and commercially available open-cell Duocel® aluminum (Al6101-T6) foam obtained from ERG aerospace Corp., with a pore density of 40 pores per inch (∼8% relative density). The above-mentioned material properties were provided by the respective manufacturers. The metal foam was cleaned and then coated with silane, γ-aminopropyltrimethoxysilane ($H_2NC_2H_4NHC_3H_6Si(OCH_3)_3$) to enhance the bond strength between the aluminum ligaments and the syntactic foam. Syntactic foam was then prepared by mixing the desired quantity of microballoons into epoxy resin. The uncured syntactic foam was then transferred into a silicone rubber mold after vacuuming (at approximately −75 kPa gage pressure) to remove any trapped air bubbles in the mixture. In case an IPC was desired, the silane coated aluminum foam was slowly inserted into the mold containing the uncured syntactic foam so that the syntactic foam fills in the open-pores of the aluminum network. After curing for at least seven days, the unfinished sample was removed from the mold for machining. A photograph of the cross-section of the cured IPC foam is shown in Fig. 1(a). The shiny metallic ligaments of the aluminum preform interspersed within the SF foam can be readily observed.

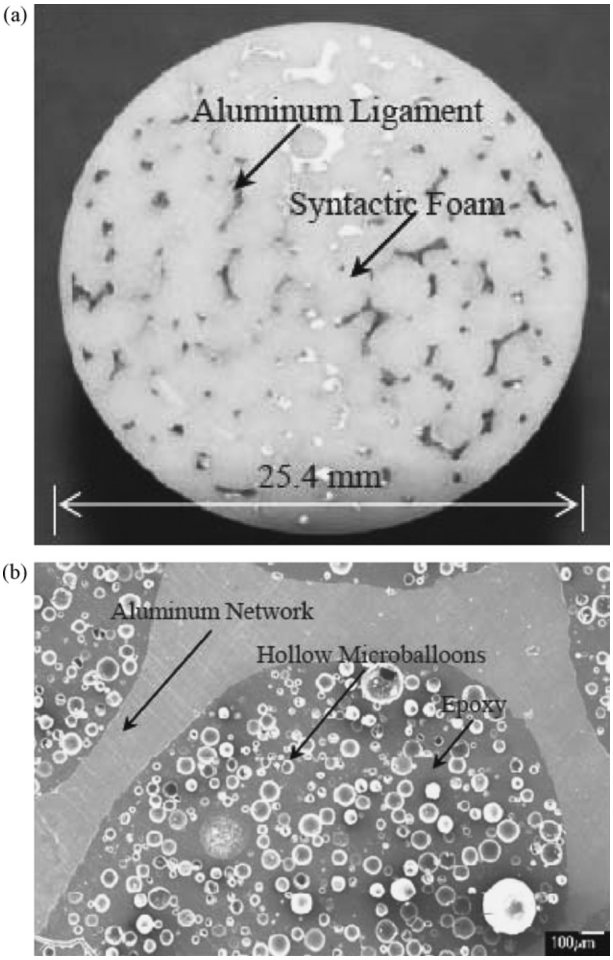

Fig. 1. (a) Cross-section of IPC foam with 30% volume fraction of SF and (b) SEM micrograph of IPC.

The cylindrical specimens used in quasi-static testing were 20 mm thick and 26.7 mm in diameter. These specimen dimensions were chosen in order to maintain the length to diameter (*l*/*d*) ratio less than 1. A higher *l*/*d* ratio has been shown to have significant effect in the compressive strength of syntactic epoxy foams by Song et al. [16]. The samples used in dynamic testing had a length of 9.5 mm and a diameter of 12.7 mm. Gibson [17] has proposed a specimen length to cell size ratio (*l*/*D*) of 8 or above, so that the specimen represents the bulk of the foam. The aluminum foam used in this work had a pore density of ∼40 pores per inch with individual cell size of approximately 0.025 in. (0.635 mm). To be conservative, an *l*/*D* ratio of 15 was used in the current work. Fig. 1(b) shows a micrograph of the cross-section of the IPC with 30% microballoon volume fraction in SF. The interface between the

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[1] Syntactic foams (SF) are structural foams with closed-cell structure made by dispersing *hollow* microballoons in a matrix to achieve lightweight characteristics. Typically they are made by dispersing thin-walled glass microballoons in a polymer matrix [13–16]. They are used by the electronic industry for their good dielectric properties [14], by the gas distribution industry for thermal insulation and in naval and aerospace applications for their excellent buoyancy and energy absorption characteristics, respectively [12,14,16]. Due to its multifunctionality SF is a worthwhile material to study as well.

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