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Sound Absorption Properties at High Sound Frequency of Open Cell Aluminium Foam

Mohd Arifhakim Azizan
Muhammad Hussain Ismail
Noor Azlina Mohd Salleh
David Valliyappan Natarajan
Faculty of Mechanical Engineering, Universiti Teknologi MARA, 40450, Shah Alam, Malaysia

ABSTRACT

Open-cell aluminium foam is a type of metallic foam that has been industrialised years ago. It has been found that due to its porous characteristic, it is suitable for sound absorption. The porous characteristic of open-cell aluminium foam is closely related to its sound absorption properties. In this research, the open-cell aluminium foam was produced by infiltration casting method and its sound absorption properties were studied. Infiltration casting is a casting method that uses space holder material in the casting mould and later the mould is infiltrated with molten material by vacuuming and gas purging inside the mould. NaCl was used as the space holder material in order to form the porous structure. The size of NaCl grains is in the range between 1mm to 3 mm. The surface structure of the fabricated open-cell aluminium foam was then observed under an optical microscope while its sound absorption properties were determined using impedance tube test, respected to the ASTM E1050 designation to analyse sound absorption coefficient. It was found that at high sound frequency ranging from 800 Hz to 5000 Hz, open-cell aluminium foam produced from infiltration method gave a higher sound absorption for bigger pore open-cell aluminium foam.

Keywords: *Open-Cell Aluminium Foam, Sound Absorption, High Frequency*

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Introduction

Conventional porous sound absorbers come in a variety of forms and their performance depends on their cell structure. The most common form of porous sound absorbers are fibrous materials and certain sorts of foams such as polymeric foams [1]. In recent years, metallic foams have emerged as an attractive research field both from a scientific viewpoint and from the prospect of industrial applications, as well as for acoustic applications. For now, many of the metal foams produce for commercial use are using aluminium [2]. As such, it is known that aluminium is an abundant metal on the Earth's crust and it has the preferable property to make foam [3]. There is also a method that was created to produce foams from other metals such as magnesium, copper, bronze, steel, titanium, lead, zinc, and even gold [2].

The metal foaming method can be grouped into several line of processes [4]. The line can be grouped into another two groups that are direct foaming and precursor foaming. In direct forming, there is an external bubble formation. There are three basic principles in precursor forming which are internal bubble formation, powder-based and melt-based [4]. Figure 1 shows two types of foaming techniques that used direct foaming and precursor foaming. Precursor material is a compound that participates in a chemical. The reaction will produce another compound from the reaction such as gases that initiate internal bubbles formation in foaming [10].

There are two types of metal foam produced in the industries which are open-cell aluminium foam and closed-cell aluminium foam. Open-cell type of foam has cell edges, or ligament so that the open space of the cell is connecting to each other [5]. It has various applications in heat exchangers, filter element, sound absorption, stiffening elements and etc. [6]. It used infiltration casting process where it utilized the prepared dissolvable mould or space holder such as NaCl [6].

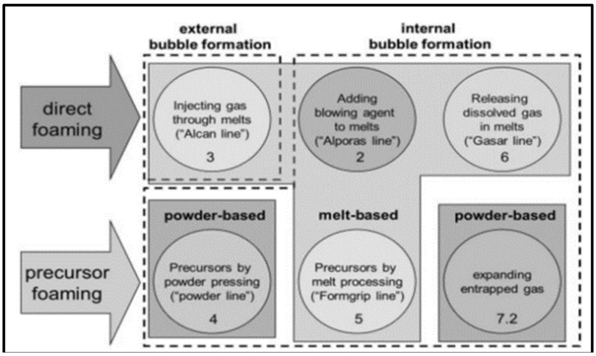

Figure 1: Principle method for metal foaming [4]

Closed-cell aluminium foam is fabricated by using the melt foaming method or it is called precursor foaming [7]. The closed-cell by means is where the cell is connected to each other. It differs from the open-cell where the cell is interconnected. Because of the individual closed-cell, the aluminium foam has the ability to float when it is immersed in the water. Closed-cell contains trap gas or air in it; thus, it acts as bubbles. Closed-cell aluminium foam, such as ALPORAS, was produced by Shinko Wire in 1986 using blowing agent [8]. Blowing agent is added in foaming process of the aluminium to expand the aluminium foam and form the closed-cell structure of the aluminium foams. Figure 2 shows the differences between structures of both open and close-cell aluminium foam.

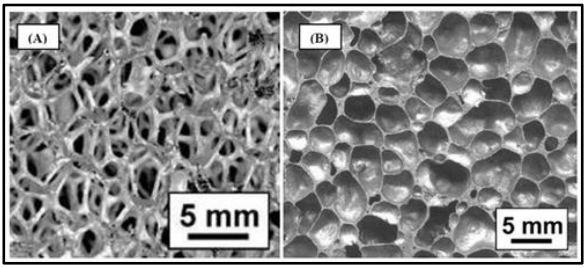

Figure 2: (A) Open-cell (ERG Duocel) and (B) Closed-cell (ALPORAS) [5]

Space holder material is a material that is used to create pore structure by conserving the spaces inside a matrix as they will be eliminated later to expose the conserved space. It is mainly used to produce open-cell structure for metal foam such as aluminium foam. A wide range of materials can serve as pore forming material such as ceramics, polymers, salts and even metals either as particles or hollow spheres [9]. The metal foams produced inherit some of the intrinsic properties of the space holder particles. For instance, the volume fraction, morphology and particle size of the space holder play an important role in altering some cellular architecture features like porosity percentage, pore shapes and cell sizes of the foam products which consequently can define structural and mechanical properties [9].

Open-cell structure in aluminium foam can be achieved by investment casting method or infiltration method. Investment casting is a method where the aluminium foam is formed without foaming the molten aluminium. One of the open-cell aluminium foam products that used investment casting method is DUOCEL foam produced by ERG in California [10]. The process starts by turning the polymer foam into a structure with open pore by manipulating the foaming process or by reticulation treatment. The foam is then filled with slurry that has heat resistance properties. The examples of slurry mixture are mullite, phenolic resin and calcium carbonate [10].

Infiltration casting is a method whereby filler material is used to obtain the open-cell structure of aluminium foam. This method requires the use of filler material such as Sodium Chloride NaCl, Silicon Si and etc. Parts of a predefined shape can be fabricated by designing a mould of the appropriate geometry. Sandwich panels have also been made using similar method [10]. Figure 3 shows the flow of infiltration casting method.

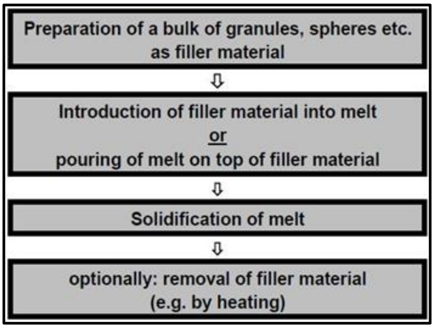

Figure 3: Infiltration casting method [10]

The density of any material can be defined and stated as mass per unit volume. Density of solid and liquid is mostly determined by temperature as compared to pressure since both solid and liquid are incompressible substances. Moreover, the variation of solid and liquid density together with pressure is usually undertaken [11]. Relative density or specific gravity is the ratio of the density of a substance to the density of some standard substance at a specific temperature [11].

$$SG = \frac{\rho}{\rho_{Al}} \tag{1}$$

Where:

SG = Specific gravity

ρ = density of substance (g/cm^3)

ρ_{Al} = Standard substance at a specified temperature (g/cm^3)

In general, porous material is known as holey materials [12]. The porosity that exists in a material, whether it is low or high, would make the material to be named as foam material [12]. The presence of the porosity in the matrix of the material will contribute to a certain potential mechanical properties of the material. Porosity can also be defined as the exposed volume that contributes to empty space in the metal matrix or network. In another definition, it is defined as the connected pores to the surface in a volume that allows fluid to flow from one side to other side of it [13]. Porosity percentage can be calculated using rough measurement technique of the open volume equal to 100% minus the part density [13].

$$\varepsilon = \left(1 - \frac{p_d}{\rho}\right) \times 100\% \qquad (2)$$

Where:

ε = Porosity (%)

ρ_d = Bulk density (g/cm^3)

ρ = Particle density (g/cm^3)

The studies revealed that the aluminium foams have excellent sound absorption properties. It is also comparable with the other sound absorbing material. Good mechanical properties means good sound absorption for aluminium foam [14]. Experimental results indicate that the thickness of the foam affects the sound absorption capability of the foam. When the thickness is optimal, there will be maximum sound absorption coefficient [14]. The experimental results also indicate that damage cell edges on the surface of the foam contribute to the enhance ability of sound absorption [14]. Many researchers have done various investigations in the sound absorption properties of aluminium foam and found that by rolling or drilling the aluminium foam, it will increase the ability of sound absorption because of the transparency of air motion [14].

The sound absorption capability of open-cell foam is better than closed cell foam [14]. The method used to determine the sound absorption of the metal foam is called standing wave tube or impedance tube method [14]. The method is used to determine the sound absorption coefficient. In impedance tube method, the measures of the pressure amplitude at antinodes (maximum pressure) and nodes (minimum pressure) are obtained. The standing wave ratio (SWR) is ratio of the pressure maximum, P_{max} (antinode) to the pressure minimum, P_{min} (node) [14]. It is expressed in equation 3.

$$SWR = \frac{P_{Max}}{P_{Min}} \qquad (3)$$

Sound absorption coefficient, α for the test sample at a given frequency, can be expressed as in equation 4.

$$\alpha = \frac{4 \times SWR}{\left(SWR + 1^2\right)} \tag{4}$$

In order to calculate the sound absorption coefficient of the material, the maximum and minimum peak-to-peak amplitudes of the CRO trace of the microphone signal are recorded. The maximum and minimum peak-to-peak amplitudes of the CRO trace of the microphone signals represent the maximum and minimum pressure of the sound waves in voltages, V1 and V2 respectively. Using equation 5, SWR can be expressed as:

$$SWR = \frac{V_1}{V_2} \tag{5}$$

Experimental Procedure

Fabrication process

The method used to fabricate the aluminium foam is infiltration method. The space holder material used is cooking salt NaCl. The NaCl is chosen as the space holder because it has a higher thermal stability than aluminium and it is soluble in water. The size of NaCl grains is in between 1 mm to 3 mm in diameter. The NaCl grain was graded using a set of sieve plate with mesh sizes of 4mm, 3mm, 2mm and 1mm.

The infiltration casting method was started by preparing the mould. The mould used was cylindrical in shape with a diameter of 28 mm. In the mould, the NaCl was inserted at the bottom part of mould and Al ingot was placed on the NaCl. Figure 4 shows the cross-section view of mould preparation process. The mould was then placed inside a furnace. After that, the furnace was heat up to 690°C for 2 hours. The mould was connected to a duct from a vacuum pump and an argon gas tank. Theoretically, at 690°C, the aluminium ingot completely melted inside the mould. The air inside the mould was pumped out and Argon gas was purged into the mould while the aluminium ingot was still in liquid form. This would push the melted aluminium into the empty spaces left between the NaCl grains at the bottom part of the mould. It would fill up all the spaces and the excess aluminium melt will gather at the top of the NaCl.

After vacuuming and gas purging process were done, the mould was pulled out from the furnace and left to cool at room temperature. The sample was extracted from the mould and it was placed in a water bath inside an ultrasonic cleaner for about 3 hours for 3 cycles. This process is known as water leaching. This was done to eliminate NaCl grains inside the sample. The sample was then cut into 30mm thick. There were two types of open-cell aluminium foam. The first type was without centre solid aluminium pillar while the other has it. Figure 5 and 6 show the structure of the fabricated aluminium foam.

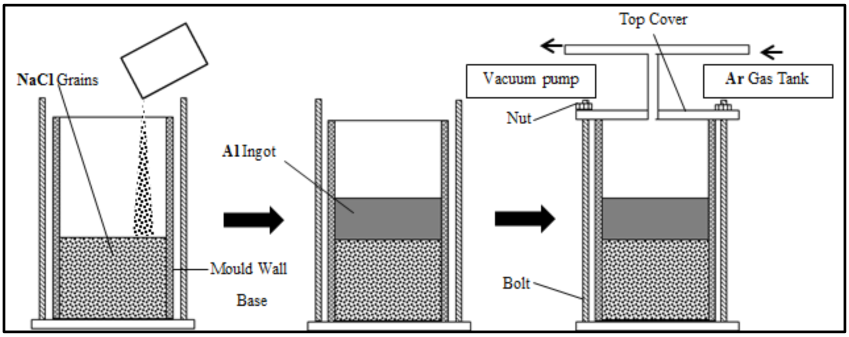

Figure 4: Flow of mould preparation (cross-sectional view)

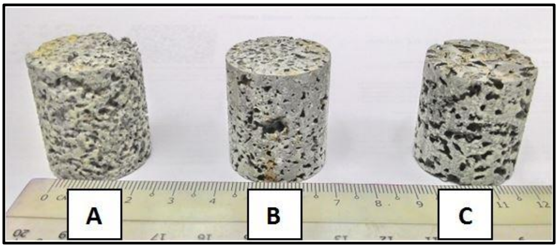

Figure 5: Open-cell aluminium with no center pillar using 1 mm, 2mm and 3 mm NaCl (A, B and C)

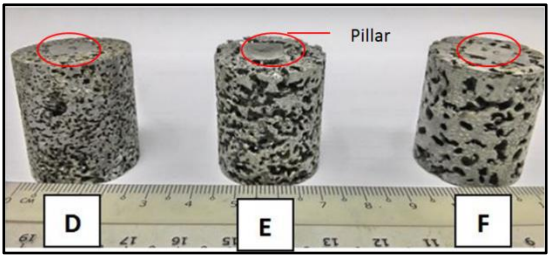

Figure 6: Open-cell aluminium foam with center pillar using 1 mm, 2 mm and 3mm NaCl (D, E and F)

Sound absorption coefficient measurement

Sound absorption ability of the samples was tested using impedance tube method. This method was used to determine the coefficient of sound absorption at a specific sound frequency. For this research, ISO 10534-2:1998 standard was used. The model of the impedance tube used in this research is SCS9020B/K model. The range of frequency used is high frequency whereby the sample size diameter must have the exact value of 27.8 mm. This is to ensure the air does not leak between the wall of the impedance tube and the surface of the sample. Sound frequency is set initially at 800 Hz. Figure 7 shows the impedance tube.

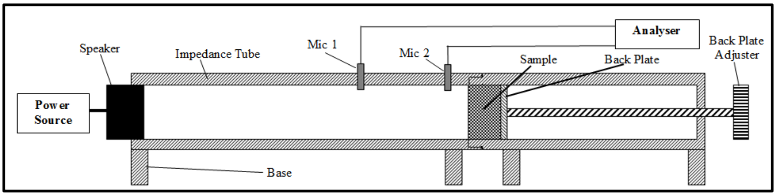

Figure 7: Impedance tube (cross-sectional view).

Result and Discussion

Structure of pore

The entire samples using 1mm, 2 mm and 3mm NaCl particle sizes were then observed through optical microscope. From Figure 8, all of the samples are magnified at the same magnification. The pore structures of each of the sample show the variation together with variation of NaCl particle size. Figures 8 shows the porous structure of open-cell aluminium foam using 1, 2 and 3 mm NaCl grains sizes respectively. Small size of NaCl grains makes the porous structure clearly link to each other. The individual cells are merging and linking together. The sizes of pore clearly differ between each other because of the NaCl grains size.

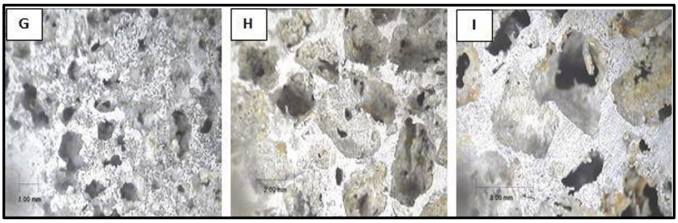

Figure 8: Microstructure of open-cell aluminium foam according to 1mm (G), 2mm (H) and 3mm (I) NaCl size

Figure 9 shows the magnification of NaCl grains. 1 mm grains size of NaCl has non-uniform shape. This indicates that the pore structure in open-cell aluminium structure varies in shapes and sizes. Pore structures from 2 mm NaCl grains show a slightly uniform shape as compared with pore structure from 1 mm NaCl grains. Pore structures from 3 mm NaCl grains have better uniformity as compared to pore structures from 2 mm and 1 mm NaCl grains. The surface of each of the NaCl particle has its own topography; thus, it may cause the wall inside the pore structure to have the same topography as the surface area on the NaCl grain that contributes to its surface roughness.

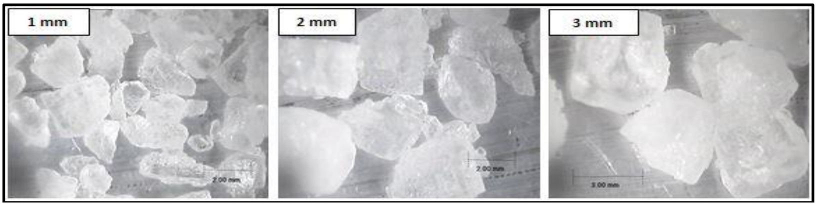

Figure 9: NaCl grains shape and sizes

Density and porosity

From the samples obtained, there are some defects that can be detected by the naked eye. The defect is mainly on the side of the sample since NaCl particle is only concentrated on one particular side. The distribution of NaCl is also not uniform; thus, reducing the weight of the aluminium foam sample and affecting on its density and porosity.

From Table 1 and 2, it can be seen that there are variations of density and porosity between each samples. Increasing the NaCl grain sizes results a significant increase in the percentage of porosities. The results obtained in the present work has a strong agreement with other researcher[15]. The porosity of overall fabricated open-cell aluminium foam ranges from 33% up to 62%. Clearly it can be seen that open cell aluminium foam with center pillar has a higher density than open cell aluminium foam with no center pillar. From the data obtained, it can be said that porosities can be controlled by varying the size of the NaCl grains. However, it took a longer time to do the water leaching process due to larger surface area. Thus, it is time consuming to produce a big pore with high porosities open-cell aluminium foam.

Table 1: Density and Porosity of Open-Cell Aluminium Foam with No Center Pillar

No Center Pillar					
1 mm NaCl		**2 mm NaCl**		**3 mm NaCl**	
Density, g/cm^3	Porosity, %	Density, g/cm^3	Porosity, %	Density, g/cm^3	Porosity, %
1.62	40.12	1.39	48.64	1.03	61.79
1.56	42.11	1.30	51.80	1.02	62.23
1.50	44.58	1.28	52.68	1.04	61.53

Table 2: Density and Porosity of Open-Cell Aluminium Foam with Center Pillar

With Center Pillar					
1 mm NaCl		**2 mm NaCl**		**3 mm NaCl**	
Density, g/cm^3	Porosity, %	Density, g/cm^3	Porosity, %	Density, g/cm^3	Porosity, %
2.01	25.61	1.71	36.79	1.53	43.39
2.19	18.97	1.84	31.75	1.61	40.33
2.37	12.33	1.98	26.70	1.70	37.27

Sound absorption coefficient

Figure 10 shows coefficient of sound absorption of open cell aluminium foam with no center pillar. Absorption coefficients expressed as α are ranging from 0 to 1. The 0 value indicates the sound is totally deflected without any absorption and 1 means that the sound is totally absorbed by the medium. It can be seen that smaller pore aluminium foam that is foam from 1 mm NaCl grains has lower sound absorption ability while the biggest pore aluminium foam from 3 mm NaCl grains has the highest sound absorption coefficient at high sound frequency range. Between the frequency ranges of 800 Hz to 5000 Hz, aluminium foam with pore structure from 3 mm NaCl grains has two peaks of highest absorption values that are at 1600 Hz and 3900 Hz. Although it is stated that smaller pore structure will have higher sound absorption properties, there are also other factors that influence sound absorption such as air resistivity and tortuosity[16].

From Figure 11, it is shown that when a pillar is inserted into the center of the samples, they show a slight improvement of sound absorption ability for 1 mm pore size foam. It can be said that it may cause the structure of the pore to be more resistive to air flow, whereby the amplitude of the sound frequency will decrease and through the tortuous air pathway inside the porous structure, it will cause friction between the air and the surface area of the pore that causes the energy of the air flow being lost as the form of heat[16]. The same goes to 2 mm pore size foam. However, samples with 3 mm pore size show a slight decrease on its sound absorption coefficient whereby the second highest peak is below than 0.8 at higher frequency as compared with samples that have the same pore size without any pillar. It is found that the thickness of the pore cell structure with the pillar causes the pillar structure to be bulkier than its original dimension and the surface area of porous structures normal to the sound source slightly decreases; thus, this resulted the sound wave to reflect and caused lower absorption.

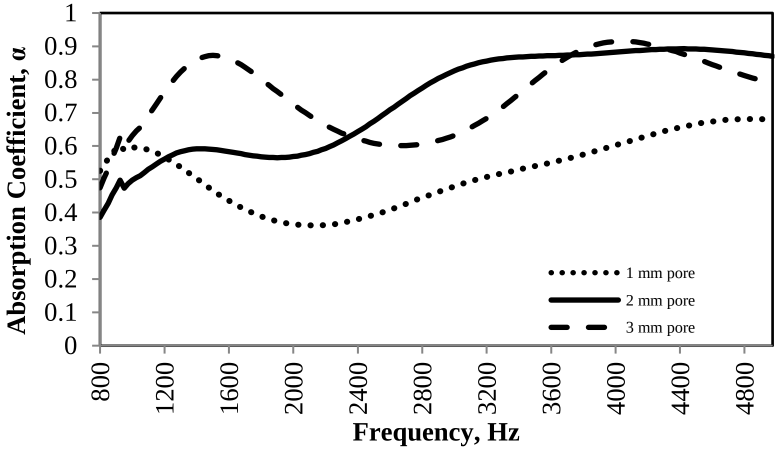

Figure 10: Coefficient of Sound Absorption of Open Cell Aluminium Foam with No Center Pillar

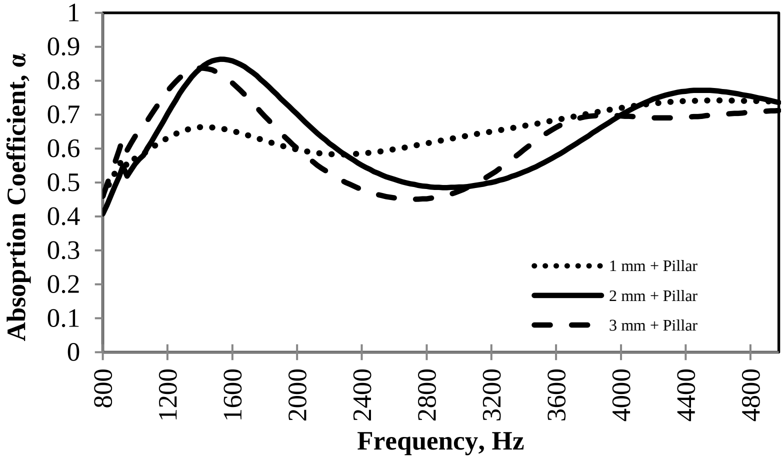

Figure 11: Coefficient of Sound Absorption of Open-Cell Aluminium Foam with Center Pillar

Conclusion

From the research conducted, it is found that the porosity of open-cell aluminium foam produced by infiltration process is very dependent on the size of NaCl grain used. Increasing size of NaCl grain used in infiltration casting method gives a significant increase in porosities of open-cell aluminium foam. At high frequency of sound, bigger pore open-cell aluminium foam has higher sound absorption properties as compared with smaller pores. The shape of NaCl particle affects sound absorption properties of open-cell aluminium foam by acting as a shaper of open-cell aluminium foam pore structure. The pore structure acts as the medium for vibrating air particle to be trapped into. In order to absorb sound, the pore structure should have a rougher surface to give resistant to the air particle. Friction of air occurs between the air particle and the pore structure. The rougher the surface of the pore wall, the higher the friction of air particle in open-cell aluminium foam resulting higher sound absorption properties. However, a method to control the porosity should be studied further because the porosity is hard to control due to irregularities of NaCl grain. Through that, the absorption coefficient data can be more precise respecting only to the size of NaCl grains. The irregularity of the NaCl may also contribute to the inconsistency of data; thus, it is recommended to use space holder that has the same properties as NaCl but has more regular shape and size.

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References

[1] M. Navacerrada, P. Fernández, C. Díaz, and A. Pedrero, "Thermal and acoustic properties of aluminium foams manufactured by the infiltration process," *Applied Acoustics*, vol. 74, pp. 496-501, 2013.

[2] "Chapter 1 - Introduction," in *Metal Foams*, ed Burlington: Butterworth-Heinemann, 2000, pp. 1-5.

[3] J. E. Hatch, A. Association, and A. S. Metals, *Aluminum: Properties and Physical Metallurgy*: American Society for Metals, 1984.

[4] J. Banhart, "Light-Metal Foams—History of Innovation and Technological Challenges," *Advanced Engineering Materials*, vol. 15, pp. 82-111, 2013.

[5] P. J. Veale, "Investigation of the Behaviour of Open Cell Aluminium Foam," Master of Science in Civil Engineering, Civil and Environmental Engineering, University of Massachusetts, 2010.

[6] W. Lucai, C. Yuyong, W. Fang, W. Jianguo, and Y. Xiaohong, "Preparation of big size open-cell aluminum foam board using infiltration casting," *China Foundary,* vol. 5, pp. 1-4, November 2008.

[7] I. C. Konstantinidis, D. P. Papadopoulos, M. Gavaises, and D. N. Tsipas, "Fabrication Methods and Properties of Open and Closed Cell Foams," *Advance Materials Research,* vol. 15-17, pp. 1-6, February 15, 2006 2006.

[8] T. Miyoshi, M. Itoh, S. Akiyama, and A. Kitahara, "ALPORAS Aluminium Foam: Production Process, Properties, and Applications," 2000.

[9] A. M. Parvanian, M. Saadatfar, M. Panjepour, A. Kingston, and A. P. Sheppard, "The effects of manufacturing parameters on geometrical and mechanical properties of copper foams produced by space holder technique," *Materials & Design,* vol. 53, pp. 681-690, 1// 2014.

[10] J. Banhart and J. Baumeister, "Production Methods For Metallic Foams," *Material Research Society,* vol. 521, 1998.

[11] Y. A. Çengel and J. M. Cimbala, *Fluid mechanics: fundamentals and applications*: McGraw-HillHigher Education, 2006.

[12] H. Nakajima, *Porous Metals with Directional Pores*: Springer, 2012.

[13] H. P. Degischer and B. Kriszt, *Handbook of cellular metals: production, processing, applications*: Wiley-VCH, 2002.

[14] J. Ghose, V. Sharma, and S. Kumar, "Acoustic Absorption Characteristics of Closed Cell Aluminium Foam," *Applied Mechanics and Material,* vol. 110-116, pp. 1-6, October, 24 2011.

[15] M. Razali, R. Noh, B. Abdullah, I. Muhammad Hussain, U. K. Ahmad, M. F. Idham, *et al.*, "Mechanical properties of aluminium foam by conventional casting combined with NaCl space holder," in *Applied Mechanics and Materials,* 2013, pp. 156-160.

[16] H. S. Seddeq, "Factors influencing acoustic performance of sound absorptive materials," *Australian Journal of Basic and Applied Sciences,* vol. 3, pp. 4610-4617, 2009.