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Investigating Compressive Properties of Closed-cell Aluminum Foams Fabricated by Melt Route Method with Addition of Mg Particles

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Abstract—*Aluminum foam due to its low specific weight and high stiffness to bending ratio is an adequate structural material however its compressive strength is low in comparison to its counter parts. Hence in this paper an attempt is made to enhance the compressive strength of aluminum foam which was prepared by melt route method by different addition of Mg particles. The objective is to deliver a better quality of foam, made of aluminum with low relative density and higher strength against compression. This material can be applicable where energy absorption and light weight property is heavily required such as automotive industries. Mg particles were successfully added directly to molten aluminum in different weight percentage to fabricate foam. Compressive strength testing of samples were performed on universal testing machine with maximum load of 400KN and pace rate of 0.001KN/sec. Pore size and distribution of work pieces were also observed before compression testing by using scanning electron microscope. The result of compression test was compared with pure aluminum foam samples and thus the effect of percentage of Mg particles on compressive strength of aluminum foam was examined. The result shows that average pore size was found to be around 1.6 mm which is very fine. The distribution of Mg element was uniform in the cell walls. The Mg containing aluminum foams possessed higher strength to weight ratio and higher energy absorption capacity than those commercially pure aluminum foams.*

1. INTRODUCTION

Metal foam is defined as a solid material surrounded by a three dimensional network of voids. Metallic foams have combinations of properties that cannot be obtained with dense polymers, metals and ceramics or polymer and ceramic foams [1]. Metallic foams typically retain some physical properties of their base material. Foam made from nonflammable metal will remain non-flammable and the foam is generally recyclable back to its base material, coefficient of thermal expansion will also remain similar [2]. Open cell metal foams, also called metal sponges, can be manufactured by several ways, especially through foundry or powder metallurgy. In the powder method, "space holders" are needed; as their name suggests, they give space to the open pores and channels during or after the foam making process. In casting processes, foams are made by replicas of open-celled polyurethane foams used as a skeleton [3, 4]. Various methods are used for preparing closed cell foam like powder metallurgy, melt foaming method, gas entrapment technique, electro-deposition, vapor deposition etc. Among both type of foams close cell type foams are used for structural applications. For preparing closed cell metal foam melt route method is found to be cheap and best method, due to this many industries are using this technique for cost driven products. Al, Zn, Mg, Fe, Ti, MMCs, metallic glasses etc foams are generally being fabricated as per the requisition in different applications. But Al foam has been found to be leading material in structural applications due to its unique property of good strength and weight savings. Kang Yingan et al. [5] investigated the mechanical behavior of two aluminum foams including open cells and closed cells with a variety of densities at room temperature and under compression loading was studied. Their response to strain rate was tested over a wide range of strain rates, from 1.0×10^{-3} to 1.6×10^{3} s^{-1}. For the open cell foams the stress is sensitive to the strain rate, the yield strength of closed cell foams exhibits little or no strain rate sensitivity. In another study M. H. Shojaeifard [6] investigated bending behavior of empty and foam-filled aluminum tubes with different cross-sections. In this paper, the energy absorption mechanism of empty and foam-filled aluminum tubes with different cross-sections (circular, square and elliptic) under bending load is investigated numerically. The result shows that that the variations of crash load displacement curves of the simulations aren't exactly the same as experimental ones, but are close to the experimental ones. A.G. Hanssen et al. [7] investigated Close-range blast loading of aluminum foam panels and found that use of a sacrificial layer ensures local control of the loads whereas the global response may be unaffected. Jae Ung Cho et al. [8] examined the impact fracture behavior at the material of aluminum foam. In this work, impact tests with drop weights are performed on closed-cell aluminum foam and the experimental results are compared with the simulation results impact energy drop weight impact yielded the following conclusions about experimental results and computational simulation. Zhao and Sun [9] have developed a technique for manufacturing of low cost open-cell aluminum foams by NaCl particles as spacer via PM route. M. Shiomi [10] fabricated aluminum foams from powder by hot extrusion and foaming. TiH_2 powder was mixed with Al6061 powder as a foaming agent to produce foam. Yang Dong, Hui et al. [11] investigated compressive properties of cellular Mg foams fabricated by melt-foaming method, by using $CaCO_3$ powder as blowing agent and Ca particles as thickening agent. Varuzan Kevorkijan [12] prepared low cost aluminum foams made by $CaCO_3$ particulates. Closed cell aluminum foam samples were prepared starting from solid, foamable precursors synthesized by powder metallurgy and the melt route. TiH_2 powder as foaming agent was successfully replaced by commercial $CaCO_3$ powders. Guoqiang LU et al. [13] Prepared closed-cell Mg foams using SiO_2-coated $CaCO_3$ as blowing agent in atmosphere. In melt foaming method, the thermal stability and foaming speed of blowing agent significantly affect the pore structure, pore size and porosity of metal foams. To retard the foaming speed and increase thermal stability, $Na_2O \cdot nSiO_2$ and dilute hydrochloric acid were used to coat SiO_2 passive layer on the surface of $CaCO_3$ which is the blowing agent of Mg foams. L.E.G. Cambronero [14] used $CaCo_3$ as a blowing agent to prepare Al-Mg-Si alloy foam. The particle size of carbonate has more influence on the foam processing variables than its nature. Partial calcium carbonate decomposition allows foam development with a low degree of aluminum drainage and pore coarsening. Andrea Adamcikova and Jaroslav Kovacik [15] find effect of powder size and foaming agent on aluminum foam expansion it can be concluded that the main influence on foaming of powder mixtures has the size of used aluminum powder. Aleksandra V. Byakova et al. [16] investigated the role of foaming agent in structure and mechanical performance of Al based foams. Compared to the conventional titanium hydride (TiH_2), coated calcium carbonate ($CaCO_3$) offers significant advantages in mechanical performance of closed cell aluminum foams produced by Alporas like route due to finely cellular structure and remarkable improvement of the cell wall microstructure. Jaroslav Kovaeik et al. [17] compared aluminum and zinc foam, the consequence were towards Al foam at similar density and foams of equal porosity shows almost identical compression strength. Xingchuan Xia et al. [18] prepared close cell aluminum foam by melt foaming method with manganese variation. Mechanical properties of Mn containing foam possess better mechanical properties. So for increasing the mechanical strength researchers had used several methods and among them adding particles in molten stage of metal with thickening agent should be effective method. Mg is found to be one of the important alloying element of Al used for reducing the weight without costing strength. However direct addition of Mg particles is yet to be examined on aluminum foam compressive behavior hence Mg particles have been used as a reinforcing agent and different aluminum foam samples are prepared and examined. The prepared metal foams were then characterized for their physical and mechanical properties.

2. EXPERIMENTAL PROCEDURE

Materials and fabrication procedure

The raw materials to be used in the present research are pure aluminum ingots with 99.5% purity, calcium powder as **t**hickening or viscosity enhancing agent. Calcium carbonate is used as foaming or blowing agent and magnesium particles with 100 meshes were used as strength enhancing agent. Melt route method was used for preparation. The samples were prepared in pit furnace with stirring arrangements coupled to it. Pure Al was put in the graphite crucible and melted, afterward Ca (2 wt. % of Al) was added as viscosity enhancer and stirred for 2 minutes at 500 rpm. Mg particles (0, 0.5, 1.0wt. % of Al) were added after that and stirred for 2 minutes. For expansion of the mixture calcium carbonate (1 wt. % of Al) was added and again stirred for 2 minutes. Crucible is released from the furnace after holding it for few seconds.

Fig. 1: Expanded foam in the crucible.

Mechanical Characterization

Specimens for microstructure observation were cut for required size and finally ground using 2000 grit emery paper, polished using 0.25 lm diamond paste and then etched using 2% nitric acid alcohol. Microstructures of the aluminum foams and the distributions of the Mg elements were examined by a SEM, Jeol Jsm-6610lv. Uniaxial compression testing was performed on Heico Mechanical testing machine with cuboidal foam specimen's size of $25 \times 25 \times 60 mm^{3.}$ Machine was equipped with a 400kN load cell and pace rate of 0.2mm/sec was selected for the tests. The results were recorded in form of load-displacement curve through PC interface attached to the UTM. All stresses and strains used in this paper were deduced from the recorded load–displacement data.

3. RESULTS AND DISCUSSION

Compression Results

The size of the specimens were taken 25x25x60 mm^3 for testing. The Fig. shows the stress strain curve of pure Al foam. Closed-cell metal foams show a characteristic compressive stress-strain curve composing of three distinct regions; linear elastic, collapse and densification.

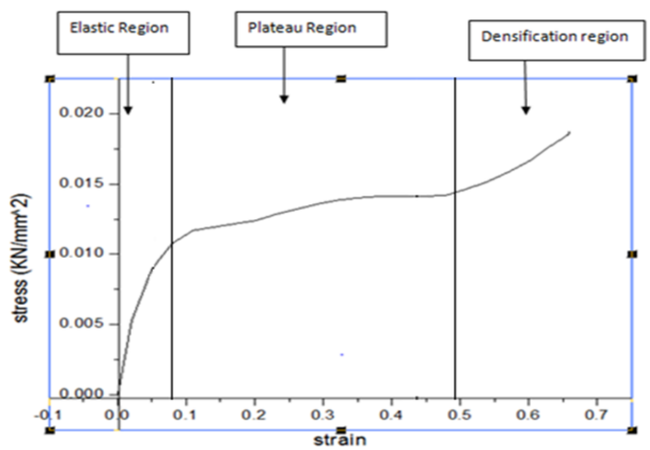

Fig. 2: Stress strain curve for pure aluminum foam.

The curve shows three regions elastic, plastic and densification. The first part of the curve is linear, here the strain is low. The next part is almost flat, here the strain increases at almost constant stress. The reason of stress being repetitive is the process of cell collapse. Here in this curve it can be clearly observed that plateau region is not constant the reason behind this is non homogeneous cell size. The last region shows the abrupt increase in stress. The maximum limit of all the region is relative density. The figures below shows the compressive stress strain curve for aluminum foam prepared by different percentage addition of Mg particles.

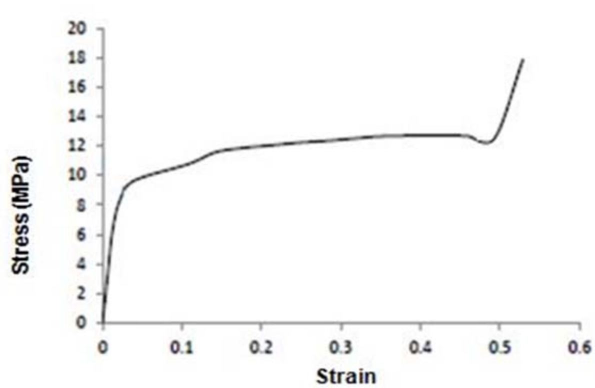

Fig. 3: Stress strain curve for 0.5 wt. % Mg containing Al foam.

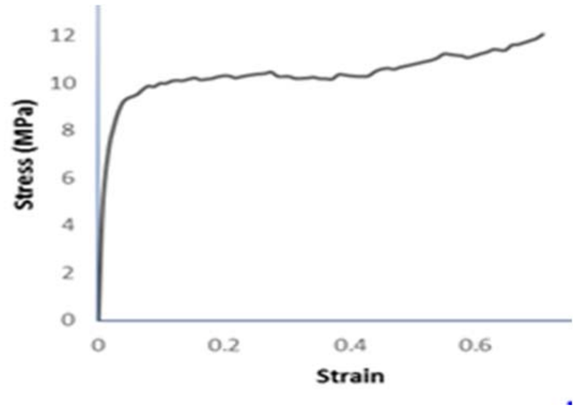

Fig. 4: Stress strain curve for 1.0 wt. % Mg containing Al foam.

The result obtained from the compression test are tabulated below:

Table 1: Density and Compressive strength of the foams.

Matrix	Mg %	Density (g/cm^3)	Foaming efficiency (%)	Compressive strength (MPa)
Al 99% Pure	0	0.61	77	11.73
	0.5	0.519	80	10.14
	1.0	0.42	84	9.45

From the table given above, it can be clearly observed that the pure Al have highest compressive value and goes on decreasing as the Mg percentage increases. But on the other hand looking over the densities, the density of foams also decreases as the addition of Mg take place. In such type case, these foams can only be distinguished by comparing strength to weight ratio.

Strength is a quantification of the samples ability to carry a load. In the case of foam F_{max} is the maximum load observed by the foam in compression before the end of plateau region. Calculating F_{max}/weight ratio, it has been found that the values Al:(Al +Mg 0.5%): (Al+Mg 1%) ratio is 1:1.32:1.36 respectively . So it can be concluded from the above result that compressive strength is measure of density. But the foam having highest strength to weight ratio will obtain the peer position among them.

4. ENERGY ABSORPTION

In most cases, metal foams are used in energy absorption fields. Energy absorption capacity per unit volume is an important aspect to evaluate the properties of metal foams. It is defined as the area under the stress-strain curve up to plateau stress region. The calculated values of energy absorbed for different foam samples are tabulated below:

Table 2: Energy absorbed by various foam samples

Matrix	Mg %	Density (g/cm^3)	Foaming efficiency (%)	Energy Absorbed (MJ/m^3)
Al 99% pure	0	0.61	77	5.114
	0.5	0.519	80	5.24
	1.0	0.42	84	7.165

Energy absorption depends upon two factors, first one is yield strength and the next is length of plateau region. Analyzing the graphs it is found that increase in Mg content shows the adverse effect on yield strength. But shows significant effect over the length of plateau region, which increase with the increase in Mg content. The values of compressive strength of different foams are in narrow region, so the length of plateau region will be the governing factor for energy absorption. Al+Mg1% foam shows the longest plateau region; which directs towards achieving maximum energy among the foams.

Micro Structure behavior of Al foams

Micro structure observation was done through digital images and SEM images. The average pore size of pure Al foam was found to be 1.6mm. It can be seen that the pore structure is homogeneous except for one or two relatively larger pores and the pores are isolated. In the Fig. 6(ii) cross-sectional image is shown. It is clearly observed from the Fig. that the pores are almost isolated instead of some places where the pores become larger due to coalescence of bubbles. Next image shows the distribution of Mg containing Al foam, here the distribution is found uniform throughout the wall.

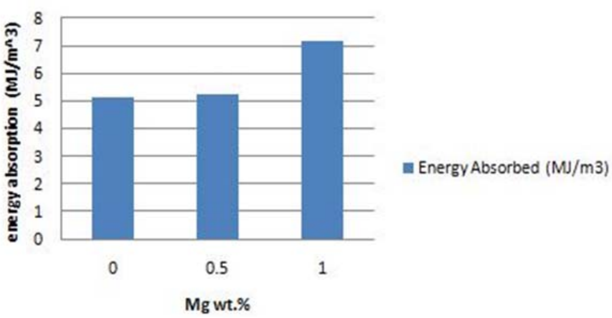

Fig. 5. Variation in absorbed energy by varying Mg content.

So after analyzing optical image, it is observed that pure Al foam produces the uniform structure. As increasing the percentage of Mg by 0.5 and 1%, there is the change in micro structural images. The Al+Mg 0.5% foam produces better structure with the uniformly distributed pore size. As the percentage of Mg increases, the size of the pores become smaller and the distribution of Mg content become uniform. But at 1% Mg addition cell walls also get corrugated. So, as increasing the more percentage of Mg can adversely affect the mechanical property.

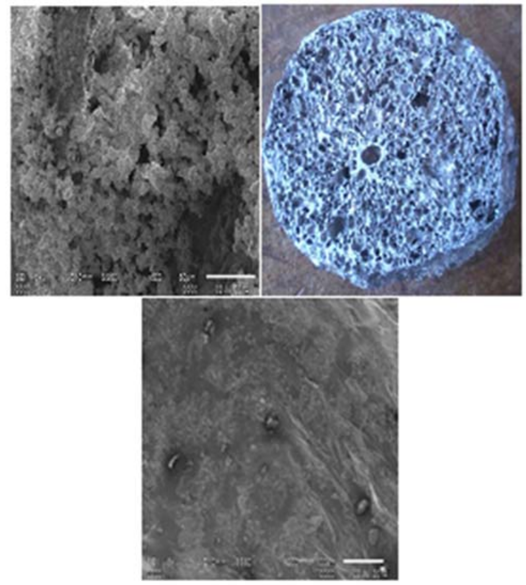

Fig. 6: (i) Optical image of pure Aluminum foam (ii) Cross section of 0.5% Mg containing Aluminum foam (iii) Distribution of Mg element in cell wall in 1%Mg containing Aluminum foam

5. CONCLUSION

Closed-cell aluminum foams with different Mg contents were fabricated by melt-foaming method using calcium as thickening agent and $CaCO_3$ as foaming agent. The result is summarized below:

1. The average pore size was found to be around 1.6 mm which is very fine. The distribution of Mg elements was uniform in the cell walls. The cross-section of the foamed metal showed that expect for one or two cells all other cells were homogeneous. The cells formed were of closed nature.
2. The compressive strength test showed that the yield strength of pure aluminum foam was maximum, but with the addition of Mg particles, compressive strength decrease as the density decreases. It was noted that there was no abrupt change in the strength. The value of compression strength depends on foam density. It has been found that the values F_{max}/weight ratio for Al:(Al +Mg 0.5%): (Al+Mg 1%) ratio is 1:1.32:1.36 respectively. So adding Mg particles helps in increasing the strength to weight ratio.
3. The Mg containing aluminum foams possessed higher energy absorption capacity than those commercially pure aluminum foams.
4. From the evaluation, it can be concluded that the increase in percentage of Mg particles aids in increasing compressive strength, plateau region and energy

absorption, on the other hand also provides better and uniform pores.

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