UDK 996.715:534:539.217
Original scientific article/Izvirni znanstveni članek

ISSN 1580-2949
MTAEC9, 57(5)423(2023)

A STUDY ON SOUND-ABSORPTION ABILITY OF CLOSED-CELL ALUMINIUM FOAMS

ŠTUDIJA SPOSOBNOSTI ABSORPCIJE ZVOKA KOVINSKIH PEN Z ZAPRTIMI CELICAMI NA OSNOVI ALUMINIJA

Vaddi Thulasikanth, R. Padmanabhan*

School of Mechanical Engineering, Vellore Institute of Technology, Chennai, India

Prejem rokopisa – received: 2023-01-12; sprejem za objavo – accepted for publication: 2023-05-08

doi:10.17222/mit.2023.741

Metallic foams have gained popularity in industrial applications and research due to their unique mechanical properties combined with light weight, vibroacoustic damping and high-temperature resistance. Generally, closed-cell foams have poor sound absorption properties due to their closed cellular structure when compared to open-cell foams. This paper investigates a new composite closed-cell foam for its acoustic properties. The new closed-cell aluminium fly-ash foam was made with liquid processing, using calcium carbonate ($CaCO_3$) as the blowing agent. The effects of the fly-ash content on the cell morphology and mechanical properties were analyzed. Acoustic studies were conducted on the prepared closed-cell foam using the impedance tube method. Samples were prepared in different ways to determine the effects of the changing parameters. The results of quasi-static compression and microstructural analyses of two different combinations of the foam revealed small pore sizes with varying relative densities and compressive strengths. It is evident from the acoustic studies that the foams are capable of improved sound absorption of medium and high frequencies.

Keywords: aluminium foams, stir casting, sound absorption, $CaCO_3$

Kovinske pene so zaradi enkratnih mehanskih lastnosti, majhne specifične gostote, sposobnosti vibroakustičnega dušenja in odpornosti proti povišanim temperaturam zelo popularne v novejših raziskavah za vrsto različnih industrijskih aplikacij . V splošnem imajo pene z zaprto poroznostjo (celice oz. pore so med seboj nepovezane) slabšo sposobnost absorpcije zvoka kot pene z odprto poroznostjo. V članku je opisana raziskave akustičnih lastnosti novega kompozita z zaprto poroznostjo. Novi kompozit z zaprto poroznostjo so izdelali z livarskim mešalno-vrtilnim postopkom pri katerem so v staljeno zlitino Al7Si2Mg dodajali pepel (2 in 5) *w*/%, ki se nabira v filtrih med livarsko proizvodno aluminijevih zlitin. Kot penilno sredstvo so pri tem uporabljali kalcijev karbonat ($CaCO_3$) in dodatek magnezija za izboljšanje omočljivosti delcev pepela s talino. Analizirali so vpliv količine dodanega filtrnega pepela na morfologijo celic in mehanske lastnosti izdelanih pen. Akustične lastnosti izdelanih pen so določili z impedančno cevno metodo. Vzorce pen so izdelali na različne načine tako, da so lahko ugotavljali vpliv spremembe procesnih parametrov na lastnosti pen. Rezultati kvazistatičnih tlačnih preizkusov in mikrostrukturne analize pen so pokazale, da imajo izdelane pene majhno velikost por in spremenjeno specifično gostoto glede na količino dodanega filtrnega pepela. Akustične raziskave so pokazale, da je pri penah z zaprto poroznostjo možno doseči izboljšanje sposobnosti za absorpcijo zvoka pri srednjih in visokih frekvencah.

Ključne besede: kovinske pene na osnovi aluminija, mešalno-vrtilno litje, absorpcija zvoka, kalcijev karbonat

1 INTRODUCTION

Noise is an unpleasant sound that upsets people and other creatures both mentally and physically. Because of the rapid urbanization, various sources of noise from industries, transportation vehicles (both conventional and electric),[1] construction and building sites[2] and even under-water vehicles[3] are regarded as a serious environmental problem all around the world. New low-cost lightweight materials with improved mechanical strength and high-efficiency noise-absorbing properties in a wide frequency range are greatly needed. Chang et al. presented several effective strategies from the previous literature, used to attenuate the acoustic waves with acoustic metamaterials and intelligent materials, especially for low-frequency acoustic absorption.[4] Cellular materials, due to their unique structures composed of solid areas and vacant pores, have gained a significant role in dissipating sound energy with various absorbing mechanisms like viscous shear, friction, Helmholtz resonance, structural vibration, etc.[5,6] Several advanced materials based on polymers,[7] metals,[8,9] ceramics,[10] elastomers[11] and their composites coupled with precision manufacturing have been developed so far.

However, aluminium foam panels are widely used in heavy machinery industries, transportation and building sectors, for sound absorbing because of their unique cellular structures with the combination of excellent properties like light weight, durability, recyclability, workability, resistance to humidity and fire.[12–15] Enhanced sound absorption capacity was achieved with Alporas (trade name) foam panels by creating cracks through rolling or compression, attributable to a viscous loss and thermoelastic damping.[12] The sound absorption coefficient increases as the pore opening diameter decreases, while the pore size has a marginal effect on the sound absorbing capacity.[13] With a higher surface pore opening density, the sound-absorption performance in-

*Corresponding author's e-mail:
padmanabhan.r@vit.ac.in (R. Padmanabhan)

creases due to an increase in the thermoelastic dissipation and viscous loss. Nosko and Kovacik[15] investigated ACCESS, ALPORAS, ALULIGHT (trade names) to determine the influence of the foam preparation method on the sound absorption capacity. An ideal porosity, of around 75 %, results in superior sound absorption. Surface opening of the pores is important for the sound wave to be absorbed.[15] Aluminium foams are classified into two types based on pore connectivity: i) open-cell foams (pores are interconnected with each other) and ii) closed-cell foams (pores are independent of each other). Previous research studies proved that open-cell foams are better sound absorbers than closed-cell foams due to their interconnected pore structure.[16,17] Because of the gas-filled individual cells in the metal matrix, closed-cell aluminium foams are better sound insulators and have superior mechanical properties than open-cell foams.[18,19] Keeping their superior mechanical properties in mind, several researchers were focused on improving the sound absorption property of closed-cell foams by altering their surface and cell structure. According to earlier studies, the post-foaming procedures, such as drilling,[20] machining,[18] rolling, compression,[21] heat treatment (heating and quenching)[22] and others, improve the sound absorption capacity by introducing pore connectivity to closed-cell foams.

Though closed-cell foams have great potential, their widely spread utilization is still limited by the need for expensive additives, delicate process conditions and difficulties in mass production at an affordable price. Among several manufacturing routes, liquid state processing at minimal costs is better for mass production.[23] In this work, aluminium foams are produced via the melt route by admixing the gas-releasing foaming agent in to the aluminium melt. Foams produced with the dissolved gas method make use of hydrides (TiH_2, ZrH_2, CaH_2 etc.) or carbonates ($CaCO_3$, $MgCO_3$, $CaMg(CO_3)_2$, etc.) as the foaming agents.[24,25] During foaming the evolved gas bubbles are moving upward due to the buoyancy force. An addition of ex-situ (SiC, Al_2O_3, Al, etc.)[26–28] or creation of in-situ (TiB_2, $MgAl_2O_4$, etc.)[29–30] oxides particles in the melt will improve the viscosity, thereby bubbles will be entrapped. Hence, there is a strong need to investigate the economic feasibility of producing aluminium foams without sacrificing the performance by employing appropriate processing techniques and using less expensive raw materials (thickening and foaming agents). Class F fly ash, which is produced at thermal power plants by the combustion of bituminous and anthracite coals, was used as a low-cost reinforcement to create non-ferrous composites with excellent mechanical and tribological properties. Previous research studies demonstrated that fly ash can also be used as an effective thickening agent in the production of aluminium foams.[31–33] Many alternative foaming agents were proposed for the processing of aluminium foams, one of which is $CaCO_3$, a low-cost foaming agent with excellent mechanical properties.[33–35]

In this work, closed-cell aluminium foams are produced through the melt route with an inexpensive thickening agent (class F fly ash, an industrial waste) and calcium carbonate ($CaCO_3$) as the foaming agent. This material combination with the resulting foam forms green technology and is little investigated; hence, this study focuses on the preparation and investigation on the acoustic characteristics. In addition, the focus is placed on the impact of two post-foaming processes, hacksaw machining and drilling holes, on the sound absorption ability of the prepared aluminium fly-ash closed-cell foams. Section 2 presents the processing of aluminium

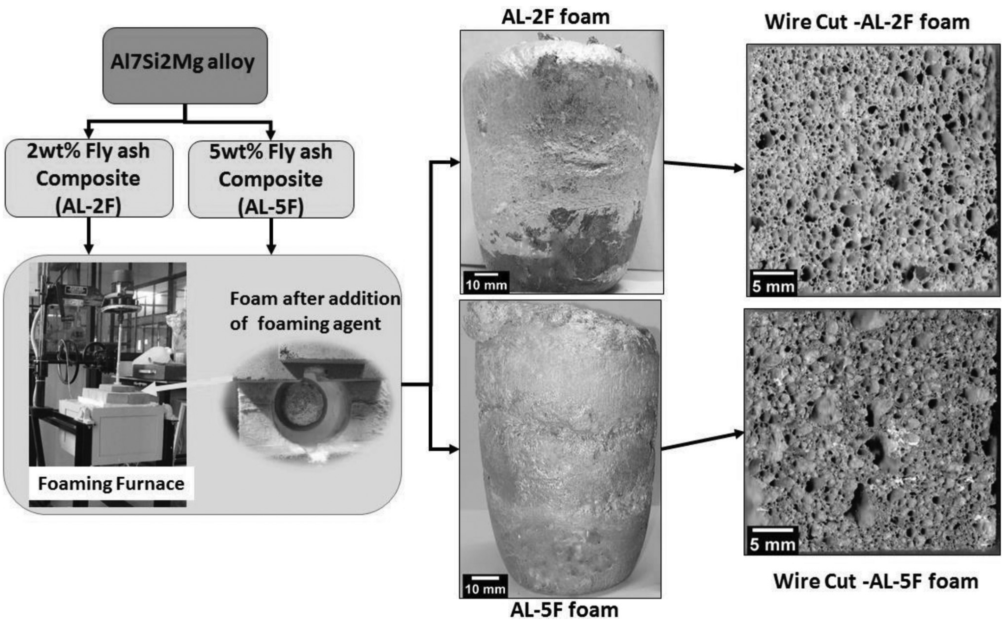

Figure 1: Process flow for composite foams Al-2F and Al-5F

foams and characterization of compression and acoustic properties. The ex-situ characterization of the foams is carried out as per standards and the correlations between the structure and properties are established in Section 3, followed by conclusions.

2 EXPERIMENTAL PART

2.1 Processing of the composite and foams

Closed-cell foams were made in-house with Al7Si2Mg alloy and fly ash (2 *w*/% and 5 *w*/%) by stir casting, using $CaCO_3$ as the foaming agent. Preheated fly ash (800 °C for 3 hr) with an average particle size of 2–3 μm was used as the reinforcement and 1 *w*/% magnesium (Mg) was added to the alloy to improve the wetting between fly-ash particles and aluminium melt. Two composite combinations were prepared in-house during a stir casting process. We produced 1kg of each composite by varying the fly ash (Al-2F and Al-5F). For the Al-2F composite, first the Al7Si2Mg alloy was melted in a furnace at 850 °C and 1 *w*/% of magnesium was immersed into the melt to improve the wettability of fly-ash particles with the molten alloy. The stirring of melt was carried out at 350 min^{-1} and the preheated fly ash (1 *w*/%) was added gradually to the melt over a period of 20 min. Finally, the composite mixture was poured in a preheated metal die and the melt was allowed to solidify at room temperature.[33] A similar procedure was used when processing 5 *w*/% of fly ash for the Al-5F composite. These are the steps used for preparing the foams, included in the process illustrated in **Figure 1**: i) the Al-2F composite in the amount of 100 g was placed in a clay graphite crucible and melted in the furnace at 680 °C; ii) preheated $CaCO_3$ (a particle size of ≈50 μm) in the amount of 3 *w*/% was added to the composite slurry and stirred at a 1200 min^{-1} speed for 120 s; iii) the foaming mixture was allowed to expand in the crucible for 180 s; iv) finally, the crucible containing the foam was taken out and allowed to solidify under rapid cooling, using compressed air. A similar procedure was used for the Al-5F composite foam as well.

As-cast foams (the second column in the figure) and wire cut EDM-sectioned cubic samples of Al-2F and Al-5F foams (the third column in the figure) are shown in **Figure 1**. Scanned images of cut foam sections were used to analyse the pore structure of the foams.

2.2 Quasi-static compression test

Cellular metals exhibit a unique stress-strain response under compression with a plateau region, in which the stress is nearly constant over a wide range of strain. This behaviour makes cellular metals appealing for energy absorption applications where a significant amount of deformation can be absorbed at a relatively low constant stress.[36] In general, the compressive strength of aluminium foams can vary depending on several factors such as the type of the alloy used, stabilizing and foaming agents used, manufacturing process, relative density of the foam, loading rate and the direction of loading relative to the foam's cellular structure.[24] Because of their porous nature, aluminum foams have lower compressive strengths than solid aluminum. They can, however, have a good strength-to-weight ratio and high energy absorption capability, making them useful in applications requiring weight reduction and impact resistance.[36] In order to find the mechanical strength of the foams under compression loads, typically observed in a vehicle upon impact, a uniaxial compression test was carried out at room temperature in the same direction as the principal foam growth, as per ISO 13314:2011 standard. The test specimens were sliced to form cubic samples of (30 × 30 × 30) mm using wire cut EDM (shown in **Figure 1**). The minimum dimensions of a sample are seven times higher than the cell size to avoid the size effect. The tests were carried out in-house using a universal testing machine (Shimadzu, AG-X plus 50KN) at a cross-head speed of

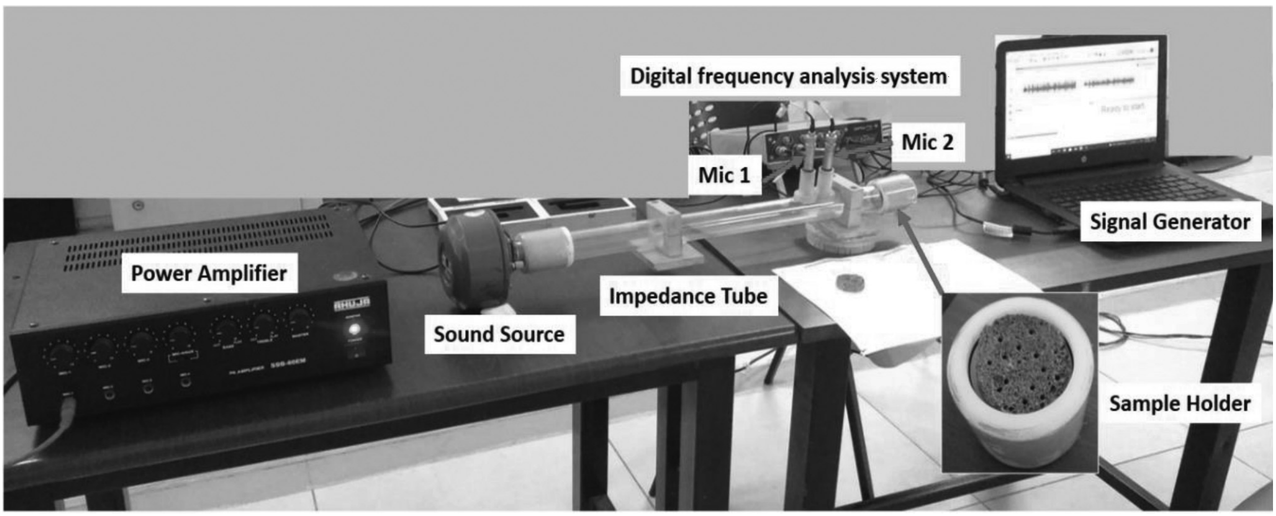

Figure 2: Acoustic testing set-up with Al-2F perforated foam

2 mm/min. The contact surface between the platens and foam was lubricated with molybdenum disulphide (MoS_2) in order to reduce friction.[37] The foam exhibited three-stage compression characteristics, which are further described and discussed in Section 3.2.

2.3 Sound-absorption ability testing

Sound-absorption ability tests were carried out in-house using an impedance tube set-up as per ASTM E 1050-98 standard, as shown in **Figure 2**. The test set-up consists of a power amplifier, sound source, impedance tube, two microphones and a digital frequency analysis system to determine the sound-absorption coefficient of the prepared foam at normal incidence, that is, 0°. An acoustic drive (loudspeaker) is mounted at one end of the impedance tube and a foam sample at the other end, with an air gap of 10 mm before the end of the tube. Plane waves are typically generated in the tube using a broad band signal from a sound source, which propagate through the tube, impact the sample normally and are reflected back, resulting in a standing wave interference pattern within the tube. Near the sample end of the tube, a pair of microphones positioned parallel to the inner wall are used to measure the sound pressure, and a multichannel spectrum analyser is used to determine the complex transfer function between the two readings. The microphone kept closer to the source is taken as the reference channel. The incident and reflected energy are separated from the measured transfer function, and the required acoustic characteristics of the test sample are estimated.

The influence of the foam surface and structure on the sound absorption is investigated. The tests were carried out at a frequency range of 500–4000 Hz. The optical microscopy and SEM analysis of the foams were carried out and all the experimental findings are explained in following section.

3 RESULTS AND DISCUSSION

3.1 Structure of the foams

The cut sections of the foam samples were scanned at a resolution of 600 dpi and the images obtained were analysed in the Image-J software to find the average cell size. The average cell diameter observed in the Al-2F foam is 1.24 mm, while that observed in the Al-5F foam is 1.87 mm as shown in **Figures 3a** and **3b**. Al-2F has a small cell size and most of its cells are separated by cell walls when compared to Al-5F. As depicted in **Figure 1**, the cells of both Al-2F and Al-5F are close to a spherical shape and only few are of an irregular shape. However, Al-2F has a larger proportion of smaller cells than Al-5F.

Foam densities were calculated from the cubic sections and relative densities (ρ_r) were determined as 0.20 and 0.17 for the Al-2F foam and Al-5F foam, respectively. The relative density is the ratio of the density of foam to the density of matrix material at the cell wall. The porosity percentage (P) of the foam was calculated with Equation (1).[38]

$$P = (1 - \rho_r) \times 100 \tag{1}$$

The percentage of porosity obtained for Al-2F is 80 % and for Al-5F it is 87 %. The Al-5F foam shows a larger expansion than Al-2F, which is evident from the obtained values.

Figure 4 shows SEM micrographs and EDS spectra of the Al-2F and Al-5F foams at the gas-solid interface. It is evident from **Figures 4a** and **4c** that the stabilizing particles formed as a result of the reaction are evenly distributed along the plateau border and cell walls, which is confirmed by the presence of elements such as O, Al, Si, Mg and Ca in Figures 4b and 4d, respectively. In order to improve the wetting characteristics and chemical reaction between the alloy and fly ash, Mg was added and its presence is confirmed with the EDS results. Moreover, compared to Al, Mg has a higher affinity for the oxygen present in the fly ash. **Figure 4e** represents the reaction products formed in the Al-5F composite such as Al_2O_3, Mg_2Si, MgO and $MgAl_2O_4$. Similar oxides are also formed in the Al-2F composite.[33, 39] According to the

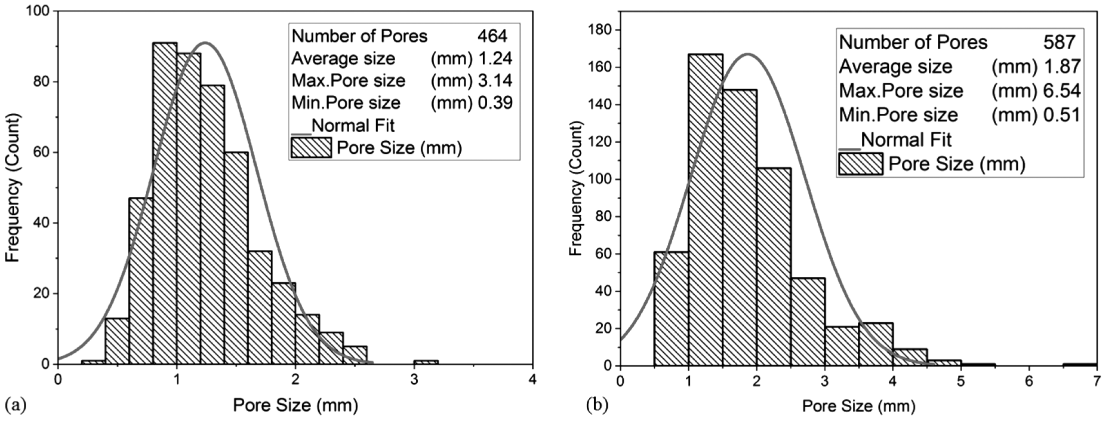

Figure 3: Pore-size distributions of: a) AL-2F foam and b) Al-5F foam

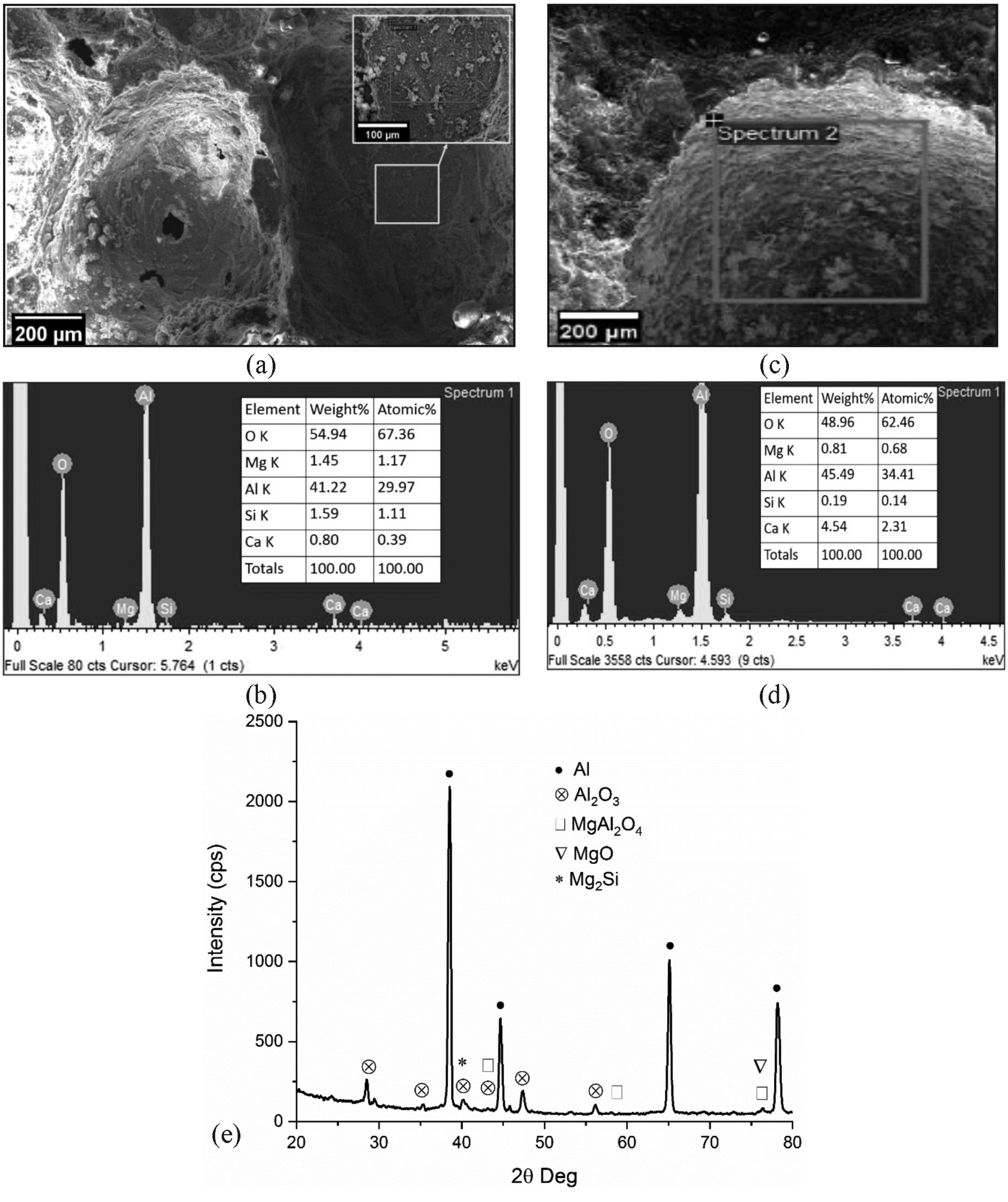

Figure 4: a) SE SEM image of Al-2F foam at the gas-solid interface, b) EDS spectra of Al-2F foam at the gas-solid interface, c) SE SEM image of Al-5F foam at the gas-solid interface, d) EDS spectra of Al-5F foam at the gas-solid interface and e) X-ray diffraction of Al-5F composite

EDS results, there is a significant decrease in the Mg content in Al-5F with the increasing fly-ash weight fraction and these results match well with an earlier research.[40] All these reaction products contribute to the stabilizing of the foam; in addition, a thin layer of solid reaction occurs early in the foaming process as a result of the $CaCO_3$ and melt reaction, stabilizing the cells by modifying the surface tension and preventing the coalescence and coarsening of the cells. Furthermore, the solid particles formed due to the thermal breakdown of carbonate (CaO) increase the melt viscosity, enhancing the foam stabilization.[34] The presence of more oxide particles in the Al-2F foam contributes to the creation of a sufficient surface tension, which enhances the formation of smaller cells with a high relative density. From the results it is evident that industrial-waste fly-ash particles can be used in the production of aluminium foams, allowing the control of the melt viscosity, decreasing the melt flowability in all directions and contributing to the stability of cells.

3.2 Compressive behaviour of the foams

Porous metals should have sufficient structural durability in order to use it for any real-time acoustic and other engineering applications, such as anti-collision energy-absorbing bars in an automobile. The compression strength of the two foams were evaluated using a uniaxial compression test at a strain rate of 1.1×10^{-3} s^{-1} and characteristic stress-strain curves are shown in **Figure 5**.

Both foams exhibited well-known three-stage deformation characteristics when subjected to quasi-static compression: the initial linear elastic region (R1), lengthened plateau region when the stress slowly increases due to cell plastic deformation (R2) and final densification region (R3) when collapsed cells are compacted together. The results show that the compressive yield stress is 2.49 MPa for Al-2F and 1.86 MPa for AL-5F, and these results are in good agreement with the reported values.[31,32] Al-2F exhibits an increased compressive strength, higher than that of Al-5F due to a higher relative density (0.20), lower pore size (1.24 mm) and lower porosity (80 %). A greater volume fraction of the solid phase in Al-2F is indicated by a higher relative density and lower porosity, which results in an earlier densification stage during the compression test. The compressive-strength range obtained for both foams are suitable for medium impact and energy-absorption applications.[36] Additionally, the foams obtained will give some structural support and bear compressive load when

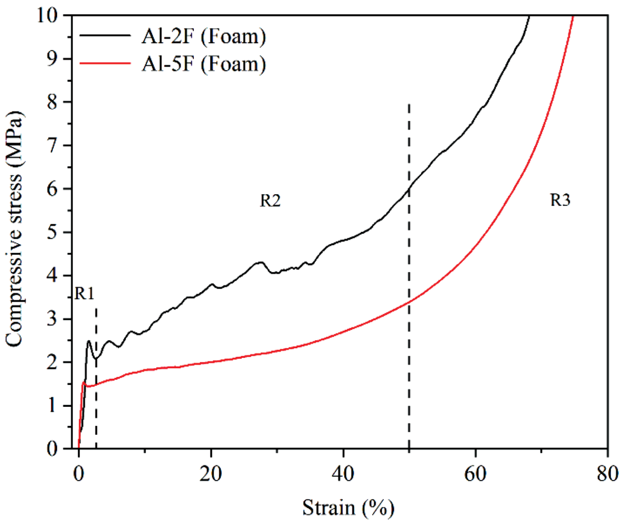

Figure 5: Quasi-static compression results for foams

used as sound-absorbing panels or slabs in automobiles, large conference rooms and factory workshops.

3.3 Acoustic behaviour of the foams

An individual anisotropic closed-cell network will restrict the permeability of incident sound waves. In order to alter these features, the permeability should be increased to enable the acoustic waves to penetrate through the cells. Earlier researches indicate that modifying the surface and structure of closed-cell aluminium foams can improve their sound-absorption capacities.[18,20–21] In this study, both Al-2F and Al-5F foams were sliced with a hacksaw and holes were drilled in order to change the surface and structure as shown in **Figures 6a**, **6c**, **6d** and **6f**. The foam samples were cut with the hacksaw blade to obtain a thickness of 10 mm and a diameter of Ø33 mm using wire cut EDM. Al-2F is shown in **Figure 6a** and Al-5F is shown in **Figure 6d**. **Figures 6b** and **6e** show the samples at a higher magnification of the incidence surface formed by the hacksaw and the difference in the pore size. Perforations of Ø1.5 mm to a depth of 5 mm were made randomly on another set of acoustic samples, denoted as Al-2F (H) in **Figure 6c** and Al-5F (H) in **Figure 6f**.

The sound absorption coefficient results for the foams were plotted in the graph for up to 2000 Hz, as shown in **Figure 6g**. It is observed that all the foam samples show a two-peak wave pattern shifting the peak from low to high frequencies with minimum sound absorption coefficient values of 0.3 to 0.4 at 500–600 Hz and maximum values of 0.78 to 1.0 at 1400–1600 Hz. The minimum peak at 500–600 Hz for all the foam samples is due to the effect of the membrane resonator mechanism by the air gap left in between the sample and rigid end of the impedance tube.[41,42] According to the pore structure analysis discussed in Section 3.1, the Al-2F foam has a higher relative density and smaller average pore size and porosity than the Al-5F foam. The higher relative density and smaller pore size of Al-2F indicate that the solid-medium amount is higher than the fluid-medium amount, lowering the permeability of sound waves and leading to a decreased sound absorption. For an improved sound absorption, the estimated pore connectivity should be at least 0.3 mm and the pore size should not be less than 1 mm because the values lower than this cause the material to reflect rather than absorb the sound.[12]

In the first case, the incidence surface finish of both Al-2F and Al-5F foams was altered by the shearing action of the hacksaw. The microscopic images of the foams from **Figures 6b** and **6e** reveal that cell faces and cell walls have rough surface profiles with a few microcracks, their edges being bent and fractured by cutting. This increases the permeability of incident sound waves in closed-cell foams, further increasing the wave energy dissipation. As the incidence surface finish was

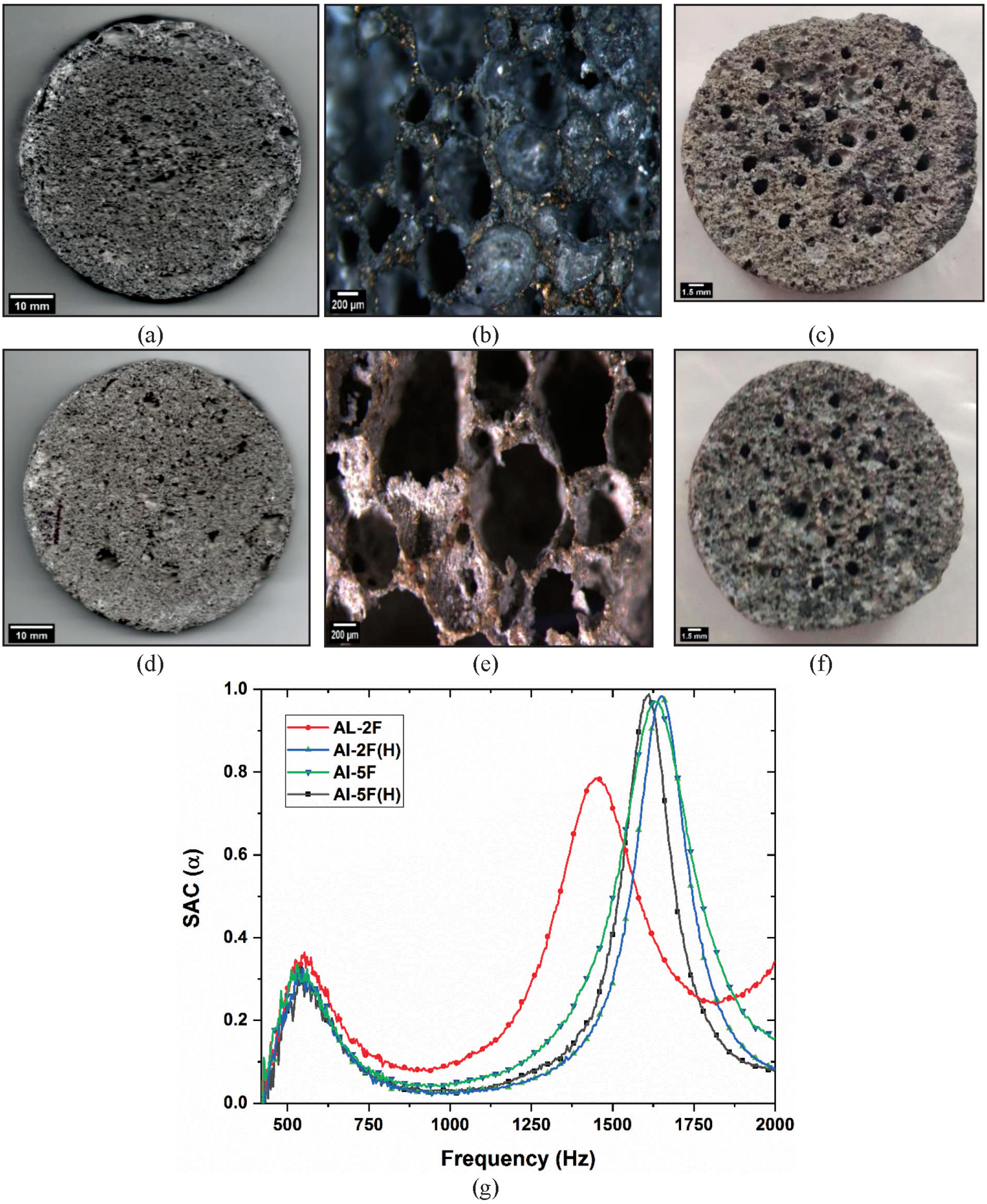

Figure 6: a) Hacksaw cut Al-2F foam without holes, b) microscopic image of the hacksaw cut Al-2F foam, c) Al-2F (H) foam with holes, d) hacksaw cut Al-5F foam without holes, e) microscopic image of the hacksaw cut Al-5F foam, f) Al-5F (H) foam with holes, and g) sound absorption coefficient results for the foams

altered by the hacksaw, sound waves propagate through tortuous porous tunnels formed by induced cracks and bends, and some energy is lost due to the viscous shear of air molecule against the boundary cell walls. The results obtained are in agreement with the observations made in earlier research works on different closed-cell foams,[12] Al-SiC composites with TiH_2 and $CaCO_3$.[18]

In general, the viscous resistance mechanism is limited for smaller material thicknesses as with this mechanism the permeability of sound occurs only via micro pores or cracks on cell faces.[19] Another easy approach to opening a closed-cell structure is drilling holes, which will lead to an absorption via the cavity resonator mechanism. In our case, holes of Ø1.5 mm were drilled and both foams showed sound absorption coefficient values that were almost 1.0. It is evident that there is not much deviation in the peak of the AL-5F foam with or without the drilled holes. In Al-2F, a significant increase in the peak is observed after drilling even though it has a higher relative density, and lower values of pore size and porosity percentage when compared to Al-5F. The increase is due to the holes drilled to a depth of 5 mm, interconnecting the closed-cells and cavities formed in the foams and finally leading to a dissipation of sound energy due to the cavity and resonance sound absorption mechanism. It can be observed from the results that the sound absorption performance of the closed-cell composite foams can be improved by altering the surface and pore geometry with two techniques used in the current work, i.e., low-cost machining using a hacksaw and conventional drilling. Additionally, it is evident from the SEM microstructures shown in **Figures 4a** and **4c** that prior to hacksaw machining and perforation of the foams, some small micropores formed in-situ in cell walls and faces, also augmenting the pore connectivity.

4 CONCLUSIONS

Closed-cell foams made by stir casting using Al7Si2Mg alloy, low-cost raw materials like fly ash and calcium carbonate as the foaming agent demonstrated good mechanical properties. The post-casting treatment additionally improved their sound-absorption capacity. It is observed that the amount of fly ash plays a significant role in stabilizing the foams by creating in-situ oxide particles during its reaction with the aluminium alloy used. It is observed from the results that an increase in the fly-ash weight contributed to an increase in the porosity and cell size, and a decrease in the relative density of the foams. Both Al-2F and Al-5F foams show an appreciable compressive strength. Our experimental investigation indicates that the post-foaming casting process (hacksaw machining) improved the sound-absorption capacity by altering the surface finish and cell structure with the viscous drag mechanism and cavity resonator mechanism. The foams subjected to hacksaw machining obtained a good sound absorption capacity due to the viscous drag mechanism. However, the sound-energy dissipation due to viscous drag is insufficient and can be further improved by drilling holes in the foams. The results for the Al-2F (H) and Al-5F (H) foams show that drilling holes on the hacksaw cut surface changed the cell structure and enhanced the sound-absorption ability via the cavity resonator mechanism. According to the microstructure analysis of the foam structure, the Al-5F foam with bigger cells has a tendency to absorb more sound waves because the surfaces of the cell walls are twisted and there are more cracks and pores, resulting in increased sound energy absorption. The sound absorption of the Al-2F and Al-5F foams is most promising for medium and high-frequency performance. A good sound absorption capacity, combined with better mechanical properties, makes the developed foams, Al-2F and Al-5F, ideal for applications such as enclosures in heavy machinery, hybrid vehicles, public buildings, etc.

Acknowledgment

We are grateful to the Vellore Institute of Technology (Chennai and Vellore Campus) for letting us use the processing and characterization facilities needed for our work. We are also thankful to Dr. S. Jeyanthi, Associate Professor, and Mr. S. Vinoth Kumar, Research Scholar, Vellore Institute of Technology (Chennai) for their support in using the acoustic testing facility, granted under the Seed Fund, School of Mechanical Engineering, VIT Chennai.

Authors' Declarations

No Funding Involved

The authors, V. Thulasikanth and R. Padmanabhan, declare that this research does not involve any source of funding, financial or non-financial interests, nor does it need any specific committee (ethics) approval as it does not involve human/animal participation.

Compliance with Ethical Standards

The two authors, V. Thulasikanth and R. Padmanabhan, have no conflict of interest and the research does not involve any human/animal participation.

5 REFERENCES

[1] T. Whitehead Bassett, S. Tate, M. Maunder, Study of high frequency noise from electric machines in hybrid and electric vehicles, Inter-noise, (2014), doi:10.1039/d1ra06493b

[2] F. Asdrubali, S. Schiavoni1, K. V. Horoshenkov, A Review of Sustainable Materials for Acoustic Applications, Building Acoustics, 19 (**2012**) 4, 283–312, doi:10.1016/j.polymertesting.2021.107115

[3] Y. Fu, I. I. Kabir, G. Heng Yeoh, Z. Peng, A review on polymer-based materials for underwater sound absorption, Polymer Testing, 96 (**2021**), 107115, doi:10.1260/1351-010X.19.4.283

[4] L. Chang, A. Jiang, M. Rao, F. Ma, H. Huang, Z. Zhu, Y. Zhang, Y. Wu, B. Li, Y. Hu, Progress of low-frequency sound absorption research utilizing intelligent materials and acoustic metamaterials, RSC Adv., (**2021**) 60, 37784–37800

[5] R. Dunne, D. Desai, R. Sadiku, A Review of the Factors that Influence Sound Absorption and the Available Empirical Models for Fibrous Materials, Acoust. Aust., (**2017**) 45, 453–469, doi:10.1007/s40857-017-0097-4

[6] L. E. Kinsler, A. R. Frey, G. S. Bennett, Fundamentals of Acoustics, American Journal of Physics, 19 (**1951**), 254, doi:10.1119/1.1932798

[7] N. Rastegar, A. Ershad-Langroudi, H. Parsimehr, G. Moradi, Sound-absorbing porous materials: a review on polyurethane-based foams, Iranian Polymer Journal, (**2022**) 31, 83–105, doi:10.1007/s13726-021-01006-8

[8] C. Perrot, F. Chevillotte, L. Jaouen, M. T. Hoang, Acoustics properties and applications, in Metallic Foams: Fundamentals and Applications, Nihad Dukhan, Ph.D. (ed.), University of Detroit Mercy, DesTech Publications, (**2013**), 285–316, 978-1- 60595-014-3

[9] F. García-Moreno, Commercial Applications of Metal Foams: their Properties and Production, Materials, 9 (**2016**), 85, doi:10.3390/ma9020085

[10] J. Zhang, B. Liu, S. Zhang, A review of glass ceramic foams prepared from solid wastes: Processing, heavy-metal solidification and volatilization, applications, Science of the Total Environment, 781 (**2021**), 146727, doi:10.1016/j.scitotenv.2021.146727

[11] S. Amares, E. Sujatmika, T. W. Hong, R. Durairaj, H. S. H. B. Hamid, A Review: Characteristics of Noise Absorption Material, IOP Conf. Series: Journal of Physics: Conf. Series, 908 (**2017**), 012005, doi:10.1088/1742-6596/908/1/012005

[12] T. J. Lu, A. Hess, M. F. Ashby, Sound absorption in metallic foams, J. Appl. Phys., 85 (**1999**), 7528, doi:10.1063/1.370550

[13] Y. Li, X. Wang, X. Wang, Y. Ren, F. Han, C. Wen, Sound absorption characteristics of aluminum foam with spherical cells, Journal of Applied Physics, 110 (**2011**), 113525, doi:10.1063/1.3665216

[14] G.-C. Yao, H.-J. Luo, Z.-K. Cao, The Manufacturing Technology of Aluminum Foam Material and Some Special Equipments, International Conference on Material Science and Applications (ICMSA 2015), 2015, 869–874, doi:10.2991/icmsa-15.2015.16

[15] M. Nosko, F. Simančík, R. Florek, P. Tobolka, J. Jerz, N. Mináriková, J. Kováčik, Sound absorption ability of aluminium foams, Metallic Foams, 1 (**2017**) 1, 15–41, doi:10.23977/metf.2017.11002

[16] T. Wan, Y. Liu, C. Zhou, X. Chen, Y. Li, Fabrication, properties, and applications of open-cell aluminum foams: A review, Journal of Materials Science & Technology, 62 (**2021**), 11–24, doi:10.1016/j.jmst.2020.05.039

[17] M. A. Azizan, M. H. Ismail, N. A. Mohd Salleh, D. Valliyappan Natarajan, Sound Absorption Properties at High Sound Frequency of Open Cell Aluminium Foam, Journal of Mechanical Engineering, SI 2 (**2017**) 1, 161–173

[18] J. Ghose, V. Sharma, S. Kumar, Acoustic Absorption Characteristics of Closed Cell Aluminium Foam, Applied Mechanics and Materials, 110–116 (**2012**), 1145–1149, doi:10.4028/www.scientific.net/AMM.110-116.1145

[19] X. Xia, Z. Zhang, W. Zhao, C. Li, J. Ding, C. Liu, Y. Liu, Acoustic properties of closed-cell aluminum foams with different macrostructures, Journal of Materials Science & Technology, 33 (**2017**) 11, 1227–1234, doi:10.1016/j.jmst.2017.07.012

[20] K. C. Opiela, T. G. Zielinski, T. Dvorak, S. Kudela Jr., Perforated closed-cell aluminium foam for acoustic absorption, Appl. Acoust., 174 (**2021**), 107706, doi:10.1016/j.apacoust.2020.107706

[21] P. Bai, X. Yang, X. Shen, X. Zhang, Z. Li, Q. Yin, G. Jiang, F. Yang, Sound absorption performance of the acoustic absorber fabricated by compression and microperforation of the porous metal, Materials and Design, 167 (**2019**), 107637, doi:10.1016/j.matdes.2019.107637

[22] A. Byakova, Y. Bezim'yanny, S. Gnyloskurenko, T. Nakamurac, Fabrication method for closed-cell aluminium foam with improved sound absorption ability, Procedia Materials Science, 4 (**2014**), 9–14, doi:10.1016/j.mspro.2014.07.573

[23] J. Banhart, Manufacture, characterisation and application of cellular metals and metal foams, Progress in Materials Science, 46 (2001), 559–632, doi:10.1016/S0079-6425(00)00002-5

[24] B. Parveez, N. Ayuni Jamal, A. Maleque, F. Yusof, N. Hani Jamadon, S. Adzila, Review on advances in porous Al composites and the possible way forward, Journal of Materials Research and Technology, 14 (**2021**), 2017–2038, doi:10.1016/j.jmrt.2021.07.055

[25] D. Bhosale, A. Devikar, S. Sasikumar, G. S. Vinod Kumar, Foaming Mg Alloy and Composite Using $MgCO_3$ Blowing Agent, Metall. Mater. Trans. B: Process Metall. Mater. Process. Sci., 52 (**2021**) 931, doi:10.1007/s11663-021-02066-0

[26] D. Kumar Rajak, N. N. Mahajan, S. Das, Fabrication and investigation of influence of $CaCO_3$ as foaming agent on Al-SiCp foam, Materials and Manufacturing Processes, (2018), doi:10.1080/10426914.2018.1532093

[27] N. Mahmutyazicioglu, Onder Albayrak, Mehmet Ipekoglu, Sabri Altintas, Effects of alumina (Al_2O_3) addition on the cell structure and mechanical properties of 6061 foams, J. Mater. Res., (2013), doi:10.1557/jmr.2013.187

[28] Z. Sarajan, M. Soltani, J. Kahani Khabushan, Foaming of Al-Si by TiH_2, Materials and Manufacturing Processes, 26 (**2011**) 10, 1293–1298, doi:10.1080/10426914.2011.551964

[29] Y. Yu, Z. Cao, J. Wang, G. Tu, Y. Mu, Compressive Behavior of Al-TiB_2 Composite Foams Fabricated under Increased Pressure, Materials, (**2021**) 14, 5112, doi:10.3390/ma14175112

[30] S. Bhogi, M. Mukherjee, Foam stabilization by magnesium, Materials Letters, 200 (**2017**), 118–120, doi:10.1016/j.matlet.2017.04.100

[31] D. P. Mondal, M. D. Goel, S. Das, Compressive deformation and energy absorption characteristics of closed cell aluminum-fly ash particle composite foam, Materials Science and Engineering A, 507 (**2009**), 102–109, doi:10.1016/j.msea.2009.01.019

[32] D. P. Mondal, M. D. Goel, S. Das, Effect of strain rate and relative density on compressive deformation behavior of closed cell aluminum–fly ash composite foam, Materials and Design, 30 (**2009**), 1268–1274, doi:10.1016/j.matdes.2008.06.059

[33] T. Vaddi, R. Padmanabhan, Processing of aluminium/fly ash composite foams for sustainable green products, Journal of Porous Materials, 30 (**2022**), 1–11, doi:10.1007/s10934-022-01360-9

[34] V. Gergely, D. C. Curran, T. W. Clyne, The FOAMCARP process: foaming of aluminium MMCs by the chalk-aluminium reaction in precursors, Composites Science and Technology, 63 (**2003**), 2301–2310, doi:10.1016/S0266-3538(03)00263-X

[35] V. Thulasikanth, R. Padmanabhan, Processing and testing of closed cell aluminium hybrid composite foams, Materials Today: Proceedings, (**2021**) 46, 1437–1440, doi:10.1016/j.matpr.2021.03.017

[36] S. U. Nisa, S. Pandey, P. M. Pandey, A review of the compressive properties of closed-cell aluminum metal foams, Proc. IMechE Part E: J. Process Mechanical Engineering, (**2022**), 1–15, doi:10.1177/09544089221112291

[37] D. Kumar Rajak, N. N. Mahajan, E. Linul, Crashworthiness performance and microstructural characteristics of foam-filled thin-walled tubes under diverse strain rate, Journal of Alloys and Compounds, 775 (**2019**), 675–689, doi:10.1016/j.jallcom.2018.10.160

[38] N. Montserrat Trejo Rivera, J. Torres Torres, A. Flores Valdés, A-242 Aluminium Alloy Foams Manufacture from the Recycling of Beverage Cans, Metals, 9 (**2019**), 92, doi:10.3390/met9010092

[39] R. Q. Guo, P. K. Rohatgi, Chemical Reactions between Aluminum and Fly Ash during Synthesis and Reheating of Al–Fly Ash Composite, Metallurgical and Materials Transactions B, 29B (**1998**), 519, doi:10.1007/s11663-998-0086-y

[40] E. Gikunoo, O. Omotoso, I. N. A. Oguocha, Effect of fly ash addition on the magnesium content of casting aluminum alloy A535, Journal of Materials Science, 40 (**2005**) 487–490, doi:10.1023/B:JMSC.0000044906.60260.19

[41] A. Elizabeth González, How Do Acoustic Materials Work, book chapter in Acoustics of Materials, IntechOpen, 2019, 1–17, doi:10.5772/intechopen.82380

[42] X. Fan, X. Chen, Y. Li, The Structure and Acoustic Properties of Aluminum Foams by Gas Injection Method, Advanced Materials Research, 146–147 (**2011**), 1049–1055, doi:10.4028/www.scientific.net/AMR.146-147.1049