Aromatic Thermosetting Copolyester Foam Core and Aluminum Foam Face Three-Layer Sandwich Composite for Impact Energy Absorption

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ABSTRACT

In this work, we introduce a three-layer sandwich composite structure having an aromatic thermosetting copolyester (ATSP) foam core with two aluminum foam face layers joined together by an *in-situ* generated foaming mechanism. The ATSP foam core was synthesized on-site between the aluminum foam layers via a heat-induced polycondensation reaction. Upon curing, the ATSP foam core adhered to the aluminum foam layers through an interfacial compatibility-enabled chemical bonding. Lap shear experiments demonstrated that the bond strength clearly surpassed the tensile performance of the bare aluminum foam parts. Drop-weight impact tests showed that the three-layer sandwich structure could absorb four times the impact energy as compared to the bare aluminum foam of the same overall thickness.

Keywords: sandwich composite, in-situ bonding, ATSP, aluminum foam, energy absorption

1. Introduction

Porous morphology allows enhanced energy absorption and impact resistance for materials [1]. In that regard, aluminum foams possess a high strength-to-weight ratio and sustain high strain rate large plastic deformations under compressive loading through a plateau-stress yield region [2, 3]. Hence, the aluminum foams can effectively transform kinetic impact energy into plastic deformation energy, which enables them to absorb substantially more impact energy than most bulk metals [4]. Likewise, polymer foams have high energy **absorption** capacity so that they can effectively minimize transmitted impact load [5]. However, the polymer foams suffer from poor resistance to localized impact due to insufficient mechanical properties of their host polymers [6]. As core materials in sandwich structures, both material systems are joined to face layers via polymer adhesives. Yet, such adhesives constitute a weak interfacial bonding between the sandwich layers, which ultimately results in delamination.

We thereby present an ATSP foam core and aluminum foam face three-layer sandwich composite structure as candidates for impact energy absorption applications. Constituent ATSP oligomers were demonstrated to develop adhesive bonding with aluminum upon thermal curing [7]. Nature of the bonding mechanism was attributed to **the** attraction of surface hydroxyls on the aluminum to polar ester bonds of the oligomers [8]. Also, we recently introduced a high-performance ATSP foam fabricated via a heat-induced polycondensation reaction releasing self-generated blowing agent [9, 10]. The proposed composite foam design builds on these earlier studies.

1. Materials and methods

Experimental details regarding fabrication of the ATSP foam were explained elsewhere [9, 10]. A356 alloy melt-route fabricated aluminum foam pieces were purchased (Duocel®, McMaster-Carr Co., USA) in $10 \times 10 \times 2.5 \text{ cm}^3$ and $10 \times 10 \times 1.25 \text{ cm}^3$ (length x width x thickness) sizes.

Lap shear experiments were performed using a tensile load frame (4483 Load Frame, Instron Testing Systems, USA) with a 1 mm/min constant crosshead speed. Three samples were tested. The test specimens had half lap-shear joint configurations where two $10 \times 2.5 \times 1.25 \text{ cm}^3$ size aluminum foam pieces lapped over $2.5 \times 2.5 \times 0.5 \text{ cm}^3$ size mating edges. About 0.25 cm thick ATSP foam was synthesized between $2.5 \times 2.5 \text{ cm}^2$ size joint faces to adhere the two aluminum foam pieces together. Tests were done in accordance with an ASTM D3163 standard.

Low-velocity impact tests were performed using an impact machine (Dynatup 8250, Instron Testing Systems, USA). The sandwich specimens were $10 \times 10 \times 3.1 \text{ cm}^3$ in size while the ATSP foam thickness was about 0.6 cm. The specimens weighed about 240 g where ATSP foam weight was about 50 g. A hardened steel impactor with a 1.9 cm diameter and a 0.95 cm **radius of curvature** was used. The impactor was measured to have a Rockwell C55 hardness. Static loads of 11.3 kg and 34.0 kg were applied to generate impact energies of 90 J and 200 J, respectively. Drop heights were about 70 cm and impact velocities were about 4 m/s.

2. Results and Discussion

Figure 1. Schematic description of the fabrication process of the sandwich composites.

The fabrication process of the sandwich composite structure is shown in Figure 1. A powder mixture of acetoxy (red color) and carboxylic acid (blue color) functional group constituent oligomers was sandwiched between two aluminum foam layers, and all were enclosed by a metal frame. The metal frame was covered with a PTFE fabric peel-ply to prevent undesired bonding to the oligomer mixture upon curing (Figure 1.a). Then, the assembly was placed into a hot press where it was held intact with a steel plate rested on it. Next, a pre-designed thermal cure cycle was applied in which the esterification reaction initiated at elevated temperatures (~ 200 °C) between the functional groups of the oligomers releasing acetic acid as a reaction by-product. As the process carried on, the oligomers crosslinked to form the ester backbone of the ATSP foam while the acetic acid generated a porous morphology. In the meantime, the molten oligomers wetted aluminum foam surfaces developing intimate contact interlayers (Figure 1.b). Upon curing, a three-layer sandwich structure was obtained wherein the ATSP foam core solid-state bonded onto the aluminum foam face layers (Figure 1.c).

Figure 2. Images of the sandwich composite structure.

In Figure 2 we demonstrate fabricated sandwich composite structures. ATSP foam successfully formed between the two aluminum foam layers having a closed-cell morphology. As seen in the cross-section, ATSP foam established a smooth continuous bond line with both aluminum foam layers wherein neither bonding layer nor flush were formed (Figure 2.a). Also, we did not observe any significant outflowed polymer from the aluminum layers. The foaming process tended to evolve inside the enclosed space between the aluminum foam layers and the metal frame (Figures 2.b and 2.c). Additionally, the ATSP foam did not expand up through pore cavities of the aluminum foams. Overall, the samples were in neat shapes, nor requiring further machining.

Figure 3. Images of a lap shear sample before (a) and after (b) testing. Results of lap shear strength measurements (c).

Lap shear experiments were done to determine adhesion characteristics between the ATSP foam and the aluminum foam layers of the sandwich composites, as shown in Figure 3. As specimens were pulled under a controlled deformation rate (1 mm/min), they all yielded over the thinner parts of the aluminum foams with a thickness of about 0.5 cm (Figures 3.a and 3.b). During this process, the ATSP foam and bonding region remained intact. Lap shear strength results were between 0.6 to 1.0 MPa, which represented mere tensile strengths of the bare aluminum foam parts (~1.2 MPa) (Figure 3.c). Such slightly lower values are attributed to uneven pore distributions caused by specimen machining process.

Figure 4. Drop-weight impact test results representing maximum load (a) and impact energy absorption (b). Images of impacted bare aluminum foams of 2.5 cm (c) and 1.25 cm (d) thicknesses, and a sandwich composite structure (e-g).

Figure 4 shows drop-weight impact test results of the bare aluminum foams and the sandwich composite structures. The 1.25 cm and 2.5 cm thick aluminum foams were able to withstand up to ~3 kN maximum load, which translates into absorption energies of 26 J and 42 J, respectively, while total applied impact energies were 90 J (Figures 4.a and 4.b). Consequently, the impactor passed through both aluminum foam specimens (Figures 4.c and 4.d). However, the sandwich

composite structure was able to completely absorb the total of 90 J impact energy, which corresponded to an 8 kN maximum load (Figures 4.a and 4.b). Furthermore, as we increased the applied impact energy up to 200 J, the sandwich composite structure was able to absorb about 150 J energy.

We additionally observed that the bare aluminum foams were deformed through broken cell walls. Although the layer thickness was doubled, the amount of the absorbed impact energy by the bare aluminum foams did not reflect such thickness effect. On the other hand, the three-layer sandwich composite structure was able to absorb up to four-fold higher impact energy, as compared to the bare aluminum foam of the same layer thickness. Its energy absorption density was calculated to be about 200 J-cm³/g. The sandwich structure successfully stopped the impactor inside the ATSP foam core region such that only a small dent was generated on the bottom aluminum foam layer. We concluded that the interfacial bonding along with strong mechanical properties of the ATSP foam core gave rise to such an enhanced impact energy absorptive sandwich composite structure. The ATSP foam cores produce robust interfacial bonding during cure with high-performance aluminum and titanium alloys, stainless steel, and high-temperature polymer composite laminate face sheets [8]. Thus, ATSP foam core sandwich structures can address structural, ballistic, crash impact energy absorption applications.

Conclusions

We developed an ATSP foam core and aluminum foam face three-layer sandwich structure bonded via the foaming process. The interlayer adhesion strength outperformed mechanical limits of the bare aluminum foam. The sandwich structure had superior impact energy absorption performance as compared to the bare aluminum foams. This work provides a framework for

more detailed studies of these materials and demonstrates their utility as composite core materials.

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