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Effect of Mn and Mg reinforcing particles on physico-mechanical behavior of close-cell Al metal foam for energy absorption material

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Abstract

A solid substance encircled by a three-dimensional network of voids not interconnected with each other is referred to as close-cell metal foam. The work is based on enhancing mechanical properties of aluminum base close-cell metal foam through the addition of reinforcing particles in varying percentages. Closed-cell aluminum foams with the addition of Mn (0.5 wt.%) and Mg (0, 1, 1.5, 2) were successfully prepared by the melt route method. Al-based metal foam's morphology and mechanical behavior were examined in order to understand the impact of reinforcing elements. From the current work, it is inferred that the addition of reinforcing elements initially helped to increase the compressive strength as found in Foam-1, but further addition of Mg did not have any beneficial effects. It was found that the value of compression strength depends on foam density. The addition of reinforcing elements increases the length of the plateau which in turn increases the value of energy absorption. It is found that proper bonding of reinforcing particles helps in improving energy absorption. From the evaluation, it was found that besides the increase in density and variations in pores uniformity, Al + Mn (0.5wt. %) + Mg (1.5wt. %) Foam (Foam-1) was found to be superior among all other foams. It can also be concluded that by fixing the percentage of Mn by 1 wt%, the best results can be obtained by addition of 1.5 wt. % Mg in the melt. Further addition of Mg shows a detrimental effect on mechanical and physical properties.

Keywords: Metal foam, Compression strength, Melt route method, Blowing agent, Energy absorption, SEM

Introduction

A solid substance encircled by a three-dimensional network of voids is referred to as metal foam. Metals, ceramics, dense polymers, and honeycomb cannot produce the same combinations of properties as metallic foams. For instance, metallic foams have much higher mechanical strength, stiffness, and energy absorption than polymer foams. They can withstand much higher temperatures than polymers and still maintain their mechanical properties because they are thermally and electrically conductive [1, 2]. Additionally, compared to polymer foams, they are typically more stable in challenging environments. In contrast to ceramics, metal foams can absorb significant amount of

energy through plastic deformation. Furthermore, honeycomb structures offer the same lightweight and energy-absorbing properties as metal foam; however, metal foam has much lower areal density and is more effective at shielding [3].

Typically, there are two types of metal foams: open and closed. In closed-cell metal foam, the pores are sealed, while open-cell foam consists of interconnected pores [4]. Closed-cell foams retain the fire-resistant and recycling capability of other metallic foams but add the ability to float in water. On the other side, open porosity foams have very large specific surface areas and are permeable, which are essential features for flow-through applications or where the surface exchange is involved [5]. Functional applications like heat exchangers, flow diffusion, water electrolysers, and lightweight optics are just a few uses for open-celled metal foams [6]. Additionally, high-temperature filters are also made up of open-cell foams, which contain very fine-scale cells that cannot be seen by the naked eye, whereas close-cell metal foams are found suitable for structural applications like crash energy absorbers, vehicle body frames, and bomb-disposing vests. Since aluminum foam has appreciable sound-damping capabilities, it is also used in building auditoriums to promote better communication. However, due to the material's high cost, it is typically used in manufacturing, aerospace, and advanced technology [7].

C. Umashankar et al. [8] prepared aluminum metal foam of different densities through powder metallurgy method and found that length of plateau depends inversely on density. L. E. G. Cambronero et al. [9] produced Al–Mg-Si alloy foam using natural carbonate powder and chemical calcium carbonate powder as blowing agents through the powder metallurgy method. The result shows that natural calcium carbonates can also be well utilized as a foaming agent for producing foam through the PM method. The density of the foams produced by natural carbonate powder was between 0.53 and 0.56 g/cm^3, whereas compressive strength obtained was 6.11 MPa and energy absorption was 1.8 kJ/m^3. M. Heidari Ghaleh et al. [10] prepared A356 close-cell aluminum foam through the melt route method without using thickening agent. The metal foam obtained in the study had density between 0.32 and 0.46 g/cm^3, and mechanical properties increase with an increase in relative densities. Furthermore, it was found that due to the homogeneous distribution of pores, foamed aluminum with 3 wt% $CaCO_3$ had a higher value of elastic modulus. Despite having several favorable properties, aluminum metal foam lacks the ability to provide the significant mechanical properties needed for structural applications.

For enhancement in the mechanical property of Al metal foam, researchers had used various techniques. Some of the researchers had chosen Al alloys for the study, while others had found a solution by adding alloying elements in the melt. According to Xia et al. [11], adding suitable alloying elements during the manufacturing process improves the mechanical properties of aluminum metal foam. In their study, Mn was used as an alloying element in particulate form, which displayed positive intent towards mechanical property when added between 0.2 and 1%. Bisht and Gangil [12] successfully prepared Al metal foam by selecting Zn as an alloying element and found significant improvement in mechanical properties when added up to 1wt%.

Mg is one of the important alloying elements used for strengthening the Al alloy. Choi et al. [13] investigated the effect of Mg on the microstructure and mechanical properties of aluminum. The findings show that by limiting dislocation mobility, solid-solution

strengthening of Mg enhances mechanical and microstructural behavior of aluminum. Horvath et al. [14] conducted a uniaxial compression test on Al–Mg alloys to understand the phenomenon behind plastic deformation. The Al–Mg solid solution strengthens the alloy by promoting mobility dislocation, affecting the stacking-fault energy and avoiding entrapment. Bisht et al. [15] prepared aluminum-based metal foam using Zn and Mg as reinforcing agents. It was found that by increasing the percentage of Mg in the melt (Zn remains to fix at 1 wt. %), mechanical and physical properties of the foam improve significantly. So, Mg can be a potential reinforcing element in the preparation of Al-based metal foam. Since the addition of alloying particles offers the liberty to the researchers to add them in requisite amount in the melt and investigate their effects, moreover, it reduces the cost of fabrication of metal foam. So, in the research, alloying elements in particulate form are added in melt to improve the properties.

The versatility of closed-cell aluminum foam makes it perfect for a wide range of structural applications, due to its high stiffness-to-weight ratio. To use metal foams effectively in any application, one must have a thorough understanding of their behavior and qualities in scenarios that are pertinent to potential applications. However, aluminum foam has low compressive strength which decreases its potential for structural application. This research aims to increase the compressive strength of the aluminum foam by choosing Mn and Mg as reinforcing particles. In this study, Ca is used as a thickening agent and $CaCO_3$ as a blowing agent to generate Al metal foam using the melt route method. The result assists in selecting the best composition which has the utmost strength-to-weight ratio and highest energy absorption with uniform pores.

Methods

Materials and manufacturing process

In the study pure, aluminum (99.5%) metal was selected as the parent metal. Ca granules were used as a thickening agent and $CaCO_3$ as a blowing agent. Mn and Mg were used as reinforcing elements in the study. The material for sample preparation was bought from Gayatri Industries, Roorkee, Uttarakhand, India. The melt route method is used in the production of foam. Samples were prepared in pit furnace which is furnished with stirrer arrangement and speed regulator. The composition used for experimentation is represented in Table 1

Fabrication procedure

The pure aluminum metal foam was placed in an A4 size graphite crucible and melted at 660 °C as illustrated in Fig. 1. Ca granules (2 wt. %) as a thickening agent were

Table 1 Designation of foam samples

Sample designation	Composition		
	Al (wt%)	Mn (wt%)	Mg (wt%)
Foam-0	100	0	0
Foam-1	98.5	0.5	1
Foam-2	98	0.5	1.5
Foam-3	97.5	0.5	2

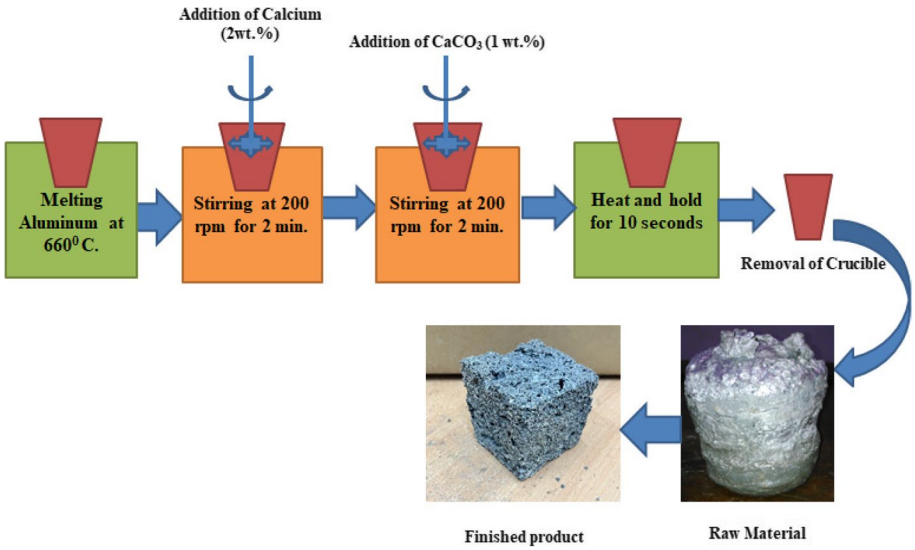

Fig. 1 Fabrication procedure of Al metal foam

added to the melt and stirred at about 200 rpm for 2 min. Whenever required, Mn and Mg were added to the melt in an appropriate percentage. The melt was stirred vigorously at 200 rpm for the next 2 min. During this step, more heat was added to the melt with the help of a blower, and the temperature was maintained at about 720 ± 10 °C. Afterward, 1 wt. % $CaCO_3$ was introduced into the melt and stirred for 3 min at 200 rpm. The crucible was held in the furnace for expansion for about 10 s. In the final step, the crucible was removed carefully and cooled in still air.

Characterization

Physical characterization

The Archimedes principle was used to determine the density of metal foam after the sample had been entirely coated by a para-film to avert liquid from penetrating the pores in the material. The percentage of porosity was measured by the standard formula given below:

$$Percentage\ of\ porosity = \frac{\rho_{al} - \rho_{foam}}{\rho_{al}}$$

where ρ_{al} and ρ_{foam} stand for density of pure aluminim and aluminim metal foam.

Microstructural characterization

In this study, the pores were examined on a high-resolution digital camera in order to determine their size, irregularity, and distribution. The pore morphology and bonding of the reinforcing particles were studied using scanning electron microscopy (SEM) with a ZEISS EVO-18.

Mechanical characterization

For understanding the mechanical behavior of the specimens, uniaxial compression test of the samples was conducted on a universal testing machine (UTM) supplied by Neelam Engineers, Agra. The pace rate of the machine was kept at 0.5 mm/s during the test. The cubic shape samples of $30 \times 30 \times 30\text{mm}^3$ dimensions were used for the compression test.

The samples were cut in cubic shape having dimensions $30 \times 30 \times 30$ mm^3. The results were obtained using a PC interface. The samples were tested for full displacement at 30 mm. The value of energy absorption per unit volume was determined by the integration of the stress–strain curve up to densification given in Eq. 1.

$$W = \int_0^{\varepsilon} \sigma(\varepsilon) d\varepsilon \tag{1}$$

where σ represents compressive stress and ε represents compressive strain in stress–strain curve.

Results and discussion

Morphology and microstructure of foam specimens

Figure 2 represents the optical images of prepared samples. It can be seen that Foam-0 produces a uniform structure, whereas Foam-1 also shows a satisfactory structure, except in some of the places. From past research, it is evident that foam's expansion and its stability depend upon the liquid metal film's strength to sustain the generated stress [16]. The stress generated is controlled by maintaining apparent viscosity which in turn helps in preventing the drainage of liquid. Since reinforcing particles are evenly spread in the cell wall matrix, as shown in the SEM image of Foam-1 in Fig. 3b, they

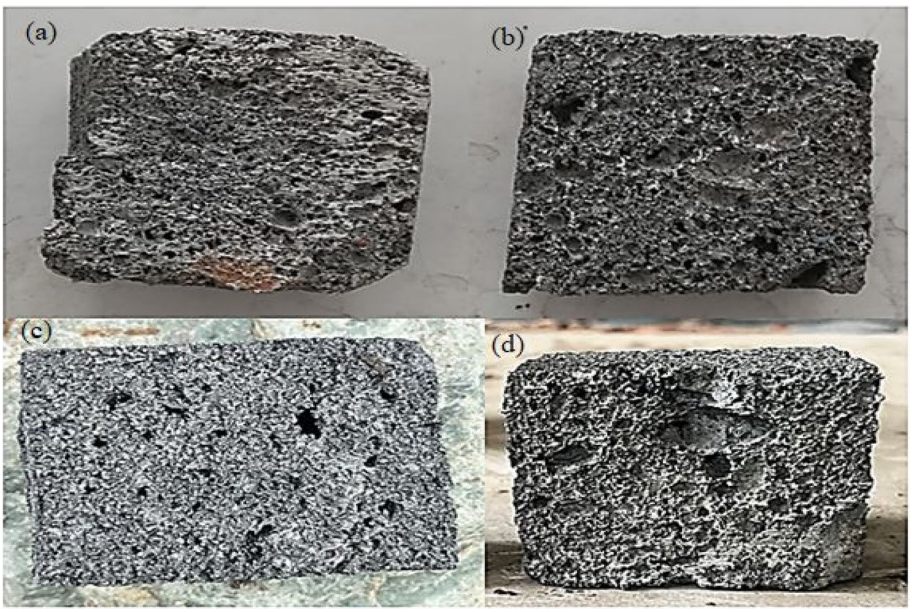

Fig. 2 Optical image of **a** Foam-0, **b** Foam-1, **c** Foam-2, **d** Foam-3

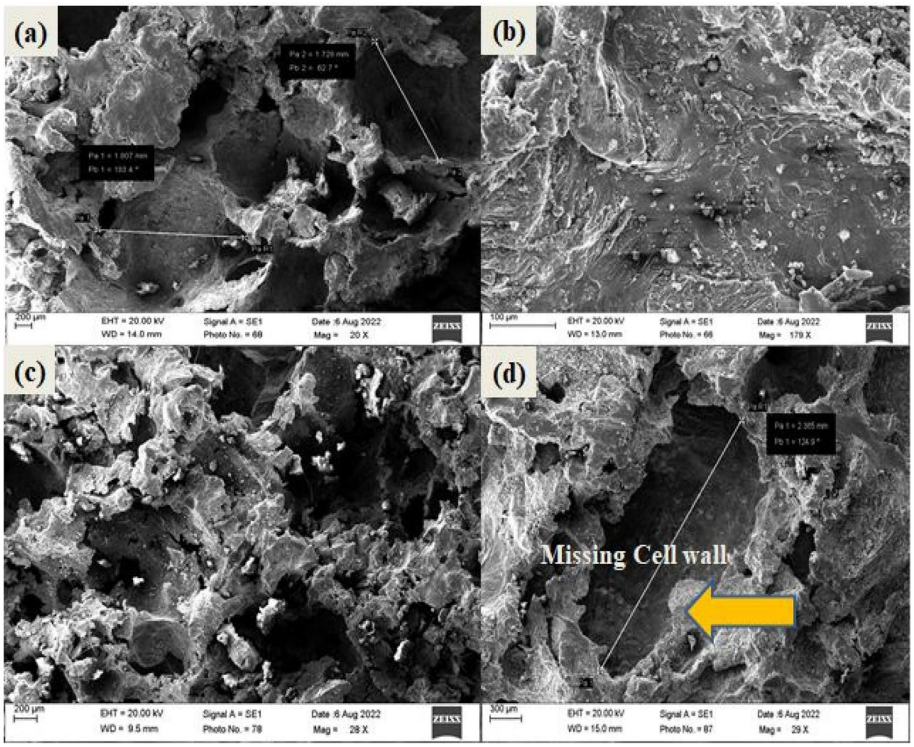

Fig. 3 SEM image of **a** Foam-0, **b** Foam-1, **c** Foam-2, **d** Foam-3

are assisting thickening agents in resisting thermal stresses, and as a result, bubbles are resisting collapse.

Foam-2, on the other hand, has the highest porosity, allowing them to make thinner cell walls. In accordance with the ideal model, the higher the foam's porosity, the weaker the cell wall. By increasing the percentage of Mg above 1 wt. % in the melt, it is found that porosity increases, which in turn reduces the cell wall thickness. The optical image in Fig. 2c represents that the pores of Foam-2 are bigger and non-uniform at the center, while at the periphery, the pores look approximately homogeneous and uniform. SEM image of Foam-2 in Fig. 3c represents thinner and broken cell walls. Some of the pores are also developed in the cell walls. This development in Foam-2 will surely dent the mechanical properties. Foam-3 has uniform pores, and only a big pore is visible at the center of the optical image shown in Fig. 2d. The SEM image of the Foam-3 provides the reason behind it. The SEM image in Fig. 3d shows that the cell walls are missing during pore genesis.

Nature of deformation and compression behavior

For finding out the compressive property of the prepared close-cell metal foam, the size of the specimen was taken as $30 \times 30 \times 30$ mm^3. Compressive stress–strain curves obtained for the foams shown in Fig. 4 represent three distinct regions: It starts from linear deformation at low strain followed by a long and flat region having almost constant stress with respect to change in strain. The last region is known as

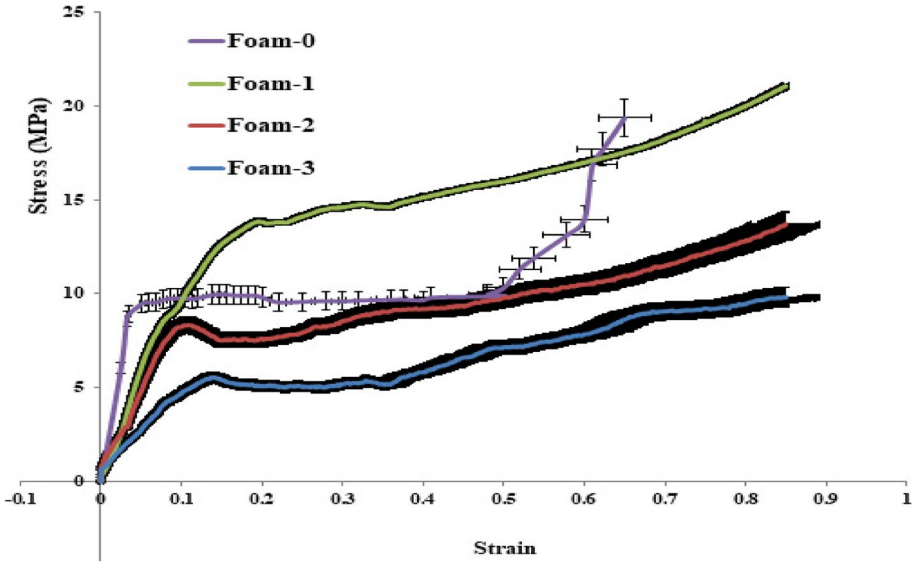

Fig. 4 Combine stress–strain curve of fabricated foams

the densification region where stress rises sharply concerning small changes in strain. This is in accordance with the standard compressive stress–strain curve of metal foam [17].

Cell wall bending or stretching in the elastic zone regulates deformation. A region of collapse is then brought about via a number of mechanisms, including elastic buckling, the creation of plastic hinges, the brittle crushing of cell walls, and others [18]. Because deformation in this area is severely constrained, the cyclical nature of cell compression and collapse results in huge oscillations in stress. The next zone is the plateau region, where the stress is constant or only slightly changes with strain, and is commonly referred to as the collapse region. The structure of the foam is a group of cells distributed in the band. The strength of the cell varies from cell to cell. The weak cell collapses earlier than the strong cell and hence provides a long and steady plateau in this region. The material densifies once the walls begin to touch each other after a certain amount of strain (densification region). The stress in this area rises sharply and gets close to the bulk Al metal's strength.

In the stress–strain curve shown in Fig. 4, the first peak stress represents yield strength. The combined compressive stress–strain curve represents that the yield strength of Foam-1 has a higher value than pure Al foam (Foam-0), and the strength-to-weight ratio is also high. It means that the addition of Mn and Mg shows significant improvement in the mechanical properties of aluminum foam. The possible reason behind this is the proper mixing of reinforcing particles in the cell wall. SEM image of Foam-1 in Fig. 3B shows the proper bonding of particles which helps in enhancing the mechanical properties.

It is worth noticing that due to the addition of Mn (0.5 wt.%) and Mg in varying percentages, initially for 1wt.% Mg, the compressive strength increases, and then finally for Mg (@ 1.5 and 2wt.%), the compressive strength of the foam decreases. In the case of Foam-2, the density of foam decreases, and yield strength reaches about equal

to Foam-0. The SEM image shows that Foam-2 has a thinner and broken cell wall in Fig. 3C. According to Kadkhodapour and Raeisi [19], the topology of the cell influences the mechanical behavior of close-cell metal foam. Since the cell walls are broken and thinner, so compression behavior of Foam-2 is showing depreciation. Foam-3 has the lowest yield strength. With the addition of a higher percentage of Mg in the melt, the possibility of the formation of MgO increases, as they are formed when Mg at a higher temperature is exposed to air [20]. Mg tends to get vaporized from the melt or react with the surrounding air at a higher temperature. As the fabrication process was completed at a very high temperature of about 700 °C, the air from the surrounding reacted with Mg and formed MgO on the surface. SEM image of Foam-3 in Fig. 5 represents the presence of MgO. It can be seen in the figure that MgO is accumulated as precipitants in the cell walls surface and does not participate in solid solution strengthening. Since magnesium does not participate in strengthening the wall, as the process progresses, internal stress arises, which leads to the breaking of the cell wall and allows drainage hence disturbing the morphology of.closed cell foam. Thus, the deposition of MgO on the cell wall, which causes the nonuniformity of the pores, appears to be a plausible cause for this reduction. As a result, the value of yield strength decreases drastically [21, 22]

Since compressive strength is proportional to density, the compressive strength of foam will vary according to its density [17]. Therefore, the strength-to-weight ratio is another parameter for comparison. Strength is a measurement of the sample's load-bearing capacity. In the context of foam, the yield is the maximal strength that can be measured during compression before the plateau zone begins. The strength-to-weight ratio of foams is represented in Fig. 6. Calculating yield strength/density, it has been

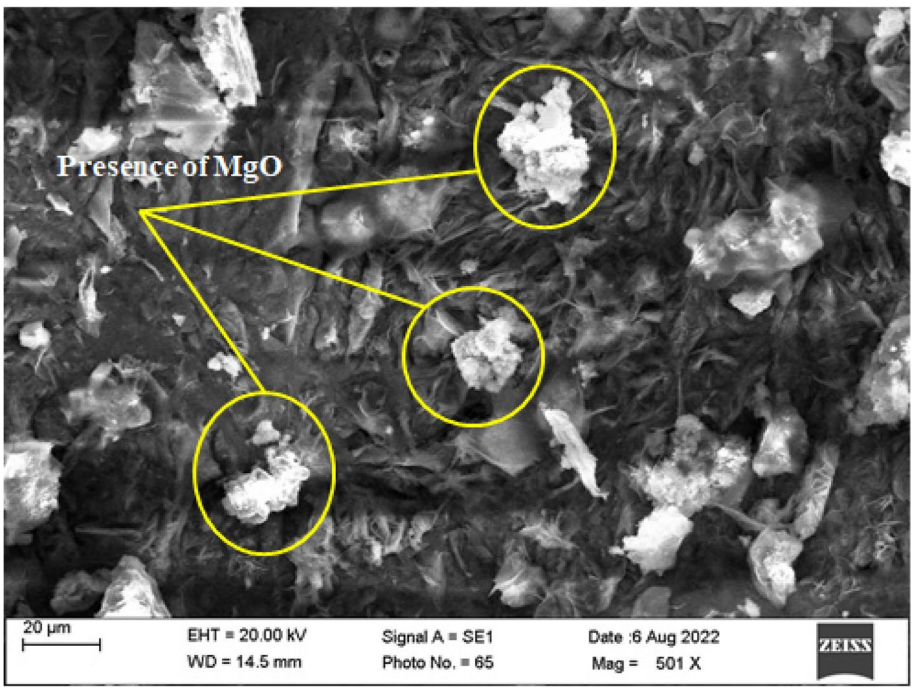

Fig. 5 SEM image of Foam-3

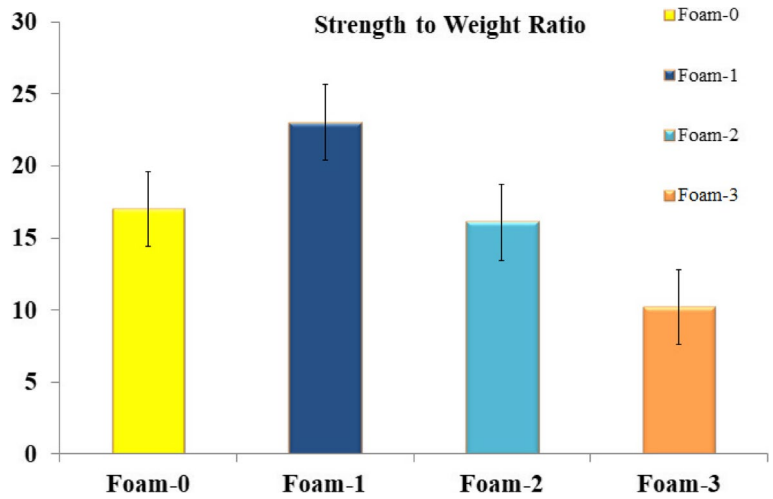

Fig. 6 Strength-to-weight ratio of foams

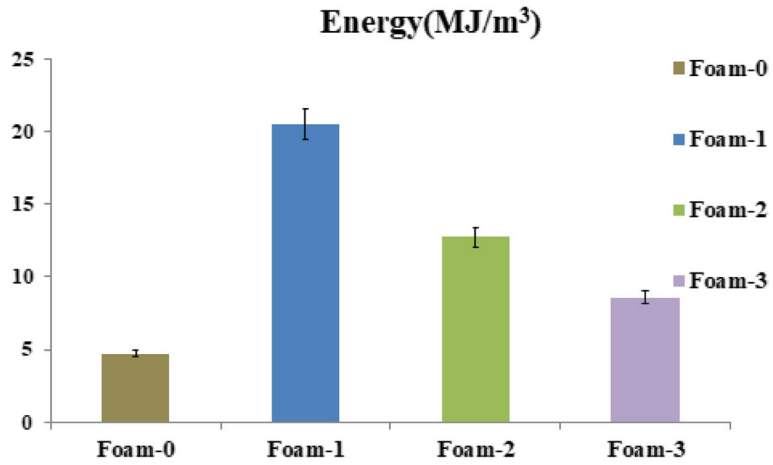

Fig. 7 Comparison of energy absorbed by foams

found that the values Foam-0:Foam-1:Foam-2:Foam-3 is in the ratio of 1:1.35:0.94:0.61. The strength-to-weight ratio shows that Foam-2 performs better than Foam-0. Foam-3 represents the lowest yield strength and lowest strength-to-weight ratio. Foam-1 performs best among all the foams.

Energy absorption of foams

An important factor to consider when assessing the characteristics of metal foams is their energy absorption capacity per unit volume. It is defined as the area under the stress–strain curve up to the end of the plateau stress region. The permissible maximum stress and the plateau length are the two curve properties that must be present for a material to be an effective energy absorber [1]. The value of energy absorption is plotted in Fig. 7. Foam-0 has the complacent value of yield strength but lacks the ability to longer plateau. The total energy absorbed up to the plateau is 4.72 MJ/m^3. Foam-1 displays the longest and smoothest plateau region of all the curves. Moreover,

the value of collapse stress is also maximum. It has been already discussed in the study that the extent of each region is a function of density. The density of Foam-1 is 0.6 g/cm^3. The value of energy absorption calculated is 20.47 MJ/m^3. This is about four times Foam-0. Looking towards the length of the plateau of Foam-1, it is found that the length reaches up to 0.9 strain (Fig. 4). It seems to be the potential reason behind the energy absorption. In this region, deformation begins in the weakest area and spreads to the stronger area until the entire area is crushed. In succeeding bands, this procedure is repeated. The compressive stress of the foam remains essentially constant because each band has nearly the same strength [4].

Foam's ability to absorb energy is largely a result of the cell walls' yielding, buckling, and friction [17]. The large size pores possess thin cell walls and hence form weaker zones in comparison to small pores with thick cell wall. Deformation in the cell walls initiates from the weaker zone and then transmits towards the next weaker regions. In the process of transfer of load, energy is absorbed without significantly changing the stress. The deformed cell walls do not bear the increasing loads very well; instead, they adapt to the surroundings by changing their shape. Therefore, after initial yielding, the stress–strain response shows a plateau [18].

The proper distribution of the Mn and Mg elements in Foam-1's cell wall matrix and the thickening agents along the cell wall edges support the material's ability to resist deformation. It is found experimentally that with an increase in the percentage of Mg element in the melt, the energy absorption increases enormously.

In the study of Foam-2, it was found that the value of collapsible stress reduces dramatically, but the length of the plateau remains longer. The value of energy absorption is found to be 12.73 MJ/m^3, which drops significantly in comparison to Foam-1. The addition of 1.5 wt. % Mg in the melt is showing a detrimental effect but still gives a comprehensive value of energy absorption.

The study of Foam-3 exhibits a substantial drop in collapsible stress, and the plateau region looks interrupted. The value of energy absorption calculated is 8.60 MJ/m^3. Among all the foams, Foam-0 has the shortest plateau. With the addition of Mn and Mg in the melt, the length of the plateau increases. It emphasizes the need for reinforcing elements in the melt to perform solid solution strengthening.

With the addition of Mg above 1wt. %, it is found that the value of yield strength and energy absorption decreases. The accumulation of precipitants in cell walls and pores' nonuniformity seems to be an appropriate reason behind this decline. Table 2 summarizes the properties of all fabricated samples in the research.

Table 2 Summary of obtained properties of fabricated metal foams

S. no	Foam	Density (g/cm^3)	Porosity (%)	Yield strength (MPa)	Strength-to-weight ratio	Energy absorbed (MJ/m^3)
1	Foam-0	0.51	80.9	8.67	17	4.716
2	Foam-1	0.6	77.5	13.806	23.01	20.475
3	Foam-2	0.5	81.27	8.05	16.1	12.7
4	Foam-3	0.48	82.02	4.9	10.21	8.6

Conclusions

Closed-cell aluminum foams with the addition of Mn (0.5 wt.%) and Mg (0, 1, 1.5, and 2) were successfully prepared by the melt route method. In the process, Ca was used as a thickening agent and $CaCO_3$ as a foaming agent. The effect of reinforcing elements on the morphology and mechanical behavior of Al-based metal foam was studied. The results are concluded as follows:

From the optical images, it is observed that Pure Al foam has uniform pores. The addition of alloying elements in Foam-1 shows satisfactory results in terms of pore size and uniformity' however, further alloying element addition causes undesirable results. Similarly, addition of reinforcing elements initially helped in increasing the compressive strength as found in Foam-1, but further addition of Mg did not have any beneficial effects. Since compression strength is proportional to density, Foam-1 provides the maximum compressive strength due to the highest density. Due to longer plateau region, the energy absorption in Foam-1, 2, and 3 was found to be better than Foam-0. It means that the addition of alloying elements helps in increasing the length of the plateau which in turn increases the value of energy absorption. The proper bonding of alloying elements in Foam-1 enables it to absorb the maximum energy in comparison to all other foams.

From the evaluation, it can be concluded that besides the increase in density and variations in pores uniformity, Foam-1 was found to be superior among all other foams. It can also be concluded that by fixing the percentage of Mn (0.5 wt. %), the best results can be obtained by adding Mg by 1 wt. % in the melt. Further, addition of Mg shows a detrimental effect on mechanical and physical properties.

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Authors' contributions
AB has performed acquisition, analysis, and interpretation of data for the work. BG drafted the work and revised it critically for important intellectual content and final approval of the version to be published. LR prepared the samples and applied analysis tools. SPG performed data analysis, interpretation, and critical revision of the article.

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Declarations

Competing interests
The authors declare that they have no competing interests.

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