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Structural and physico-mechanical characterization of closed-cell aluminum foams with different zinc additions

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Abstract: Closed-cell aluminum foams with different percentages of zinc content were successfully prepared and investigated. The foamable precursors were prepared in a pit furnace by adding calcium as thickening agent, calcium carbonate as blowing agent and different percentages (0 wt.%, 0.5 wt.% and 1 wt.%) of zinc particles at 650–750°C. The distribution of Zn elements and quasi-static behavior of the foams at room temperature were investigated. The experimental results show that Zn element is uniformly distributed in cell wall matrix. The distribution of Zn elements had a significant effect on the quasi-static compressive behavior of aluminum foams; from the results, it is obvious that zinc-containing foams possessed higher compressive strength and energy absorption capacities than pure aluminum foams. Hence, it can be concluded that increase in percentage of Zn particles helps to increase the compressive strength, plateau region and energy absorption, in addition to providing better and uniform pores.

Keywords: compressive strength; melt route method; metallic foam; SEM.

1 Introduction

Cellular metals have potential applications in the aerospace industry, ship building and railway industry, building industry, machine construction, sports equipment and biomedical, etc. [1–3]. Metal foams are cellular solids that exhibit an interesting set of physical and mechanical properties owing to their complex

morphology. Functional applications for metals foams with a certain degree of open porosity are: filtration and separation, heat exchangers and cooling machines, supports for catalyst, storage and transfer of liquids, fluid flow control, silencers, battery electrodes, flame arresters, electro-chemical applications, water purification, acoustic control, decoration, etc. [2]. High stiffness to weight ratio, the low specific weight, the high energy absorption during plastic deformation, good mechanical strength and recyclability are among the properties which have made them attractive for current and future applications in the automotive and construction industries among others [1–4]. Structural applications are oriented to close cell foams, while functional applications are based on open porosity. Therefore, various methods are used for preparing foam like powder metallurgy, melt foaming method, gas entrapment technique, electro-deposition, vapor deposition, etc. [4–8]. Generally, two techniques are used by researchers, i.e. powder metallurgy and the melt route method. The melt route method is an effective technique for preparation of metal foam, and many industries are using this technique for reducing the cost of foam and moreover the same technique is also being used in cost driven products. As per the requirement, several metals and alloy foams are being developed, e.g. Al, Zn, Mg, Fe, Ti, metal matrix composites, metallic glasses, etc. However, Al foams are widely used in structural and functional applications due to their unique properties of good strength and weight saving. Byakova et al. [9] compared the structure and energy absorbing ability of the aluminum based foams manufactured by two different types of blowing agents, i.e. calcium carbonate and conventional titanium hydride, and reported that in comparison to the conventional titanium hydride, coated calcium carbonate offered a significant advantage over mechanical performance of closed-cell aluminum foam. This was due to the remarkable improvement of the cell wall microstructure. Moreover, calcium carbonate foam of pure aluminum shows more ductile compressive behavior than that of titanium hydride foam, suggesting higher toughness of the cell wall materials for calcium carbonate foam than for titanium hydride foam. In

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another study, Yang et al. [10] concluded that the compressive properties of cellular Mg foams were remarkably enhanced by using calcium carbonate powder as the blowing agent and calcium particles as the thickening agent. Neu et al. [11] studied Mg and Mg-Al alloy foams prepared by two different methods, with conventional foaming under 1 bar and pressure induced foaming. When Al is varied from 0% to 17%, the ductility of foam increases, which in turn increases consolidation. Al was also responsible for large expansion. Lu et al. [12] prepared closed-cell Mg foam using SiO₂ coated CaCO₃ as the blowing agent in atmosphere. The results show that the thermal stability of coated CaCO₃ is improved. Fathi et al. [13] manufactured Al closed-cell foam by accumulative roll bonding using CaCO₃ as the blowing agent. The results show that foaming temperature and time have significant effects on the foaming process. Abravi et al. [14] investigated the effect of ceramic particles on the cell structure of Al foam. It was found that cell size and the cell wall thickness of the sample foam increases with increasing SiC particle concentration at constant foaming temperature, while the plateau border size decreases with increase in particle concentration. Shen et al. [15] investigated the compressive behavior of closed-cell aluminum foams at high strain rates and concluded that the energy dissipation capacity per unit volume of the foam increases favorably with the strain rate. Jaroslav and Frantiek [16] compared aluminum and zinc foam, and found that the compression strength of zinc foams was significantly lower at similar density; foams of equal porosity possess almost identical compression strength. Nevertheless, due to low mechanical properties of pure aluminum foam, they were unable to fit in all the functional and structural applications. Generally, for obtaining high strength aluminum foam, aluminum alloys are purposefully used as matrix material. Li et al. [3] prepared silicon carbide filled aluminum composite foams by powder metallurgical methods using calcium carbonate as the foaming agent. The compressive curves revealed that the introduction of silicon carbide particles was helpful in improving compressive yield strength and energy absorption capacity and at the same time, such foam also shows a brittle nature. Huang et al. [17] examined the effects of Sc elements on the quasi-static compressive behavior of Al-Sc foams. Consequently, addition of Sc particles shows a dramatic effect on the improvement of compressive strength of Al-Sc foam. Ghorbani et al. [18] investigated the effect of manganese additions on the tensile properties of Al-15%Mg₂Si alloy; the results showed that ultimate tensile strength rises to a significant level. Xingchuan et al. [19]

successfully prepared closed-cell aluminum foam by the melt foaming method with manganese variation. The results reveal that the foams with manganese exhibit better mechanical properties than pure aluminum foam. To increase the mechanical properties, three methods are essentially used by researchers; using alloys, composites or adding the significant particles. Zinc element is generally used as the enhancement additive in casting to increase strength, and the zinc foam shows comprehensive compressive strength with easy formation into net shape complex 3-D parts, involves no recycling problems and is used for corrosion protection of steel [20]. Therefore, adding an appropriate amount of zinc elements into aluminum metal could be a possible method to obtain high strength aluminum foams. In light of the above literature study, the present investigation aimed to fabricate aluminum metal foam by adding zinc particles after the addition of thickening agent Ca via the melt route method, using calcium carbonate as the blowing agent. The prepared metal foams were then characterized for their physical and mechanical properties.

2 Materials and methods

2.1 Materials and fabrication procedure

In the present research, commercially pure aluminium ingots (Al, with purity of 99.5%), calcium granules (Ca, thickening agent, commercially pure, granularity between 1 and 2.5 mm), calcium carbonate (CaCO₃, foaming agent commercially pure) and zinc (Zn, commercially pure, 100 mesh) were selected. All of these items were purchased from Jain Suppliers, Roorkee, Uttarakhand, India. For experimentation, a pit furnace was used with a proper stirring mechanism consisting of a three phase A.C. motor and impeller shaft speed regulator. Hard coke of grade 1 was used in the study. The mixture of graphite and clay crucible of A8 size was used as per standard. The compositional variations and designations of the foams are given in Table 1.

Table 1: Details of foam composition and designation.

Designation	Composition (wt.%)	
	Aluminum	Zinc
Foam-0	100	0
Foam-1	99.50	0.5
Foam-2	99	1

The fabrication procedure was mainly included the following steps:

- Step I: A certain amount of pure Al was placed in the crucible for complete melting.
- Step II: After this, 2 wt.% Ca granules were added and stirred for 5 min at 600 rpm, but in the case when Zn was taken, initially stirring of Al + Ca (2 wt.%) was done for 3 min and then Zn was introduced in the crucible and stirred for 2 min at the same rpm.
- Step III: CaCO_3 was added in the ratio of 1:100 wt.% of Al, and properly stirred for 2 min at 200 rpm.

Matrix Al 99.5%	Zinc		Calcium (2 wt.%) Quantity in g	CaCO_3 (1 wt.%) Quantity in g
	Wt.%	Quantity in g		
1 kg	0	0	20	10
	0.5	5	20	10
	1	10	20	10

Step IV: The crucible was hold for a short interval of time for 5–10 s for complete expansion of foam.

Step V: The crucible was removed from the furnace and air cooled.

During the entire procedure, except for the last step, the temperature of the melt was maintained at 953 ± 5 K.

2.2 Characterization

Uniaxial compression testing was performed with cuboidal foam specimens of $25 \times 25 \times 60$ mm³ size on a Heico mechanical testing machine equipped with a 400 kN load cell which was used for the uniaxial compression test and

uniaxially compressed with a pace rate of 0.2 mm/s. The load-displacement curves were recorded using a PC interface and converted into stress-strain curves. Microstructure and the distribution of the Zn particles in the foam were characterized by using a scanning electron microscope (SEM, Jeol Jsm-6610lv). The densities of the foam samples were determined experimentally by Archimedes principle.

3 Results and discussion

3.1 Structure of produced foam

The cross-sectional view of Foam-0 (pure Al foam) is as shown in Figure 1A. The distribution of the pores in Foam-0 is shown in Figure 1B. As observed from Figure 1B, the pores are non-uniformly distributed and few locations of the pores are not developed completely, due to incomplete reaction during the birth phase in foam development. The pore sizes are between 2 mm and 4 mm and there are internal voids of different sizes varying from $84.848 \mu\text{m}$ to $615.801 \mu\text{m}$, respectively.

The cross-sectional view of Foam-1 is shown in Figure 2A. The pores are completely developed and non-uniformly distributed. The large size is due to the coalescence of bubbles during foaming. The SEM image (Figure 2B) shows that internal pores are of smaller size in comparison to those of Foam-0 and range from $31.20 \mu\text{m}$ to $66.588 \mu\text{m}$. However, few internal pores in the cell walls are missing, which gives rise to larger pore size. Figure 2C shows the distribution of Zn particles in the cell wall matrix. Most of the Zn particles are deposited in a fix zone. The cross-sectional view and SEM micrographs of Foam-2

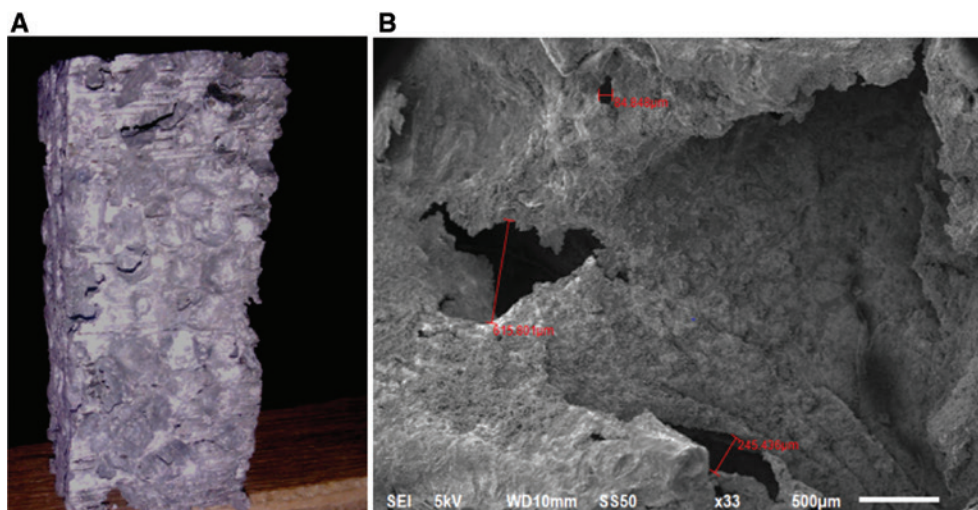


Figure 1: Foam-0 (A) Cross-sectional image (B) SEM image.

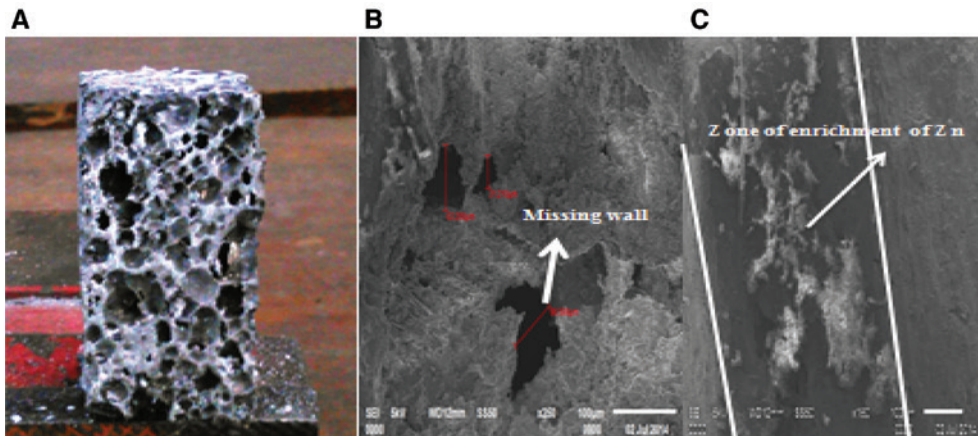


Figure 2: Foam-1 (A) Cross-sectional image (B) SEM image (C) Distribution of Zn particles in inner cell wall.

are shown in Figure 3A–C. The SEM images (Figure 3B and C) show that the Zn particles are uniformly distributed in the Al matrix and the voids are regular and uniformly distributed throughout the matrix. At the same time, there is cell wall corrugation. According to the ideal model, the plateau stress of foam depends only on the porosity. Lower porosity of the foam provides a thicker cell wall, so the foam can bear a greater load and a higher value of plateau stress is achieved for aluminum foam. Due to corrugation of cell walls, Young's modulus is affected by 70%. Therefore, it might be possible that adding a greater percentage of Zn particles can affect the properties of the foam.

3.2 Physico-mechanical properties

The details of physical and mechanical properties of the foams are shown in Table 3 and depicted in Figures 4–6.

As shown from Table 2, the density of the fabricated foams was in the range of 0.67–0.769 g/cm³. The experimental results show that density of the foam increases first, followed by a decrease with increase of Zn content. The foam expansion depends upon the ability of a liquid metal film to withstand the stress generated, rather than the gas available for foaming. Stability of foam is a key priority to obtain quality foam and one of the important factors for stability is cell wall thickness, which depends upon particle diameter, composition of the alloy foaming temperature and particle material [21]. From this, it is clear that adding Zn in 1 wt.% helps to stabilize the foam, which helps to decrease the density.

Figure 4 depict three regions: (i) elastic region, (ii) plateau region and (iii) densification region. The elastic limit shows linear deformation when strain is low. As the strain increases, from the curve it is clear that the stress remains almost constant in the region. At last stress

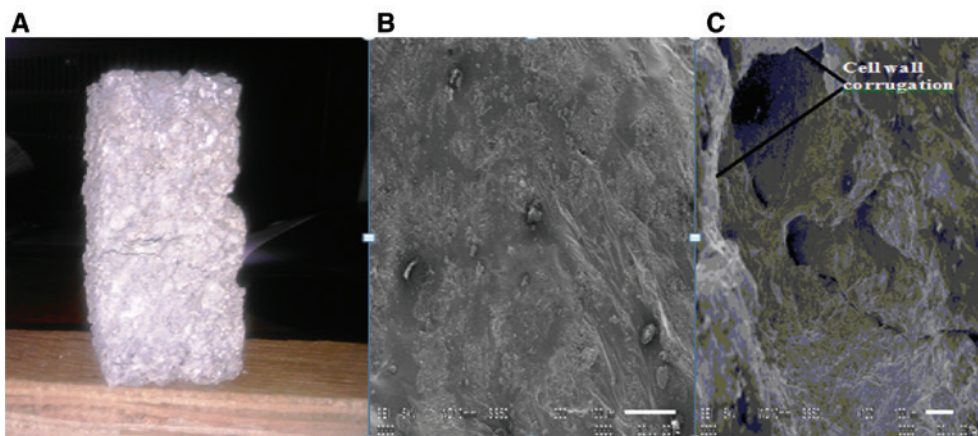


Figure 3: Foam-2 (A) Cross-sectional image (B) SEM image of distribution of Zn particles in inner cell wall (C) cell wall corrugation.

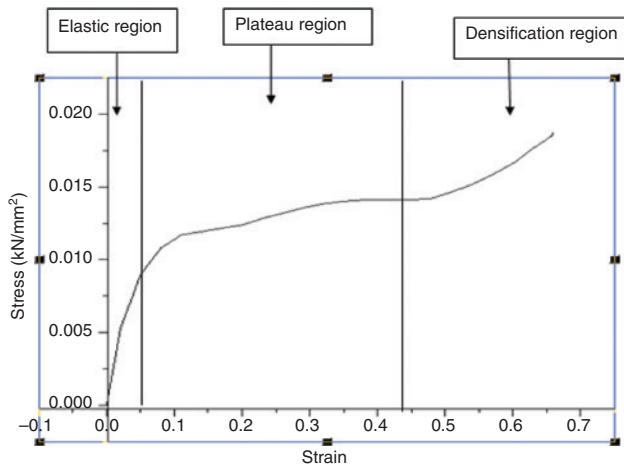


Figure 4: Compressive stress-strain curve of Foam-0.

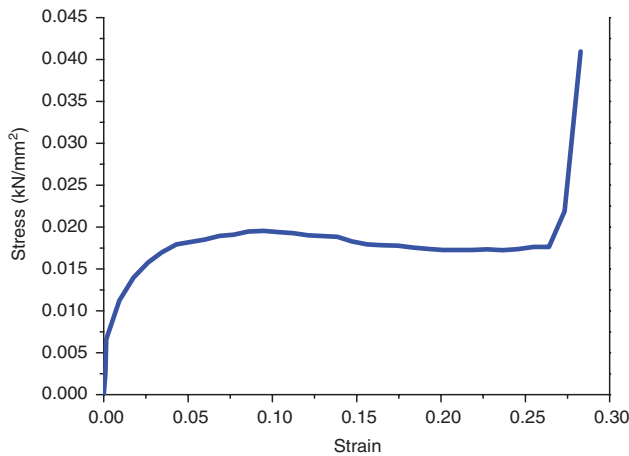


Figure 5: Compressive stress-strain curve of Foam-1.

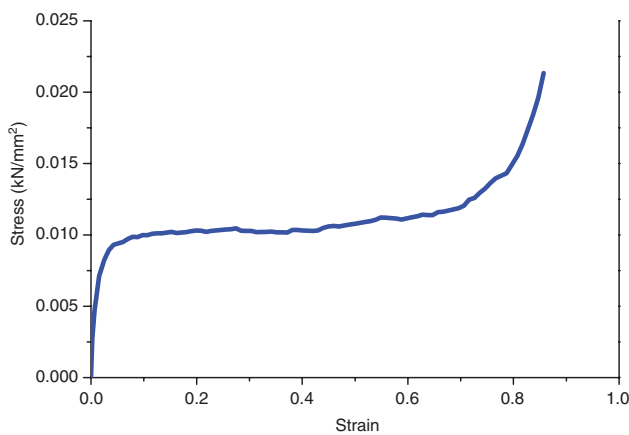


Figure 6: Compressive stress-strain curve of Foam-2.

increases sharply with strain, and the region is known as the densification region. At lower values of strains, the foam deforms elastically and the deformation is controlled

Table 2: Density and compressive strength of the foams.

Type of foam	Density (g/cm ³)	Compression strength (MPa)
Foam-0	0.6700	11.73
Foam-1	0.7692	17.77
Foam-2	0.3946	09.45

by cell wall bending or stretching. This region is followed by a collapse region, which occurs by several different mechanisms, i.e. elastic buckling and brittle crushing of cell walls and formation of plastic hinges, whereas deformation in this region is highly limited. Since the deformation is limited, large oscillations in stress occur due to the repetitive nature of the process of cell collapse and densification. The collapse region is mainly known as the plateau region, where the stress remains constant or increases slightly with strain. After a certain value of strain, the cell wall starts to collapse with each other, and as a result of this, the material densifies (densification region). The stress in this region increases sharply and approaches the strength of the bulk Al metal. The extent of each region is a function of relative density. It is also noted that plateau stresses of foams are not constant and increase with increasing strain. It is supposed that foams having homogeneous cell size show steady plateau stress in the collapse region. However, in reality, differences in cell size and cell distribution cause the collapse of weak cells before the collapse of strong cells. The stress level of the plateau region is the characteristic compressive stress for each matrix material and foam density [21].

The stress-strain curve of Foam-0 shows that the calculated yield strength is 11.77 MPa. In this graph, it is clearly observed that the plateau region is not smooth. The Foam-1 curve shows yield strength of 17.73 MPa and the plateau region is smooth in comparison to pure Al foam. The third curve shows the stress-strain curve of Foam-2, which exhibits yield strength of 9.45 MPa and the smoothest plateau region. The mechanical properties of Al foam are proportional to relative densities. Due to this, Foam-1 shows the highest yield strength. These foams can be compared on the basis of strength to weight ratio. It is calculated that the ratio of Foam-0, Foam-1 and Foam-2 is 1:1.32:1.36. Therefore, it is clear that the increase in percentage of Zn particles improves the yield strength. Among all of the curves, Foam-2 shows the smoothest plateau region. In this region, deformation first occurs in the weakest region and propagates in this region until it is completely crushed. This process is repeated in succeeding bands. As each band has nearly the same strength, the compressive stress of the foam remains relatively constant

Table 3: Energy absorption result for the different foams.

Type of foam	Maximum energy absorbed (Joule)	Energy absorption at $d=15$ mm (Joule)	Efficiency
Foam-0	191.790	156.49	0.822
Foam-1	160.090	164.43	0.860
Foam-2	268.707	88.530	0.910

during the collapse band propagation. SEM images depict the internal pore sizes. Among all of the foams, Foam-2 has uniform pore distribution, which gives a smooth plateau region.

3.3 Energy absorption characteristic

The amount of absorbed energy, $E(d)$, is the integral of the compressive force by the compression distance. The efficiency, E_d , is the quotient of the absorbed energy and the product of the maximum force and the defined deformation length. The $E(d)$ and E_d are calculated as:

$$E(d) = \int_0^d F(x) dx \quad (1)$$

$$E_d = \frac{E(d)}{F_{\max}(d) \times d} \quad (2)$$

where F_{\max} stands for the maximum force at defined deformation length (d) which is taken as 15 mm for the force-displacement curves of all the manufactured Al foam.

As shown in Table 3, Foam-1 has the lowest value of energy absorption. However, with increasing percentage, the value of energy absorption is increased. These are compared by calculating the efficiency. It is quite clear from the calculation that efficiency of the foam increases with the increase in percentage of Zn. Energy absorption capacity of foam is mainly due to yielding, buckling and friction of cell walls. Zn elements are properly distributed in the cell wall matrix and the thickening agents are distributed along the cell wall edges. The distribution of Zn element helps in the deformation process of the Zn-containing foam.

4 Conclusion

Closed-cell aluminum foams with different Zn contents were fabricated by the melt-foaming method using Ca as the thickening agent and CaCO_3 as the foaming agent. The

effects of Zn elements on the compressive properties of Al foams were studied and the results were summarized as follows:

- From the present work, it is examined that addition of Zn particles helps to increase the compressive strength of metallic foam.
- Foam with 1 wt.% Zn particles produces the highest strength to weight ratio. From the analysis, it is examined that the compression strength depends on foam density.
- The value of energy absorption depends on the distribution of Zn particles. As the percentage of Zn increases, the length of the plateau region increases, which helps to increase the energy absorption.
- From SEM images it is observed that pure Al foam has uniform pores. When the Zn is added in 0.5 wt.%, the distribution of the pores becomes non-uniform, and some walls are missing due to the coalescence of bubbles.
- When the percentage of Zn is increased to 1 wt.%, the pore distribution and size become uniform. From this, it can be concluded that the increase in percentage of Zn particles helps to increase the compressive strength, plateau region and energy absorption, and at the same time also provides better and uniform pores.

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