

**ARTICLE**

Improving the Cellular Characteristics of Aluminum Foam for Maximum Sound Absorption Coefficient Using Genetic Algorithm

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ABSTRACT

Fabricating of metal foams with desired morphological parameters including pore size, porosity and pore opening is possible now using sintering technology. Thus, if it is possible to determine the morphology of metal foam to absorb sound at a given frequency, and then fabricate it through sintering, it is expected to have optimized metal foams for the best sound absorption. Theoretical sound absorption models such as Lu model describe the relationship between morphological parameters and the sound absorption coefficient. In this study, the Lu model was used to optimize the morphological parameters of aluminum metal foam for the best sound absorption coefficient. For this purpose, the Lu model was numerically solved using written codes in MATLAB software. After validating the proposed codes with benchmark data, the genetic algorithm (GA) was applied to optimize the affecting morphological parameters on the sound absorption coefficient. The optimization was carried out for the thicknesses of 5 mm to 40 mm at the sound frequency range of 250 Hz–8000 Hz. The optimized parameters ranged from 50% to 95% for porosity, 0.1 mm to 4.5 mm for pore size, and 0.07 mm to 0.6 mm for pore opening size. The result of this study was applied to fabricate the desired aluminum metal foams for the best sound absorption. The novel approach applied in this study, is expected to be successfully applied in for best sound absorption in desired frequencies.

KEYWORDS

Acoustic model; Genetic Algorithm (GA); metal foam; optimization; Sound Absorption Coefficient (SAC)

1 Introduction

Noise control is generally carried out using passive and active methods [1]. In the passive method, the absorbing materials are used to control the noise [1]. The porous absorbent materials can be classified as



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foam, fibrous or granular absorbents [2]. In this regard, the metal foam has been considered as a sound absorbent since 1950 [3]. Due to its interesting features, it has attracted a lot of attention in various fields of the industry [4]. Low density, high mechanical strength, high heat resistance, and anti-corrosion are among these attractive characteristics [4–7]. The use of metal foams are rapidly expanding in engineering applications [4,8]. Generally, there are two kinds of open-cell and closed-cell metal foams [9]. Lu et al. [10], Han et al. [7] and Hakamada et al. [11] stated that open-cell metal foam has a better sound absorption capacity compared with closed cells; mainly because the sound wave is easily transmitted to the material in open cell foam [7]. Given that the air movement which is controlled by the morphological parameters of the cell and the cell structure, also affects the sound absorption capacity. The significant property of metal foams is their sound absorption [7].

Many parameters may affect the sound absorption coefficient (SAC) in metal foams, including porosity, pore size, pore opening, thickness, static flow resistance, etc. [12]. Some of These parameters including morphological parameters can be considered while fabricating metal foams. In other words, it is possible to fabricate metal foams with desired morphological parameters. So far, the trial and error methods are applied in laboratory to select the best metal foam for the highest sound absorption from the available metal foams. If the optimized morphological parameters could be determined in advance it would be possible to fabricate the desired metal foam for the best sound absorption using the sintering technology.

Therefore, to have a metal foam with best sound absorption, it is necessary to determine The optimized morphological parameters of the foam. For this purpose, theoretical models which describe the relationship of the sound absorption coefficient with morphological parameters are required [13,14]. So far, such models which describe the relationship between cell structure and the sound absorption coefficient in porous materials have been proposed [7,10,15–17]. Lu model of sound absorption describes the relationship between 3 morphological parameters of porosity (Ω), pore size (D) and pore opening size (d) with sound absorption coefficient (SAC). Thus this model seems to be the best candidate for this purpose. It is expected to improve the morphological parameters of a metal foam for the best absorption coefficient using the optimization algorithms.

In the previous study [18], the morphological parameters of metal foam were optimized using local search algorithm.

Different optimization algorithms including General Local Search (GLS) and genetic algorithm (GA) [19], Ant Colony Optimization [20] and Particle Swarm Optimization [21] have been proposed so far. GLS algorithm explores neighborhood by iteratively expanding searching domain in the neighborhood of the current solution and moving from current solution to an enhancing neighborhood [22]. This process is repeated until the current solution cannot be improved anymore. This process continues until the optimum locale is reached. The GLS approach may stuck and trapped in a local optimum disregarding other optimums in the neighboring [23]. So there need to be avoided from trapping in these local optimums [22]. Dumitrescu et al. [24] believe that the disadvantages of local search algorithms are typically 1. they cannot prove optimality, 2. they cannot provably reduce the search space, and 3. they often have problems with highly constrained problems where feasible areas of the solution space are disconnected.

For more complex problems, meta-heuristics such as genetic algorithm (GA) [19], Ant Colony Optimization [20] and Particle Swarm Optimization [21] can be considered. The meta heuristic algorithm becomes very popular because of its stability, flexibility and its ability in avoiding from trapping in local optimums [25]. The meta-heuristic GA is inspired by Darwinian evolution theory [26]. Today, it is widely used in solving optimization problems and learning processes [27].

GA has a distinguished advantage compared to other stochastic methods. In this method it is extremely easy to parallelize the algorithm. It is due to the fact that the calculations of each iteration are independent of

one another [28]. Due to different design parameters and constraints, the optimization of sound absorbents has always been a challenge in acoustic engineering [29].

Usually, the pore size, pore opening, porosity, and thickness are not known for fabricating the foam for sound absorption. Therefore, available foams with approximate dimensions are investigated through trial and error method to find the best foam absorbent. However, if it is possible to predetermine the morphology of metal foam to absorb a specific sound with best SAC, it can be claimed that a great step has been taken to fabricate porous foams intelligently. The study aimed to optimize the morphological parameters affecting the sound absorption coefficient (α) in metal foams. For this purpose, first the General Local Search approach was applied to optimize the morphological parameters of a metal foam [18]. This part of the study, discusses the applicability of the GA in improving the optimal set of metal foam parameters, including porosity, pore size and pore opening at any thickness and frequency for fabrication of an optimized foam.

2 Structure

The study was carried out according to the following flowchart (Fig. 1).

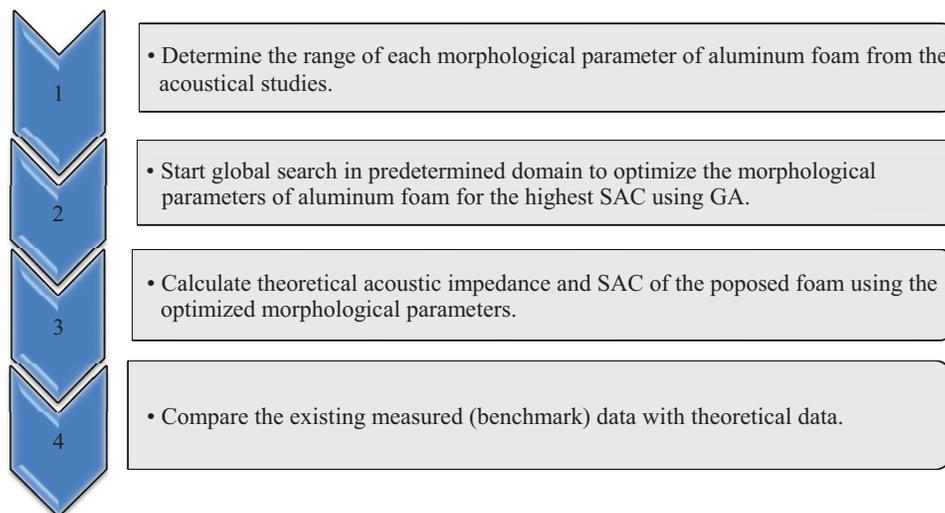


Figure 1: Study process

2.1 Lu Model

The relationship between sound absorption coefficient (α) and morphological parameters, including pore size, pore opening, and porosity are well described [10]. In present study, the equations presented in Lu model [10] were numerically solved to optimize the morphological parameters for the highest value of SAC. These equations are shown in Tab. 1.

2.2 Optimization by GA

The porosity, pore size, and pore opening parameters were optimized for a frequency range of 250 Hz to 8000 Hz and a thickness of 5 mm to 40 mm. Avoiding from trapping in any local search and affirming the global optimization was essential. A typical GA flowchart is shown in Fig. 2.

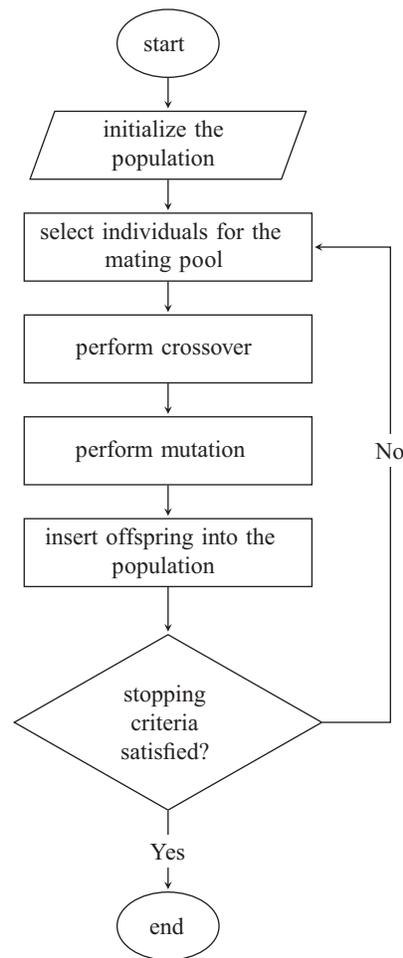


Figure 2: A typical GA flowchart [30]

The summary of the steps taken by the GA used in this study were [31–33]:

- Step 1. Read input data
- Step 2. Create primary population randomly
- Step 3. Consider initial parents
- Step 4. Determine mutation (considering P_m)
- Step 5. Calculate all parameters
- Step 6. Select the best answer
- Step 7. End; if SAC=1 or the number of iteration is <150
- Step 8. Else; go back to Step 4

Roulette Wheel and tournament methods were used to select the members for making generation and mutation. The population included 50; the generation rate 80% ($P_c = 0.8$); the percentage of mutation 30% ($P_m = 0.3$); the mutation rate 0.02, the stopping criteria was SAC = 1 or the number of iterations = 150 [34]. Furthermore, the uniform crossover method was used for making generation. In order to obtain each number in the last tables, the problem solving process was used 5 times using the roulette wheel method and 5 times with the tournament method and the best result was noted. The results showed that the

tournament method is better for this particular problem. The number of specified iterations (150) was used to prevent the program from hanging if there is no improvement in calculated SAC (Fitness Function).

Table 1: Equations of the Lu model

Parameter	Formula	Variables
Z_D air-specific acoustic impedance inside a cell	$Z_D = -i\rho_0 c_0 \cot\left(\frac{0.806D\omega}{c_0}\right)$	$\rho_0 = 1.184$ [kg/m ³] is the air density, $c_0 = 346.5$ [m/s] is the sound speed in air, D is the pore size, $\omega = 2\pi f$ is the angular frequency (f is the sound wave frequency), and $i^2 = -1$
Z_0 acoustic impedance of the open cell	$Z_0 = R_0 + iM_0$ $R_0 = \left(\frac{32\eta t}{d^2}\right) \left(\sqrt{\frac{1+\beta^2}{32}} + \sqrt{\frac{\beta d}{4t}}\right)$ $M_0 = \omega\rho_0 t \left(1 + \frac{1}{\sqrt{\frac{9+\beta^2}{2} + \frac{0.85d}{t}}}\right)$ $t = \frac{(1-\Omega)D}{3.55 - 6(d/D)^2}$	R_0 is the special acoustic resistance, M_0 is open cell reactance between the pores, $\eta = 1.849 \times 10^{-5}$ [kg/m·s] is the air dynamic (absolute) viscosity, t is cell wall thickness, and β can be defined as $\beta = \sqrt{\Omega\rho_0\eta d/2}$
Z_1 acoustic impedance	$Z_1 = z_0 + Z_D$	where $z_0 = (0.909 D/d)^2 Z_0$ is the relative specific acoustic impedance of the apertures
Z_n acoustic impedance	$Z_n = z_0 + \frac{1}{1/Z_D + 1/Z_{n-1}} = R_n + iM_n$	When the number of cells in the direction of sound propagation n is greater than 1
α sound-absorption coefficient (SAC)	$\alpha = \frac{4R_n/\rho_0 C_0}{(1 + R_n/\rho_0 C_0)^2 + (M_n/\rho_0 c_0)^2}$	–

The input data required for GA to run are summarized in [Tab. 2](#). These parameters were selected by repeating the algorithm many times and in accordance with the best results.

Table 2: Parameters setting for GA

The GA parameters	Value
rate of crossover	0.8
mutation percentage	0.3
rate of mutation	0.02
size of population	50
maximum iteration	150
maximum SAC (α)	1

The searching domain for optimization of each parameter was considered according to Tab. 3. All three morphological parameters were optimized at frequencies of 0.5, 1, 2, 3, 3.5, 4, 6 and 8 kHz.

The verification and validation of the proposed codes were carried out as in Jafari et al. [18].

Table 3: The searching domain of each parameter

Porosity [%]	Pore size [mm]	Pore opening [mm]
$50 < \Omega < 95$	$0.1 < D < 4.5$	$0.01 < d < 0.7$

3 Results

In Fig. 3, for a thickness of 5 mm to 40 mm at the frequency of 4 kHz, the convergence chart of the GA is drawn. Considering the convergence chart, it is clear that the value of the answer does not change from one iteration to the next one. Therefore, the number of iterations chosen is appropriate for achieving the desired answer. The highest value of the sound absorption coefficient is 1. Therefore, the answers must converge to the number 1.

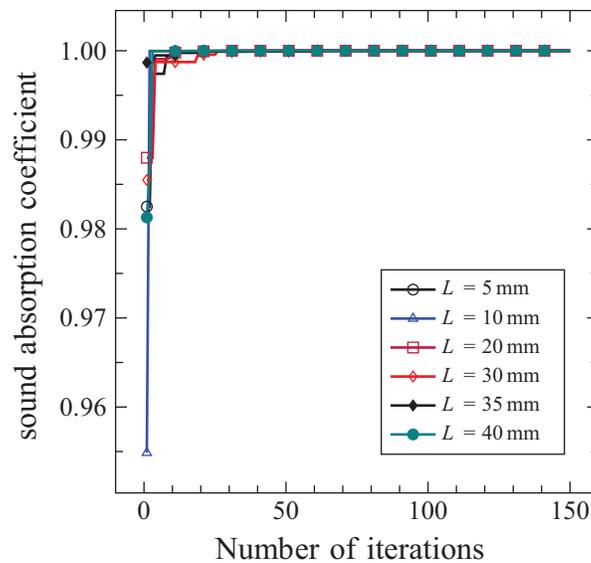


Figure 3: Convergence authentication of GA for different thicknesses at 4000 Hz

Fig. 4 depicts the optimized morphological parameters at different frequencies for the highest sound absorption coefficient (α) in an aluminum foam barrier with 5 mm thickness. Fig. 4 shows that at high frequencies (3 kHz to 8 kHz), when porosity (Ω) is between 60 to 95 percent (0.6–0.95 in figure), the pore size is 0.33 mm to 2.5 mm, the pore opening size is 0.09 mm to 0.2 mm, and the sound absorption coefficient (α) is 0.9 and 1. Furthermore, at low frequencies from 250 Hz to 2 kHz, the α is not increased; since according to previous studies, the main limitation is low thickness. Therefore, the parameters have been improved only at high frequencies. According to the results of Fig. 4 at optimized parameters, the pore size decreases as the frequency increases. Meanwhile, the porosity and pore opening do not follow a special correlation.

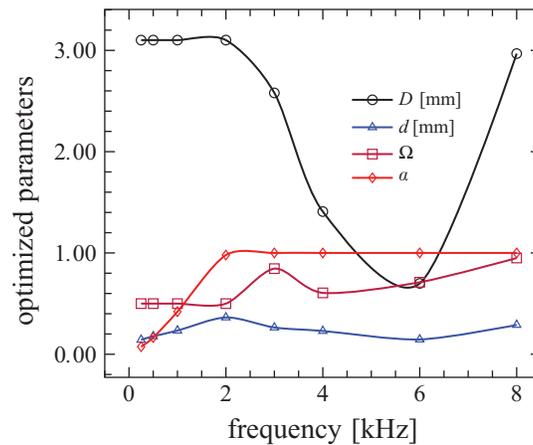


Figure 4: The optimized morphological parameters at different frequencies for the highest sound absorption coefficient (α) in an Al foam barrier with 5 mm thickness

The optimized morphological parameters at different frequencies for the highest sound absorption coefficient (α) in an aluminum foam barrier with 10 mm thickness are shown in Fig. 5. The sound absorption coefficient (α) is close to 1 at the frequency range of 2 kHz–8 kHz when the porosity is between 70 and 95% (0.7–0.95 in figure), pore size is 0.1 mm to 2.3 mm, and pore opening is 0.07 mm to 0.3 mm. The results show that at optimized values, the pore size decreases by increasing frequency, and the porosity and pore opening size do not follow any special correlation.

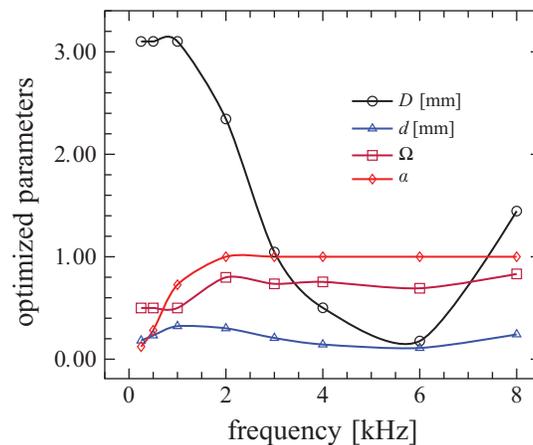


Figure 5: The optimized morphological parameters at different frequencies for the highest sound absorption coefficient (α) in an Al foam barrier with 10 mm thickness

The optimized morphological parameters at different frequencies for the highest sound absorption coefficient (α) in an aluminum foam barrier with 20 mm thickness are shown in Fig. 6. This figure shows that the sound absorption coefficient (α) is close to 1 at the frequency range of 2 kHz–8 kHz when the porosity is between 61% to 95% (0.61–0.95 in figure), the pore size is 0.1 mm to 4.4 mm, and the pore opening is 0.08 mm to 0.5 mm. Fig. 6 shows that the pore size decreases by increasing frequency, while the porosity and pore opening do not follow any special correlation.

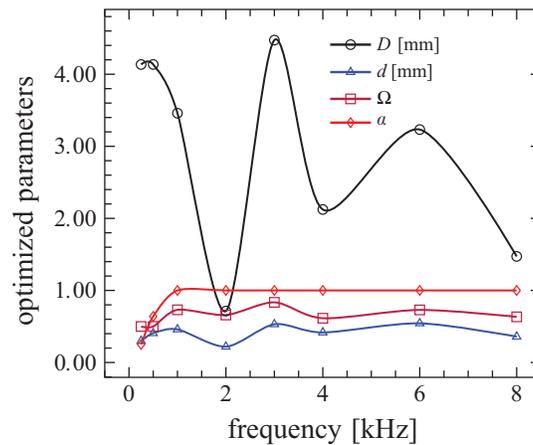


Figure 6: The optimized morphological parameters at different frequencies for the highest sound absorption coefficient (α) in an Al foam barrier with 20 mm thickness

The results revealed that at 30 mm thickness, when the porosity is between 0.6 to 0.95, The pore size is 0.1 mm to 2.08 mm, and the pore opening is 0.09 mm to 0.43 mm, the sound absorption coefficient (α) is almost equal to 1 at the frequency range of 1 kHz to 8 kHz (Fig. 7). For most frequencies, the pore opening is 0.1 mm. Porosity, pore size, and pore opening do not follow a certain correlation, and their values vary at each studied frequency.

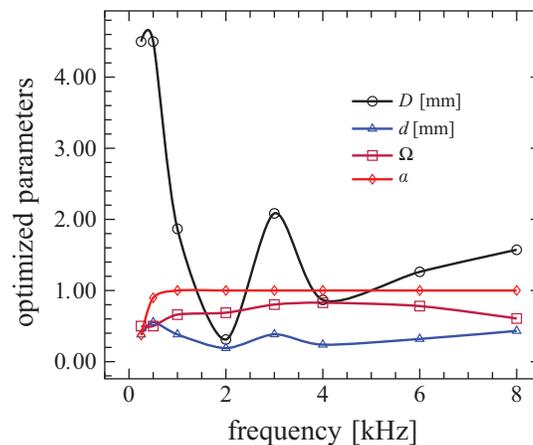


Figure 7: The optimized morphological parameters at different frequencies for the highest sound absorption coefficient (α) in an Al foam barrier with 30 mm thickness

Fig. 8 shows the optimized morphological parameters at different frequencies for the highest sound absorption coefficient (α) in an aluminum foam barrier with 35 mm thickness. This figure reveals that in frequencies of 0.5 kHz–8 kHz, when the porosity is between 0.5 to 0.85, the pore size is from 0.1 mm to 4.4 mm, and the pore opening is between 0.09 mm and 0.6 mm, the sound absorption coefficient (α) is close to one. Porosity, pore size, and pore opening do not follow any special correlation, and their values vary at each studied frequency.

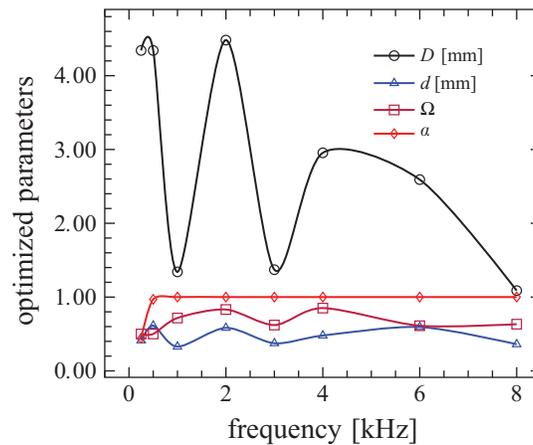


Figure 8: The optimized morphological parameters at different frequencies for the highest sound absorption coefficient (α) in an Al foam barrier with 35 mm thickness

The results show that when the thickness is 40 mm, the sound absorption is close to 1 at frequencies of 0.5–8 kHz with a porosity of 0.51 to 0.95, a pore size of 0.1 mm to 4.5 mm, and a pore opening of 0.1 mm and 0.6 mm (Fig. 9). It is worth mentioning that in the thickness of 40 mm, the improved porosity and pore opening are fixed at 0.95 mm and 0.1 mm, respectively. According to the results, the pore size decreases by increasing frequency, and the porosity and pore opening do not follow any special correlation. Furthermore, at a relatively low frequency of 0.5 kHz to 2 kHz, there is an increase in the sound absorption coefficient (α) relative to the thickness of 5 mm. Therefore, at low frequencies, the sound absorption coefficient (α) increases by increasing the thickness.

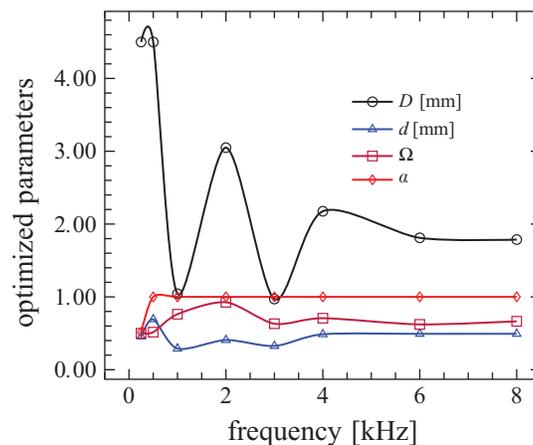


Figure 9: The optimized morphological parameters at different frequencies for the highest sound absorption coefficient (α) in an Al foam barrier with 40 mm thickness

The best sound absorption coefficients (α) determined for each frequency at different thicknesses of aluminum foam are presented in Tab. 4. The highest sound absorption coefficient (0.5134) for the challenging low frequency of 250 Hz is determined for an aluminum foam at the thickness of 40 mm.

Table 4: The highest sound absorption coefficients determined at studied frequencies for aluminum foam at different thicknesses

Frequency [kHz]	$L = 5$ mm	$L = 10$ mm	$L = 20$ mm	$L = 30$ mm	$L = 35$ mm	$L = 40$ mm
0.25	0.0747	0.1227	0.2498	0.3725	0.4418	0.5134
0.5	0.1645	0.2818	0.6391	0.8972	0.9689	0.9993
1	0.4204	0.7267	1	1	1	1
2	0.9794	1	1	1	1	1
3	1	1	1	1	1	1
4	1	1	1	1	1	1
6	1	1	1	1	1	1
8	1	1	1	1	1	1

4 Discussion

In this study, a novel approach was applied to improve the morphological parameters of metal foams including porosity, pore size and pore opening for the highest sound absorption coefficient at different frequencies. The method was applied to determine these parameters at different thicknesses of 5 mm to 40 mm. These improved parameters along with the highest sound absorption coefficient (α) at the frequency range of 250 Hz to 8000 Hz are presented in Figs. 4–9 for different foam thicknesses. These measures can be used to intelligently fabricate aluminum foam for the best sound absorption coefficient using sintering technology.

Kuromura et al. [35] believe that it is very important if it would be possible to fabricate better absorbents materials that have openings connected to the adjacent cells through controlling pore opening size, pore size, and porosity. The present study shows the way it is possible to fabricate such materials.

According to the results, the sound absorption coefficients determined using this approach is almost 1 for the frequency range of 500 Hz to 8000 Hz. Controlling of low frequency sound has always been a challenging task for the engineers. The application of this approach showed that it is possible to get sound absorption coefficient of 0.5134 using aluminum foam with 40 mm thickness.

Absorption for the frequencies less than for all frequencies higher it was found that for the maximum SAC at each frequency and thickness, the porosity has a certain value; however, in previous studies, it was stated that the SAC increases by increasing porosity [36–38]. In the study of Wang et al. [39], it was found that for constant porosity, sound absorption increases by increasing cell size.

The results showed that in the thickness of 5, 10, 20, and 40 mm for the maximum SAC, by increasing frequency, the pore size decreases. According to the previous results, the SAC increases by decreasing pore size [7,37,38]. The study by kuromura et al. [35] stated that the SAC differs with pore size variations, which is in line with the results of the present study. In the study of Hakamada et al. [11], the sample B, with the smallest pore size of 212 μm to 300 μm , had the highest SAC, which was consistent with previous studies [7,37,38], and this pore size in the range of optimal parameters obtained in this study. In some studies including [10,39], the diameter of the pores was reported in the range of 0.5 mm to 2 mm, which were in the optimization range of this study. In the study carried out by Wang et al. [39], using computational method, the optimal amount of pore size for the best sound absorption capacity was estimated to be at least 100 μm . However, in this study, the pore size differs in various frequencies and thickness.

The results of studies including [11,40,41] show that in general, reducing the pore size increases the SAC; however, according to the obtained results, for the constant SAC of nearly one, the pore size

decreases by increasing frequency. Li et al. [42] stated that there is no definitive correlation between the pore size and the SAC of aluminum foams with spherical cells, which is in line with the results of this study. Hakamada et al. [11] argued that there is no apparent correlation between the pore size and the SAC due to the significant effects of the pore opening, which is consistent with the results of this study. Recently, the importance of pore opening size in the resistance to the flow of porous metals has been emphasized [11,43].

It has been accepted that there is an apparent relationship between the SAC and the resistance to the flow [11]. Therefore, it is suggested that the pore opening size strongly affects the sound absorption behavior and controlling pore opening size is very important for achieving higher SACs [11]. When the sound wave propagates from the cells to the pore openings, the air velocity substantially increases; since pore opening channels are narrower than the cells [35]. Loss of energy increases by increasing air velocity [35]. Hence, the sound wave through friction by transferring from cell to pore opening is significant [35]. Obviously, when the pore opening size is too high, the air flow velocity changes slightly when passing through the pores, resulting in no deviation from friction [35]. Conversely, if the pore opening size is very small, the resistance to the air flow will be very high and the maximum sound waves will not be entering into the material, but reflected from the surface of the sample. It also leads to poor sound absorption [10,11,39,42].

Therefore, the pore opening size needs a certain range that needs to be optimized for each thickness and frequency. In the present study, the amount of pore opening is 0.07 mm to 0.6 mm, which has no correlation with the SAC in various thickness and frequencies. Li et al. [42] pointed out that, by increasing pore opening diameter, the SAC reduced and the pore size was within 0.3 mm–0.4 mm. It was suggested that the optimal pore opening is 0.1 mm [10,39], which is in line with the optimization results of this study. Hakamada et al. [11] stated that the presence of a pore opening smaller than 100 μm , especially for porous metals produced by the spacer method, greatly improves the sound absorption properties. In another study, they pointed out that high-sound absorption cannot be achieved when the pore opening size is 10 μm or 100 μm [44]. Therefore, it has been conclusively shown that the pore opening size strongly affects the porous aluminum absorption behavior produced by the spacer method, and controlling the pore opening size to achieve the sound absorption capacity is very important [11].

According to the results of this study show that, in order to increase the amount of sound absorption, the thickness of the panel must be increased at frequencies below 2000 Hz. However, at higher frequencies, for each thickness (the optimal value of d , D , and Ω) can be found, so that the amount of sound absorption reaches the maximum value. According to Hakamada et al. [11], the SAC increases due to an increase in sample thickness in the frequency range of approximately less than 2000 Hz. The effect of sample thickness on sound absorption is understandable due to the long distances in relatively thick samples, which increases the interaction of the sound wave with the pores walls [42]. In the study of Li et al. [42], the peak in the SAC increases, and changes to lower frequencies by increasing the thickness of the sample. It is also found that at frequencies above 2000 Hz, increasing the sound absorption efficiency does not require an increase in thickness, and this can only be achieved by changing the amount of porosity, pore size, and pore opening. In this study, it was found that porosity, pore size, and pore opening have important factors in optimizing the SAC; however, pore size and pore opening have a more important role than porosity, which is similar to Meng study [45].

5 Conclusion

A novel method was introduced to optimize the morphological parameters of metal foams for the best sound absorption coefficients. Controlling the porosity, pore size, and pore opening is a useful strategy for sound absorption spectrum in open cell foams. The Lu model is reliable for simulating sound absorption in porous metals with difficult structures and can be used as a tool for optimizing porous structures using porosity and their permeability as variables. The results presented in Figs. 4–9 can be applied to fabricate

aluminum foams with best sound absorption coefficients at different frequencies. The GA used in this study can provide an effective way to develop optimized metal foam absorbents for any selected frequency for the industry.

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