Lista a 10 publicații științifice relevante

Conf. dr. ing. Emanoil LINUL

Informaţiile relevante precum „factorul de impact (IF)”, „cuartila (Q)” şi „domeniul” ale fiecarui Jurnal sunt furnizate pentru anul în care lucrarea a fost publicată.

Lucrările din „Lista a 10 publicații științifice relevante” sunt încadrate în *cuartila Q1 (zona roşie)*, iar candidatul este *prim autor* sau *autor corespondent* în toate articolele.

Cele 10 lucrări (publicații) selectate, considerate a fi relevante pentru realizările științifice, academice şi profesionale care susțin activitățile prezentate în teza de abilitare, sunt următoarele:

[1] **E. Linul** (Autor corespondent), D. Pietras, T. Sadowski, L. Marşavina, D.K. Rajak, J. Kovacik (2021) Crashworthiness performance of lightweight Composite Metallic Foams at high temperatures, *Composites Part A: Applied Science and Manufacturing* (ISSN: 1359-835X), 149, 106516, doi.org/10.1016/j.compositesa.2021.106516 (WOS: 000689332300002), IF_{2020}=7,664 (Q1 – Materials Science, Composites).

[2] **E. Linul** (Autor corespondent), O. Khezrzadeh (2021) Axial crashworthiness performance of foam-based composite structures under extreme temperature conditions, *Composite Structures* (ISSN: 0263-8223), 271, 114156, doi.org/10.1016/j.compstruct.2021.114156 (WOS: 000663802700012), IF_{2020}=5,407 (Q1 – Mechanics).

[3] N. Movahedi, **E. Linul** (Autor corespondent) (2021) Radial crushing response of ex-situ foam-filled tubes at elevated temperatures, *Composite Structures* (ISSN: 0263-8223), 277, 114634, doi.org/10.1016/j.compstruct.2021.114634 (WOS: 000703117500002), IF_{2020}=5,407 (Q1 – Mechanics).

[4] D.K. Rajak, **E. Linul** (Autor corespondent) (2021) Crushing response of Composite Metallic Foams: Density and High Strain Rate effects, *Journal of Alloys and Compounds* (ISSN: 0925-8388), 871, 159614, doi.org/10.1016/j.jallcom.2021.159614 (WOS: 000645004000010), IF_{2020}=5,316 (Q1 – Metallurgy & Metallurgical Engineering).

[5] G. Epasto, F. Distefano, L. Gu, H. Mozafari, **E. Linul** (Autor corespondent) (2020) Design and optimization of Metallic Foam Shell protective device against flying ballast impact damage in railway axles, *Materials & Design* (ISSN: 0264-1275), 196, 109120, doi.org/10.1016/j.matdes.2020.109120 (WOS: 000588266900001), IF_{2020}=7,991 (Q1 – Materials Science, Multidisciplinary).

[6] **E. Linul** (Autor corespondent), D. Lell, N. Movahedi, C. Codrean, T. Fiedler (2019) Compressive properties of Zinc Syntactic Foams at elevated temperatures, *Composites Part B-Engineering* (ISSN: 1359-8368), 167, 122-134, doi.org/10.1016/j.compositesb.2018.12.019 (WOS:000465060200013), IF_{2019}=7,635 (Q1 – Materials Science, Composites).

[7] **E. Linul** (Autor corespondent), L. Marşavina, P.A. Linul, J. Kovacik (2019) Cryogenic and high temperature compressive properties of Metal Foam Matrix Composites, *Composite Structures* (ISSN: 0263-8223), 209, 490-498, doi.org/10.1016/j.compstruct.2018.11.006 (WOS: 000454690700042), IF_{2019}=5,138 (Q1 – Mechanics).

[8] D.K. Rajak, N.N. Mahajan, **E. Linul** (Autor corespondent) (2019) Crashworthiness performance and microstructural characteristics of foam-filled thin-walled tubes under diverse strain rate, *Journal of Alloys and Compounds* (ISSN: 0925-8388), 775, 675-689, doi.org/10.1016/j.jallcom.2018.10.160 (WOS: 000450981100080), IF_{2019}=4,650 (Q1 – Metallurgy & Metallurgical Engineering).

[9] **E. Linul** (Autor corespondent), N. Movahedi, L. Marsavina (2018) The temperature and anisotropy effect on compressive behavior of cylindrical closed-cell aluminum-alloy foams, *Journal of Alloys and Compounds* (ISSN: 0925-8388), 740, 1172-1179, doi.org/10.1016/j.jallcom.2018.01.102 (WOS: 000425494200138), IF_{2018}=4,175 (Q1 – Metallurgy & Metallurgical Engineering).

[10] **E. Linul** (Autor corespondent), N. Movahedi, L. Marsavina (2017) The temperature effect on the axial quasi-static compressive behavior of ex-situ aluminum foam-filled tubes, *Composite Structures* (ISSN: 0263-8223), 180, 709-722, doi.org/10.1016/j.compstruct.2017.08.034 (WOS: 000410632800057), IF_{2017}=4,101 (Q1 – Materials Science, Composites).

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Crashworthiness performance of lightweight Composite Metallic Foams at high temperatures

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ABSTRACT

Based on their special stochastically distributed pores, Composite Metallic Foams (CMFs) represent a promising alternative to the conventional high-density solid structures. However, due to their high sensitivity to temperature changes, the effect of testing temperature on the compression behaviour of CMFs should not be neglected. In this paper, the compressive response of expanded metal mesh (EMM) reinforced metallic foams, manufactured by powder metallurgical route, were evaluated under impact tests (strain rate 95 s^{-1}) as a function of testing temperature (i.e. 25, 75, 150, 250 and 350 °C). The impact properties of high-strength CMFs including strength properties and energy absorption performances, are measured and compared with those obtained under quasi-static (strain rate $5.77 \cdot 10^{-3}$ s^{-1}) loading conditions. The effect of EMM reinforcements on the CMFs properties and collapse mechanisms at the cell-level were discussed according to the testing temperature. The deformation behaviour of the lightweight CMFs was found to be strongly temperature-dependent, highlighting a brittle-to-ductile transition with increasing testing temperature. Finally, based on the quasi-static experimental results, empirical formulae are proposed to predict the impact properties of newly-developed CMFs, i.e. compression strength and energy absorption.

1. Introduction

High-performance engineering materials that can withstand high operating temperatures, without failure or damage, are required for a wide range of critical structural engineering applications in various industries [1–3]. Following the continuous demand for reducing the weight of the structural components, the bio-inspired cellular materials with metallic [4–6], polymeric [7–9] or ceramic [10,11] matrix represent a promising alternative to the conventional high-density solid structures (e.g. steel, aluminium, etc.). Compared to other types of cellular materials [12,13], metallic foams (MFs) are excellent candidates for this purpose due to their unique properties - high stiffness-to-weight ratio, high ability to absorb impact energy, good formability and corrosion resistance, recycling potential, etc. – that can be attained by controlling their microstructure or pore distribution [14–16]. Based on their special structure, MFs consist of a 3D network of stochastically distributed pores with the potential to achieve the lightweight construction and improve the crashworthiness performances. All of these controllable and easily predictable features lead to the use of MFs on a large scale in energy absorptions, impact mitigation and blast protection applications [17,18].

The main use of MFs is under compression loads, and especially under impact conditions [19–21]. Most of the published works on the compressive crushing response were focused on quasi-static loads [22–24], while impact studies are significantly reduced [25–27]. Moreover, the majority of these impact studies were performed at room temperature (RT). However, due to a high sensitivity to temperature changes, the effect of testing temperature (TT) on the compression behaviour of MFs should not be neglected. Linul et al [28,29], Cady et al. [30], Yu [31], Fiedler et al [32], investigated the effect of cryogenic temperatures (CT) on foam properties (compressive strength, σ_{max} and energy absorption, W), under quasi-static testing conditions. Regardless of the type of foam used (regular MFs [28,30], MSFs [32], reinforced MFs [28] or polyurethane foams (PUFs) [29,31]), the authors observed a properties enhancement as TT decreases. For example, Linul et al [28]

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Axial crashworthiness performance of foam-based composite structures under extreme temperature conditions

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Collapse mechanisms
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ABSTRACT

Due to their unique properties, metal foams can be used under extreme temperature conditions. To this end, this paper investigates the influence of temperature (−196, −25, 25 and 250 °C) on the axial crashworthiness performance of foam-based composites. The composite structures are made of aluminum thin-walled circular tubes, filled with aluminum alloy (A356) foam. It is found that the highest mechanical characteristics are obtained at the cryogenic temperature (−196 °C) due to the hardening behaviour of the matrix material in both foam and tube. Contrary, the softening behaviour of the matrix material at high temperature (250 °C) decreases the mechanical properties of the composite material. Between two extreme temperatures, a transition from brittle-to-ductile deformation occurs. The deformation transition is observed both on the stress–strain curves (gradual reduction of oscillations of the plateau region) and the macroscopic images of the compressed samples (changing the crushing mode from non-axisymmetric < *Diamond* > to axisymmetric < *Concertina* >). Moreover, due to the foam-tube interaction effect, the experimental results show that the quasi-static compressive behavior and collapse mechanisms of the composite structures has considerably improved (over 50% in some cases). Furthermore, the strength properties and energy absorption performances of the foam filled tube shows significantly higher values (almost double) compare to empty one.

1. Introduction

In recent years, cellular materials such as metallic [1–3] and polymeric [4–6] foams have gained applications in almost all engineering fields. Their application in different industries is directly related to their cellular structure [7–9]. Compared to fully dense solid materials [10–12], foams [13–15] highlights many advantages, among which the most important are: lightness, high compression strengths combined with good energy absorption performances and large deformations (up to about 60–70% strain) at almost constant stress. All these performances are governed by their main collapse mechanisms during compression deformation. Compared to polymeric foams (PFs) [16–18], metallic foams (MFs) are stronger and stiffer. They also show higher amounts of energy absorption under compressive loadings. Their structure is also more resistant to temperature, ultraviolet (UV) radiations, humidity and fire. Due to these features, closed-cell MFs are predominantly used for structural applications such as weight-saving and impact-absorbing in automobile industry. On the other hand, the open-cell MFs are ideal for functional applications such as filtration, damping, catalysis, heat exchange and medical implants [19–21]. In general, the applicability of the MFs is directly related to their manufacturing process. Different manufacturing techniques show significant effects on the mechanical, physical or thermal properties of the foams [22–24].

Over the years, many teams of researchers have characterized experimentally [25–27], numerically [28–30] and analytically [31,32] MFs obtained through various production processes. Most characterizations of MFs were performed under compressive loadings at room temperature (~25 °C) [33–35]. This type of investigation was also used for newly developed metallic syntactic foams (MSFs) [36–38]. However, some researchers have investigated the compressive behavior of MFs [39–41] and MSFs [42,43] at elevated temperatures (range 25–550 °C). All these researchers concluded a decrease in the investigated mechanical properties of the MFs due to softening of their metallic matrix at high temperatures.

Furthermore, only a few papers are related to the investigation of the compressive behavior of MFs at sub-zero temperatures [44–46]. Khezrzadeh et al [44] investigated the anisotropic compressive

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Radial crushing response of *ex-situ* foam-filled tubes at elevated temperatures

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ABSTRACT

The current research investigates the mechanical properties and deformation mechanisms of foam-based composites under radial compressive loadings at different temperatures between 25 to 450 °C. The radial compression tests are performed at 10 mm·min⁻¹ on aluminum foams (AFs), empty tubes (ETs) and foam-filled tubes (FFTs) within a heating chamber. The obtained force–displacement curves are analyzed to investigate the main mechanical properties of the samples such as yield, plateau and densification forces. The deformation mechanism of each individual component is studied at room temperatures. According to obtained results, the radial compression of AFs does not show any shear failure in the early stages of their deformation at room temperature. Instead, the shearing delays at higher displacement during the radial loading of AFs. In addition, unlike axial loadings, the radial compression of the ETs does not progress through successive folding at all tested temperatures. The interaction effect between tubes and foams is observed at all testing temperatures, highlighting a maximum at temperatures close to room temperature. The mechanical properties of FFTs outperform the AFs and ETs. However, at temperatures close to melting point of AF, there is no significant difference in energy absorption capacity of the FFTs and ETs.

1. Introduction

Advanced composite structures, which consist of a lightweight core and high-strength cover/skin that are made of either metal matrix or composite materials, have received increasing attention from researchers around the world [1,2]. Metallic foams are considered as one of the promising energy absorber materials in automobile and structural industries [3]. Their porous structures give them an ability to absorb a considerable amount of energy under compressive loading conditions [4]. According to pore morphology, they are conventionally classified in closed or open [5,6] cell structures. However, other groups such as metal syntactic foams [7–9], auxetic structures [10] and additively manufactured metals [11] have been considered as a class of metallic foams in recent years. The closed-cell aluminum foams (AFs) because of their high strength to weight ratio are more favorable in applications such as railway [12] and buildings [13]. Due to their broad spectrum of application, their mechanical properties were characterized under different loading velocities [14,15]. In addition, different structural combinations of metallic foams with metallic tubes such as foam-filled tubes (FFTs) [16–18] and tube-filled foams (TFFs) [19] are investigated. Different research studies on FFTs confirmed their higher energy absorption capability due to the interaction effects between individual components (metallic foam and tube). In [20], the bending properties of an aluminum alloy tube filled with different types of low-cost cellular metal fillers was investigated. To this end, advanced pore morphology (APM) foam, hybrid APM foam and Metallic hollow spheres were selected as the core materials. Three-point bending tests were performed on the structures under quasi-static and dynamic loading conditions. Then, the results were compared with *in-situ* and *ex-situ* closed-cell aluminum alloy foams. The results indicated the higher peak load for *ex-situ* FFTs and hybrid APM structures. In addition, it was shown that the APM, metallic hollow sphere structures and *in-situ* FFTs behave ductile with a predictable deformation mode. Duarte *et al.* [21] manufactured a very thin-walled aluminum alloy tubes filled with aluminum alloy foam using powder metallurgy technique. The manufactured *in-situ* FFTs were then compressed axially at quasi-static and dynamic loading modes. It was shown that the strong metallic bonding between the foam core and aluminum tube enhanced the mechanical performance of the *in-situ* FFTs. The tube wall thickness also influenced the deformation and failure mode of the FFTs. The specific energy absorption of the FFT using

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Crushing response of Composite Metallic Foams: Density and High Strain Rate effects

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ABSTRACT

The emerging demand for lightweight materials has had an impact in several industries, including biomedical, marine, and space forum applications wherein weight-reduction, impact energy, vibration and noise absorption are mandatory. In this paper, the crushing response of newly developed composite metallic foams (CMFs) with different relative densities (0.289, 0.293, 0.307 and 0.312) were experimentally investigated. As reinforcement, 10 wt% silicon carbide (SiC) particles (size: 20–40 µm) were used, while the foam behavior consisted of microstructure characterization, uniaxial compression tests and statistical analysis. The compressive properties of CMFs were determined using a Split Hopkinson Pressure Bar apparatus over a strain-rates range of 520–1560 s^{-1}. It was found that the strength properties and energy absorption performance of the manufactured foams are strongly affected by the above-mentioned factors. However, the Analysis of Variance technique showed that the most contributing factor is the strain rate (89.10%), followed in order by the relative density (5.90%) and microstructure (3.10%).

1. Introduction

In the last 20 years, porous materials such as conventional metal foams (MFs) [1,2], composite metal foams (CMFs) [3,4] and metal syntactic foams (MSFs) [5,6] have shown a great promise for use as a multifunctional material in terms of research and development. Being lightweight materials, metal matrix foams offer remarkable mechanical as well as physical properties [7–9]. Depending on the morphology of the microstructure, the MFs are divided into two main categories: open-cell and closed-cell foams [10–12]. Open-cell MFs have special properties to be used in sound and noise absorption, heat exchangers, filters and many other engineering applications [13–15]. Closed-cell MFs show excellent characteristics in impact or crash applications, especially where high energy absorption is required [16–18]. Due to the deformation mechanisms that occur at the microstructure level, closed-cell MFs have higher energy absorption performances than their solid parent metals [19–21]. The cellular structure of the foams facilitates the direct conversion of impact energy into plastic energy [22–24]. Highlighting such properties that are difficult to achieve for other materials, MFs have been used as prominent protection measures in crash-box devices, bumpers, roofs, etc. [25–27].

There have been several studies on the strength properties and energy absorption capacities of MFs, CMFs and MSFs [28,29]. Moreover, different methods have been used to manufacture MFs to satisfies the needs of absorbing impact energy with different combinations of alloys (aluminum, magnesium, copper, zinc, titanium, etc.) and additional materials such as foaming agents (TiH_2, $CaCO_3$, etc.) or reinforcements (hollow spheres, particles, sheets, bars, etc.) [30–34]. To assess the energy absorption capacity of MFs, compressive loading is used in previous studies. The energy absorption of aluminum foam is directly related to the area obtained under the compressive stress-strain curve. In order to have higher energy absorption performance, the plateau region should be sufficiently widespread. For this purpose, in order to obtain a higher plateau stress level, different methods are considered to harden the MFs, such as fly ash, Carbon Nano-Tubes (CNT), Silicon Particles (SiC), graphene, etc. Deshpande et al. [35] studied the high strain rate (HSR) behavior of two different foams (Alulight and Duocel), and found that its impact properties are quite similar to quasi-static ones. In addition, the authors mentioned that the plateau stress is insensitive to the strain rate. The effect of low strain rate (LSR) and HSR on the mechanical and energy absorption properties of composite MFs was investigated by Tabrizi et al. [36]. Their results show that increasing the loading rate improves the strength of the foams

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Design and optimization of Metallic Foam Shell protective device against flying ballast impact damage in railway axles

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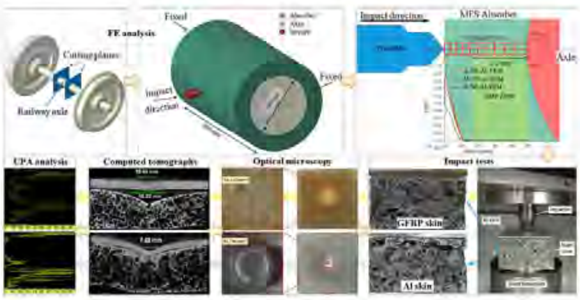
HIGHLIGHTS

- A novel Metallic Foam Shell (MFS) protective device against flying ballast impact damage in railway axles is designed.
- By using impact tests and non-destructive evaluation methods, the most optimal MFS configuration is proposed.
- The newly developed MFS device can absorb up to 90% of the initial impact energy with total protection of the axle.
- The suggested MFS device can be effectively evaluated by means of the most common non-destructive techniques.

GRAPHICAL ABSTRACT



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ABSTRACT

Ballast impacts can initiate surface defects that cause abrupt failure of the axle and derailment of the railway vehicle. According to the Federal Railroad Administration the axle and bearing failure costs around 89 million dollars and causes 46 derailments in the US per year (2005–2010). In this study, the authors have suggested a novel protective mechanism (Metallic Foam Shell – MFS) by using a lightweight sandwich panel. At the first step, a preliminary study is conducted, followed up by the numerical simulations to determine the applicable materials. At the next step, experimental tests were performed to assess the efficiency of the suggested device against flying ballast impacts. An extended non-destructive (NDT) evaluation has been performed in order to find the most suitable technique for damage detection of the proposed device when on-service. The studied cases were GFRP and Aluminium sandwich panels, having an aluminium foam core with different densities and thicknesses. The results showed that the MFS can absorb up to 90% of the initial impact energy and significantly decrease the chance of rebounding impact to the other components. Moreover, the results were also analysed in order to propose the most reliable NDT method for this specific application.

1. Introduction

Railway axles are known as the most loaded parts in the railway vehicles since they account for about 70% of wagon mass. Axles are designed against endurance limit [1]. However, formation of crack and failure significantly decreases their fatigue life. According to the Federal Railroad Administration (FRA) in 2005–2010, the axle and bearing failure costs around 89 million dollars and causes 46 derailments per year in the US [2].

Two main axle failure mechanisms are overheating of the roller bearing, known as 'hot box' [3] and fatigue from sub-surface and surface

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Compressive properties of zinc syntactic foams at elevated temperatures

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ABSTRACT

This paper investigates the effect of temperature on the microstructure, failure mechanism and compressive mechanical properties of newly developed ZA27 syntactic foams. Two different types of filler particles are considered, i.e. expanded perlite (P) and expanded glass (G). Metallic syntactic foam (MSF) has been produced via a counter-gravity infiltration process of packed particle beds, followed by controlled thermal exposure. Quasi-static compressive tests were carried out on cylindrical samples at five different in-situ testing temperatures between 25 °C and 350 °C. At all considered temperatures, P-MSF exhibits superior mechanical properties compared to G-MSF. The mechanical properties of both foam types decrease significantly with increasing testing temperature. For comparison, solid ZA27 samples were compressed at the same testing temperatures. Due to microstructural changes, a significant strength degradation of solid ZA27 was observed starting at 100 °C. Comparison of results indicates that the temperature-dependent mechanical properties of P-MSF and G-MSF are strongly controlled by the matrix material. However, the addition of particles decreased the relative reduction of plateau stress and volumetric energy absorption of ZA27 MSF at elevated temperatures.

1. Introduction

Closed-cell porous materials, such as traditional metallic foams (TMFs) [1–4] and metallic syntactic foams (MSFs) [5–8], have gained significant attention in recent years in the context of replacing fully dense solid materials for structural and functional engineering applications [9–11]. Due to their cellular structure (low relative density) and unique ability to tailor mechanical/thermal/physical properties (higher stiffness-to-weight ratios, excellent energy absorption capacity, high vibration absorption, high specific strength etc.), the TMFs and MSFs have found favorable applications in the automotive, acrospace and railway industries [12–14]. A complex three-dimensional interconnected network of solid struts and membranes/plates (cell walls) makes up the foam meso-structure. It shows exclusive capacity to undergo very large deformation (up to 60–70% strain) at an almost constant stress in compression. As a result, these cellular structures are able to dissipate large amount of kinetic energy at low and nearly constant reaction loads [15,16].

The effect of microstructure [17–19], heat treatment [20], particle shape [21], and particle size [22,23] on mechanical/thermal/structural properties and deformation mechanisms of MSFs were investigated by different teams of researchers under static and dynamic loading conditions [24–28]. Kadar et al. [29] presents the analysis of the compressive deformation mechanisms of hollow ceramic spheres syntactic foams using the acoustic emission technique. Their analysis revealed three dominant deformation mechanisms: plastic deformation of the cell walls, sphere fracture and cell wall collapse. Taherishargh et al. [20] showed that heat treatment enabled a significant improvement of the mechanical properties of aluminum-based MSF. Also, due to their regular positioning and less structural defects, foams containing rounded perlite particles showed higher mechanical strength at a constant density [21]. In addition, the compressive deformation can be controlled by decreasing the particle size resulting in smoother and steeper stress-strain curves [22]. Orbulov [23] investigated the aspect ratio effect of the aluminum matrix syntactic foams specimens on their mechanical properties. He found a higher structural stiffness with increasing aspect ratio. Simultaneously, the fracture strain and the absorbed energy decreased significantly. Al-Sahlani and co-workers [30,31] have investigated the effect of particle size (1–1.4, 2–2.8 and 4–5.6 mm) and particle shrinkage on the structural and compressive mechanical properties of recently developed expanded glass-metal syntactic foams (G-MSF). They found that the elastic stiffness and yield stress increase with particle size, while foams with smaller particles exhibit a near constant plateau stress and therefore a high-energy absorption efficiency. The authors observed that particle shrinkage is widely prevented by limiting the exposure time at high furnace

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Cryogenic and high temperature compressive properties of Metal Foam Matrix Composites

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ABSTRACT

The cryogenic (−196 °C), room (25 °C) and high (250 °C) temperature compressive crushing performances of recently developed metal foam matrix composites was investigated with respect to the position of reinforcements on foam samples. Closed-cell aluminum alloy foams were produced via powder metallurgical route from AlSi10 matrix material; while diamond shape expanded stainless steel were used as reinforcements. The deformation behavior and main mechanical properties of the unreinforced and reinforced metallic foam was found to be strongly temperature dependent under quasi-static loading. Reinforced foams exhibited much higher strength properties and energy absorption capability compared to unreinforced foams at almost the same overall weight of the samples, i.e. up to 11 times. The properties percentage reductions of the reinforced foams are significantly below the reduction of the unreinforced foam. Furthermore, it was observed that the collapse mechanisms and mechanical properties of the reinforced foams depends on reinforcement position.

1. Introduction

Conventional Composite Metal Foams (CMFs) [1–4] and recently developed Metal Matrix Syntactic Foams (MMSFs) [5–9] are a new class of advanced composite cellular materials of great interest that can be found in every field of today's engineering world. Their particular porous structure gives them unique mechanical and physical properties that allow a broadening in the range of properties of their solid counterparts [10–12]. The applications of these foamed closed-cell porous materials in advanced composite structures (ACSs) are thus very extensive, while the use of fully dense solid materials have lost slowly their applicability [13–15]. Due to its outstanding energy absorption capabilities, high stiffness-to-weight ratio, good fracture and shear strength and exceptional heat transfer ability, they are of special interest in construction, automotive and aeronautics industries [16–19].

Different lightweight and less expensive ACSs capable of low and high temperature operation are also required for many future space exploration missions (and not only). Some typical cold and hot environmental temperatures, applicable for our Solar System, are: the chilly night side of the Mercury (−180 °C), Moon Titan surface temperature (−180 °C), Moon Europa Icy surface temperature (−188 to −143 °C), Saturn cloud tops mean temperature (−185 °C), Uranus (−195 °C) and Neptune (−200 °C) mean temperatures, Venus atmosphere (150 °C between 40 and 48 km altitude and 325 °C at 18 km altitude), the day side of the Mercury (from 150 °C up to 427 °C with an average of 167 °C), on Venus (from −173 °C to 467 °C) etc. [20,21].

Over the past few decades, extensive studies have been performed exploring porous materials suitability for Earth living conditions applications [22–24], while a very limited number of studies have focused on space extreme exploration conditions [25–27]. Even so, the vast majority of these studies were conducted for closed-cell polymeric foams and open-cell metallic foams (MFs) regarding their thermal performances [28–30]. The main cryogenic characteristics of chopped fiber reinforced polyurethane foams [31,32], polymeric foams [33] and sandwich-type insulation board composed of E-glass/epoxy composite and polymeric foams [34] are reported in the literature under both static and impact loading conditions. Fesmire and co-workers [35] have studied the cryogenic thermal performance of Spray-on foam insulation (SOFI) under large temperature differentials. The authors also address recent advancements and applications of SOFI systems on future launch vehicles and spacecraft. More recently, Dixit and Ghosh [36,37] and Chunhui and co-workers [38] have investigated the thermal conductivity of high porosity open-cell MFs as advanced thermal storage unit at low temperatures. The results show that the thermal

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Crashworthiness performance and microstructural characteristics of foam-filled thin-walled tubes under diverse strain rate

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ABSTRACT

The implementation of Aluminum Alloy Foam (AAF) has made an impact in automobile and aerospace applications where crash energy absorption, vibration and sound damping and weight reduction is obligatory. The AAF is an emerging lightweight material providing high strength and stiffness at relatively low density. This research is carried out to quantify the energy absorption of mild steel reinforced AAF having empty mild steel and foam-filled tubes for different strain rates and geometry parameters. The AAF used in the current study is AlSi10Mg foam of densities 0.45, 0.65, 0.85 g/cm^3, which is produced using melt route process. The circular, square and rectangular geometries were tested at strain rates of 0.1, 1, 10 mm/s. From the obtained compressive stress-strain curves Specific Energy Absorption (SEA), Total Energy Absorption (TEA), plateau stress of the empty and filled sections were determined, which were then evaluated. AAF was assessed by both light and electron microscopy. Field Emission Scanning Electron Microscope (FESEM) and Analysis of Variance (ANOVA) technique was employed to investigate the highest contributing factor in energy absorption. It was observed that foam filled tube can absorb more energy than empty tubes before reaching densification point.

1. Introduction

Tubular structures are most commonly implemented and recognised energy-absorbing devices in the field of structural and automotive industries. With all current advancements in technologies, safety is an important aspect. To avoid fatal losses and harms during mishaps, there is an urge of energy absorbing devices. Energy absorbing devices are essential for the prevention of injuries and undesirable losses to crucial components of the system. Energy absorption can be defined as the capability of material or system to absorb the energy in various consequences of loading, which is achieved by conversion of kinetic energy into some another form of energy. The advantage of tubular structures are, they are lightweight, low cost and easy manufacturing processes. From the last two decades, these tubular structures are employed in automobiles to improve crashworthiness, which hand in hand increases the safety level of various vital components as well as occupants [1,2]. In automobile body in white (BIW), the crash box is widely used for crash energy absorption. This crash box is merely a thin walled metal tube, usually made up of aluminium. These structures can be circular, rectangular, pentagonal or any polygonal shape. Also, these structures are useful in shipbuilding, aerospace, defence sector and many more [3–5].

Use of dense solid materials has been on downline in the last 20 years. Engineers have always searched for materials with lightweight, high strength, excellent vibration damping characteristics, especially high-energy absorption capabilities and recyclability [6]. The researchers have focused on developing class materials whose properties can be tailored as per the necessity of the application [7–9]. These materials include various alloys, metal and polymer composites, metal foams. Aluminium foams are most preferred present-day materials because of remarkable mechanical and physical properties. The improvement in production processes, foaming and thickening agents, these foams have gained popularity in numerous applications. Aluminium foams have boundless applications in structural as well as functional applications. They can be used for improvement in energy absorption with minimal increment in weight. Also, they have low density, high strength to weight ratio with sound and vibration suppressing properties. Due

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The temperature and anisotropy effect on compressive behavior of cylindrical closed-cell aluminum-alloy foams

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ABSTRACT

In this paper, the main mechanical properties of the closed-cell aluminum-alloy foams under different quasi-static loading conditions and different temperatures (25, 150, 300 and 450 °C) were experimentally investigated. In order to illustrate the effect of anisotropy, two loading positions of the cylindrical foam samples, axial and lateral (20 mm diameter and 20 mm height), during the compressive loads, were considered. The results showed a decrease in mechanical properties of the foam material, for both axial and lateral loading conditions, with increasing the temperature during compression tests. Also, it was found that at all tested temperatures, the porous structure, when compressed laterally, tolerates the lower level of loads and energy absorption in comparison to axial loading. Finally, it was observed that the main mechanical properties in axial loading direction are more affected by the increase of the testing temperature than lateral one.

1. Introduction

Due to their unique physical and mechanical properties [1–5], aluminum foams became more interesting in recent years, compared to the fully dense metallic materials [6–9]. Its light-weight structure, as well as crashworthiness properties of this type of porous material, has made it as a promising candidate for applications that require absorbing a lot of energy during collisions [10–12]. Automotive industry is one of the most important systems that can widely use aluminum foam as one of the principal components.

In order to evaluate the main mechanical properties, a considerable number of experimental [13–15] and numerical [16–18] research studies have been conducted on conventional aluminum foams and recently developed metal matrix syntactic foams [19–24]. Most of the previous works have focused only on static [25–29], dynamic [30–34] and cyclic [35–38] **axial** compressive behavior. On the other hand, the direct effect of temperature on the mechanical properties of aluminum foam is one of the interesting subjects that have been also studied [39–41]. Wang et al. [42] investigated the effect of temperature on the mechanical behavior of aluminum foams under dynamic loadings. Recently, Movahedi et al. [43] performed axial compression loading tests on the closed-cell aluminum alloy foam specimens at different temperatures under static loading condition and concluded that increasing the temperature directly affects the energy absorption and mechanical properties of the porous structure. Also, they observed that the fracture mechanism of the aluminum foam structure has changed from brittle to ductile mode at temperatures more than 150 °C.

In fact, because of their wide range of applications, this type of cellular material will face compressive loadings at different directions both axially and laterally. Although a very large number of studies in the axial direction were performed under different load conditions [44,45], it is important to study the effect of **lateral** loading direction on the mechanical properties and energy absorption of the closed cell aluminum alloy foams, which have extensive applications. Therefore, the aim of this research is to investigate and compare the quasi-static mechanical crushing behavior of closed-cell aluminum-alloy foam, using different loading conditions (**axial and lateral** loading directions) and different testing temperatures (from room temperature to 450 °C). According to author's knowledge, up to now, there is not literature report with respect to the mechanical behavior of lateral loadings of aluminum foams for both room temperature and higher

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The temperature effect on the axial quasi-static compressive behavior of *ex-situ* aluminum foam-filled tubes

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ABSTRACT

This study focuses on the effect of temperature on the mechanical behavior of closed-cell aluminum-alloy foam filled tubes (FFTs) under quasi-static compressive loads. The results of the compressive testing indicated that at each tested temperature the closed-cell aluminum foam improves the mechanical properties of the empty steel tubes. This behavior is related to the interaction effect between the aluminum foam as filler material and the empty tubes. Also, it was observed that the deformation mechanism of FFTs at all tested temperatures is axisymmetric concertina mode with formation of two folds. Due to the softening phenomenon of the steel tube matrix with increasing of temperature the distribution and size of propagated micro-cracks on both loading surfaces and peripheral folds decreased significantly from the order of millimeters up to micrometers. Finally, it was observed that the increasing of the working temperature reduces the ability FFTs to absorb energy during compression test.

1. Introduction

In recent years, vehicle manufacturing companies always try to find a solution to increase the safety of the passengers during accidents. One of the most important parts of the automobile bodies are hollow sections that reveal the energy absorption capacity [1–3]. In order to enhance the mechanical properties of these sections, foam filled thin walled tubes have been gained a lot of attention in recent years owing to their excellent energy absorption behaviors [4–6]. Different types of foam and tube materials have been used [7–9]. Yan et al. [10] investigated the effect of polyurethane foam on flax fabric reinforced epoxy composite tubes. Their results showed that the foam filled tubes have better crashworthiness than empty tubes. Hussein et al. [11] found that inserting the polyurethane foam and aluminum honeycomb structure on the square hollow aluminum tube under quasi-static compressive loads changes the deformation mode from progressive folding for square hollow aluminum tube to splitting mode for filled aluminum sections. Also their results indicated that inserting the both polyurethane foam and aluminum honeycomb within aluminum tube shows the highest level of axial crashworthiness.

On the other hand, metallic foams are another type of filler material extensively used in different industrial hollow sections [12,13]. Duarte et al. [14] filled thin walled aluminum tubes with Advance Pore Morphology (APM) elements and tested the quasi-static axial crush performance of the structures. The results indicated that the capability of the energy absorption of such structure increased in comparison with aluminum tubes. Among the different types of cellular metals, aluminum foam was used predominantly in empty strength and stiff tubes [15]. This filler reveals interesting mechanical properties for automotive and building application due to its unique properties such as light weight, appropriate energy absorption capacity and high strength to weight ratio [16,17]. Both *ex-situ* foam filled tubes (FFTs) and *in-situ* FFTs have fabricated by using aluminum foam as the core material [14–16]. The bending strength results of aluminum FFTs obtained by different researchers indicate an enhancement of the bending behavior of these composite structures under quasi-static and dynamic loadings [18]. It was demonstrated, by Durate et al. [19], that the presence of Al foams as filler inside the tube in their produced ex-situ composite presents a much more stable crushing manner under compression loadings. Also they found that the energy absorption of the aluminum foam filled structure enhanced by increasing the foam density. Tu et al. [20] studied the damping level of aluminum foam filled steel tubes. They found that under high level of vibration, the FFTs have the ability of highest level of damping.

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