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Energy absorption capabilities of aluminium foam-filled square

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ABSTRACT

In this study compression behavior and energy absorption capacity of aluminium foam-filled square tubes under the divers strain rate in between 0.01 to 1/s at room temperature were studied. The foam-filled thin-wall square tube were made up of aluminium tube, aluminium tube as its shell and closed–cell LM 30 + 15% SiCp Al-alloy foam as its core. The result shows that the plateau region of the stress-strain graph exhibited marked fluctuant serration which is clearly related formation of the folds. The axial deformation mode of foam-filled square tube were the same as the empty sample tube, but the fold number of foam-filled sample tube were more than that of empty sample tubes. The axial compression load and specific energy absorption rate of foam-filled sample tubes were higher compared to the sum of the empty sample tubes and aluminium foam due to the contact between tube & foam-filled. When compare with empty aluminium tube samples to foam filled samples, energy absorption increases considerably. This work indicates the excellent ability of Al-alloy foam in application in which it is necessary to absorb compressed energy. Copyright © 2015 VBRI Press.

Keywords: Aluminium foam; foam-filled square; compression test; energy absorption capacity.

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Introduction

In the last 10 year, due to low relative density of metallic foam, high strength, good energy absorption capacity, high damping and electromagnetism shield properties **[1-3]**.Therefore an increasing attention in aluminium alloy foam in aerospace and automobile industries where light-weight, eco-friendly and improvement of safety are requisite. Most important things are that in metallic foam has excellent crash energy absorption and it can convert crash energy into deformation energy & absorb the maximum energy **[4-12]**. Increasing demands of safety and weight reduction in automobile industries and one of the importance application of aluminium foam is as filling material to increase the stiffness of hollow structure. Therefore already substantiation that mild steel tube with aluminium foam. Several studied were carried out in characteristics of aluminium foam, such as the compression behavior, energy absorption and their relationship of relative foam density & pore size, but less effort was made up mild steel foam-filled tubes. The compression behavior of thin-wall metallic tubes subjected to axial load has been studied for many years ago. Such types of tubes have been known as good energy absorption, because of their progressive axial folding **[13-19]**. Recently we have seen that an increasing interest in using aluminium foams as inside the thin-wall aluminium tubes for maximum specific energy absorption rate.

Aluminium foam properties

Aluminium alloy melt can be foamed by mixing thickening and foaming agent. SiCp is used as thickening agent and metal hydride is used as foaming agent. Metal hydride releases hydrogen gas when added in liquid metal. Large volume of hydrogen gas is released, which creates bubbles that lead to foam structure. When foaming is complete, the foam structure is cooled by compressed air. In this experiment we have taken LM 30+15% SiCp foam and foam sample is cut using a slow speed cutter, cold mounted and polished metallographically using standard polishing technique. The pore structure was scanned using a scanner shows shown in **Fig. 1**(**A**) and (**B**) the pore size distribution using Material Pro software around 75% pores are in the size range of 0.5-1.5 mm respectively. The advantage of foam becomes observable, when energy absorption capacities are measured as a utility of weight in lightweight constructions and comparatively high stiffness &low relative density. It is essential to note that if only direct strength is measured, foams often have a comparable than solid material of the similar weight **[11-17]**. The mass delivery of cellular structures increases at the whole moment of inertia of the foam, giving a far higher specific stiffness and strength than for the corresponding weight of vastness metal.

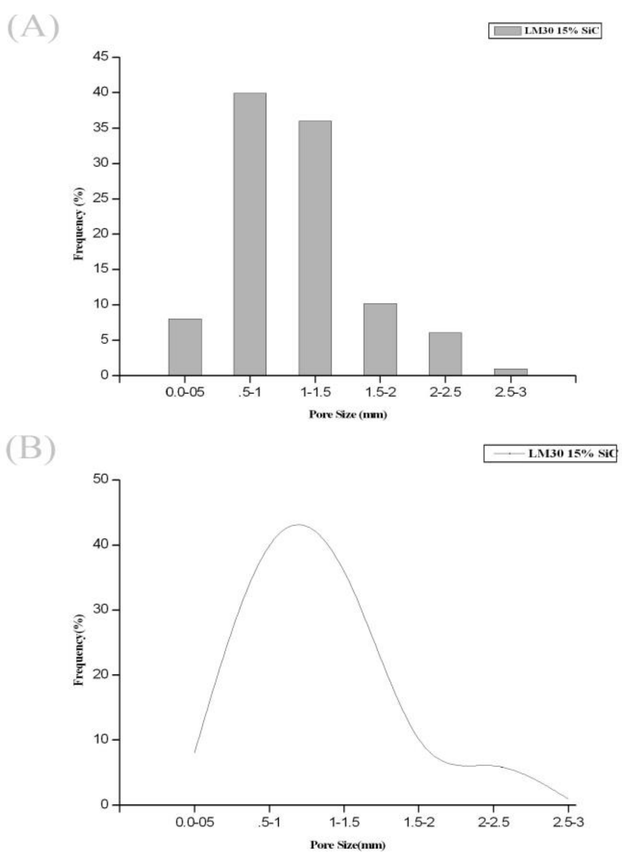

Fig. 1. (A) And (B) percentage frequency distribution of cells v/s size of cells of LM 30+15% SiCp foam.

Mechanical properties

Various literature studies have been undertaken on the mechanical properties of LM 30+15% SiCp foams. A wide review of the understanding of the mechanical behavior of a wide range of cellular solids is provided **[1-7]**; others have carried out test to study the behavior of metallic foams under diverse loading conditions, particularly the properties of LM 30+15% SiCp foams under impact loading. The chance of controlling the stress-strain behavior by a proper selection of cellular geometry, matrix material and relative density make foam a supreme material for energy absorbing structure. Along with the some mechanical testing methods existing, compressive mechanical test is generally used to calculate the compressive behavior and energy absorbed of these foams **[8]**. The stress-strain curve of closed cell LM 30+15% SiCp foam shows either plastic or brittle fracture depending on foam manufacture and microstructure **[9]**. Al-alloy foam is regularly used as stuffing material in lightweight structures subject to crash load and aural insulation devices. The energy absorption aptitude of this foam can be well expected from the stress-strain compression behavior of the materials **[20-23]**.

In the present study the foam-filled thin-wall square tubes was made up with aluminium tube as its shell and closed cell LM 30+15% SiCp alloy foam as its core. The longitudinal compression behavior and energy absorption capacity under quasi-static pressing were studied. The energy absorption capacities of foam-filled section (LM 30 + 15% SiCp Al-alloy foam) are investigated for the first time using melt route method in CSIR-AMPRI, Bhopal.

Experimental

Materials properties

LM 30 Al-alloy (Manufacture NALCO, India) contains 4.56 wt% Cu, 0.57 wt% Mg, 0.67 wt% Fe and 0.4 wt% Mn, 16.05 wt% Si, and rest is aluminium. LM 30+15% SiCp foam samples were manufacture through the melt route patented method by CSIR-AMPRI Bhopal .The porosity of aluminium foam varied from 78% to 92% shows in **Fig. 2** and the cell sizes of aluminium foam varied from 0.5 to 3 mm .The aluminium foams with the dimension of 23x23x60 mm were prepared using a wire-cutting machine as the filling cores.

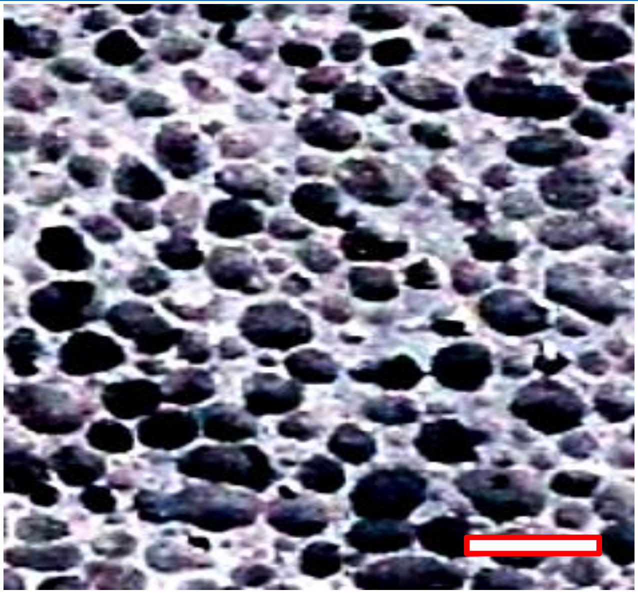

Fig. 2, Porosity varied from 78 to 92% of Al foam **[3]**.

To compare the influence of the height on the axial compression deformation properties, two different heights of 60 and 80 mm were chosen. Aluminium tubes with outer cross-section dimensions of 25x25x60 mm^3 and wall thickness of 0.80 mm were prepared as the shell materials. Aluminium foam cores and aluminium tubes were made up with an epoxy to get aluminium foam-filled square tubes. The data were the average value of six samples i.e. empty & foam-filled. The compression test of empty aluminium tubes and foam-filled tubes were performed on a universal testing machine (INSTRON-8801) at a loading speed from 0.01 to1 mm/min in an axial direction and all samples were prepared at RRL, Bhopal laboratory.

Compression test

The prepared foam samples were cut conforming to the size of the mild steel square section. The foam pieces were tightly fitted inside the empty aluminium square section and were tested for compressive behavior. Square foam filled section and aluminium empty section were performed on Universal test machine (Instron-8801) at various strain rates from 0.01, 0.10 and 1/s for the compressive test

Determination of energy absorption was carried out at the AMPRI, Laboratory for mechanical and physical properties testing. A universal test machine shows **Fig. 3** (**A**) and (**B**) during compression was used to determine energy absorption capability of aluminium foam, a compression test carried out an aluminium tube square section.

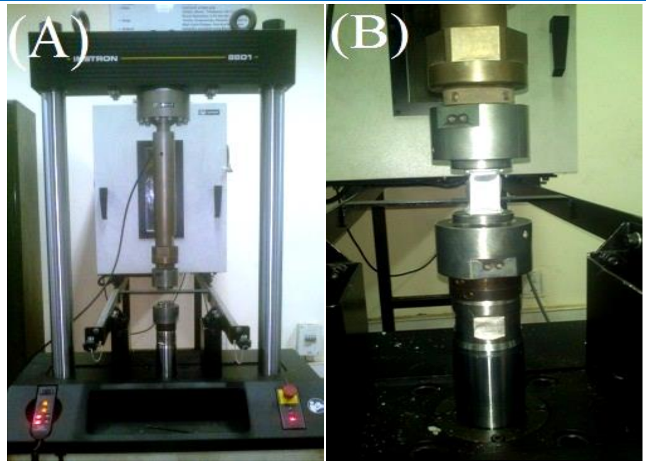

Fig. 3. (A) Universal test machine, (B) during compression test.

Results and discussion

Compression test result

Fig. 4 (**A**) and (**B**) - Aluminium tube empty sample prepared of cross-section 25x25 mm, wall thickness 0.8 mm and height 60 mm. The area of sample is 529 mm^2.While other aluminium sample filled with Al foam is prepared of 25x25 mm and height 60 mm. The area of Al foam filled sample is 625 mm^2. These three samples are compressed under strain rate of 0.01, 0.10 and 1/s; the stress-strain diagram of samples tested shown in **Fig**. **4** (**A**) and (**B**); sample 1, 2 and 3 respectively. The absorbed energy per unit volume is calculated by measuring the area under the stress-strain diagram. Empty aluminium tube sample absorbs energy up to 7.28 MJ/m^3 but Al foam filled tube sample absorbs energy up to 14.80 MJ/m^3. The absorbed energy of Al foam filled tube sample is improved by 49.10% under strain rate of 1. **Fig. 4** (**C**) and (**D**) - Aluminium tube empty sample prepared of cross-section 25x25 mm, wall thickness 0.8 mm and height 80 mm.

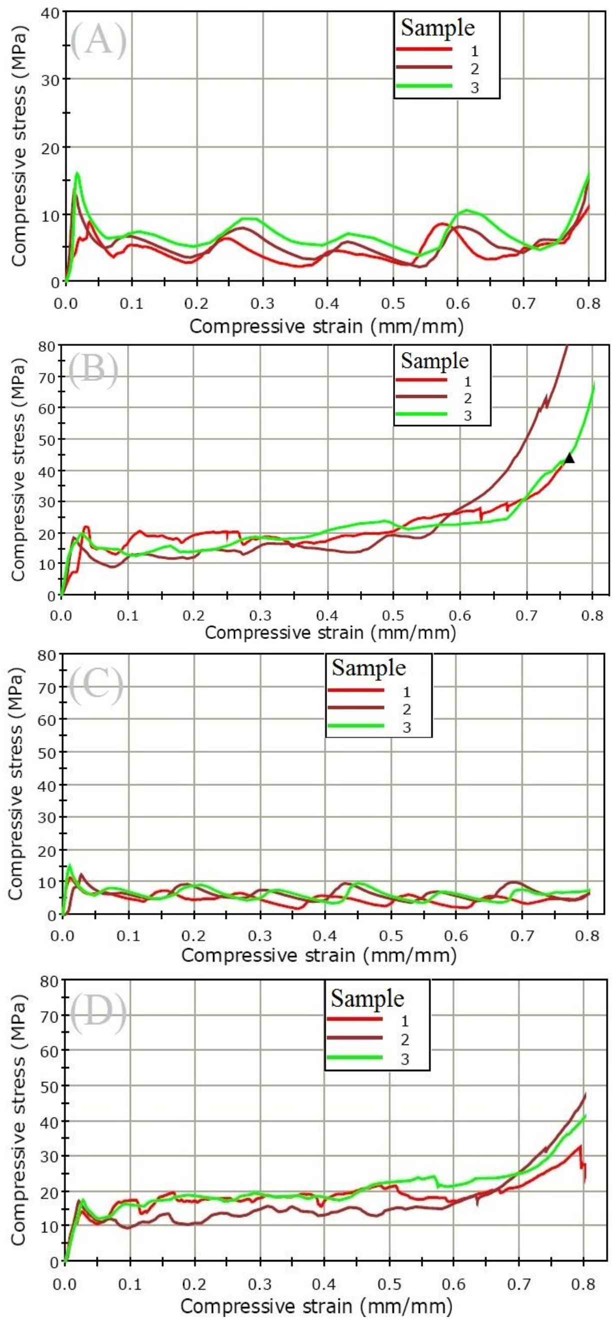

Fig. 4. Compressive stress and compressive strain relationship of (A) empty and (B) filled aluminium tube with height 60 mm; and (C) empty and (D) filled aluminium tube with height 80 mm, respectively.

The area of sample is 529 mm^2.While other aluminium sample filled with Al foam is prepared of 25x25 mm and height 80 mm. The area of Al foam filled sample is 625 mm^2. These three samples are compressed under strain rate of 0.01, 0.10 and 1/s; the stress-strain diagram of samples tested shown in **Fig**. **4** (**C**) and (**D**); sample 1, 2 and 3 respectively. The absorbed energy per unit volume is calculated by measuring the area under the stress-strain diagram. Empty aluminium tube sample absorbs energy up to 7.12 MJ/m^3 but Al foam filled tube sample absorbs energy up to 15.28 MJ/m^3. The absorbed energy of Al foam filled tube sample is improved by 46.59% under strain rate of 1.

Energy absorption

The Energy absorbing per unit volume of aluminium alloy (LM30+15%SiCp) composite foam filled sample and empty sample is calculated by measuring the area under the stress-strain diagram .The energy absorbed by aluminium foam filled sections is a function of fracture of cell wall and the energy released due to friction between cell wall. The energy absorbed per unit volume with foam sample and without foam sample is found diverse at various strain rates **[24-28]**. It is a well established fact that when a foam material is deformed it follows the process of band deformation. In an ideal the plateau stress in a stress-strain diagram is constant throughout the densification region .In this case it is observed that the plateau stress with strain is happened due to the strain hardening of the cell walls material in the deformation band .The straining of the wall material leads to the enhancement of the strain and thus increased in the plateau stress with strain **[29-31]**.

The energy absorbed per unit volume with foam filled and empty sample is found at different strain rates. The absorbed energy per unit volume in a certain strain interval, i.e. (ε_1, ε_2) is calculated by measuring the area under the stress-strain diagram. The area under the stress-strain diagram is calculated by plateau stress. The plateau stress in the stress-strain diagram is constant throughout the densification region, can be expressed as **[25]**.

$$E \text{ (absorbed energy)} = \int_{\varepsilon 1}^{\varepsilon 2} \sigma_{p1}(\varepsilon)\, d\varepsilon \quad (1)$$

Microstructure characterization

Microstructure analysis, aluminium alloy **[32-33]** foam samples is cut from top to bottom portion of the rectangular casting, prior to the micro-structure analysis, the sample are mechanically polished using standard metallographic practices **[5]**. The metallographically polished Al foamed sample are etched with Keller's reagent, sputtered with gold shown in **Fig. 5** (**A**) and (**B**). The micro-structure of foam samples is analyzed using Scanning Electron Microscope (SEM) (Model: Hitachi S-3400N, Japan).A typical SEM micrograph of aluminium alloy (LM30+15% SiCp) foam shown in **Fig**. **5** (**C**). It shows the pores (marked P) and cell wall (arrow marked) and higher magnification micrographs of the cell wall shown in **Fig. 5** (**D**). The thickness of the cell wall is measured to be around 100 µm. **Fig. 5** (**E**) shows a SEM micrograph the wall thickness measured to be around 500 µm and higher magnification micrograph of cell wall clearly shows SiCp.

Effect of strain rate and plateau stress

The plateau stress and energy absorption found to be almost invariant to different strain rate from 0.01, 0.10 and 1. The strain rate sensitivity calculated in these materials in the used domain.

Table 1 depicts the plateau stress with different strain rate; empty and filled sample with height of 60 mm and 80 mm. **Fig**. **6** (**A**) and (**B**); (**C**) and (**D**) shows the compressed sample empty and filled respectively.

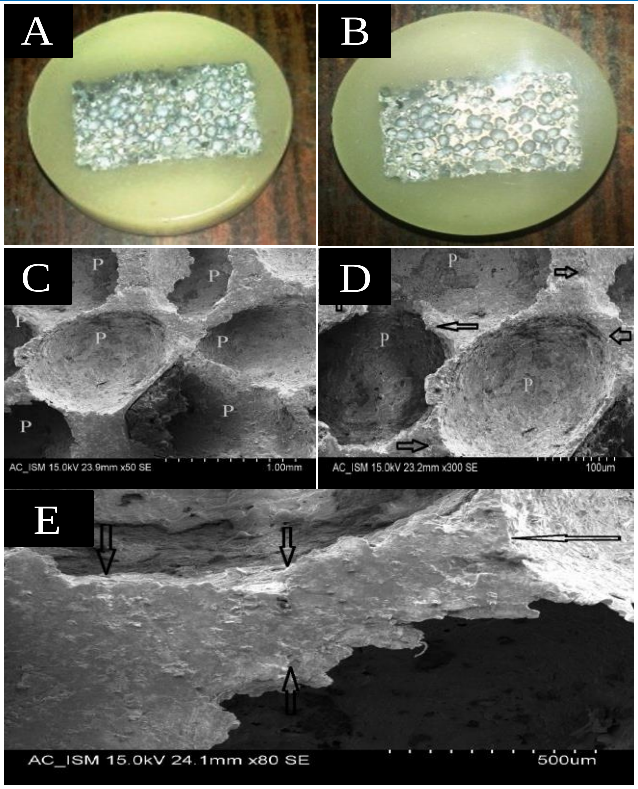

Fig. 5. (A) and (B) The metallographically polished Al foamed sample are etched with Keller's reagent, sputtered with gold, (C) SEM micrograph of aluminium alloy foam showing pores and (D) Higher magnification micrograph showing cell wall and (E) Higher magnification micrograph of the cell wall showing distribution of 15% SiCp in the aluminium alloy matrix **[1]**.

Table 1. It shows the plateau stress with different strain rate.

Sl. No	Strain rate/s	Plateau Stress(Mpa) Empty tube (H=60mm)	Filled tube (H=60mm)	Empty tube (H=80mm)	Filled tube (H=80mm)
1	0.01	5.67	14.20	5.10	14.20
2	0.10	7.10	17.20	8.20	16.80
3	1.00	9.10	18.50	8.90	19.10

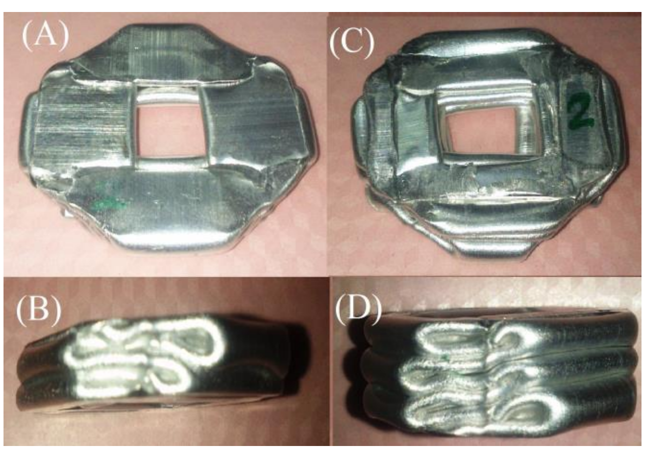

Fig. 6. (A), (B) and (C), (D) shows empty and filled aluminium tube sample with height 60 mm and 80 mm after compression test on UTM.

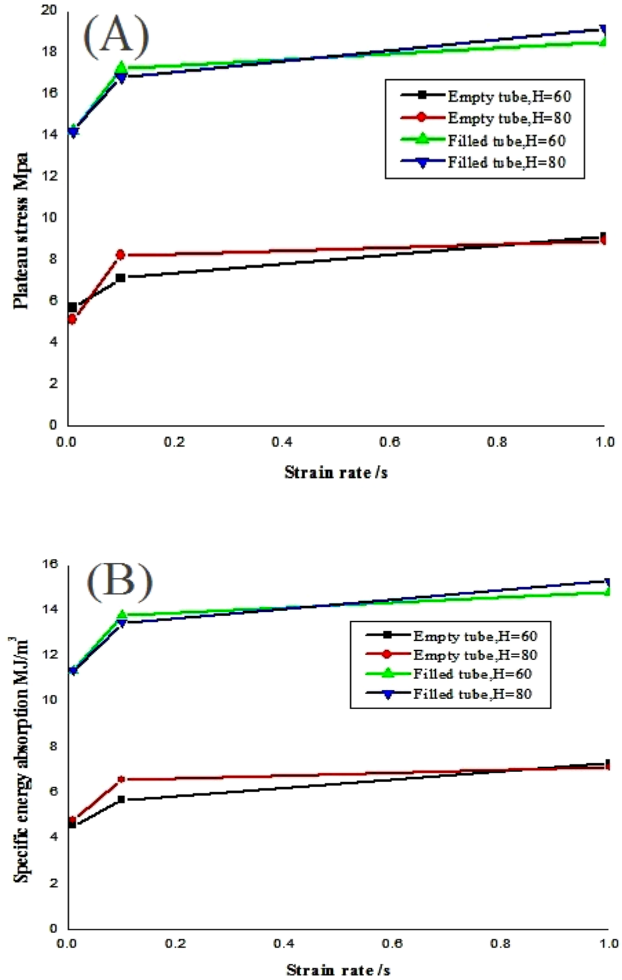

Fig. 7. (A) and (B) is shows the plateau stress and specific energy absorption after compression test.

Density measurement and sample dimension

The density of empty and filled sample is calculated by mass and volume measurements. **Table 2** depicts the samples dimension of empty and foam filled with height 60 mm and 80 mm. The density of the sample depends on the basic parameter such as mass and volume of the sample either empty or filled. Several studies have been carried out to understand the effect of mass and volume on density of the sample; calculated specific energy absorption shows the **Table 3**. **Fig**. **7** (**A**) depicts the plateau stress for empty and filled section with diverse strain rate whereas **Fig**. **7** (**B**) depicts specific energy absorption for both sample. Result revealed that both properties are higher in case of filled section.

Table 2. It shows the density and dimension of the sample.

Height (mm)	Empty sample Mass (g)	Volume (mm^3)	Density (g/cm^3)	Filled sample Mass (g)	Volume (mm^3)	Density (g/cm^3)
60	10.23	31740	0.322	--	--	--
80	14.31	42320	0.338	--	--	--
60	--	--	--	27.92	37500	0.744
60	--	--	--	26.59	37500	0.709
60	--	--	--	32.96	37500	0.878
80	--	--	--	42.91	50000	0.858
80	--	--	--	34.36	50000	0.687
80	--	--	--	41.57	50000	0.831

Table 3. It shows the specific energy absorption with different strain rate.

Sl. No	Strain rate/s	Specific energy absorption(MJ/m^3) Empty tube (H=60mm)	Filled tube (H=60mm)	Empty tube (H=80mm)	Filled tube (H=80mm)
1	0.01	4.53	11.36	4.80	11.36
2	0.10	5.68	13.76	6.56	13.44
3	1.00	7.28	14.80	7.12	15.28

Conclusion

In the present study, when compare with empty aluminium tube samples to foam filled samples, energy absorption rate increases considerably. Aluminium foam filled section used for maximum specific energy absorption rate. In summary,

- LM 30 Al alloy foam can be produced with the addition of 15% SiCp as a thickening agent and CaH_2 foaming agent by melt route.
- Compressive tests from strain rates 0.01 to 1/s have been conducted an empty aluminium tube and filled with LM 30+15% SiCp composite foam. The stress-strain curve for all the tested foam samples is similar. They all have four characteristics, an initial linear elastic region, yield point, plateau and densification region. The densification strain is almost invariant to the relative density, the strain rate and plateau stress depends highly upon the relative density of the Al alloy.
- Energy absorption of foam filled aluminium tube samples increasing with higher plateau stress in same sample. When compare with empty aluminium tube samples to foam filled samples, energy absorption increases considerably.
- A compression test revealed good properties at the crash energy absorption, and also it was observed that lower density foams can be absorb maximum energy. The application of aluminium foam filled structure would improve the energy absorption.

According to the present research the energy absorption in case of form filled square section has been extensively increases whereas further research with different sections has to be carried out in order to get exact behavior and strength of these foam filled section in extreme engineering applications.

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