

Compressive Behavior and Energy Absorption Capability of Reinforced Closed-Cell Aluminum Alloy Foams

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Abstract. In recent years aluminum foams and lightweight composite structures with foam core became popular in aerospace as well as in the automotive industry, because of their unique mechanical properties combined with a very low density. This paper investigates and compares the mechanical behavior, the collapse modes and energy absorption capability of unreinforced and reinforced (with 2 different reinforcement positions) aluminum foam composite structures. Quasi-static compressive tests have been undertaken under three different directions and the reinforcement effect on the main mechanical properties (Young's modulus, yield stress, plateau stress and densification) was investigated. The tested closed-cell aluminum alloy foams with a density of 325 kg/m³ were reinforced with stainless steel mesh. It has been shown that the compression strength and energy absorption performances of the composite foams can be optimized through the correct positioning of the reinforcements.

1. Introduction

The current interest in every field of today's engineering world is to increase the use of lightweight materials and integrate them into vehicle designs in order to improve the economy efficiency and reduce the structure weight, without affecting other attributes such as cost, performance, comfort, safety etc. [1-4]. During the last two decades, the fully dense solid materials (e.g. steel, Al, Cu, polymers etc.) have lost slowly their applicability, while the use of porous materials (metallic foams, polymeric foams etc.) has experienced a rapid growth mainly due to their applications as core material in advanced composite structures [5-8]. Porous materials are a relatively new class of structural and functional materials exhibiting unique mechanical, physical and other properties that make them attractive in a many wide range of critical structural engineering applications [9-12]. Moreover, these cellular materials have high stiffness-to-weight ratio, high ability to absorb impact energy, exceptional heat transfer ability, good formability, good corrosion resistance and recycling potential that makes them ideal candidates for replacing high density materials [13-16].

Different types of foam materials [17-21] have been investigated experimentally under static [22-24] and impact [25-27] loading conditions. Of the most commonly used metal foams are those produced from aluminum alloys and in particular closed-cell aluminum alloy foams [28, 29]. Most studies have been carried out on conventional aluminum foam [30-32] while a small number of investigations have focused on metal matrix syntactic foams or composite foams [33, 34]. Thermal properties of closed-cell aluminum foams prepared by melt foaming technology was evaluated by Wang et al. [35], while Xia



and coworkers [36] investigated the acoustic properties of closed-cell aluminum foams with different macrostructures. On the other hand, the mechanical behavior of aluminum foams is investigated in Refs. [1, 5, 17, 25, 28-34]. These studies have focused on the effect of temperature, density, microstructure, anisotropy, strain rate, reinforcements and foaming parameters on main mechanical properties of aluminum foams.

Therefore, this paper investigates the compressive behavior and energy absorption crush performances of different types of closed-cell aluminum alloys foams (unreinforced and reinforced foams) under quasi-static loads. Two types of composite foams with both longitudinal and transversal reinforcements were evaluated, and the optimal foam design is highlighted.

2. Materials and methods

Stainless steel mesh with diamond shape of 6 mm $\times$ 3 mm and 1 mm (width) $\times$ 0.5 mm (thickness) was used as reinforcement materials (Fig. 1a). The austenitic Cr-Ni stainless steel reinforcements (X5CrNi 18-10) with a composition of Cr 17-19.5 %, Ni 8-10.5%, C<0.07% presents a square weight of 3.4 kg/m². Powder metallurgical route was used for manufacturing of metal foam matrix composites [37].

The stainless steel mesh were inserted into the mold together with precursor and during the foaming process the reinforcements were infiltrated with molten material, thus forming a metallurgical bond between foam and steel (Fig. 1b). Foamable AlSi10 precursor material containing 0.4 wt.% of TiH₂ as foaming agent was foamed, kept at high temperatures (620°C) and solidified. The chemical composition of obtained closed-cell aluminum alloy foam is 10 wt.% Si and aluminum balanced.

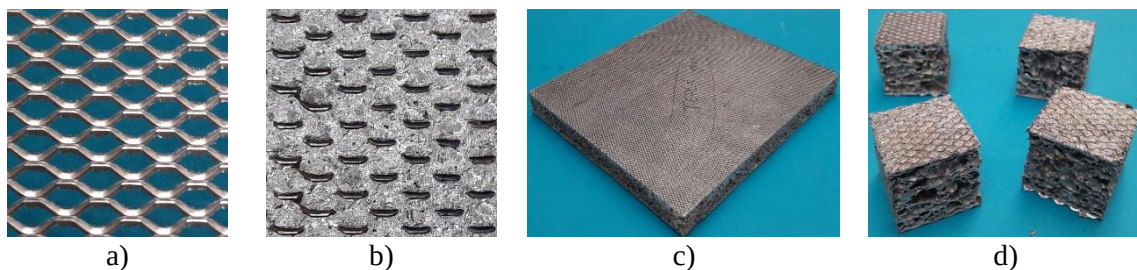


Figure 1. Used materials: stainless steel mesh as reinforcement (a), formed metallurgical bond (b), obtained aluminum foam plate (c) and processed cubic specimens (d)

Large composite foam plate was foamed (Fig. 1c), and processed as cubic specimens (25 mm $\times$ 25 mm $\times$ 25 mm) (Fig. 1d). In order to prevent any damage to the cellular structure, the cubic foam samples were cut by Electric Discharge Machining (EDM).



Figure 2. The macrostructure morphology of the investigated composite foams

All cubic specimens were cut from the same reinforced plate under three different loading directions, as follow: direction (1) – unreinforced aluminum foams (**UR-AFs**); direction (2) – foams with longitudinal reinforcements (**LR-AFs**) and direction (3) – foams with transversal reinforcements (**TR-AFs**). The macrostructure morphology of the investigated composite foams is presented in Fig. 2 for each direction. The obtained average foam density was 325 kg/m^3 .

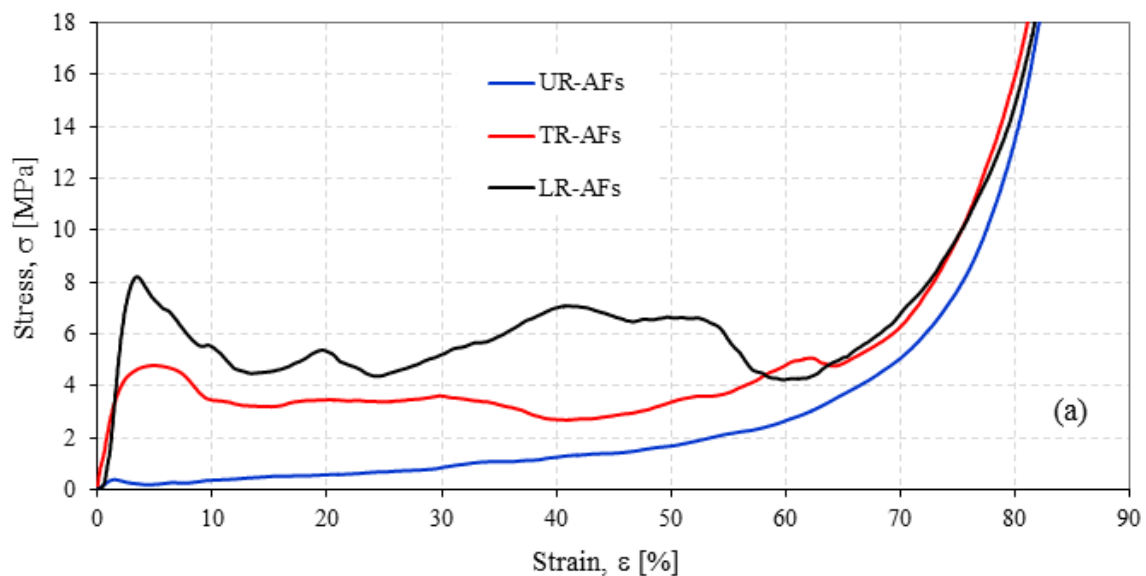
Quasi-static compression tests were carried out at room temperature ($\sim 25^\circ\text{C}$) on a 100 kN LBG testing machine, with a constant crosshead speed of 10 mm/min. Five specimens were provided for each loading direction according to the ISO13314-11 standard [38]. Figure 3 shows the initial and deformed specimens after mentioned three different loading directions.



Figure 3. Initial and deformed specimens

3. Results and discussion

Figure 4a presents the typical stress-strain curves up to approximately 80% engineering strain, while Fig. 4b presents different deformation sequences (0%, 20%, 40%, 60% and 80%) of unreinforced and reinforced aluminum foams.



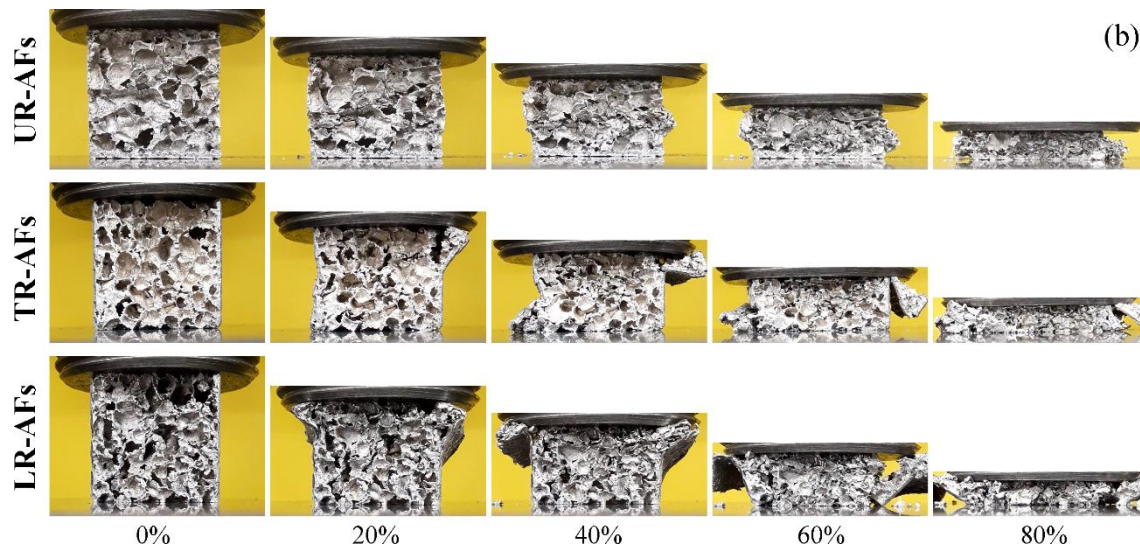


Figure 4. Stress-strain curves (a) and deformation sequences (b) for different investigated AFs

The main mechanical properties of investigated closed-cell aluminum alloy foam specimens were determined based on [38] and are presented in Table 1, depending on the loading directions.

Table 1. The main mechanical properties of investigated closed-cell aluminum foams.

Reinforcement type	Linear-elastic region			Plateau region			Densification region		
	E [MPa]	σ_y [MPa]	ε_y [%]	$\sigma_{20\%}$ [MPa]	$\sigma_{50\%}$ [MPa]	σ_p [MPa]	σ_D [MPa]	ε_D [%]	W_D [MJ/m ³]
UR-AFs	34.17	0.39	1.49	0.57	1.68	0.88	1.14	38.25	0.23
TR-AFs	235.69	4.78	5.06	3.46	3.38	3.33	4.33	57.87	1.98
LR-AFs	476.80	8.20	3.44	5.32	6.63	5.40	7.02	70.46	3.93

In Table 1, the following notations were used: E is the compressive modulus determined from this linear-elastic region; σ_y - compressive yield stress (the first point on the σ - ε curves from which an increase in strain occurs without an increase in stress); ε_y - yield strain corresponding to σ_y ; $\sigma_{20\%}$, and $\sigma_{50\%}$ compressive strength at 20% and 50% strain; σ_p - plateau stress; ε_D - onset strain of densification (OSD); σ_D - compressive strength corresponding to OSD.

The obtained stress - strain curves of investigated AFs are commonly to those studied by other groups of researcher both for unreinforced and reinforced cellular structures or porous structures [39-42]. The σ - ε curve exhibits three different definite regions: (i) an initial linear-elastic behavior at low stresses (<5% strain), controlled by the cell-wall bending and stretching; (ii) a long plateau region where foam cells collapse through cell-wall buckling, cell-wall plastic yielding, cell-wall brittle crushing and/or cell-wall fracture; and (iii) a densification region at large compressive strains (>40% strain), when the cells have almost completely collapsed [43, 44].

It has been observed that UR-AFs foam shows approximately a linear increase in stress after the yield limit (on the plateau region), while the both reinforced (TR-AFs and LR-AFs) foams exhibit oscillating character during plateau region from the very early stages of compression up to onset strain of densification.

By using reinforcements, the compressive modulus increase by 7 times for TR-AFs and 14 times for LR-AFs, compared to unreinforced foams. On the other hand, as it can be observed from Table 1, the compressive strength increases much more (up to 21 times for LR-AFs and 12 times for TR-AFs) for

reinforced foams than those unreinforced. Also, reinforced foams show a much longer plateau region, with an onset strain of densification with 33.90% (for TR-AFs) and 45.71% (for LR-AFs) higher, compared to UR-AFs which presents an OSD of 38.25%. At the same time, the energy absorption values at OSD are up to 17 times higher for reinforced than for the unreinforced ones.

According to the obtained results (Fig. 4a and Table 1) it was found that the drop stress (which occurs after the first maximum compressive strength) reaches up to 67% of the yield stress for reinforced foams, while this value is about 49% for unreinforced foams. Figure 5 presents the drop stress amplitudes ($\Delta\sigma$) of investigated foams under different loading directions. The difference of amplitudes between the unreinforced and reinforced foams, in terms of drop stress, increases linearly.

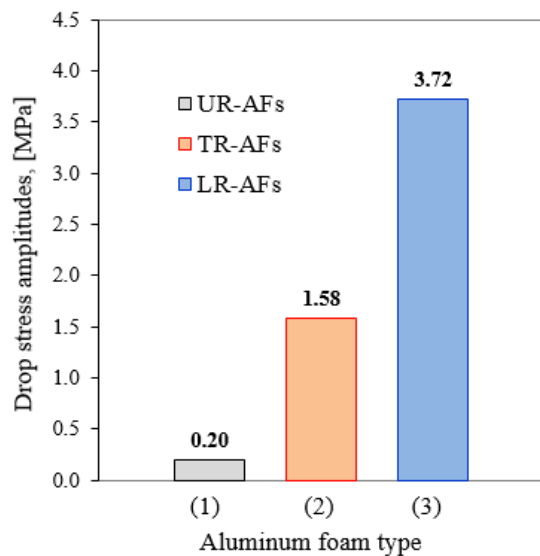


Figure 5. $\Delta\sigma$ amplitudes of AFs.

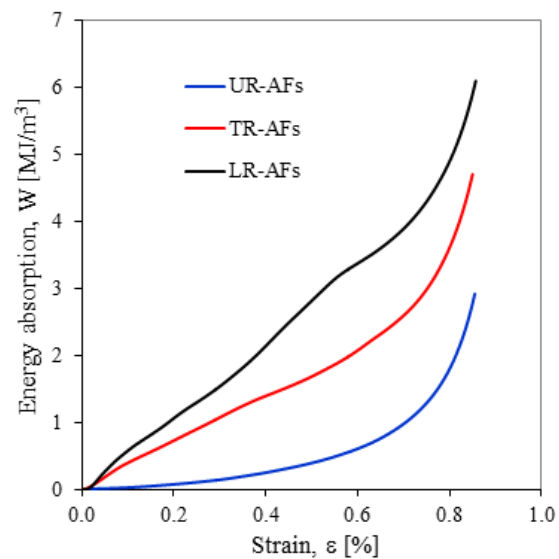


Figure 6. $W - \varepsilon$ variation of AFs.

Due to their cellular structure, the closed-cell foam structures presents high energy absorption capability than the solid materials from which they are made [45, 46]. The energy absorption-strain variation of closed-cell aluminum alloy foams is presented in Figure 6 for all loading directions. The area under true stress - strain curve, from its origin up to a given value of strain, represents the energy required or stored in the material before its failure [47]. Most of the energy (around 80% of the total amount of energy) is absorbed in the plateau region of the $\sigma - \varepsilon$ curve because the collapse mechanisms occur [48].

Table 2. The energy absorption values of investigated AFs for different loading directions.

Reinforcement type	Energy absorption at different strains, W [MJ/m ³]							
	10%	20%	30%	40%	50%	60%	70%	80%
UR-AFs	0.03	0.07	0.14	0.25	0.39	0.61	0.98	1.81
TR-AFs	0.4	0.73	1.08	1.4	1.69	2.08	2.6	3.62
LR-AFs	0.58	1.07	1.54	2.14	2.82	3.38	3.9	4.91

As can easily be seen from Figure 6, but especially from Table 2, the use of reinforcements significantly increases the ability of the aluminum foams to absorb energy. Major differences have been achieved in the area of small deformations (around 10%) where LR-AFs foam has up to 20 times better energy-absorption capacities than UR-AFs foam, while TR-AFs up to 14 times compared to UR-AFs foam. In the case of large deformations (over 60% strain), this difference considerably decreases

approximately linearly to about 4 times for LR-AFs and about 3 times for TR-AFs, compared to unreinforced aluminum foams. Moreover, remarkable W differences can be seen also between the two directions where reinforcements are positioned differently. The foams with longitudinal reinforcements shows energy absorption capacities up to 40% better than the foams with transversal reinforcements. Therefore, a correct positioning of reinforcements leads to a significant increase of foam crush performances, which can sometimes be very important.

4. Conclusions

The uniaxial quasi-static compressive behavior and energy absorption capabilities of unreinforced and reinforced closed-cell aluminum alloy foams are experimentally investigated.

The following conclusions can be drawn:

- The reinforced foams show higher mechanical properties than unreinforced foams (up to 21 times);
- The LR-AFs shows significantly higher crush performances compared to TR-AFs;
- It has been found that the compression strength and energy absorption values of composite foams can be optimized through the correct positioning of the reinforcements. In this case the foams with longitudinal reinforcements shows the optimal design of foam composite structures.

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Acknowledgment

This work was supported (partial supported) by research grants PCD-TC-2017.