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Research Paper

A Study on the Quasi-static Compression Behavior of 5056 Aluminum Alloy Foams

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ABSTRACT

In this paper, 5056 aluminum alloy foams with different percentages of calcium carbonate as foaming agents have been produced, and the physical and mechanical properties of the foams have been studied. Quasi-static compression tests have been carried out to determine the mechanical properties of foamed material. The effects of the amount of calcium carbonate on the size of the pores, the minimum thickness of the walls, density, compressive strength and energy absorption capacity of foams have been investigated. The uniform structure of the pores has been observed in foam specimens with 1.5, 1.8 and 2.1 wt% $CaCO_3$. Increasing the amount of $CaCO_3$ foaming agent from 1.5% to 2.1% has increased the average size of the pores by more than 180% and reduced the thickness of cell walls by 90%. So, the density and the relative density of the aluminum foams have been reduced by 28.6%. The results also show that increasing the amount of $CaCO_3$ foaming agent decreases compressive strength, the absorbed energy and the elastic modulus of 5056 aluminum foams. By increasing the amount of foaming agent from 1.5% to 2.1%, the elastic modulus has reduced by about 16%, and a decrease of 21% has been seen in the energy absorbed by the foam at the strain of 0.4.

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1. Introduction

Aluminum foam has received a lot of attention due to its good physical and mechanical properties [1-3]. Owing to its unique structural applications, closed-cell aluminum foam has been widely used in the aerospace and automotive industries [4-6]. There are several foam manufacturing technologies with their advantages and disadvantages. The challenging factor in all of these technologies is the simultaneous interaction of solid, liquid, and gaseous phases during the foam manufacturing process [5,6]. The interaction of these phases finally yields the production of solid metal foam with a special character. Foamability and mechanical properties are prominent, which, to a great extent, determine the foam characteristics.

Researchers have been producing metal foams using different types of stabilizers and blowing agents over the past decades and have shown that by changing the percentage of each of them, foams with new physical and mechanical properties can be obtained [7,8]. Furthermore, Alloy composition has a significant role in both foamability and mechanical properties of metal foams, which both have an impressive effect on energy absorption and compressive strength. In the foaming of melts by blowing agents in the Alporas method, elements or second phases are added to the molten metal for two functions: thickening agent and alloying effects, which both give the foams more desirable properties. In fact, it isn't easy to distinguish the exact effect of an element in either of the functions. In practice, an alloying element or a second phase is effective in both functions [9]. Metal foams can be mentioned as a reinforcement of empty structures under pressure and impact, which perform an essential role in improving mechanical properties, such as increased resistance to external forces and increased energy absorption of structures, thereby preventing increased damage to them [9-11]. Many experimental studies have been carried out on the compressive strength of aluminum foams with different structures and conditions, which have had different results depending on the use of alloy in foaming.

In general, the compression process of aluminum foam can be divided into three regions: the linear elastic deformation region, the plastic deformation region and the densification region. In the plastic deformation region, the stress in the foam under compression reaches a steady-state while the strain rate reaches the highest value, which improves its energy absorption capacity [12-15]. Kumar et al. [16] investigated the effects of the particle size of the blowing agent $CaCO_3$ on the physical properties of Al-Si foams. They observed that as the grain size of $CaCO_3$ increases, the number of pores per inch and the density decrease. In some studies, researchers investigated the effect of adding $CaCO_3$ on the physical properties of foams made of different aluminum alloys. It has been found that increasing the amount of $CaCO_3$ blowing agent increases porosity and decreases density [17,18]. A reduction in density is associated with lower compressive strength and energy absorption [16,19,20]. Sutarno et al. [20] optimized the amount of $CaCO_3$ blowing agent to achieve the highest compressive strength of Al-1000 foam. They concluded that compressive strength of the aluminum foams is directly proportional to its porosity and inversely proportional to its relative density, wall thickness and roundness of its pore cavity. Also, the produced porosity is only affected by the wt% of $CaCO_3$. They achieved the lowest relative density (0.15) and highest porosity (85.29%) by 4 wt% of the $CaCO_3$ blowing agent. Linul et al. [21] investigated the mechanical characterization of closed-cell foams made of AlSi12Mg0.6 with surface skin under quasi-static and dynamic compressive loading. The observations showed that in both dynamic and quasi-static experiments, mechanical properties of foams increase with increasing of density. Hajizadeh et al. [22] produced metal foams of AA332 and AA1067 alloys using a technique called pressurized infiltration. The mechanical properties of aluminum foams were investigated under quasi-static compression loading. They found that by increasing the size of NaCl particles as the space holder, all parameters, including relative density, energy absorption capacity and specific absorption energy decreased, except absorption energy efficiency. They also showed that the energy absorption capacity in AA332 foams is higher than in foams produced by AA1067. In another study, Hasanli and Paydar [23]studied the effect of structural design on the mechanical properties of aluminum foams Aluminum fabricated through powder metallurgy. They concluded that correct modification in pore distribution can improve the mechanical properties of the foams by compensating for the undesirable density gradient created in the foam structure due to the die wall friction. In a study conducted by Wang et al. [24], the multiaxial dynamic failure behavior of closed-cell aluminum foams has been investigated. They found that the initial fracture strength is dependent on the strain rate. They also established an empirical relationship to relate the initial fracture strength to the relative density and the nominal strain rate. In addition, the multiaxial failure behavior is characterized based on the developed microscopic computed tomography (micro-CT) image foam models. Verma et al. [25] studied the effects of cell size, cell wall thickness and cell circularity on the compressive performance of closed-cell aluminum foam experimentally and with FEM. Their results showed that the energy absorption capacity and plateau strength decrease with an increase in cell sizes. Saleem et al. [26] used micro-computed tomography (micro-CT) imaging and finite element (FE) analysis to investigate the static and dynamic yield strength, energy absorption, and the effect of strain rate and relative density on closed-cell aluminum foams. They found that the relative density and strain rate Strongly influence the yield strength, collapse stress, plateau stress, densification strain and energy absorption capacity of closed-cell aluminum foams subjected to compression.

In this paper, aluminum alloy 5056 foams made by the Alporas method using calcium carbonate as a foaming agent are studied. The effect of the amount of foaming agent on the physical and mechanical properties of the produced foam, such as the pore size, the thickness of the walls, density, compressive strength and the ability to absorb energy is investigated.

2. Experimental procedure

2.1. Material properties

Aluminum alloy 5056, with the composition shown in Table 1, was used to produce the aluminum foam. Mechanical and physical properties of 5056 aluminum alloy are given in Table 2. Calcium metal was used as the stabilizer. $CaCO_3$ was utilized as the blowing agent. $CaCO_3$ decomposes at temperature range of 657 °C to 839 °C to release CO_2 gas as per Eq. (1) [14], which causes porosity in the melt.

$$CaCO_3 = CaO + CO_2 \quad (1)$$

Table 1. Chemical composition of 5056 Aluminum alloy [27]

Element	Al	Mg	Fe	Si	Mn	Cr	Other
Weight percentage	95.4	5.3	0.4	0.3	0.1	0.1	0.15

Table 2. Mechanical and physical properties of 5056 aluminum alloy [27]

Variables	Values
Material	Al 5056
Density (g/cm^3)	2700
Young's modulus, E (MPa)	71000
Poisson's ratio	0.33
Shear strength, τ (MPa)	170
Ultimate strength, σ_u (MPa)	290

2.2. Production of aluminum foam

The materials used were 5056 aluminum alloy ingots, calcium metal as a thickening or stabilizing agent and CaCO3 powder as the blowing agent. The work steps are as follows.

1. 800 gr of aluminum alloy was placed in a graphite crucible. An electric resistance furnace was used for melting aluminum at 750 °C.
2. 1.5 wt% calcium metal was added to the molten alloy to adjust the viscosity. After the complete dissolution of calcium in the melt, the product was agitated with 1000 rpm of rotational speed for 10 min in ambient for thickening and viscosity enhancement.
3. The thickened aluminum alloy was held for 2 min at a higher temperature 780 °C, for increasing viscosity.
4. The blowing agent, $CaCO_3$ powder, was added with 1.5, 1.8, and 2.1 weight percentages, mixed, and stirred by a 1400 rpm stirrer.
5. The melt was held at a temperature of 750–780 °C to allow the blowing agent to be completely decomposed.
6. Finally, mold was taken out of the furnace and was quenched by water. After cooling down to room temperature, the foam block was removed.

During the blowing agent decomposition, aluminum oxide is formed, which is located in the inner wall of the pores and helps the stability of the pores. In order to observe the cellular structure and pores of aluminum foam, an Olympus model optical microscope was used. Different visualization methods are generally available to analyze and characterize the architecture of cellular material, such as pore structure, size, and distribution. ImageJ is a proper software for analyzing images widely used in various studies [28]. For analyzing the pore structure and mean pore size with ImageJ, all samples were polished, and then images of the surfaces were taken. The specimens were cut into cubes with a cross-section of 50×50 mm and a height of 50 mm to ensure that the size of the pores was more than 10 times that of the foam. The average density, relative density and porosity of all samples were calculated using Eq. (2), (3) and (4):

Table 3. Physical properties of the 5056 Aluminum foams

Variables	Sample 1	Sample 2	Sample 3
$CaCO_3$ (wt %)	1.5	1.8	2.1
Ca (wt %)	1.5	1.5	1.5
Weight (gr)	71.2	62.5	51.3
Density, ρ (g/cm^3)	0.57	0.5	0.41
Density of base metal, ρ_s (g/cm^3)	2.7	2.7	2.7
Relative density, ρ_{rel}	0.21	0.18	0.15
Porosity, φ (%)	78.2	81.4	84.8

$$\rho = M/V \quad (2)$$

$$\rho_{rel} = \rho^*/\rho_s \quad (3)$$

$$\varphi = (\rho_S - \rho)/\rho_S * 100 \quad (4)$$

where V is the volume of sample (mm^3), M is the weight of the sample (g), ρ is the sample density (g/cm^3), ρ_s is the density of base material, ρ_{rel} is the relative density, and φ is the porosity of samples [29-31].

2.3. quasi-static compression test

Quasi-static compression tests were performed on aluminum foams by the STM-250 test machine. The force was applied uniaxially to the specimens in the direction of pores growth at a rate of 0.5 mm/min. The compression of each specimen continued until the strain reached 70%. Three samples from each type of foam were tested for repeatability and reproducibility of results, and the average of the obtained results was reported. The stress–strain curves for each specimen were obtained, and compressive strength, elastic modulus and energy absorbed for each specimen were measured. The density of the specimens was calculated before the tests.

3. Result and discussion

3.1. Foam structure

The physical properties of the metal foams are presented in Table 3. The pore structures of foams with different percentages of $CaCO_3$ blowing agent 1.5, 1.8 and 2.1% are shown in Fig. 1. The microstructure of the metal foam specimens is also shown in Fig. 1. The relatively uniform structure of the pores can be observed. Spherical and homogeneous pores in the foam specimen with 1.5 wt% of blowing agent indicate proper decomposition of the blowing agent and show that the pores do not merge with each other. Increasing the amount of $CaCO_3$ to 1.8% and 2.1% increases the volume of CO_2 gas resulting from the decomposition of the blowing agent, thereby increasing the pores and reducing the thickness of the cell wall. This causes instability in the walls; thus, the pores merge together, and the porosity of the metal foams increases. The circularity of the pores has a significant influence on the thickness of the cell wall, which is essential for enhancing the energy absorption of closed-cell metal foam [19].

As can be observed, the minimum pore size and the maximum relative density occur at foam with 1.5 wt% $CaCO_3$. The thickness of the cell wall is also thicker than the foam with 1.8 and 2.1 percent foaming agents (Table 4), which demonstrates the influence of the amount of foaming agent on the formation of pores.

A decrease in the minimum wall thickness and an increase in the size of the average pores can be observed in the foam with 1.8% blowing agent (Table 4). This amount of foaming agent has properly decomposed, produced bubbles and constructed foam with a lower density than foam with 1.5 wt% $CaCO_3$. In foam with 2.1 wt% $CaCO_3$, the mean pore size is the highest and the wall thickness is almost thin (Table 4). Thus, the decrease in the density of foams could be thoroughly attributed to the foaming factor. Fig. 2 shows the variation of the pore size with increasing the amount of $CaCO_3$ as foaming agent. It can be seen that the average pore size increases with increasing the amount of foaming agent. Increasing the amount of foaming agent from 1.5% to 2.1% has caused the average size of the pores to increase by almost 2.8 times (increasing the size of the pores from 0.39 mm to 1.1 mm, an increase of 182%). Increasing the pore size decreases the density and the relative density of the specimens. So, the relative density shows a decreasing trend with increasing the amount of foaming agent in Fig. 3. By increasing the foaming agent from 1.5% to 2.1%, the relative density decreased by 28.6%

Table 4. Average minimum wall thickness and average pore size in foams with different amounts of $CaCO_3$

Variables	Sample 1	Sample 2	Sample 3
$CaCO_3$ (wt %)	1.5	1.8	2.1
Average Minimum wall thickness (mm)	0.1	0.08	0.01
Average cell size (mm)	0.39	0.62	1.1

1.5 wt% $CaCO_3$ 1.8 wt% $CaCO_3$ 2.1 wt% $CaCO_3$

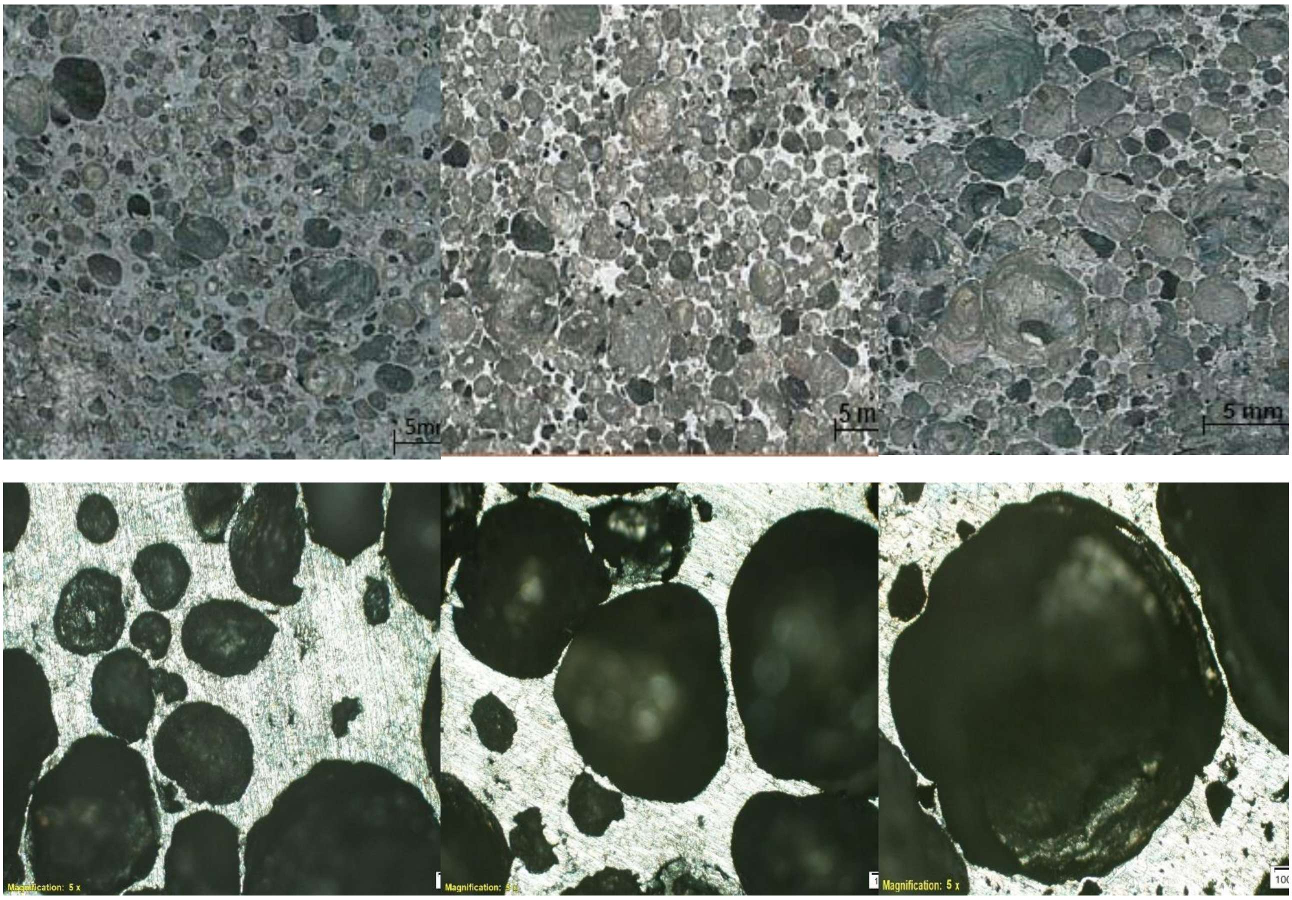


Fig. 1. Structure of 5056 aluminum alloy foam with 1.5, 1.8 and 2.1 wt% $CaCO_3$

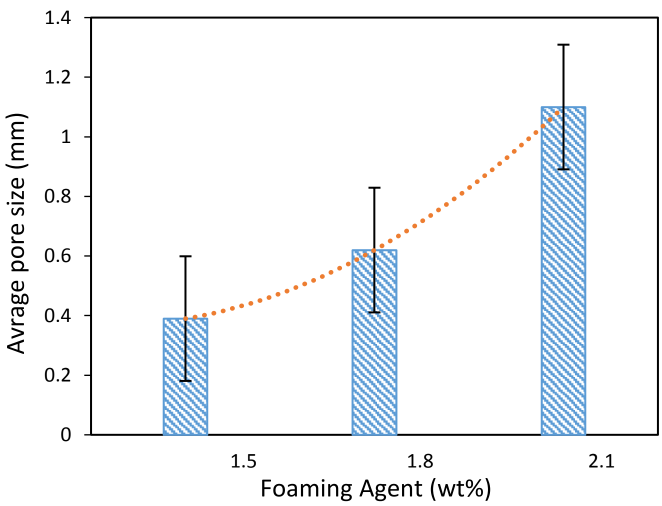


Fig. 2. Variation of average Pores size with increasing the amount of $CaCO_3$

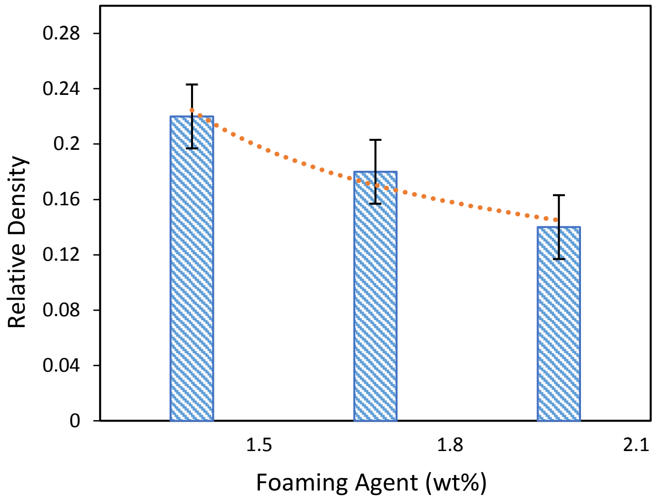


Fig. 3. Variation of relative density with increasing the amount $CaCO_3$

3.2. Compressive Strength

Fig. 4. illustrates the compressive stress-strain curves of 5056 aluminum alloy foam with 1.5, 1.8, and 2.1 wt% $CaCO_3$. Stress-strain curves have three regions: the elastic deformation region, the plastic deformation region, and the densification region. The stress-strain behaviors of the three types of foam are relatively similar, especially in the elastic region. The first peak marks the beginning of the plastic region. Collapse in foams gradually spreads to all walls, and finally, with the collapse of all walls, the voids in the foam specimen begin to condense, which is observed with a rapid increase in stress with strain. The difference between the stress-strain curves for foams with various amounts of foaming agent in the elastic region is less than those in the plastic and the densification regions. This difference increases with increasing the strain value. The densification strain is the point at which a majority of the cell space has been compacted, and the cell walls begin to jam together. This could happen when compression strain is equal to the porosity Eq 4. In practice, a small number of cells may still exist in the crushed foams, and the cell walls may have undergone a certain degree of plastic deformation Fig. 5. The amount of cells and deformation is considered to be related to cell morphology; the collapse mechanisms and the deformation behavior of the cell walls [14]. Fig. 4. also shows that the behaviors of the aluminum foams with 1.5 and 1.8 wt% $CaCO_3$ (relative densities of 0.21 and 0.18, respectively) are very close together up to strain of 0.08, and their difference increases as the strain increases. While, the stress-strain curve for aluminum foam with 2.1% wt% $CaCO_3$ (relative density of 0.15) is significantly different from others. The results show that decreasing the amount of $CaCO_3$ foaming agent and as a result, increasing relative density is associated with increasing the stress values in stress-strain curves of aluminum foams. In general, a precise definition for compressive strength for foams is not provided. The stress-strain behavior varies according to the type of alloy used for foaming. The effect of $CaCO_3$ foaming agent on the compressive strength of aluminum foams is shown in Table 5, which is obtained from the stress-strain curves of Fig. 4. It is observed that the compressive strength of aluminum foams decreases with increasing the amount of $CaCO_3$ foaming agent. This is because of the increasing pores size resulting from the increasing amount of $CaCO_3$.

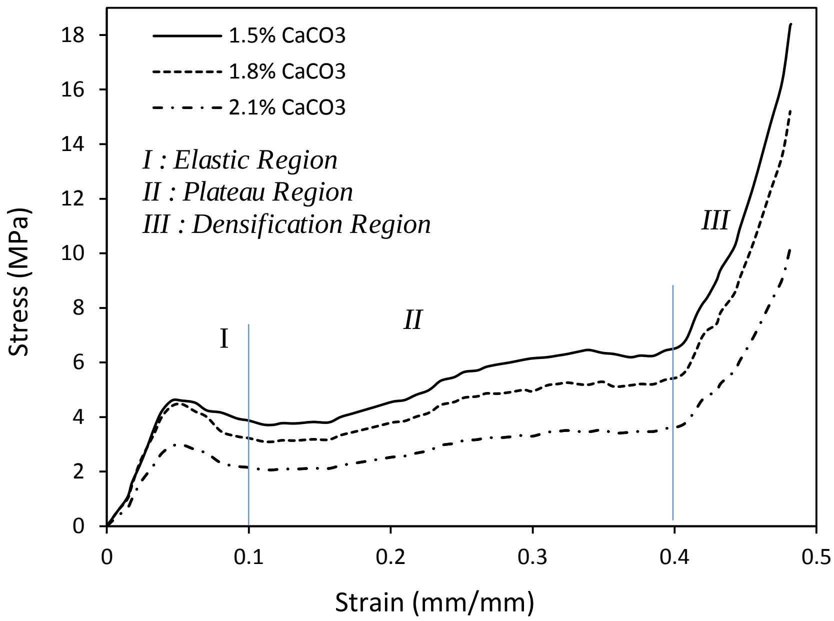
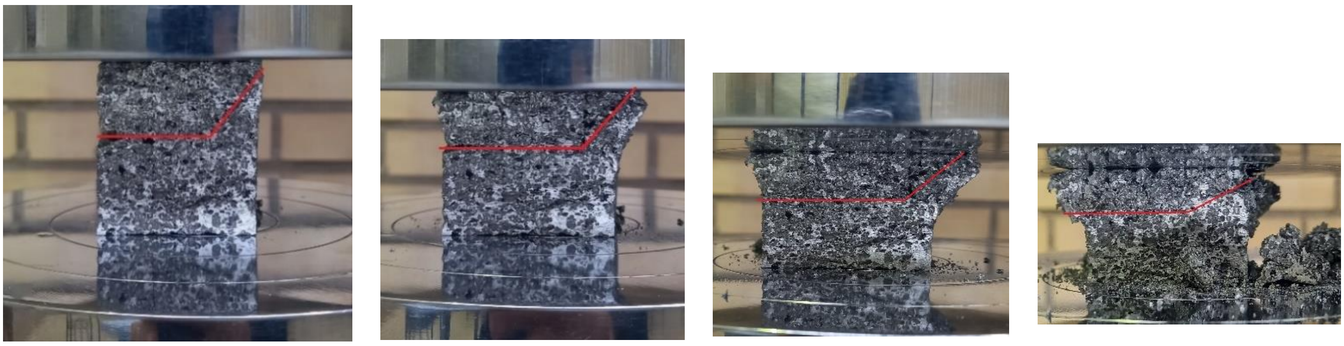


Fig. 4. Stress–strain curves of foamed aluminum with 1.5, 1.8 and 2.1 wt% $CaCO_3$, mixing time =15 min and holding time =1.5 min

Table 5. Compressive strength of aluminum foam (MPa)

Variables	Sample 1	Sample 2	Sample 3
$CaCO_3$ (wt %)	1.5	1.8	2.1
Relative density, ρ_{rel}	0.21	0.18	0.15
Stress at 20% strain (MPa)	4.3	4	2.5
Stress at 40% strain (MPa)	4.5	3.8	2.3
Stress at 60% strain (MPa)	6	5.2	3.3



0% Strain 20% Strain 40% Strain 60% Strain

Fig. 5. Compressive deformation process of closed-cell aluminum alloy foams at the quasi-static loading

3.3. Energy absorption

One of the most essential features of metal foams is their energy absorption, and this unique feature leads to the extensive use of metal foams in industry. Eq 5, related to the area under the stress-strain curve, can be used to calculate the energy absorption capacity [32-34].

$$W = \int_0^{\varepsilon_D} \sigma d\varepsilon \quad (5)$$

where W is the amount of absorbed energy. The final densification strain(ε_D) can be determined by drawing two lines tangent to regions II and III and calculating the strain corresponding to the intersection of these two lines.

Fig. 6. shows the energy absorption (the area under the stress-strain curve) of aluminum foams with 1.5, 1.8, and 2.1 wt% $CaCO_3$. The energy absorption of aluminum foams decreases with increasing the amount of $CaCO_3$ foaming agent. In other words, the energy absorption of 5056 aluminum foams decreases as the porosity increases. At a strain of 0.4, by increasing the amount of foaming agent from 1.5% to 2.1%, the energy absorption has decreased by 21%.

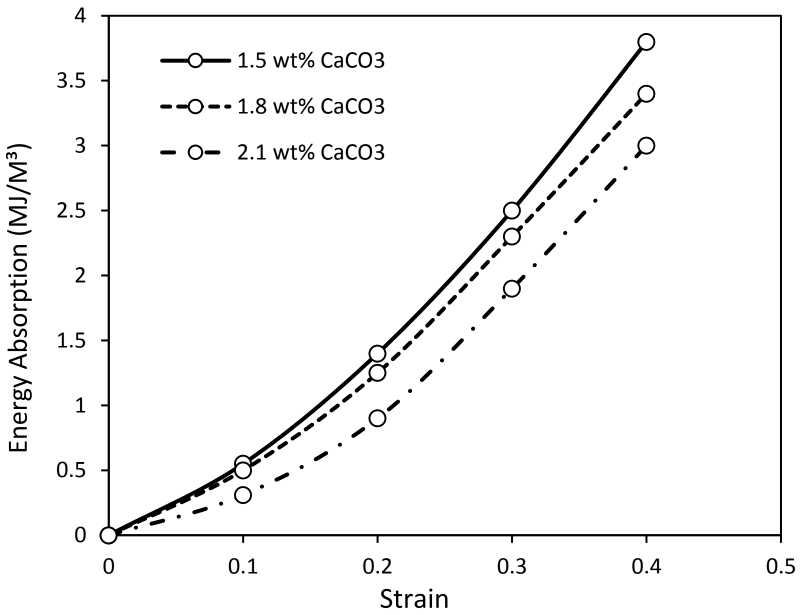


Fig. 6. Energy absorption of aluminum foams with different $CaCO_3$ percentage

3.4. Elastic Modulus

Table 6 shows the elastic modulus of aluminum foams with a relative density of 0.21 to 0.15 (with 1.5, 1.8 and 2.1 wt% $CaCO_3$). It is observed that increasing the amount of $CaCO_3$ blowing agent has led to a decrease in the elastic modulus of aluminum foams from 73 to 61 MPa. In other words, increasing the amount of foaming agent from 1.5% to 2.1% has reduced the elastic modulus of the foam by about 16%.

Table 6. Elastic modulus of foamed aluminum with 1.5, 1.8, and 2.1 wt% $CaCO_3$

Variables	Sample 1	Sample 2	Sample 3
$CaCO_3$ (wt %)	1.5	1.8	2.1
Relative density, ρ_{rel}	0.21	0.18	0.15
Elastic modulus, E (MPa)	73	70	61

The elastic modulus of aluminum foam with a relative density of 0.21 is higher than other samples. This behavior is due to the high density compared to other samples. Homogeneity can also play a role in increasing the density and elastic modulus.

Fig. 7. shows that the aluminum foam produced with 1.5% $CaCO_3$ has a more homogeneous structure than other samples. As the foaming agent increased, inhomogeneity became apparent; the cause is the reduction in wall thickness between pores, which causes inhomogeneity, thereby reducing density and young modulus.

Fig. 8. illustrates the relative Young's modulus (E/E*) of aluminum foams versus the amount of foaming agent. It can also be seen that increasing the amount of foaming agent has a significant effect on reducing the relative elastic modulus. Meanwhile, for example, the foams produced with LM13 aluminum alloy show different behavior [35]. The conflicting results regarding the effect of pore size and degree of homogeneity on the elastic modulus may be due to the mechanical properties of aluminum alloy and the different morphology of the foam structures [36].

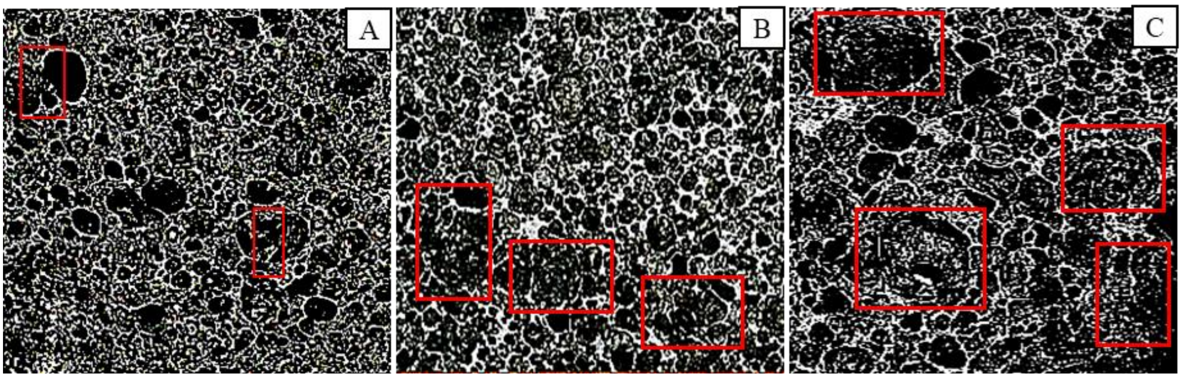


Fig. 7. Inhomogenetiy in foamed aluminum with **a** 1.5 **b** 1.8 **c** 2.1 wt% $CaCO_3$

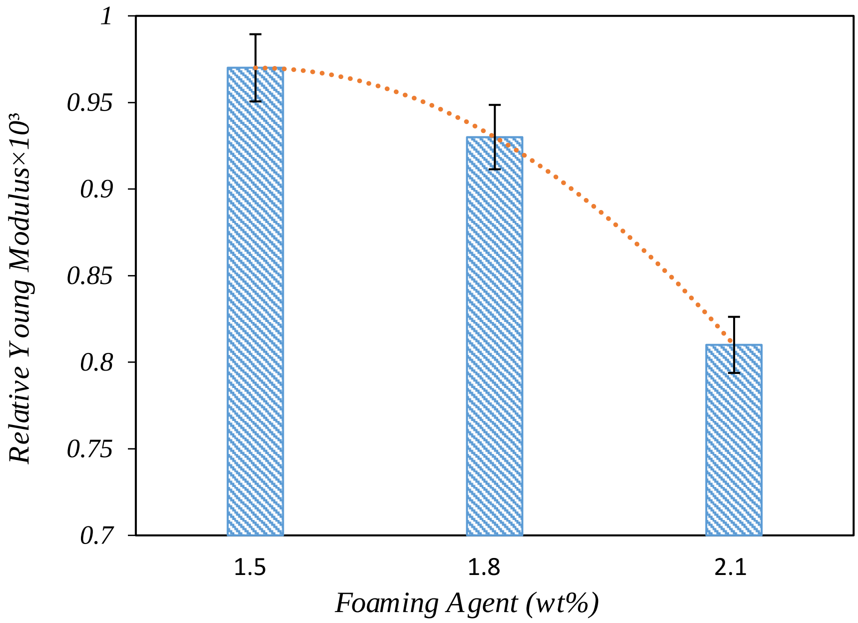


Fig. 8 Variation of relative elastic modulus with increasing the amount of $CaCO_3$

4. Conclusions

In this article, 5056 aluminum alloy foams were produced by Alporas method using calcium carbonate ($CaCO_3$) as foaming agent and calcium metal (Ca) as stabilizing particles. The effects of the amount of foaming agent on the size of the pores, the minimum thickness of the walls and the density were evaluated. The mechanical behavior of foams was studied using uniaxial compression test. The influences of the amount of calcium carbonate on compressive strength, elastic characteristics and energy absorption capacity of foams were investigated. The results include:

1. A relatively uniform structure of the pores was observed in foam specimens. Increasing the amount of $CaCO_3$ increases the pores and reduces the thickness of cell walls. Increasing the pore size decreases the density and the relative density of the aluminum foams. By increasing the foaming agent from 1.5% to 2.1%, the average size of the pores and porosity increased by 182% and 8.4%, respectively, and the minimum thickness of cell walls was reduced by 90%; as a result, the relative density decreased by 28.6%.
2. Compressive strength of aluminum foams decreases with increasing the amount of $CaCO_3$ foaming agent.
3. Increasing the amount of foaming agent decreases the energy absorption of 5056 aluminum foams. At a strain of 0.4, by increasing the amount of foaming agent from 1.5% to 2.1%, a 21% decrease in the energy absorbed by the foam was observed.
4. Increasing the percentage of $CaCO_3$ blowing agent decreases the elastic modulus of foamed aluminum. Increasing the amount of foaming agent from 1.5% to 2.1% decreased the elastic modulus of the foam by about 16%.

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