Evaluation of mild steel hollow and foam filled circular tubes under axial loading

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Abstract

AAF (Aluminium alloy foam) has turned out to be a beneficiary content in the automotive sector across the globe. It has been in applications due its light weight tendency and providing high strength and energy absorbing capacity. The content of paper marks a plot on the energy absorption capability of the AAF filled circular tubes. AlSi10Mg has been produced by the melt route method. Aluminium foam filled circular tubes, mild steel (MS) thin walled hollow tubes were tested under compression loading to note the energy absorption and deformation behavior. The compression was carried out with a strain rate of 0.1/s. FESEM tests was conducted to obtain the data at micro and macro levels. The test results portray that the foam filled circular tubes shows more energy absorption than the hollow (ERW) tubes at 0.1/s strain rate. Copyright © 2018 VBRI Press.

Keywords: Aluminium alloy foam, compression and strain rate, FESEM, macro and micro structures.

Introduction

Along the lifespan of so many years, several studies are carried out on energy absorption capabilities of cellular structural metal and alloys. AAF are extremely porous materials having property to absorb deformation energy. The novel combination of high energy absorption and light weight, signifies greater influence of Al-alloy foam in automotive sector. Al-alloy foam due to inimitable properties is been widely used in aerospace, construction and automotive field **[1-2].** To upgrade the energy absorption capabilities, foam filled thin-walled structures are considered nowadays. With respect to hollow thin walled structures, foam filled thin-walled structures can absorb more deformation energy with less weight **[3]**. Many of the researchers have invested their time in this stage of enhancing and upgrading the ideas of energy absorption in this field. Rajak **[4]** *et al*. studied the energy absorption behavior using Al-alloy foam at various strain rates and found filled thin walled structures better in energy absorption. According to their studies they found various deformation mode with regard to dimensions of tube and foam filling **[5]**. Ahmad et al. [6] studied deformation behaviour of conical tubes in their research work and found that energy absorption can be maximized by increasing wall thickness, increasing leap angle or increasing density of filler foam. There have been various finite element studies carried out for simulating complex phenomenon of deformation of thin-walled structures. From both, experimental and finite modelling of thin-walled structures, it is found that in case of hollow structures, energy is absorbed by deformation by folding patterns and then it is transferred to next part. This folding pattern is dependent upon height, wall thickness and geometry of the structure **[7-10]**. In hollow structures, due to low surface area available there is relatively less energy absorption. But in case of foam filled structures, the axial crushing force is absorbed by deformation of pores and thus greater availability of surface area. It is found that specific energy absorption is higher in case of foam filled tubes. Rajak et al. **[11]** studied and compared the results by experiments and FEM model. They also studied microstructure of the Al-alloy foam by SEM, XRD. From all the research work till now, it is found that foam filled structures are more energy absorbent. Al-alloy foams give extra-ordinary stress-strain curve under compressive stress. But in last five years, due to advancement in technology and better methods, manufacturers are finding better ways to produce better Al-foam and cheaper cost.

In this study of Al alloy foam (AlSi10Mg) is considered as inner matrix material and circular (ERW) mild steel tube is chosen to be outer element. AlSi10Mg is not widely used yet and there is still scope to more research on it, the thin-walled hollow tubes, foam filled tubes and only foam is put on to compression test to find energy absorption. The energy absorbing test efficiency is verified using the UTM that works on variable strain rates. Compression is performed on 0.1/s strain rate to obtain the results. The samples were well prepared and carefully handled during the entire testing procedure.6 specimen are taken into consideration out of which 3, 3 are divided as foam filled and only hollow tubes. Microscopic analysis of AlSi10 foam is done to find out pore size, wall thickness and other parameters. It is found that foam filled tube absorb more energy than other two sample types.

Experimental and methods

Sample preparations

Circular foam samples

Aluminium foam square sheet of 40mm thickness was procured. AlSi10Mg aluminium foam was processed in Germany by Havel metal foam. The foam was prepared by melt route process. Samples were cut into circular shape using the EDM (Electrical Discharge Machining) wire cut machine with utmost accuracy **[15].** 6 samples were cut on the machine. 3 samples of circular foam were left to be used with hollow tubes and the rest 3 for pure compression as shown in **Fig. 1**.

Fig. 1. 3 circular samples of 40mm were cut over EDM machine.

Circular MS tubes

The hollow tubes used in the experimentation are of mild steel. Mild steel is low-carbon low-alloy steel, having less than 0.25wt % of carbon. ERW hollow circular tubes were procured and then were cut into required dimensions using a slow speed cutter. The hollow tubes of thickness 1.2 mm are used in the study [16]. Six hollow tubes of length 40mm were cut down from the procured full length of pipe. Out of 6, 3 samples were filled with AlSi10 aluminium foam. The tubes were cleaned and checked for any corrosion to its outer and inner surfaces and thus can now be further used for the experimentation purpose. Cut samples are shown in **Fig. 2**.

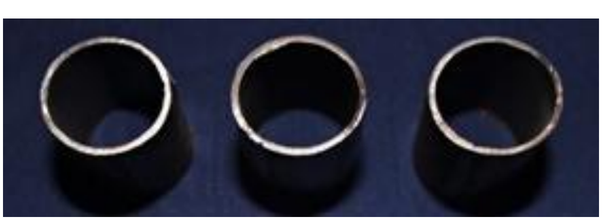

Fig. 2. 3 hollow tubes of 40mm height were cut using slow speed cutter.

Foam filled tubes

Addition of foam to the hollow tubes gives better energy absorption as compared to only foam or hollow tubes. Foam was cut in the accurate dimensions as that of the hollow tubes for perfect fit using an EDM wire cut machine. 3 samples were prepared of circular foam filled tubes with utmost care **[17-19]**. As shown in **Fig 3**. Finally, 9 samples were segregated as 3 being foam filled tubes, 3 being only foam and the rest 3 being hollow tubes without foam.

Fig. 3. Foam filled samples.

Macro and micro structure of foam

The foam is observed for its macro and microstructure under the standard test with the required outcomes. The wall thickness, pore distribution the accurate pore size and its effects on the foam, etc. are the firm properties of foam. The macro structural observations are basically done with superior resolution cameras and perfect lenses. For the better understanding of the details of the structure one must go for the microstructure observation and evaluation. Mounting of the specimen is an important step before the microstructural observation. It might be hot or cold mounted. The AlSi10Mg foam was hot mounted using backelite powder at about 180°C. The settling time is about 15-20 minutes. Once the specimen is ready they are grinded using 80, 120, 320 grit silicon carbide paper. Later for pure accuracy the specimens are polished using 600, 800, 1200 grit paper and also the mirror finish is obtained by using the velvet paper and diamond suspension. The polished specimen is then etched with Keller's reagent **[20]**. Once the final etching is processed the specimen is the placed under the optical microscope for further microstructural observations. FESM test (Field Emission Scanning Electron Microscope) is also carried out on the specimens for more accurate and fine results.

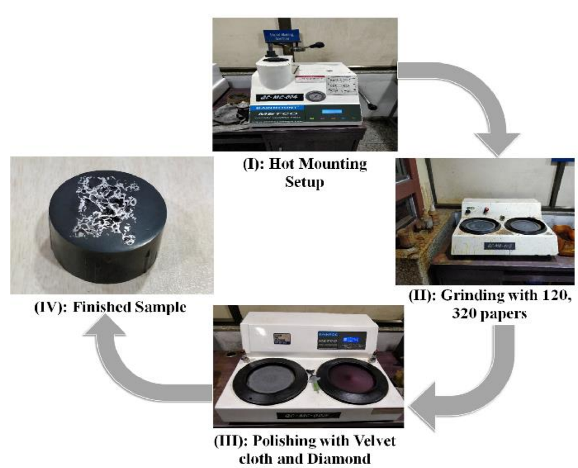

Fig. 4. Sample preparation by Hot mounting method.

Mathematical modelling

With the measurement of volume and mass of the specimens the densities of Aluminium foam, hollow tubes and the foam filled tubes can be estimated. For the following experimental investigation 6 samples were taken into consideration and were prepared. The density of hollow tubes varies from 7.07582 to 6.84606 g/cm^3, foam filled tubes from 1.8453 to 1.97925 g/cm^3. Average density of empty tube, foam filled tube and al-alloy foam is 6.37001, 1.58949 g/cm^3 **[21]**. The actual calculation of the densities is shown below in the **Table**.

Sample	Height (mm)	Mass (g)	Width (mm)	Thick-ness (mm)	Cross sectional area (mm^2)	Volume (mm^3)	Density (g/cm^3)
Al-alloy foam	39.98	13.57	23.14	-	420.718	16820.3	0.80676
	39.94	14.25	23.13	-	420.355	16789	0.84877
	39.96	14.42	23.12	-	419.991	16782.9	0.85921
Hollow thin walled MS tube	39.89	26.57	25.56	1.2	94.1349	3755.04	7.07582
	39.85	25.63	25.51	1.2	93.9463	3743.76	8.84606
	40.05	27.06	25.52	1.2	93.984	3764.06	7.18905
Foam filled tube	39.82	37.63	25.53	-	512.114	20392.4	1.8453
	40.06	39.15	25.56	-	513.318	20563.5	1.90386
	39.96	40.44	25.51	-	511.312	20432	1.97925

The AlSi10Mg alloy has composition as in the **Table 2**. Energy dispersive X-ray was performed to investigate the composition. **Fig. 5** shows the EDX analysis of the given sample at spectrum 1.

Table 1. Composition of AlSi10Mg Alloy.

Element	Aluminium	Copper	Iron	Magnesium
Percentage	balance	≤ 0.05	≤ 0.55	0.2-0.45
	Manganese	**Silicon**	**Titanium**	**Zinc**
	≤ 0.45	9.0-11.0	≤ 0.15	≤ 0.10

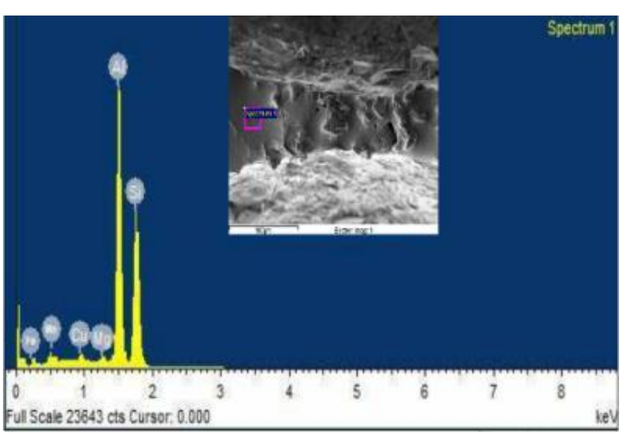

Fig. 5. EDX analysis of AlSi10Mg.

Compression test

The deformation behavior can be tested using the compressive stress on the prepared samples of circular mild steel hollow tubes, foam filled tubes and the foam samples alone for a strain rate of 0.1/s. While compression testing considers the ERW hollow sections pipes to be 96-97% pores and that the foam (AlSi10Mg) being pores around 80-85%. 3 samples of each of foam and foam filled tubes was taken into consideration and was tested for strain rate of 0.1/s at normal room temperature **[22]**. 3 samples were considered from each group to obtain perfect results with utmost accuracy. The compressive behavior is tested by servo hydraulic UTM Instron-8801. The UTM has capacity of 100 KN and as the gauge length is 40mm, the velocity of top plate was chosen to be 400 mm/s. The specimens are placed on the lower plate and the upper plate is used to apply the required load onto the specimen. The yield stress and plateau stress were quantified from obtained stress-strain diagram. The energy absorption and the deformation behavior of the used samples are obtained from the test results. Thus, the final outcomes are plotted over the stress strain graphs and the energy absorption behavior can be noted.

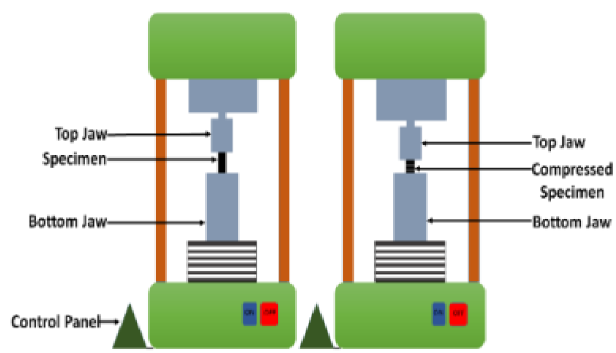

Fig. 6. Universal testing machine.

Results and discussion

Compression test results

The 3 samples of each group from empty, filled are tested with strain rate 0.1/s. The energy absorption per volume is calculated using area under the stress-strain curve **[23-24].** Energy absorption is function of plateau stress. The results are as in the **Table 3** below. It is observed that energy absorption per volume increases in the filled sample than empty samples.

Table 3. Energy absorption per unit volume for hollow and filled tubes.

Sr. No.	Strain rate (/s)	Hollow tubes (Plateau stress MPa)	Foam filled tubes (Plateau stress MPa)	Improvement in Plateau Stress (Plateau stress MPa)
1	0.1	9.8	21.5	12
2	0.1	10	21.2	11.2
3	0.1	9.7	21.4	11.3
	Average Value:	9.833	21.36	11.5

At strain rate of 0.1/s, the average energy absorption in hollow tubes is 9.833 MJ/m^3 and that in foam filled tubes is 21.36 MJ/m^3. There is improvement of 11.5MJ/m^3 (average) in case of foam filled tube. It can be concluded that foam filled tubes can be used as energy absorbers. There is increment in energy absorption per volume in case of filled tubes.

Macro and microscopic result

The most prominent factors upon which the microstructure analysis of the Aluminium foam depends upon the Pore size and the wall thickness. In the metal foam the pore size and the density of the pores varies due to which the estimation of the microstructure becomes complex. Both macro and micro structures are observed to gain a better understanding of the structure. Macro structure is analyzed by high resolution cameras as in Fig. 6 and the subsequent figure shows the pore distribution of the same. Macro structure helps to determine average pore density in a sample. Actual detailing will not be observed in the macro level analysis for better understanding the microstructure observations have to be made under the microscope.

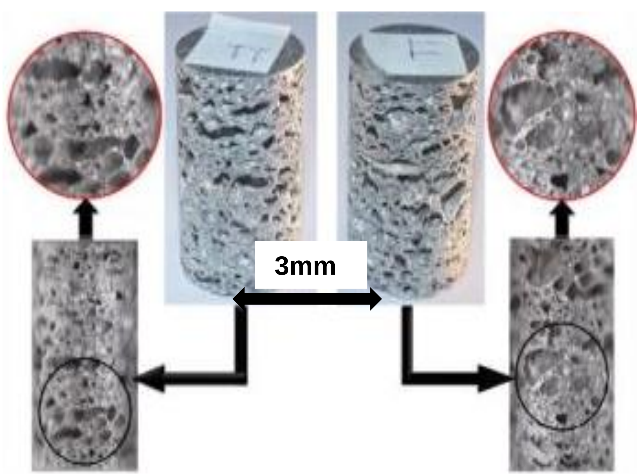

Fig. 7. Macrostructure observation.

Microscopic analysis defines itself as the detailed study under high resolution machines and setups. Hot mounted specimens are required for the observation. Initially the specimen is tested under the simple microscope and the following results are portrayed in the figure. The simple microscope works on principle of reflection of light. The detailing of the walls and the pore size can be observed in the figure. Even though the images provide a detail structure it does not reveal proper microstructure of the Aluminium foam. AlSi10Mg foam requires imaging at much higher magnification and accuracy. Field emission scanning electron microscopy (FESEM) is employed for fulfillment of the purpose. This test uses the electron instead of light **[25].** Electrons are released by field emission source. The samples used in the test are gold coated for better electron back scatter. Special care is taken before mounting specimen in microscope, moisture is being removed from all specimen to avoid any damage to the system. **Fig. 8(a)** shows the pores. A higher magnification micrograph shows the measured thickness of the pore wall to be around 100 µm (arrow marked). The silicon particle over the cell wall (circle marked) is shown in **Fig. 8(b). Fig. 8(c)** shows the SEM micrograph of the cell wall thickness which is measured to be around 30 µm.

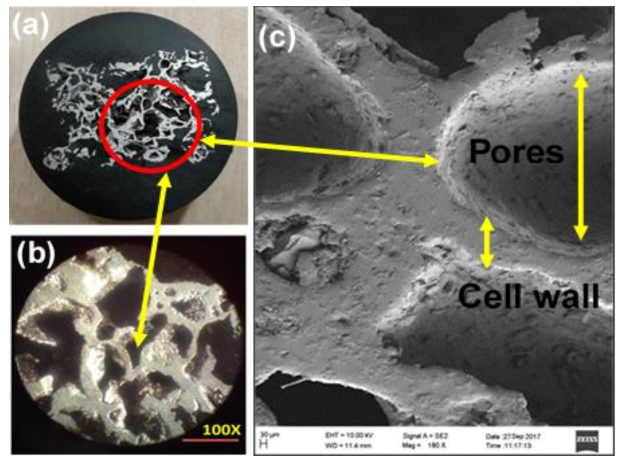

Fig. 8. **(a), (b), (c)** Microstructure analysis using FESEM.

Conclusions

In the recent study when empty MS tubes were compared to the Aluminium foam filled tubes, energy absorption rate had gradually increased. The foam filled tubes were used for maximum specific energy absorption rate as an when required by the application.

- The foam filled mild steel circular tube has more energy absorption capacity as compared to the empty mild steel tubes.
- Aluminium foam filled mild steel tubes have been tested in compression and their energy absorbing behavior has been examined.
- Energy absorption of the mild steel foam filled tube increases with higher stress in the sample that are been tested while compared with empty mild steel tubes considerably.
- High strain rate of deformation was also observed in the following test procedures.
- Energy absorption in hollow tubes is 9.833 MJ/m^3 and that in foam filled tubes is 21.36 MJ/m^3.
- The improvement in the compressive strength and the energy absorption capacity is due to the microstructure of the foam and the gradual increasing strength of the cell wall thickness.

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