

Energy absorption capacity of empty and foam filled mild steel tube under low strain rate at room temperature

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ABSTRACT

Aluminium foam is an isotropic porous metal of cellular structure in the order of 75-80 vol. % of the pores. In turn the novel mechanical, physical and chemical composition, properties depends on the density of foam, i.e. lies in between 0.4-2.4 g/cm³. Aluminium foam filled structures are used in collide, energy absorption, sound absorbing and vibration damping applications. In this article the compressive deformation behaviour of rectangular, square and round aluminium foam (LM 25 + 10wt% SiCp) filled and empty mild steel samples respectively are analyzed to identify the more energy absorption rate per unit volume in diverse strain rate by means of the compressive testing at room temperature. The experiments were performed on a universal testing machine the results showed that the round cross-section had more energy absorption than the rectangular and square cross section respectively. Also the amount of energy absorption will be greater with low foam density for round section tubes. We have seen that an increasing interest in using aluminium foams as inside the thin-wall mild steel tubes for maximum specific energy absorption rate. This work shows the admirable capability of aluminium alloy foam in applications in which it is essential to absorb compression energy. Copyright © 2015 VBRI Press.

Keywords: Aluminium foam; energy absorption; mild steel tube; compression test; SEM.



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Introduction

Aluminium foam is a cellular construction of a solid metal containing a large volume portion of gas-filled pores. The pores can be sealed (closed-cell foam) and it can form an interconnected network (open-cell foam) the defining feature of metal foams is a very high porosity making these ultra-light materials [1-4]. The unique properties of foams secure a variety of applications in automobile industries, transport, ships and potential energy absorption [5-9]. Aluminium foams with a high fraction of porosity which is a quickly emerging class of novel materials for a range of batch production [10-13]. The attributes of aluminium foams essentially lend themselves to special applications

requiring high stiffness-to-weight ratio and able crash energy absorption [14-17]. Foams are made of non-flammable metal, the lightweight material in combustible ecologically nontoxic and easy recycling. Lightweight aluminum foam filled with different sections, panels, crash energy dissipation and decrease passenger impact injury were explored [18-21]. In terms new strategies of crash energy absorption and new equipment have provided a safer traveling environment in this article found that aluminum foam filled different sections have outstanding performance in terms of compressive load [22-26]. In the last 40 years, several attempts have been made to create metallic foam structures their research was not quite successful due to high costs associated with it [27-32]. Further it was not possible to create metallic foam with reproducible properties. Problems occurred with low foam's ability of the mould metal the varying size of cellular structures [33]. Recently these issues have been solved by broad research that has shown the way to the development of new production technologies in this area. These new research foaming technologies allow the production of foam of a considerably higher quality [23]. In particular the foaming of aluminium alloy was successful. Foams are light weight energy absorbing structure and have incombustible properties. Other applications are also possible in engineering, household goods, building, and chemical industry. The aluminium foams are very expensive mostly it is not produced in a large scale. It is to be expected that aluminium foam products will find broad applications in the future [28].

Mechanical properties of aluminium foam

Aluminium alloy (LM 25) melt can be formed by mixing thickening and foaming agent. 10wt% SiC particle is used as thickening agent and metal hydride is used as foaming agent i.e. TiH₂. Metal hydride releases hydrogen gas when added in liquid metal. The 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 25 + 10wt% SiCp foam and foam sample is cut using a slow speed cutter, cold mounted and polished metallographically using standard polishing technique. 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.

A wide review of understanding of the mechanical behaviour of a large range of cellular solids is provided [1-4]. Others have carried out test to study the behaviour of metallic foams under diverse loading conditions, particularly the properties of Al-alloy foams under impact loading. The chance of controlling the load-displacement behaviour by a proper selection of cellular geometry matrix material and relative density makes foam a supreme material for energy absorbing structure. Along with the some mechanical testing methods existing compressive test is generally used to calculate the compressive behaviour and energy absorbed of these foams. The stress-strain curve of closed-cell, Al-alloy foam shows either plastic or brittle fracture depending on foam manufacture and microstructure [9]. Al-alloy foam is regularly used as filling material in lightweight structures subject to crash load. The

energy absorption aptitude of this foam can be well expected from the stress-strain compression behaviour of the materials [29]. Now we have seen that a rising attention in using Al foams as inside the thin-wall mild steel tubes for highest specific energy absorption.

In this study, consideration and suggestion towards energy efficient closed cell aluminium foam filled structure are made with the mechanical energy absorption characteristics. The foam-filled thin-wall were made of mild steel tube as its shell and closed cell Al-alloy (LM 25 + 10wt% SiCp) foam as its core. The compression behaviour and energy absorption capacity under quasi-static pressing were studied. The study shows that the energy absorption capacity of the foam-filled section is investigated for the first time using the melt route method.

Experimental

Material properties

LM 25 Al-alloy (Manufacture NALCO, India) contains 0.15 wt% Cu, 0.57 wt% Mg, 0.34 wt% Mn and 0.48 wt% Fe, 7.20 wt% Si, and rest is aluminium. The compression deformation behaviour of eighteen samples, i.e. rectangular, square and round aluminium foam filled mild steel (MS) and empty mild steel samples was studied in this work. Specification and density of empty and aluminium foam-filled rectangular, square and round mild steel samples were depicted in **Table 1**.

Table 1. Specification and density of Al foam-filled and empty MS rectangular, square and round mild steel samples.

Parameters	Height (mm)	Mass (g)	Width (mm)	Wall Thickness (mm)	Cross Section Area (mm ²)	Volume (mm ³)	Density (g/cm ³)
Foam-filled Rectangular	32	35	24.80	24.40	605.12	19363.84	1.81
Empty MS Rectangular	32	26	24.80	24.40	605.12	19363.84	1.34
Foam-filled Square	32	34.5	23.60	1.50	556.96	17822.72	1.93
Empty MS Square	32	25	23.60	1.50	556.96	17822.72	1.40
Foam-filled Round	32	15.5	21.80	0.60	373.25	11944	1.30
Empty MS Round	32	8	21.80	0.60	373.25	11944	0.67

Table 2, 3 and **4** shows the various strain rates, plateau stress, absolute energy and specific energy absorption of foam-filled and empty MS rectangular, square and round sample, respectively.

Compression test

Foam sample prepared using the melt route process of CSIR-AMPRI Bhopal .The foam sample was cut conforming to the size of the mild steel rectangular, square and round section .The foam piece was tightly fitted inside the empty mild steel rectangular, square and round section [29-33] and were tested for compressive behaviour. Rectangular, square and round foam filled section and mild steel empty section were performed on a Universal test machine (Instron-8801) at a diverse strain rate from 10⁻³/s to 1/s for the compressive test. Empty and filled with aluminium foam, rectangular, square and round mild steel sample all specification and density depicted in Table 1. Determination of energy absorption was carried out at the

AMPRI, Laboratory for mechanical and physical properties testing. A universal test machine shows **Fig. 1** was used to determine energy absorption capability of aluminium foam compression test carried out with mild steel different sections, i.e. rectangular, square and round at room temperature.

Table 2. Plateau stress, absolute energy and specific energy absorption of Al foam-filled and empty MS rectangular sample at various strain rates.

Sl. no.	Strain rate (s)	Plateau stress (MPa)		Strain	Area under curve (N/mm ²)		Absolute energy (J)		Specific energy absorption (J/g)		Specific energy absorption (MJ/m ³)	
		Filled	Without		Filled	Without	Filled	Without	Filled	Without	Filled	Without
01	0.001	32.00	24.00	0.80	25.60	19.20	495.71	371.78	14.16	14.30	25.60	19.20
02	0.010	32.25	24.50	0.80	25.80	19.60	499.59	379.53	14.27	14.60	25.80	19.60
03	0.100	34.00	25.00	0.80	27.20	20.00	526.61	387.28	15.04	14.89	27.20	20.00
04	1.000	35.00	25.50	0.80	28.00	20.40	542.19	395.02	15.49	15.19	28.00	20.40

Table 3. Plateau stress, absolute energy and specific energy absorption of Al foam-filled and empty MS square sample at various strain rates.

Sl. no.	Strain rate (s)	Plateau stress (MPa)		Strain	Area under curve (N/mm ²)		Absolute energy (J)		Specific energy absorption (J/g)		Specific energy absorption (MJ/m ³)	
		Filled	Without		Filled	Without	Filled	Without	Filled	Without	Filled	Without
01	0.001	31.50	23.25	0.80	25.20	18.60	449.13	331.50	13.02	13.26	25.20	18.60
02	0.010	31.75	23.75	0.80	25.40	19.00	452.61	338.63	13.12	13.54	25.40	19.00
03	0.100	33.25	24.20	0.80	26.60	19.40	474.08	345.76	13.74	13.83	26.60	19.40
04	1.000	34.25	25.00	0.80	27.40	20.00	488.34	356.45	14.15	14.25	27.40	20.00

Table 4. Plateau stress, absolute energy and specific energy absorption of Al foam-filled and empty MS round sample at various strain rates.

Sl. no.	Strain rate (s)	Plateau stress (MPa)		Strain	Area under curve (N/mm ²)		Absolute energy (J)		Specific energy absorption (J/g)		Specific energy absorption (MJ/m ³)	
		Filled	Without		Filled	Without	Filled	Without	Filled	Without	Filled	Without
01	0.001	14.00	05.00	0.80	11.20	04.00	133.77	47.78	08.63	05.97	11.20	04.00
02	0.010	14.50	05.31	0.80	11.60	04.25	138.55	50.76	08.94	06.35	11.60	04.25
03	0.100	15.50	05.63	0.80	12.40	04.50	148.10	53.75	09.55	06.72	12.40	04.50
04	1.000	16.00	06.25	0.80	12.80	05.00	152.88	59.72	09.86	07.46	12.80	05.00



Fig. 1. Universal test machine.

Pore size distribution

Fig. 2. (a) and (b) The pore size distribution using Material Pro software around 85% pores is 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.

Density measurement

The density of the empty and filled sample is calculated by volume and mass dimensions. Table 1, depicts the samples dimension of empty and foam filled with height 32 mm. The density of the samples depends on the fundamental parameter such as volume and mass of the sample either empty or filled. Some studies have been carried out to understand the effect of mass and volume on the density of the sample; calculated plateau stress, absolute energy, specific energy absorption shows the **Table 2, 3 and 4** respectively.

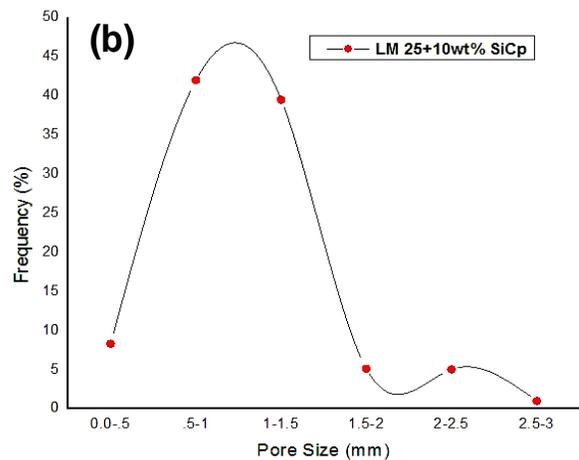
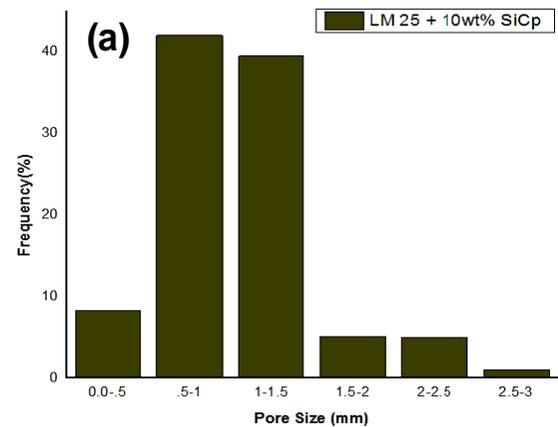


Fig. 2. (a) and (b) percentage frequency distribution of cells v/s size of cells of LM 25 + 10wt% SiCp foam.

Results and discussion

Energy absorption of aluminium alloy foam

Energy absorbing per unit volume of aluminium alloy (LM 25 + 10wt% 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 strain rates. 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. An illustrative example of a potential application of aluminium alloy foams is the protective compression energy absorber. Due to their ability for the keep stress while absorbing kinetic energy, foams are in general, outstanding energy absorbers are shown in Fig. 3.

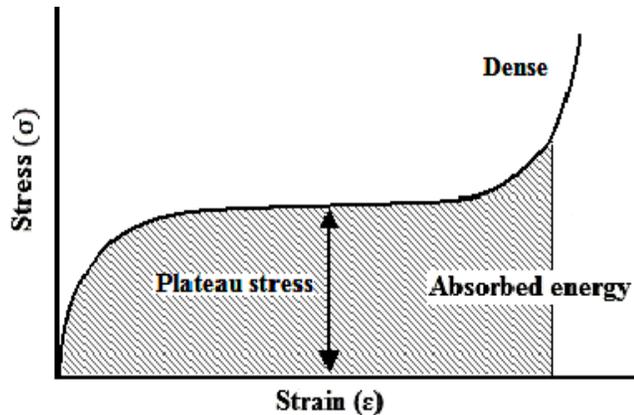


Fig. 3. Energy absorption by foam.

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 curve. The area under the stress-strain curve is calculated from plateau stress. The plateau stress in the stress-strain curve is constant throughout the densification region, can be expressed as [6]

$$E \text{ (absorbed energy)} = \int_{\epsilon_1}^{\epsilon_2} (\epsilon) \sigma_{pl} d\epsilon \quad (1)$$

Microstructure characterization of foam

Microstructure analysis, aluminium foam samples is cut from top to bottom portion of the rectangular casting, prior to the micro-structure analysis, the samples are polished using standard mechanical metallography practices [8, 11]. The micro-structure of foam samples is analyzed using Scanning Electron Microscope (SEM) (Supra 55, Carl Zeiss, Germany) at ISM Laboratory. A typical SEM micrograph of aluminium alloy (LM 25 + 10%SiCp) foam shown in Fig. 4 (a) and (b). It shows the pores (marked P) and cell wall. A higher magnification micrograph of the cell wall shown (arrow marked) in Fig. 4 (c). The thickness of the cell wall is measured to be around 85 X. Fig. 4 (d) shows a SEM micrograph the wall thickness measured to be around 143 X and higher magnification micrograph of cell wall clearly shows SiC particles (arrow marked).

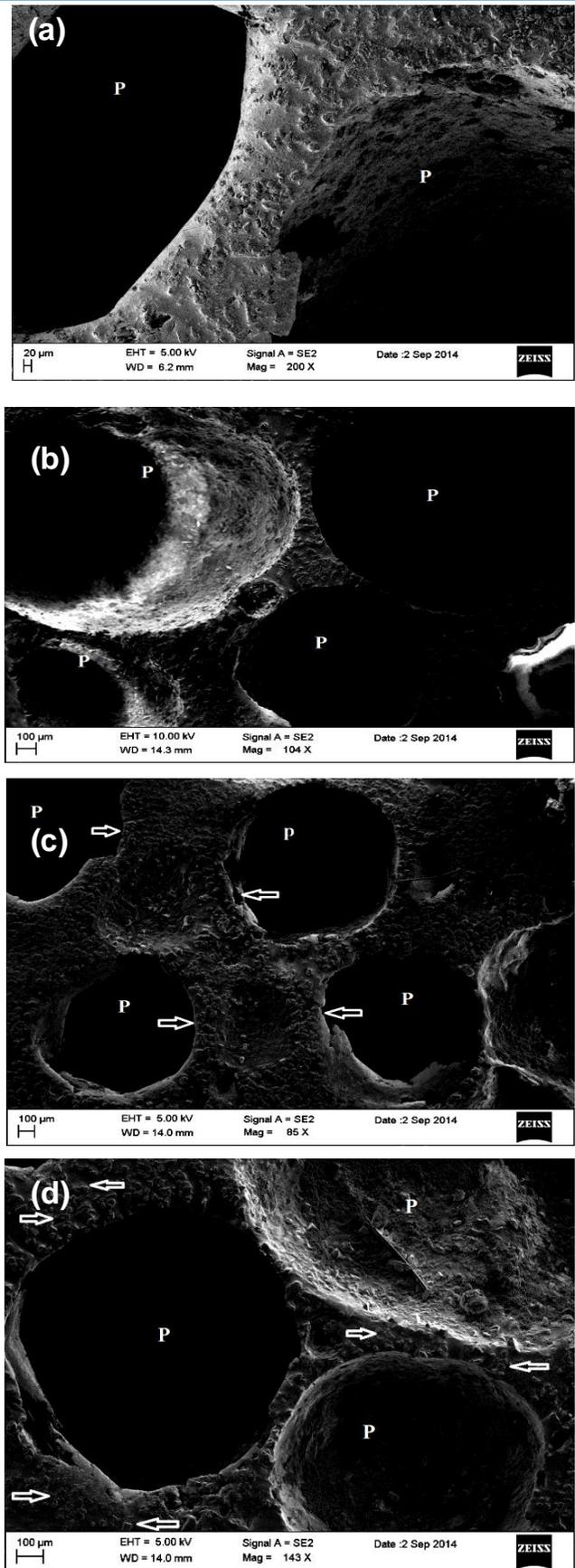


Fig. 4. (a) and (b) SEM micrograph of aluminium alloy foam showing cells (b) higher magnification micrograph showing cell wall (c) higher magnification micrograph of the cell wall showing distribution of SiC particle in the aluminium alloy (LM 25 + 10%SiCp).

Effects of strain rates on rectangular, square and round, filled with Al foam and empty MS samples respectively

Fig. 5 (a), it is observed that energy absorption increases with strain rate and the specific energy absorption of aluminium foam filled rectangular, square and round samples are more than rectangular, square and round mild steel empty samples. When the strain rate is increased from 0.001 to 1, energy absorption of aluminium foam filled sample increases from 25.60 MJ/m³ to 28.00 MJ/m³, 25.20 MJ/m³ to 27.40 MJ/m³ and 11.20 MJ/m³ to 12.80 MJ/m³, respectively. **Fig. 5 (b)**, the energy absorption of rectangular, square and round mild steel empty samples increased from 19.20 MJ/m³ to 20.40 MJ/m³, 18.60 MJ/m³ to 20.00 MJ/m³ and 4.00 MJ/m³ to 5.00 MJ/m³, respectively.

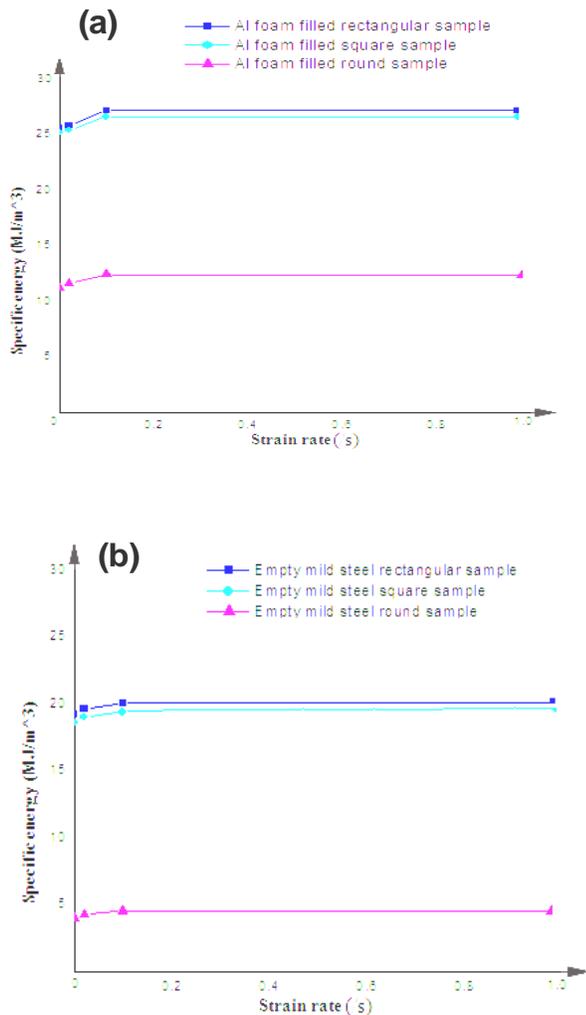


Fig. 5. (a) Specific energy absorption of foam filled mild steel sample at various strain rates and (b) Specific energy absorption of empty mild steel sample at various strain rates.

The energy absorption of aluminium foam filled round mild steel sample is increased as compared to rectangular and square foam filled sample (**Fig. 6**). The above results indicate that aluminium foam filled rounds; mild steel sample can be high energy absorption due to its shape. **Table 5** shows highest improvement in the plateau stress.

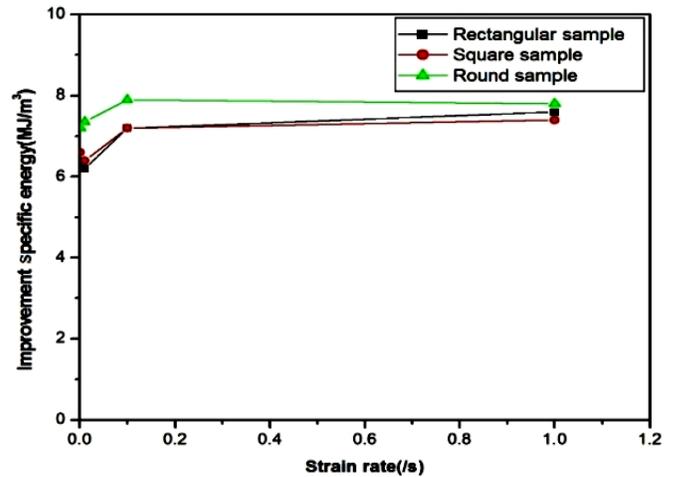


Fig. 6. Improvement specific energy absorption of foam filled mild steel sample at various strain rates.

Table 5. Improvements in the plateau stress of Al foam filled rectangular, square and round as compare to empty rectangular, square and round sample at various strain rates.

Strain rate (s)	Improvement in the specific energy absorption (MJ/m ³) (Rectangular sections)	Improvement in the specific energy absorption (MJ/m ³) (Square sections)	Improvement in the specific energy absorption (MJ/m ³) (Round sections)
0.001	6.40	6.60	7.20
0.010	6.20	6.40	7.35
0.100	7.20	7.20	7.90
1.000	7.60	7.40	7.80

Conclusion

In this study the summary of compression deformation behaviour of Al-alloy (LM 25 +10wt% SiCp) foam at diverse strain rate (10⁻³/s to 1/s) at room temperature and the calculated value of the experiment during compression test as,

- LM 25 Al-alloy foam can be produced with the addition of 10wt% SiCp as a thickening agent and CaH₂ foaming agent by melt route.
- The compressive stress-strain diagram shows three distinct regions; linear elastic region, plateau region and densification region. The energy absorption of foam filled mild steel samples increasing with higher plateau stress (σ_p) in same sample. When compare with empty mild steel samples to Al foam filled mild steel samples, energy absorption increases considerably.
- The cell wall thickness of LM 25 +10wt% SiCp Al-alloy foam is measured in the range of 85 X to 200 X and the presence of SiCp in the cell wall retards the cell wall drainage enabling increase in the cell wall thickness. It is also noted that the shape of the cell is largely controlled by the solidification behavior.
- 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 foam filled different section has been extensively increased, whereas further research with different geometry

has to be carried out in order to get accurate performance and strength of these foam filled segment in excessive engineering applications.

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