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Crush performance of multifunctional hybrid foams based on an aluminium alloy open-cell foam skeleton

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Abstract

Multifunctional hybrid foams were developed and tested by combining aluminium alloy open-cell (OC) foam specimens with polymers, epoxy resin and silicone rubber. The rectangular OC foam specimens were impregnated with polymer, completely filling the voids. The aim of this work was to evaluate the effect of the polymer presence in the voids of aluminium alloy OC foam specimens (varying their size, e.g. height to width ratio) on the crush performance of the resulting hybrid foams. Quasi-static and dynamic uniaxial compressive tests and infrared thermography were used to compare the behaviour of hybrid foams with conventional (unfilled) OC foam specimens. Results show an improvement of the compressive strength and energy absorption capacity of hybrid foams, especially when infiltrated with epoxy resin. The results show that the epoxy leads to higher capacity of specific energy absorption of the hybrid foams, while silicone leads to lower capacity of specific energy absorption in comparison to the OC foam specimens. The high energy absorption values of OC foams embedded with silicone are not enough to compensate for the mass increase due to the

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silicone filler. The use of the polymers as a void filler changes the typical layer-wise collapse mechanism of the OC foam. The silicone rubber causes a non-symmetric deformation, being much more complex and unstable in the case of the longer hybrid foams, which deform by buckling (lateral instability). The epoxy resin enforces a symmetric deformation by folding in the middle of the hybrid foams.

Keywords. Open-cell aluminium foams; Polymer filler; Hybrid foams; Compressive behaviour; Deformation modes; Energy absorption.

1. Introduction

Cellular metals (e.g. open- and closed-cell foams) are being increasingly used in modern engineering structures due to many advantageous properties. Closed-cell foams exhibit high stiffness-to-weight ratio and high energy absorption capacity that make them ideal as energy absorbers in vehicles [1]. Closed-cell foams have been tested or used as a filler or core of thin-walled structures [2-4] or as a core in sandwich panels [5-6]. Open-cell (OC) foams exhibit increased thermal and electrical conductivities due to the network of open cells and high internal surface area of interconnected pores. They are being used or tested as filters, catalysts, heat exchangers, or even in biomedical applications as orthopaedic prosthesis, scaffolds and bone implants [7].

However, it is much easier to control the cellular structure of OC foam than closed-cell foams during fabrication, ensuring the fabrication of high quality foams [8]. In fact, there is still no fabrication method available that would allow for efficient control of closed cell foam cellular structure during its formation [9]. Commonly, closed-cell foams have a non-uniform pore distribution, exhibiting pores with different shapes and sizes with imperfections and structural defects [10]. Therefore, it is more difficult to predict the mechanical properties of closed-cell foams in comparison to OC foam specimens, which somewhat limits their application as structural materials.

We developed and tested hybrid foams by combining open-cell foam and polymers (epoxy resin and silicone rubber), to be used as structural materials. The open-cell foam specimens were completely impregnated with polymers to enhance their mechanical strength, thus creating a multifunctional material. We believe that in this way it is possible to achieve desired functionality necessary to satisfy requirements of a specific application. Few works have been published in this field [11-19], developing and testing hybrid foams based on both metal open-cell structures [12-15] and closed-cell foams [16-19]. Herein, further research in this field is presented in which the hybrid foam specimens of different sizes, combining aluminium alloy open-cell foam and two different polymer types, were developed, fabricated, tested and mechanically characterized.

2. Materials and experimental methods

2.1. Preparation of the specimens based on open-cell foam

A plate of AlSi7Mg0.3 open-cell (OC) foam ($300 \times 150 \times 50 \text{ mm}^3$) with pore sizes of 10 ppi (pores per inch) fabricated by the investment casting method [19] was used in this study. The OC foam was fully filled by the silicone polymer rubber and epoxy resin. The silicon polymer was supplied by company TKK d.o.o. (Slovenia) [20] and comprised of component A (80 wt. %; $\rho = 1260 \text{ kg/m}^3$, $\mu = 25\text{--}30 \text{ Pa}\cdot\text{s}$), component B (4 wt. %; catalyst) and component C (16 wt. %; silicone oil). The epoxy resin was supplied by company KGK d.o.o. (Croatia) [21] and had a density of 1100 kg/m^3 and compression strength of 90.4 MPa.

Thirty foam specimens of two different sizes (15 of size $22 \times 22 \times 25 \text{ mm}^3$ and 15 of size $22 \times 22 \times 50 \text{ mm}^3$) were cut from the original OC foam plate. They were used to prepare six specimens of each size of the OC foam and silicone filled open-cell (SOC) foam type and three specimens of each size of the epoxy filled open-cell (EOC) foam of each size. The SOC and EOC foam specimens were prepared by pouring or injecting the silicone and epoxy, respectively, into a thin-walled tube containing an OC foam specimen. The inner surface of the tubes was cleaned, polished and greased before inserting the OC foam specimen. The SOC foam specimens were prepared by injecting the liquid silicone rubber mixture under vacuum (0.5 MPa). The liquid mixture was further left in the vacuum chamber to avoid formation of residual air bubbles after filling the foam with silicone rubber. The EOC foam specimens were prepared by simply pouring the liquid epoxy mixture at room temperature, since there was no danger of bubbles appearing due to lower viscosity of epoxy. The SOC and EOC foam specimens were extracted from the thin-wall tubes after the filler polymer cured completely. **Fig. 1** shows the resulting specimens: the OC foam (**Fig. 1a**), the SOC foam, (**Fig. 1b**) and the EOC foam (**Fig. 1c**). Their physical characteristics are listed in **Table 1**.

2.3. Mechanical characterisation

All specimens were mechanically characterised with uniaxial compression tests. The OC foam and SOC foam specimens were tested using a servo-hydraulic dynamic INSTRON 8801 testing machine with the maximum load of 50 kN at cross-head rates of 0.1 mm/s (quasi-static) and 284 mm/s (dynamic). The EOC foam specimens possessed higher mechanical strength and were tested using an electro-mechanical RAAGEN testing machine with the maximum load of 250 kN only at quasi-static loading conditions. In both cases, the upper compression plate was fixed while the lower plate compressed the specimens at prescribed rate. The specimens were monitored during testing by a high definition video camera and by a cooled middle-wave infrared (IR) thermal camera Flir SC 5000 (with frame rates up to 700 Hz) [22]. All foam specimens tested under dynamic condition were sprayed with black paint for easier monitoring of thermal emission. The compressive performance of studied structures was analysed according to ISO 13314: 2011 [23]. The engineering stress-strain diagrams were determined through load-displacement data and the initial dimensions of the specimens. Energy absorption characteristics of all foam specimens were analysed using the energy absorption capacity (absorbed energy per unit volume), specific energy absorption and energy absorption efficiency. The absorbed energy per unit volume (strain energy density) was calculated by integrating the stress-strain curves. The specific energy absorption was calculated by dividing the strain energy density with the mass of the foam specimen. The energy absorption efficiency was calculated according to Eq. (1) [23],

$$\frac{\int_0^{\epsilon_d} \sigma(\epsilon) d\epsilon}{\sigma_{\max}(\epsilon) \epsilon_d} \times 100 [\%] \quad \text{Eq. (1)}$$

where σ is the stress and $\sigma_{\max}$ is the maximum stress, which occurs up to densification strain (ϵ_d). According to this standard, the plateau stress was determined as the mean stress between the 0.2 and 0.4 strain, while the densification strain corresponds to the strain where stress reaches 1.3 of the plateau stress.

3. Results and discussion

3.1. Compressive behaviour

Sequences of images recorded during uniaxial compression tests of the OC foam, EOC foam and SOC foam specimens with different heights (25 and 50 mm) subjected to quasi-static loading condition are shown in the **Figs. 2, 3 and 4**, respectively. The results clearly show that the deformation mode of the OC foam changed due to the presence of a polymer in the voids of the foam, and is governed by the properties of the polymer used (epoxy and silicone).

The failure of OC foam specimens under compression loading (**Fig. 2**) is characterized by progressive ductile plastic collapse due to the bending and buckling of individual ligaments [7]. These specimens deform initially at several weak points (e.g. pre-existing defects) throughout the cellular structure, followed by the layer-by-layer collapse perpendicular to the loading direction. The results clearly show that the influence of the specimen size (height-to-width ratio) on the deformation and failure mode of the OC foam specimens is negligible.

However, the presence of the polymer filler significantly changes the deformation and failure mode of the OC foam specimens. The results indicate that the chemical nature of the polymer has a strong influence on the deformation and failure mode of these specimens. Non-symmetric deformation was observed for SOC foam specimens (**Fig. 3**), being much more complex and unstable in the case of the longer specimens (height $\approx$ 50 mm). The aspect ratio (height-to-width ratio) effect on the deformation and failure mode of the OC foam is significant if compared to the OC foam specimens without polymer filler. The shorter SOC foam specimens (height $\approx$ 25 mm) show slight barrelling which is more pronounced at one side of the sample (**Fig. 3a**). No deformation bands are visible in these hybrid foams. The longer SOC foam specimens (**Fig. 3b**) deformed by buckling, i.e. they lost their stability under axial compressive load, which leads to lateral instability. Hence, the longer SOC foam specimens deflected laterally and their failure was primarily caused by bending, rather than direct uniaxial compression. A change from axial compression to lateral bending of the overall

specimens with several buckles, as observed (**Fig. 3b**). The initial deformation starts at the loading and support plates, where the material accumulates, while the cross-section in the middle of the specimens remains almost unreformed. Consequently, the buckling is initiated in the middle of the specimen. This behaviour is undoubtedly associated with the presence of the silicone rubber in the voids of the OC foam, since this effect has not been observed in the case of the larger OC foam specimens without polymer filler (**Fig. 2b**). Low adhesion of the silicone to the struts of the OC foam specimens is observed, as well as a lower friction coefficient between them. The silicone rubber is a chemically stable elastomer in which the silicon atoms are linked to carbon, hydrogen and oxygen atoms [24]. It has weak intermolecular forces among polymer chains, in which the Si–O bond has greater bond length and fewer alkyl groups than C–C bond. Due to this, the silicone rubber has lower mechanical strength, which limits its structural application [25]. As is known, elastomers, e.g. silicone, behave differently in comparison to the other polymers (e.g. epoxy resin), since their structure is highly deformable and self-restoring. This feature is the reason why they are used in numerous applications, [26]. Silicone rubbers are widely used in the automotive industry due to their excellent thermal properties, exceptional durability, stable mechanical performance over wide temperature range and high corrosive resistance. Thus, they are incorporated in a wide range of car parts, such as tyres, heat-resistant engine seals, airbags, engine gaskets, headlamps, hydraulic bearings, ignition cables, radiator seals and hoses, shock absorbers, electronics and cable insulation [27]. Nonetheless, they exhibit lower mechanical strength compared to other polymers, such as epoxy resin, which has also been used in this work.

Very different behaviour was observed for the EOC foams, i.e. hybrid foams with epoxy resin filler. Under compression, they exhibited symmetric deformation, i.e. barrelling in the centre of the specimen (**Fig. 4**). The deformation and failure modes were similar at both specimen lengths. The epoxy resin obviously contributes to better stability of the cellular network of the OC foam during compression in comparison to silicone rubber (**Fig. 3**). The epoxy resin is a macromolecular polymer

composed of long carbon chains with very strong chemical bonds between the carbon atoms [28]. The failure mode of epoxy resin is attributed to the breaking of their long chains, separating the molecules across planes and changing the orientation of the carbon chains. Epoxy resin usually exhibits brittle behaviour, which can be clearly observed from **Fig. 7**.

The failure and deformation modes of the OC and SOC foam specimens were also studied using the IR thermography when the specimens were tested under dynamic loading conditions, as shown in **Figs. 5** and **6**, respectively. The temperature (heat) distribution on the cellular structure surface and the plastification front propagation was observed by IR thermography [29]. IR thermography has proven to be an efficient technique to detect plastification zones in structures based on cellular metals, such as open-cell foam [30], closed-cell foam [31], syntactic foam [32], advanced pore morphology spherical foam [33] or even hollow structures filled by cellular metals (e.g. foam filled tubes) [34].

From the IR images (**Fig. 5**), it can be clearly observed that the OC foam starts to deform at several weak points (pre-existing defects or structural imperfections) and then the deformation spreads throughout the cellular structure. The deformation of shorter OC foam specimens was located only at the bottom of specimens and no significant deformation was observed at the top. On the other hand, the longer foam specimens showed similar deformation at their top and bottom. These two deformation regions came closer to each other during compression, until they formed a single deformation band. Random or layer-wise plastification was clearly observed in the OC foam specimens, where the plastification wave propagated from layer to layer. The dynamic compression of the OC foam is thus characterized by layer-wise collapse of their intercellular struts.

IR thermography was also used to observe the plastification process of the SOC specimen (**Fig. 6**). The effect of the height-to-width ratio on the global deformation mode of the SOC foam specimens was observed by the IR thermography, especially the formation of the significant transversal deformation in longer foam specimens, which was accompanied by heat release (blue colour).

Tangential shear bands were observed in the cross-section of the shorter SOC foam specimens. There was no layer-wise collapse mechanism observed for these hybrid foams. However, a deformation front propagating from the lower moving compression plate towards the upper fixed plate is visible. In the case of shorter SOC foam specimens, no horizontal plastification front is observed, as in the case of OC foam specimens without polymer filler. The silicone rubber seems to prevent the self-contact of struts. The stress distribution throughout the SOC foam specimens strongly depends on the incompressibility of the silicone. The results indicate that the information provided by IR thermography depends on the type of structures studied.

The appearance of different deformed foam specimens after the compression test (quasi-static loading condition) is shown in **Fig. 7**, demonstrating their different deformation modes.

Fig. 8 shows the compressive stress-strain relationships of the hybrid foams. The comparison of the OC and SOC foam specimens for both specimen lengths is shown in **Fig. 8a**, while the comparison of the OC and EOC foam specimens is shown in **Fig. 8b**. It can be clearly observed that the mechanical performance of the OC foam specimens was enhanced by impregnating the OC foam specimens with a polymer filler, either silicone (**Fig. 8a**) or epoxy (**Fig. 8b**). However, the level of enhancement strongly depends on the chemical nature of the polymer filler used. The polymer filler creates additional viscous resistance at failure of individual pores of the foam. This effect is less pronounced in the SOC foam specimens (**Fig. 8a**). Nonetheless, the SOC foam specimens still exhibit higher strength than the OC foam specimens, especially in shorter specimens. The values of the initial stress peak are ~ 0.47 MPa and ~ 0.17 MPa for the short and long SOC foam specimens, respectively. The OC foam specimens exhibit slightly lower values, e.g. 0.31 MPa and 0.14 for short and long specimens, respectively.

As expected, the compressive stress-strain response of shorter foam specimens is superior to the response of longer foam specimens due to aspect ratio effect. The values of the initial peak stress

change from 0.31 MPa, 0.47 MPa and 75 MPa to 0.14 MPa, 0.17 MPa and 22 MPa for short and long OC, SOC and EOC foam specimens, respectively.

The OC and SOC foam specimens exhibit a typical plateau- stress response of the conventional foam specimens, which is clearly divided into three regions: (i) the initial elastic region, where the foam deformation is controlled by deformation of the pore-wall due to bending and axial forces; (ii) the plateau region, where the foam exhibits a long stress-plateau due to progressive layer-by-layer pore collapse by elastic buckling, plastic collapse or brittle crushing; (iii) the densification region, where the foam densifies due to the contact of the cell struts, resulting in an abrupt increase of the stiffness. However, there are some differences between the specimens. The stress fluctuation observed in the OC foam specimens, in particular in the plateau region (**Fig. 8a**), are due to the layer-wise brittle collapse described above. The silicone in SOC specimens effectively smoothens and stabilizes the response of the OC foam specimens, decreasing the stress oscillations in the plateau region and increasing the values of their mechanical properties.

The OC foam specimens show much longer plateau regions compared to the hybrid foams that were the first to enter the densification region due to polymer filler. The stress state of the SOC foam specimens increases slightly through the plateau region, while the stress state remains much more constant throughout the plateau region of the OC foam specimens (**Fig. 8a**). The compressive response is much more unstable in the case of longer specimens.

The results also demonstrate that OC and SOC foam specimens are sensitive to strain rate, but not in the same manner. The observed dynamic response of the OC foam specimens was higher than the static compressive response. This is in agreement with our previous research that demonstrated the strain rate sensitivity of the closed-cell aluminium foam prepared by powder metallurgical method [10]. In contrast, some other published studies demonstrated that aluminium foams are strain rate insensitive [28]. The SOC foam specimens are also strain rate sensitive. Curiously, the dynamic response (red curves, **Fig. 8**) is below the static response (black curves, **Fig. 8**), in the initial region

up to strain ~ 0.2 . This behaviour is similar to that observed for integral-skin closed-cell aluminium alloy foams with radial constraints [31].

The compressive stress-strain curves of the SOC foam specimens are strongly related to the chemical nature of the silicone rubber and are associated with their deformation mode discussed above. The silicone rubber (gel-like material) behaves as an elastomer, showing weak intermolecular interactions and high chain mobility. This leads to low adhesion and low friction coefficient between the silicone rubber and the struts of the OC foam. On the other hand, the stiffness of the silicone rubber ($\sim 5\text{--}11\text{ N/mm}^2$) is inferior in comparison to the stiffness of the base material, i.e. aluminium alloy ($\sim 270\text{ N/mm}^2$). This may explain the small enhancement of the mechanical strength when compared to the other studied polymer (epoxy resin).

The EOC foam specimens exhibit a significantly higher level of compressive stress (**Fig. 8b**) with rather high values of the initial peak stress of 75 MPa and 22 MPa for short and long specimens, respectively. This is clearly attributed to the presence of the brittle epoxy resin in the voids of the OC foam specimens that have a high stiffness (compressive strength $\approx 190\text{ N/mm}^2$). The EOC foam specimens do not exhibit a stress-strain relationship typical for the metal foams. The compressive stress-strain curves of the EOC foam specimens are in fact very similar to the curves obtained for the empty aluminium tubes as well as the *ex-* and *in-situ* foam filled tubes [3,4]. The curves can be divided into the following regions: the initial linear elastic region up to the peak stress, followed by a rapid stress drop region to a given minimum value of stress, the stress fluctuation region and finally the short densification region. The EOC foam specimens deform with the formation of a fold in the middle of the specimen with visible cracking during the folding at both quasi-static and dynamic loading conditions (**Figs. 4 and 7**). The cured epoxy is very brittle, which leads to the development of small cracks that are associated with the barrelling deformation. An unstable crushing region before the densification region is attributed to the formation of larger cracks (**Fig. 7**).

The observed results are in good agreement with published studies on the investigation of metal foams (steel and aluminium foams) impregnated with polymers, such as polyethylene, polyamide, epoxy, expandable polystyrene and polyurethane [11-15]. They report that all of these polymers have a positive effect on the thermal and mechanical parameters of the hybrid foams (e.g. peak load), with improved energy absorption capability, while retaining a typical long plateau region. The combination of the OC foam and polymer filler ensures an increase of mechanical properties, in which the polymer and the foam contribute to the strength and thermal stability, respectively. The same conclusions were demonstrated by Stöbener and Rausch [16], who developed a novel hybrid foam by bonding spheres of closed-cell aluminium foam called Advanced Pore Morphology (APM) foam elements by (5-20 wt.%) polymers. Vesenjok et al. [12-15, 35] also demonstrated through experimental and computational studies that the mechanical behaviour of OC foam specimens is influenced by the polymer filler, increasing their energy absorption capability. Structures with higher relative density are more influenced by the filler due to higher flow resistance. The results also show that the compressive strength of the hybrid foams increases by increasing the density of the foam. Thus, the influence of the density on the mechanical properties of hybrid foams is similar to the OC foam [7]. Results reveal that the density is the superior parameter that influences the compressive strength of hybrid foams.

3.2. Energy absorption capacity

The energy absorption density (EAD) to strain relationship for the hybrid foam specimens (SOC and EOC foam specimens) in comparison to the OC foam specimens is shown in **Fig. 9**. The values were calculated by integrating the compressive stress-strain curve from 0 up to the strain at the end of each test. The EAD values given in **Table 2** have been integrated up to the densification strain (according to ISO 13314: 2011). From the figure, it can be observed that the polymer filler (silicone and epoxy) contributes to the increase of the energy absorption capacity of the OC foam specimens. For

instance, the values of EAD of SOC foam specimens are about 3 times higher in comparison to the OC foam specimens. This effect is much more pronounced in the case of the shorter specimens (**Fig. 9a, left**) than the longer specimens (**Fig. 9a, right**). Also, the specific energy absorption decreases with increase of the specimen length. The shorter hybrid foams and OC foam specimens have a capacity to absorb much more specific energy than the longer specimens due to different deformation modes, as observed previously. The EOC foam specimens demonstrate very high energy absorption capacity (**Fig. 9b**), even if compared to the closed-cell aluminium foams [10]. The EAD increase of the SOC and OC foam specimens is exponential (**Fig. 9a**), while the EOC foam specimens exhibit linear increase (**Fig. 9b**).

3.3. Energy absorption efficiency

Table 2 lists the energy absorption efficiency (EAE) for all analysed foam specimens. The obtained results indicate that the EAE increases with the increasing of the length of the foam specimens. For example, the EAE for shorter OC foam specimens are 73.9% (quasi-static) and 77.9% (dynamic), while for longer OC foam specimens they are 81.5% (quasi-static) and 81.6% (dynamic). The EAE of the OC foam specimens is also sensitive to the strain rate, showing higher values at the dynamic loading conditions. These results demonstrate that OC foam specimens possess a higher mean values of EAE compared to the hybrid foams. The EAE of SOC foam specimens under dynamic loading conditions show lower values (63% and 70.6% for shorter and longer specimens) in comparison to the EAE of SOC foam specimens under quasi-static loading conditions (61.4% and 64.1% for shorter and longer specimens). It should be noted that the EAE is an important energy absorption parameter, but its values are not exclusively enough to select the best material or structure for a given application.

3.4. Specific energy absorption capabilities

The specific energy absorption (SEA, energy absorption capacity per unit mass) of the hybrid foams (SOC and EOC foam specimens) in comparison to the OC foam specimens is shown in **Fig. 10**. The SEA to strain relationship is similar to the EAD to strain relationship, as the SEA relationships were determined by simply dividing the EAD by mass of each specimen. The SEA of SOC foam specimens are inferior to the SEA of OC foam specimens (**Fig. 10a**), while the SEA of EOC foam specimens are superior to the SEA of simple OC foam specimens (**Fig. 10b**). This effect is more evident for the longer specimens. The SEA of shorter OC foam specimens is 1854 % lower than that of EOC foam specimens, while at the same time 79.5 % higher than that of the SOC foams specimens. For longer specimens, the SEA of OC foam specimens is 1333 % lower than that of the EOC foam specimens and 90 % higher than that of the SOC foams.

The results indicate that the increase of the SEA observed for SOC foam specimens in comparison to the OC foam specimens is not enough to compensate for the mass increase of these hybrid foams due to the silicone filler (**Table 1**). The SEA is an important indicator to evaluate the energy absorption capability of a lightweight structural component to determine its mechanical energy absorption efficiency. In general, a higher value of SEA is a good indicator of efficient lightweight crush structures. High value of SEA is achieved by decreasing the absorber mass or by increasing the EA capability, as in the case of the EOC foam specimens. The SOC foam specimens collapse in an unstable mode, which leads to low values of SEA.

As expected, it was also observed that the SEA decreases by increasing the density of the hybrid foams. The results show that the hybrid foams used as fillers of the thin-walled tubes should be extensively studied in the future, since they pose advantageous properties to be used as efficient energy absorbers, e.g. in the transportation industry.

4. Conclusions

The paper presents the results of studying the influence of polymer (silicone rubber and epoxy resin) fillers of aluminium alloy OC foam on the mechanical performance of the resulting hybrid foams. For that purpose, two hybrid foam types (silicone based open-cell (SOC) and epoxy based open-cell (EOC) foam specimens) and the open-cell (OC) foam specimens having different height-to-width ratio were fabricated and tested. The effects of the specimen size and the loading conditions (quasi-static and dynamic) on the compressive response (including the deformation and failure mode) were studied. The motivation of this work was to develop multifunctional structures with predictable mechanical behaviour and failure. This is needed for applications where optimised response is of crucial importance, e.g. in transportation engineering. The results of the undertaken study lead to the following conclusions:

- (i) The use of polymers as void filler changes the typical layer-wise collapse mechanism of the OC foam specimens, preventing the self-contact of struts. The silicone rubber (gel-like material) promotes non-symmetric deformation in the SOC foam specimens. The longer SOC foam specimens deform by buckling showing lateral instability with formation of several folds, whereas the shorter SOC foam specimens do not experience buckling, due to the lower height-to-width ratio. In contrast, the epoxy resin promotes symmetric deformation by folding in the middle of the specimens at both (quasi-static and dynamic) loading conditions. However, the brittleness of the EOC foam specimens leads to the development of cracks during the fold formation.
- (ii) The chemical nature of the polymers is responsible for the way in which the hybrid foams deform. Silicone is an elastomer with weak intermolecular interactions and high chain mobility. It promotes low adhesion and a low friction coefficient with the struts of OC foam specimens. On the other hand, the brittle epoxy resin in solid state displays barely any chain mobility.

- (iii) The stress oscillations in the plateau region of the compressive stress-strain curves, usually observed in the OC foam, were significantly diminished with the presence of the polymer fillers.
- (iv) The polymer fillers (silicone and epoxy) contribute to the increase of the compressive response of the hybrid foams, leading also to an increase in the energy absorption capacity. This effect is more pronounced for EOC foam specimens than SOC foam specimens.
- (v) The dynamically tested OC and SOC foam specimens are sensitive to the strain rate.
- (vi) Inefficient load transfer is observed in the SOC foam specimens that results in lower mechanical strength, when compared to the EOC foam specimens. The EOC foam specimens are lightweight hybrid foams that present more stable behaviour and show high compressive strength. However, they develop cracks during deformation that could limit their application.
- (vii) Lightweight EOC foam specimens possess higher capacity of specific energy absorption in comparison to the OC foam specimens. On the other hand, SOC foam specimens exhibit lower capacity of specific energy absorption, indicating that the energy absorption values are not high enough to compensate for the increase of the mass due to the silicone polymer.

The hybrid foams should be studied further for use as fillers of the key thin-walled components for increased mechanical energy absorption in transportation industry.

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Figure Captions

Fig. 1. Fabricated foam specimens: (a) the OC foam specimens, (b) the SOC foam specimens (c) the EOC foam specimens with length of 25 mm (above) and 50 mm (bellow).

Fig. 2. The quasi-static deformation sequences showing the progressive deformation of the OC foam specimens with length of 25 mm (above) and 50 mm (bellow).

Fig. 3. The quasi-static deformation sequences showing the progressive deformation of the SOC foam specimens with length of 25 mm (above) and 50 mm (bellow).

Fig. 4. The quasi-static deformation sequences showing the progressive deformation of the EOC foam specimens with length of 25 mm (above) and 50 mm (bellow).

Fig. 5. The IR imaging sequences showing the dynamic progressive deformation of the OC foam specimens with length of 25 mm (above) and 50 mm (bellow).

Fig. 6. The IR imaging sequences showing the dynamic progressive deformation of the SOC foam specimens with length of 25 mm (above) and 50 mm (bellow).

Fig. 7. Deformed OC, SOC and EOC foam specimens with the initial length of 25 mm (a) and 50 mm (b) after quasi-static compression tests.

Fig. 8. Quasi-static and dynamic compressive stress-strain relationship of (a) SOC and (b) EOC hybrid foam specimens with length of 25 mm (left) and 50 mm (right), compared to the OC foam specimens.

Fig. 9. Energy absorption density of (a) SOC and (b) EOC hybrid foam specimens with length of 25 mm (left) and 50 mm (right), compared to the OC foam specimens.

Fig. 10. Specific energy absorption of (a) SOC and (b) EOC hybrid foam specimens with length of 25 mm (left) and 50 mm (right), compared to the OC foam specimens.

Table Captions

Table 1. Physical properties of the fabricated specimens.

Table 2. Absorption energy characteristics of all foam specimens.

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Table 1.

Initial OC foams								Initial OC foams							
25 x 22 mm	Porosity (%)	Mass (g)	Mass (g)	Width (mm)	Length (mm)	Height (mm)	Density (g/cm ³)	50 x 22 mm	Porosity (%)	Mass (g)	Mass (g)	Width (mm)	Length (mm)	Height (mm)	Density (g/cm ³)
OC foams								OC foams							
OC-25-1	96.4	1.127	1.127	21.85	21.90	24.70	0.0954	OC-50-1	96.4	2.258	2.258	21.80	21.60	49.97	0.0960
OC-25-2	96.4	1.108	1.108	21.65	21.95	24.58	0.0949	OC-50-2	96.3	2.277	2.277	21.51	21.75	50.01	0.0973
OC-25-3	96.5	1.105	1.105	22.20	22.15	24.28	0.0926	OC-50-3	96.3	2.276	2.276	21.47	21.64	50.01	0.0980
OC-25-4	96.6	1.056	1.056	20.85	21.95	25.18	0.0917	OC-50-4	96.3	2.235	2.235	21.67	21.42	49.41	0.0975
OC-25-5	96.6	1.061	1.061	21.95	21.90	24.13	0.0915	OC-50-5	96.3	2.308	2.308	21.80	21.47	49.97	0.0987
OC-25-6	96.3	1.140	1.140	21.70	21.65	24.35	0.0997	OC-50-6	96.3	2.393	2.393	22.09	21.75	49.98	0.0997
Average	96.5	1.100	1.100	24.53	21.700	21.917	0.0954	Average	96.3	2.291	2.291	21.72	21.61	49.89	0.098
Stand. dev.	0.12	0.034	0.034	0.38	0.46	0.16	0.0949	Stand. dev.	0.05	0.055	0.055	0.23	0.14	0.23	0.001
SOC foams								SOC foams							
SOC-25-1	96.5	1.054	14.93	21.66	21.36	24.39	1.323	SOC-50-1	96.3	2.429	33.95	22.28	22.48	49.83	1.360
SOC-25-2	96.1	1.178	14.87	21.42	21.97	24.04	1.314	SOC-50-2	96.4	2.336	34.47	21.68	22.46	49.93	1.418
SOC-25-3	96.5	1.033	14.81	21.71	21.04	24.18	1.341	SOC-50-3	96.3	2.361	32.8	22.05	21.88	49.86	1.364
SOC-25-4	96.6	1.049	14.78	21.82	21.73	24.36	1.280	SOC-50-4	96.4	2.437	33.26	22.78	22.63	49.75	1.297
SOC-25-5	96.5	1.068	14.37	21.87	21.68	24.18	1.254	SOC-50-5	96.3	2.526	33.29	22.53	22.58	49.99	1.309
SOC-25-6	96.1	1.112	14.51	20.83	21.86	23.37	1.364	SOC-50-6	96.3	2.482	33.06	21.98	22.78	49.91	1.323
Average	96.4	1.082	14.33	21.55	21.61	24.08	1.313	Average	96.3	2.429	33.47	22.22	22.47	49.88	1.345
Stand. dev.	0.23	0.054	0.221	0.39	0.35	0.37	0.040	Stand. dev.	0.07	0.071	0.620	0.40	0.31	0.08	0.045
EOC foams								EOC foams							
EOC-25-1	96.5	1.110	14.29	22.22	22.35	24.08	1.195	EOC-50-1	96.3	2.448	28.22	21.25	22.20	49.94	1.198
EOC-25-2	96.3	1.090	14.30	21.70	20.95	24.33	1.293	EOC-50-2	96.4	2.273	28.28	22.75	21.85	49.97	1.139

EOC-25-3	96.1	1.177	14.36	21.90	21.80	24.00	1.253	EOC-50-3	96.3	2.454	28.46	21.3	21.32	49.89	1.256
Average	96.3	1.126	14.32	21.940	21.700	24.133	1.247	Average	96.3	2.392	28.32	21.77	21.79	49.93	1.198
Stand. dev.	0.19	0.046	0.038	0.262	0.705	0.170	0.049	Stand. dev.	0.06	0.103	0.125	0.85	0.44	0.04	0.059

Table 2.

Specimen size: 25 x 22 mm	Stress $\sigma_{\varepsilon=0.2}$ (MPa)	Stress $\sigma_{\varepsilon=0.4}$ (MPa)	Plateau stress σ_{Plateau} (MPa)	Densification strain ε_d (-)	Energy absorption density EAD (MJ/m ³)	Energy absorption efficiency EAE (%)	Specimen size: 50x22 mm	Stress $\sigma_{\varepsilon=0.2}$ (MPa)	Stress $\sigma_{\varepsilon=0.4}$ (MPa)	Plateau stress σ_{Plateau} (MPa)	Densification strain ε_d (-)	Energy absorption density EAD (MJ/m ³)	Energy absorption efficiency EAE (%)
OC foams							OC foams						
static							static						
OC-25-1	0.289	0.261	0.275	0.594	0.143	67.3	OC-50-1	0.123	0.151	0.137	0.462	0.056	68.3
OC-25-2	0.252	0.239	0.246	0.599	0.153	80.0	OC-50-2	0.084	0.119	0.102	0.414	0.048	88.2
OC-25-3	0.215	0.256	0.236	0.510	0.116	74.3	OC-50-3	0.104	0.095	0.099	0.458	0.052	88.0
Average	0.252	0.252	0.252	0.568	0.137	73.9	Average	0.104	0.121	0.113	0.445	0.052	81.5
Stand. dev.	0.037	0.012	0.021	0.050	0.019	6.4	Stand. dev.	0.019	0.028	0.021	0.027	0.004	11.4
dynamic							dynamic						
OC-25-4	0.274	0.278	0.276	0.523	0.150	79.9	OC-50-4	0.125	0.118	0.121	0.475	0.062	82.8
OC-25-5	0.250	0.343	0.297	0.385	0.110	74.1	OC-50-5	0.142	0.142	0.142	0.419	0.062	80.3
OC-25-6	0.294	0.274	0.284	0.537	0.158	79.7	OC-50-6	0.098	0.100	0.099	0.462	0.049	81.8
Average	0.273	0.298	0.286	0.482	0.139	77.9	Average	0.122	0.120	0.121	0.452	0.058	81.6
Stand. dev.	0.022	0.039	0.010	0.084	0.026	3.3	Stand. dev.	0.022	0.021	0.021	0.029	0.008	1.28
SOC foams							SOC foams						
static							static						
SOC-25-1	0.542	0.773	0.658	0.435	0.224	60.2	SOC-50-1	0.219	0.252	0.236	0.626	0.144	75.1
SOC-25-2	0.543	0.719	0.631	0.441	0.254	70.2	SOC-50-2	0.166	0.172	0.169	0.589	0.091	70.6
SOC-25-3	0.562	0.818	0.690	0.432	0.227	58.6	SOC-50-3	0.209	0.261	0.235	0.449	0.091	66.1
Average	0.549	0.770	0.660	0.436	0.235	63.0	Average	0.198	0.228	0.213	0.555	0.109	70.6
Stand. dev.	0.011	0.050	0.030	0.005	0.017	6.3	Stand. dev.	0.028	0.049	0.038	0.093	0.031	4.6
dynamic							dynamic						
SOC-25-4	0.579	0.858	0.719	0.436	0.259	63.6	SOC-50-4	0.191	0.269	0.230	0.439	0.084	64.1
SOC-25-5	0.517	0.879	0.698	0.412	0.236	63.1	SOC-50-5	0.231	0.328	0.280	0.446	0.105	64.8
SOC-25-6	0.566	0.910	0.738	0.418	0.230	57.4	SOC-50-6	0.225	0.319	0.272	0.443	0.099	63.5

Average	0.554	0.882	0.718	0.422	0.242	61.4	Average	0.216	0.305	0.260	0.443	0.096	64.1
Stand. dev.	0.033	0.026	0.020	0.012	0.015	3.5	Stand. dev.	0.022	0.032	0.027	0.004	0.011	0.7
EOC foams							EOC foams						
static							static						
EOC-25-1	50.925	63.021	56.973	0.680	39.829	79.1	EOC-50-1	16.277	22.999	19.638	0.691	12.763	72.4
EOC-25-2	51.728	68.231	59.980	0.447	25.396	72.9	EOC-50-2	16.506	22.504	19.505	0.439	7.858	70.6
EOC-25-3	51.440	69.634	60.537	0.450	25.577	72.2	EOC-50-3	15.924	22.366	19.145	0.689	12.593	73.5
Average	51.364	66.962	59.163	0.526	30.267	74.7	Average	16.236	22.623	19.429	0.606	11.071	72.1
Stand. dev.	0.407	3.484	1.917	0.134	8.281	3.8	Stand. dev.	0.293	0.333	0.255	0.145	2.784	1.4

(a)

(b)

(c)

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0.7

0.8

(a)

(b)

A

B

A

B

Highlights

- Multifunctional hybrid foams are prepared by infiltrating the aluminium alloy open-cell foams with polymers.
- The use of polymers as a void filler changes the typical layer-wise collapse mechanism of the open-cell foam.
- An improvement of the compressive strength and energy absorption capacity of hybrid foams has been observed.
- The silicone rubber causes a non-symmetric deformation, resulting in more complex and unstable deformation mechanism.
- The epoxy resin enforces a symmetric and predictable deformation.