Compressive behaviour of glass fiber reinforced aluminium foam

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Abstract : The goal of this study was the analysis of the flatwise and edgewise compression response of closed-cell aluminium foam reinforced by the outer skins made of glass fiber reinforced epoxy matrix and the results were compared with those obtained for aluminium foams without glass fiber skins. Aluminium foams were produced by powder metallurgy method. Glass fiber skins were produced in various orientation angles in order to investigate their effects to the efficiency and capacity of absorbing energy of the sandwich. Glass fiber skins were bonded onto the aluminium foam core by epoxy resin in order to fabricate sandwich panels. As a result, the sandwich panels produced has particular importance for transport industries, such as automotive, aerospace, ship structures.

Keywords: Aluminium foam, powder metallurgy, transport application, sandwich panel

Introduction

Sandwich structures, consisting of glass fiber reinforced plastic (*GFRP*) skins bonded onto low density cores, offer great potential for use in various high performance composite structures which are nowadays widely used in transport industries (aerospace, marine, automobile, shipbuilding), defense because of their high specific stiffnesses and strengths, excellent thermal insulation, fire retardancy, ease of machining and forming among others. Most current sandwich structures are based on polymeric foams (such as *PVC*, *PUR*) and aluminium honeycomb bonded to *GFRP* skins. Recently a great number of metal foams have been developed to replace polymer foams in applications where multi-functionality is important. For instance, acting as a structural component in a sandwich composite but also as a fire retardant, acoustic damper or heat exchanger (Cantwell & Villanueva, 2004).

Several methods have been used to produce multifunctional metal foams. One of them is based on powder metallurgy technique. In this method, the precursor made by hot pressing or extrusion of metallic powder with foaming agent, usually TiH_2, is foamed by heating above the melting temperature of the material (Koza et al., 2003). The advantage of this method is the possibility to produce net shape lightweight parts. This makes these foams especially attractive for automotive, railway and aerospace industries, lifting and conveying systems because of their high capacity of absorbing energy (Yi et al., 2001, Ashby et al., 2000, p. 151-169, Banhart, 2001). As a new multi-function engineering material, aluminium foams *(AF)* have many useful properties such as low density, high stiffness, good impact resistance, high energy absorption capacity, easy to manufacture into complex shape, good erosion resistance, etc. [Banhart, 2001, Degischer & Kriszt, 2002]. This fact opens a wide range of potential applications for sandwich structures with aluminium foam core. As an example, aluminium foam sandwiches (*AFS*) (Ashby et al., 2000, p. 151-169, Gibson & Ashby, 1997), obtained by combining metal face sheets with a lightweight metal foam core, are suitable for applications in automotive industry and ship construction (Banhart et al., 1998), as they allow a speed increase with good passenger comfort, thanks to their specific weight and high damping capacity. The weight minimization influences the energy efficiency of the transport vehicles, reducing fuel consumption and environmental emissions and increasing payload carrying capacity and allowable speed. A design procedure for designing weight minimized hull structures for smaller high-speed craft was developed by Stenius et al. (Stenius et al., 2001).

Characterization of sandwich materials has been investigated in scientific literature. The specification of the sandwich material behaviour under crushing loads and the measurements of absorbing energy capacity and the ductile fracture limits is usually done by means of compression tests (Hayman et al., 2008, p. 417-427, ISO 844:2007, 2007). By this way, it has been understood that cores are the weakest part of sandwich structures and they fail due to shear.

The goal of the present research was the investigation of the flatwise and edgewise compression response of glass fiber reinforced aluminium foam (*GFR-AF*) and the comparison with the *AF* without *GFRP* outer skins in terms of absorbed energy. Primarily, aluminium foams were produced by powder metallurgy method using TiH_2 as foaming agent. Then, hand lay-up method was used to produce the outer skins, made of glass fiber reinforced epoxy matrix, and the skins were bonded onto the both faces of *AF* using same epoxy which was used for the production of GFRP skins. The glass fiber reinforced skins can be easily bonded to the sandwich and it is possible to design the best configuration (base materials, fiber angle orientation, and number of layers) for a specific application. The flatwise and edgewise compression tests were carried out on *AF* and *GFR-AF* specimens by a universal test machine in order to compare and analyze influence of fiber orientation angles of *GFRP* to the efficiency and absorbing capacity of energy.

The obtained results have particular importance for applications that require multifunctional and lightweight structures with a high capacity of energy dissipation, such as the transport industry, where problems of collision and crash have increased in the last years.

Materials and Methods

The specimens were realized bonding two *GFRP* skins to *AF* cores using a commercial epoxy which was used for the production of outer skins (Fig. 1).

Figure 1. *GFR-AF* sandwich sample

The *GFR-AF* sandwich panels produced differ according to the fiber orientation types of *GFRP* skin material. Five different orientation types of outer skin have been investigated: first one $[0^{\circ}]_s$ with four layers, second one biaxial $[0^{\circ}/90^{\circ}]_s$ with four layers, third one biaxial $[45^{\circ}/-45^{\circ}]_s$ with four layers, fourth one symmetrically oriented$[0^{\circ}/90^{\circ}]_s/[45^{\circ}/-45^{\circ}]_s$ with two layers for each and the fifth one antisymmetrically oriented $[0^{\circ}/90^{\circ}]_s/[45^{\circ}/-45^{\circ}]_s$ with two layers for each. The physical and geometrical properties of the *GFR-AF* panels are reported in Table 1.

Table 1. Configuration and properties of the GFR-AF panels.

	Sequence	Number of layers	Material		Orientation Type	density	thickness
			GFR-AF for flatwise compression	GFR-AF for edgewise compression		[kg/m^3]	[mm]
Upper and Lower skin	1 and 3	4	Glass fiber and epoxy resin		$[0^{\circ}]_s$	1180	2.5
					$[0^{\circ}/90^{\circ}]_s$		
					$[45^{\circ}/-45^{\circ}]_s$		
					$[0^{\circ}/90^{\circ}]_s/[45^{\circ}/-45^{\circ}]_s$ symmetric		
					$[0^{\circ}/90^{\circ}]_s/[45^{\circ}/-45^{\circ}]_s$ antisymmetric		
Core	2	1	Aluminium Foam		-	784	30

In the investigation, powder metallurgy method was used to produce aluminium foam cores. According to this method, primarily aluminium powders, with 44 microns, 99.7% purity and 99% of weight ratio, and foaming agent (TiH_2) powders, with 44 microns, 98% purity and 1% of weight ratio, were mixed using 3D mixer during 45 minutes in order to obtain homogenous mixture. Then, pressing at room temperature and 350 MPa pressure, extrusion at room temperature and under 350 MPa pressure and rolling after sintering of the material at 500 ºC processes were performed respectively. And then, the specimens for compressive tests were sawed according to the dimensions given in ASTM standards and inserted into a mould which was made of steel. Finally, the specimens were separately foamed under 700ºC in a furnace observing of foaming process. After the foaming of a sample, it was cooled at room temperature.

Hand lay-up method was used to produce the outer skins, made of glass fiber reinforced epoxy matrix, and the skins were bonded onto the both faces of *AF* using same epoxy which was performed for the production of GFRP skins. According to the hand lay-up method, primarily the type and the number of the layers of the fibers were considered according to the dimensions of *AF* samples and the epoxy resin was prepared according to the mixture ratio given by the company. Then, a release agent was applied to the lay-up surface and finally glass fibers were laid up and impregnated with epoxy resin. It has been waited for about forty eight hours for curing of resin in order to produce *GFRP*. After curing, *GFRP* outer skins were bonded onto aluminium faces of *AF* using same epoxy in order to produce *GFR-AF* compressive test specimens. For curing of epoxy as an adhesive, it has been waited for about forty eight hours, too. All the production process of *GFR-AF* test specimens were schematically presented in Fig.2.

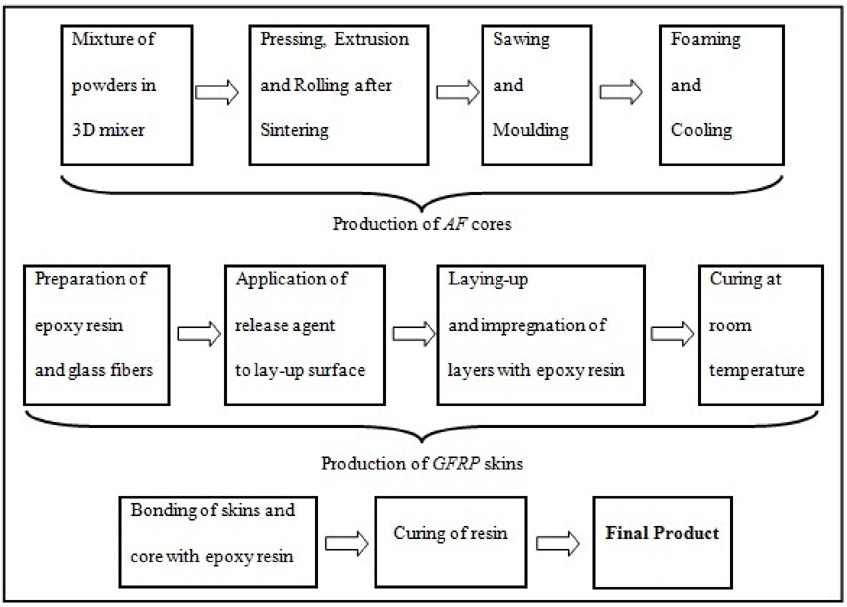

Figure 2. Illustration of production process of *GFR-AF* panels

The presence of the outer skins produces an increment of weight and thickness of about 1.3 and 1.2 times, respectively.

Experimental Investigation

Static flatwise and edgewise compression tests were performed on *AF* (30 x 30 x 30 mm) and *GFR-AF* panels (30 x 30 x 35 mm) with the presence of outer skins. The load was applied at a constant rate of 0.5 mm/min.

Figs. 3 and 4 show the stress-strain curves obtained under flatwise and edgewise compression tests.

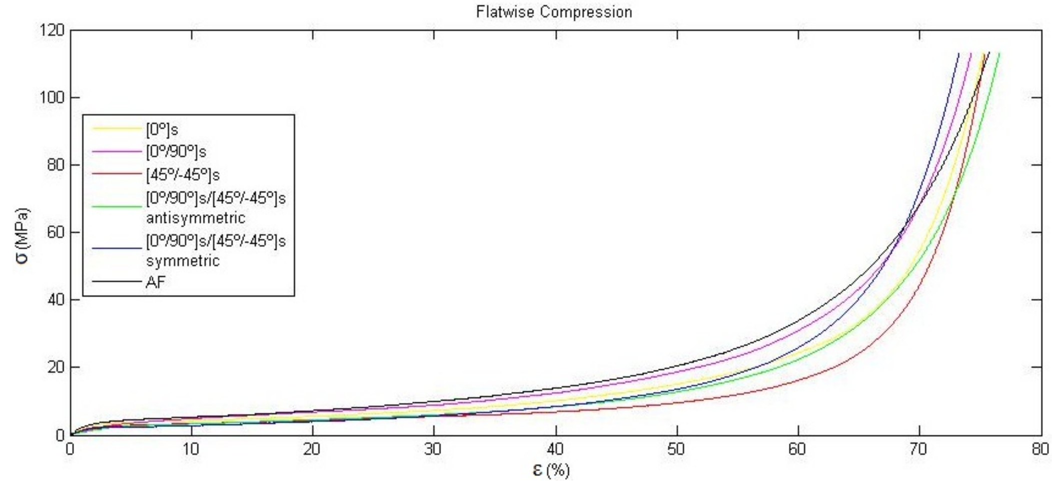

Figure 3. Stress-strain curves measured under static flatwise compression

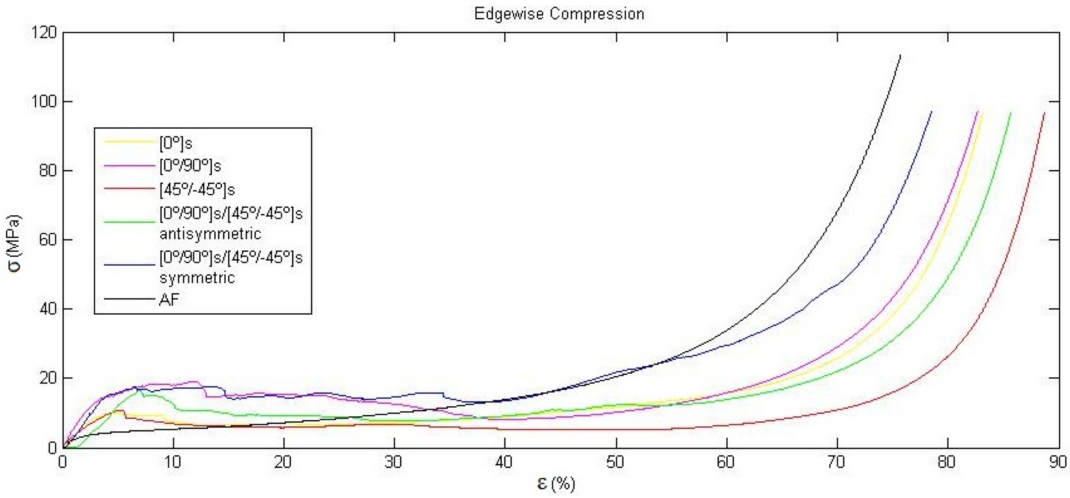

Figure 4. Stress-strain curves measured under static edgewise compression

From the Figs. 3 and 4, it is clear that all the panels exhibit an initial linear elastic behaviour, which is followed by a plateau region with an almost constant flow stress and afterward densification region starts with significantly increment of flow stress. During the flatwise compressive tests, the specimens were collapsed as core crushing and core shear while edgewise compressive specimens were collapsed as core shear and debonding and buckling of *GFRP* skins (Fig.5).

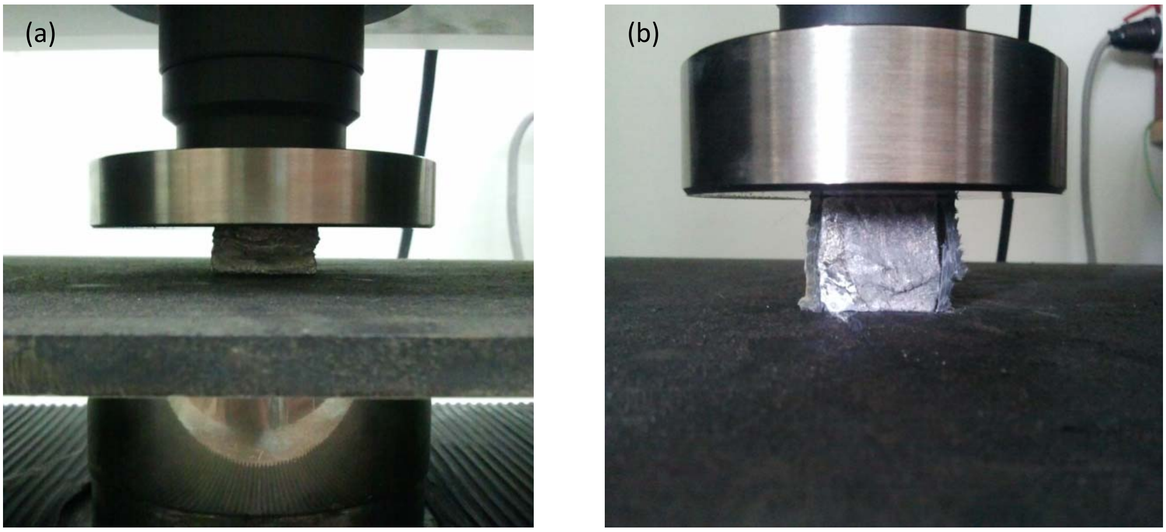

Fig. 5. Collapsed sandwich specimens during (a) flatwise compression with crushing and shear of the core (b) edgewise compression with crushing and shear of the core and debonding and buckling of facesheet.

When the sandwich specimen with foam core is subjected to compression test, the energy absorption capacity is defined as the energy required deforming a given specimen to a specific strain. That's why the energy absorbed per a unit volume of a sample, up to any given strain ε_0, can be evaluated by integrating the area under the stress-strain curve as given by the following expression:

$$E_{abs} = \int_0^{\varepsilon_0} \sigma(\varepsilon)\, d\varepsilon \qquad (1)$$

The energy absorption efficiency η is defined as the energy absorbed up to given strain divided by multiplication of this given strain and the corresponding stress.

$$\eta = \frac{1}{\sigma_0 \varepsilon_0} \int_0^{\varepsilon_0} \sigma\, d\varepsilon \qquad (2)$$

In Eqs. (1) and (2), ε_0 is the given strain, σ_0 is the corresponding compressive stress and σ is the compressive stress as the function of strain ε.

The maximum η during whole compression process and energy absorbed at certain strain are presented in Table 2. η_{max} and E_{abs} values are energy absorption efficiency and energy absorbed during compression at strain of 30% respectively.

Table 2. Energy absorption of samples under flatwise and edgewise compressive loading

		Flatwise Compression		Edgewise Compression	
		η_{max} [%]	E_{abs} [MJ.m^{-3}]	η_{max} [%]	E_{abs} [MJ.m^{-3}]
GFR-AF	$[0^\circ]_s$	67	1.47	71	2.13
	$[0^\circ/90^\circ]_s$	63	1.68	77	4.42
	$[45^\circ/-45^\circ]_s$	69	1.14	70	1.98
	$[0^\circ/90^\circ]_s/[45^\circ/-45^\circ]_s$ symmetric	61	1.04	83	4.34
	$[0^\circ/90^\circ]_s/[45^\circ/-45^\circ]_s$ antisymmetric	64	1.15	74	2.80
AF	without skins	63	1.87	63	1.87

The results show that the effects of the configuration of the *GFRP* skin materials are not as significant as those on energy absorption capacity and energy absorption efficiency under flatwise compression. Configuration with $[0^{\circ}/90^{\circ}]_s$ and symmetrically oriented $[0^{\circ}/90^{\circ}]_s/[45^{\circ}/-45^{\circ}]_s$ show the largest energy absorption capacity and energy absorption efficiency among all orientations under edgewise compression in our study.

Conclusions

The investigation presented in this paper is a part of a larger project aimed at the introduction of lightweight structures, made of *GFR-AF* sandwiches, in transport industry (such as aerospace, automotive and shipbuilding industry).

The static flatwise and edgewise compressive responses of *AF* reinforced by *GFRP* outer skins were investigated and compared with those of *AF* without outer skins.

The experimental tests have demonstrated that the light-weight aluminium foams are efficient energy absorbers and the amount of energy absorption under edgewise compression tests can be improved up to about 2.5 times reinforcing them by means of *GFRP* outer skins which have various orientation angles although *AF* reinforced by *GFRP* skins under flatwise compression tests can not show effects as significant as those on the amount of energy absorption comparing them *AF* without outer skins.

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