



# Software Simulation for Mechanical Properties of Aluminium MMC Foam

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**Abstract:** Aluminium foams, which may replace all the energy absorbing materials in near future, are produced by melting Aluminium alloy (LM6) containing blowing agent(s) and with continuous stirring of the melt.  $TiH_2$  is a known blowing agent for this. As  $TiH_2$  begins to decompose into Ti and gaseous  $H_2$  when heated above about 738K (465°C), large volumes of hydrogen gas are rapidly produced, creating bubbles that leads to manufacture of closed cell foam. Cellular materials like this produced foams has to be machined into pieces with desired shape for further investigation. In order to define the Compressive and impact properties of this material, LS-DYNA modeling and crashing simulation, which uniquely defines the mechanical behavior of this modified Al-MMC foam has been discussed in details.

**Keywords:** Al-Si MMC Foam, LS DYNA, Simulations, Dual Foaming Agent

## 1. Introduction

Metal foam is a type of cellular solids, having a combination of properties such as high stiffness with very low density and a capability to absorb impact energy. These unique combinations of properties indicate various potential applications such as packaging materials for protection of sensitive devices, machinery enclosures, automobiles, and as sound absorbing material under difficult situations. Mechanical testing of aluminium foams is a prerequisite for any application. The study of compressive and impact properties of metallic foams is necessary as its major applications are primarily load-bearing and energy absorption. The compressive stress-strain diagram of metal foam as defined by Gibson and Ashby [1] consists of three distinct regions namely linear elastic region, collapse region and densification region. Fig. 1 shows a representative stress – strain curve of metal foam under compressive loading. The first zone (linear elastic zone) is recorded up-to small strain (about 2-3%). The second zone i.e. plateau region, continues up to about 70% of strain, characterized by a small slope of the stress-strain curve. In some cases the curve is even horizontal. In second zone collapsing of cell continues till the

foam behaves like a solid material. The third zone (densification zone) shows a rapidly increasing stress, here the cell walls become pressed together and the material attains bulk-like properties.

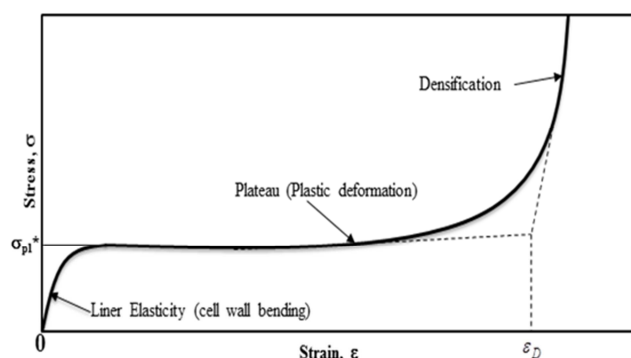


Figure 1. Stress strain curve for metal foams [1].

The main aim of the present investigation is to determine the compressive characteristics of the closed cell Aluminium Metal Matrix Composite (Al-MMC) foams developed in the laboratory [16]. The outcomes of the experimental investigation are compared with LS-DYNA

models so that it can be further referred for different industrial applications.

## 2. Synthesis of Al-MMC Foam

The material under investigation is closed cell aluminium foam, manufactured through liquid metallurgy route in the Foundry Laboratory of Jadavpur University, Kolkata, using aluminium alloy (LM6: consisting of 0.1% Cu, 0.1% Mg, 0.13% Si, 0.6% Fe, 0.5% Mn, and trace amount of Zn, Pb, Sn and rest Al). The aluminium alloy used is of density ( $\rho_s$ ), 2.7gm/cm<sup>3</sup>, having compressive elastic modulus ( $E_s$ ) of 69 GPa and compressive yield strength ( $\sigma_s$ ) of 120 MPa. The ingot is melt in a tilting resistance furnace. The formation of foam requires a high melt viscosity which is achieved by the addition of Silicon Carbide (SiC) particulate to the melt. The amount of Aluminium is 1000 gm. 5% SiC (pre-heated) are added to the melt, which also increases the mechanical strength of the foamed component. For homogeneous mixture of SiC in Al matrix, continuous stirring is required. The achieved high viscosity allows liquid Aluminium to be stable at a temperature of TiH<sub>2</sub>-decomposition (465°C) which is much lower than the freezing temperature of liquid Aluminium [17].

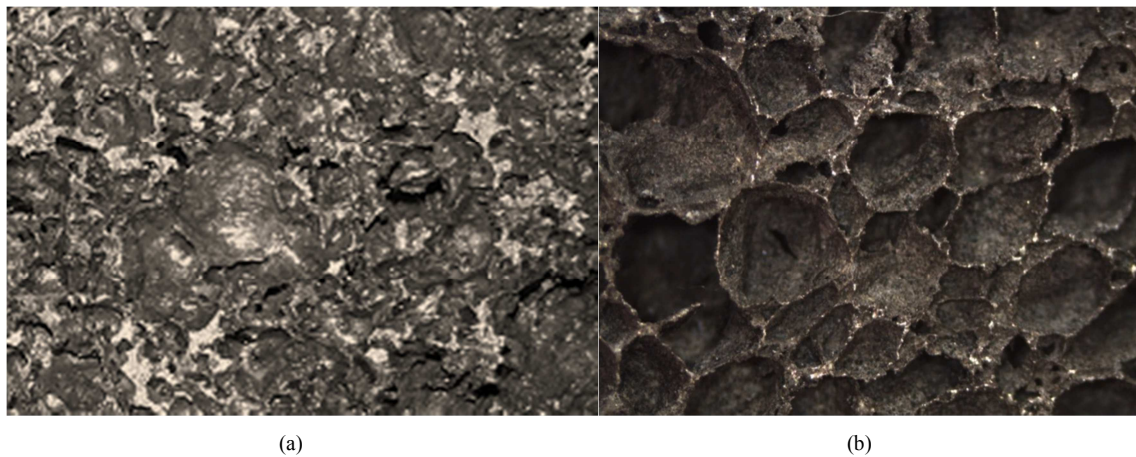
The homogeneous Al-SiC mixture is then poured into a pre heated mold (which is fitted with a stirring arrangement) after removal of slag as much possible. 2.5% blowing agent (Titanium Hydride) is added to the mold. TiH<sub>2</sub> begins to decompose into Ti and gaseous H<sub>2</sub> when heated above about 465°C. By adding titanium hydride particles to the aluminum melt, large volumes of hydrogen gas are rapidly produced, creating bubbles that leads to a closed cell foam. It is needed to stir the mold with constant speed for good foaming.

As TiH<sub>2</sub> is a very costly material, so, manufacturing of Al-SiC foam by this method is not so cost effective. The solution to this problem is Calcium Carbonate (which is very cheap in cost). So, instead of adding 2.5% TiH<sub>2</sub>, a dual foaming agent (2% CaCO<sub>3</sub> and 0.5% – 1.0% TiH<sub>2</sub>) is added separately and this produces same result with minimum cost. Addition of Ca in Al matrix slightly changes the mechanical properties but it is nearly identical.

The properties of metal foams depend on many morphological features, such as pore size distribution, cell wall curvature, defects, etc. [3]. Although the exact interrelationship between properties and structure is not yet sufficiently known, one usually assumes that a uniform distribution of convex pores free of defects is highly desirable. The task for the experimentalist is to produce such structures. A short look at existing foams shows that there is still much potential for development since these often tend to be irregular [4].

Thus, the foams fabricated by this method are usually non-uniform which leads to inferior mechanical properties. The reason for this can be non-adoption of TiH<sub>2</sub> to the melting range of the alloy to be foamed. This is avoided by pre treatment of titanium hydride (TiH<sub>2</sub>) in the form of 10-15  $\mu$ m diameter particles by selective oxidation [16].

Pre-treatments of the TiH<sub>2</sub> powder were carried out isothermally at various temperatures (450, 480, 510°C) and times (30, 60, 120 and 180 min) under air in a chamber furnace. For heating, the ceramic crucible (with required amount of TiH<sub>2</sub>) is placed into a volume chamber muffle furnace and is left there for the time specified. After pre-treatment all powders were gently homogenized by tumbling in a container.



**Figure 2.** Sample section: (a) using untreated TiH<sub>2</sub>, (b) using Pre treated (480°C, 60 mins) TiH<sub>2</sub>.

Hydrogen starts to be released from TiH<sub>2</sub> at about 405 – 470°C with some variations between powders of different origin. However, most of TiH<sub>2</sub> powder starts decomposing at 465°C.

As heating is carried out under air, an oxide layer grows which is roughly 100 nm thick after 180 min at 480°C and contains an outer shell of TiO<sub>2</sub> and an inner shell of Ti<sub>3</sub>O. Pre-treatment under air also reduces the amount of hydrogen

and shifts the temperature of decomposition by 160°C. Using pre-treated TiH<sub>2</sub> for foaming Al alloys delays foaming and leads to a more uniform distribution of rounder pores. The best parameters found are close to 60 min at 480°C. It is noted that at higher pre-treating temperature (510°C), the amount of available hydrogen is not sufficient to produce uniform foam (Fig. 2).

### 3. Simulating with LS-DYNA

LS-DYNA is an advanced general-purpose multi-physics simulation software package developed by the Livermore Software Technology Corporation (LSTC). While the package continues to contain more and more possibilities for the calculation of many complex, real world problems, its origins and core-competency lie in highly nonlinear transient dynamic finite element analysis (FEA) using explicit time integration. LS-DYNA is being used by the automobile, aerospace, construction, military, manufacturing, and bioengineering industries.

LS-DYNA consists of a single executable file and is entirely command line driven. Therefore all that is required to run LS-DYNA is a command shell, the executable, an input file, and enough free disk space to run the calculation.

**Material Library:** LS-DYNA's material library includes Metals, Plastics, Glass, Foams, Fabrics, Elastomers, Honeycombs, Concrete & soils, Viscous fluids and also User-defined materials.

**Element Library:** LS-DYNA's element library includes Beams (standard, trusses, discrete, cables, and welds) (with over 10 beam element formulations), Discrete Elements (springs and dampers), Lumped inertias, Lumped masses, Accelerometers, Sensors, Seatbelts, Pretensioners, Retractors, Sliprings, Shells (3, 4, 6, and 8-node including 3D shells, membranes, 2D plane stress, plane strain, and axisymmetric solids) (with over 25 shell element formulations), Solids (4 and 10-node tetrahedrons, 6-node pentahedrons, and 8-node hexahedrons) (with over 20 solid element formulations), SPH Elements and Thick Shells (8-node).

**Contact Algorithms:** LS-DYNA's contact algorithms include Flexible body contact, Flexible body to rigid body contact, Rigid body to rigid body contact, Edge-to-edge contact, Eroding contact, Tied surfaces, CAD surfaces, Rigid walls and Draw beads.

#### 3.1. Why Is LS-DYNA Used for Present Work

LS-DYNA is the only software which is having 'foam' in its materials library. It also includes the Honeycomb and Modified Honeycomb. The unique characteristics of a metal foam (as Density before and after compression, Average Cell wall thickness, etc.) can be fed to the software. So, the required equations of the material behaviors to solve a given problem are not necessary to provide all the times. When the material is defined it can automatically recall the material properties equations to run the analysis. For this current work modified honeycomb material was needed, which is available only in this software and the required simulations (drop test and compression) on desired materials can also be done here. So, mainly for the ease of work and available working facility with required material (modified honeycomb), this software LS-DYNA is chosen.

**Required Inputs:** All input files are in simple ASCII format and thus can be prepared using any text editor. Input files can also be prepared with the aid of a graphical preprocessor such as Ansys, Pro-E, Catia etc. Though, LS-

DYNA has its own preprocessor named LS-Prepost. First of all a CAD model is produced. Then loading condition [the amount of force with directions, kind of force (concentrated or distributed, explosive or static), nodes (location) where the force is applied] is applied on the model. Input files are saved in .k or .iges file format and then fed to the LS-DYNA for analysis.

**Outputs:** After the analysis is done, the outputs are found in ASCII (glstat, matsum) format and also in .binout, XY Data etc. Stresses of each element in different directions, change of different energies (kinetic, sliding, internal, total etc.), strains, with respect to time can be achieved by the analysis.

#### 3.2. Simulations

The sample, which was fabricated using pre treated TiH<sub>2</sub> (480°C, 60 mins) experimentally found out as best in quality for energy absorption during compression. The measured properties of foam material is chosen as a 'test material' and steel is chosen as rigid material with density ( $\rho$ ) = 7850 Kg/m<sup>3</sup>, elastic modulus (E) = 200 GPa and poisson's ratio = .5. The values taken as input are given below in table 1.

#### 3.3. Impact Test Simulations

*Table 1. Material Properties used in LS-DYNA simulation.*

Properties	Unit	Closed Cell Aluminium Foam	Rigid Material (Steel)	Solid Aluminium
Density ( $\rho$ )	Kg/mm <sup>3</sup>	.54405x10 <sup>-6</sup>	7.85x10 <sup>-6</sup>	2.7x10 <sup>-6</sup>
Elastic Modulus (E)	KN/mm <sup>2</sup>	.115	200	70
Poisson's Ratio ( $\mu$ )	Nil	.32	.5	0.39

Two spheres of 25mm radius are modeled first. One of them (solid sphere) is modeled using the properties of solid aluminium (LM6) metal. The other one is made of modified honeycomb material (foam sphere). Properties of the foam, achieved from the experiments, are assigned for the foam sphere. The properties used as input is given above in table 1. The LS-DYNA set up is shown in figure 3.

The spheres are then set to impact on a (set as perfectly rigid) plate made of steel with same and constant velocity 10mm/sec. It has been seen that the solid sphere bounce back from the rigid plate after the collision and the foam sphere crashes. This LS-DYNA graphical is also given below in figure 4.

The rate of change of different energies with respect to time are found and plotted from the LS-DYNA software. Change of velocities with respect to time are also found and plotted by the software.

The rate of change of total kinetic energy of solid sphere is found out from figure 5. The rate of change of total kinetic energy of foam sphere is found out from figure 6. Figure 7 shows the Curve of Change of Total Internal Energy of solid sphere w. r. t. Time. Curve of Change of Total Internal Energy of Foam sphere w. r. t. Time is plotted in Figure 8. Figure 9 and 10 shows the Displacement of CG of Solid sphere and Foam sphere respectively with respect to time.

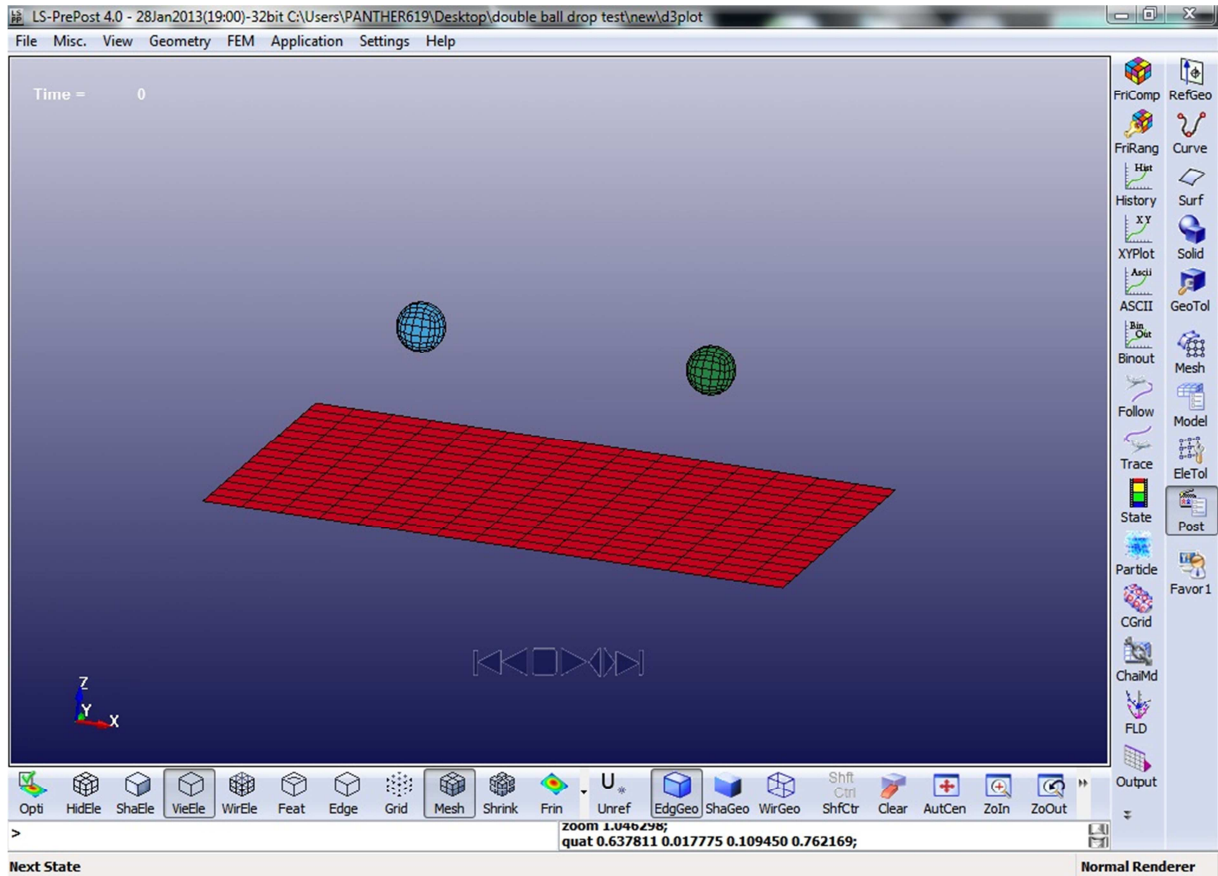


Figure 3. The set up of spheres and plate in LS-DYNA.

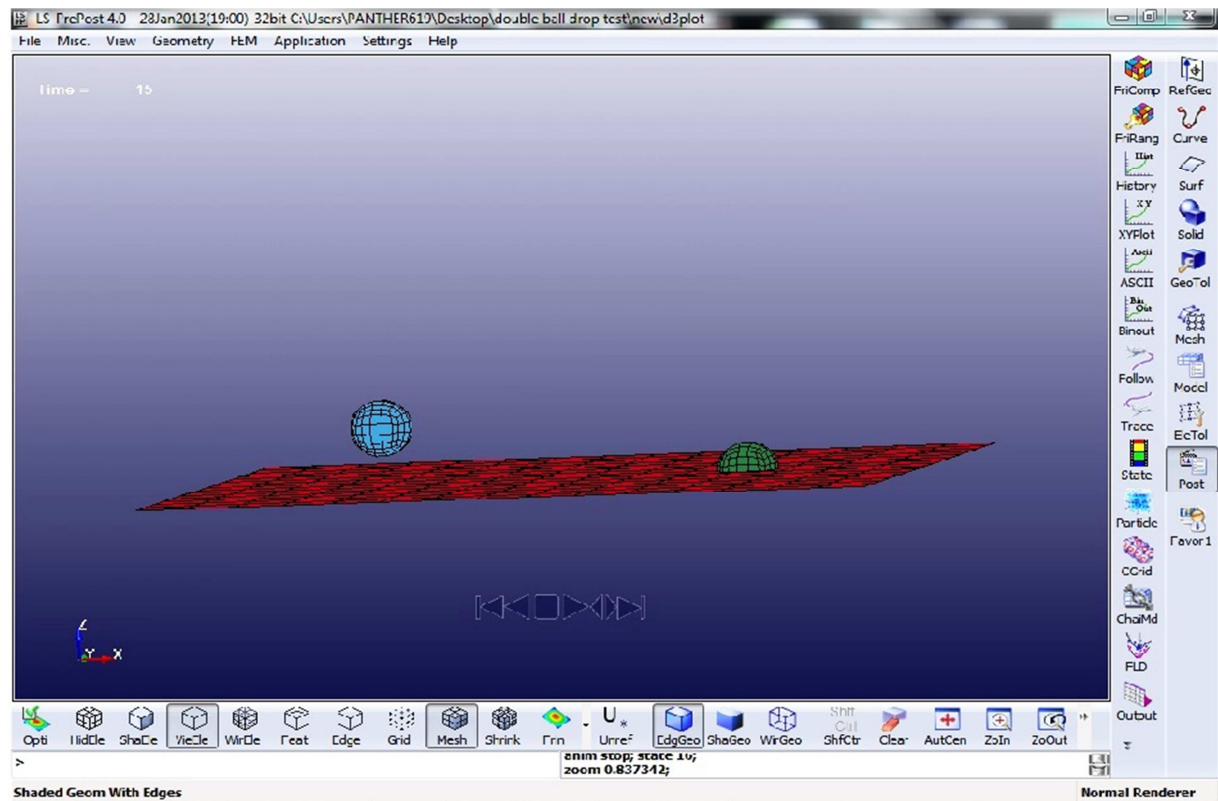


Figure 4. The state of spheres and plate at the end of collision in LS-DYNA.



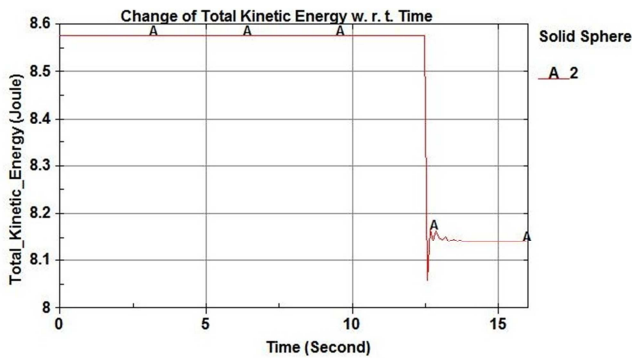


Figure 5. Curve of Change of Total Kinetic Energy of solid sphere w. r. t. Time.

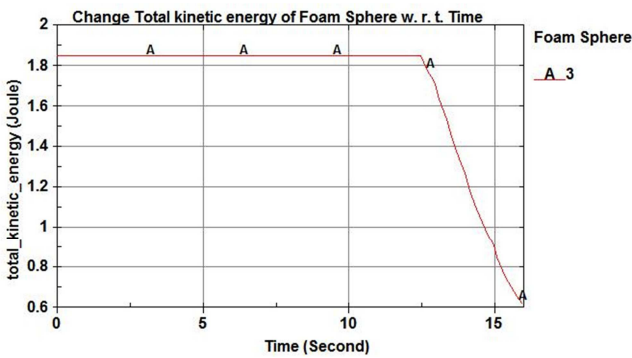


Figure 6. Curve of Change of Total Kinetic Energy of foam sphere w. r. t. Time.

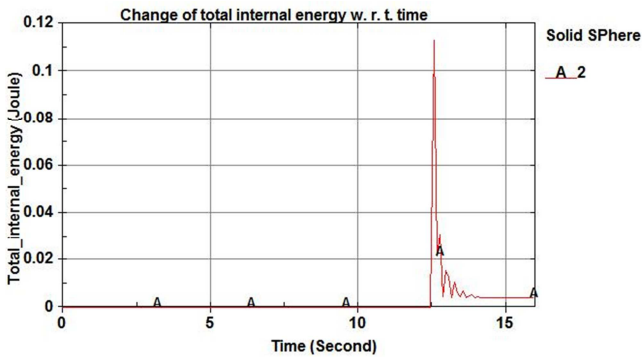


Figure 7. Curve of Change of Total Internal Energy of solid sphere w. r. t. Time.

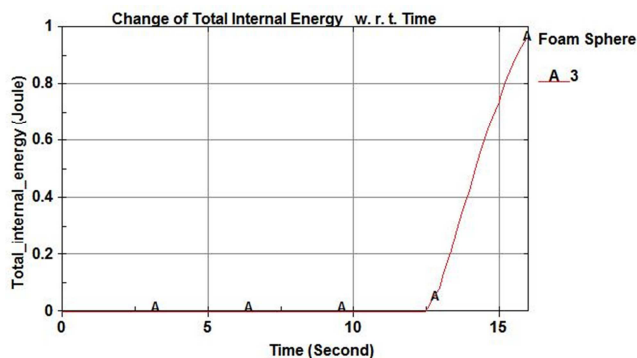


Figure 8. Curve of Change of Total Internal Energy of Foam sphere w. r. t. Time.

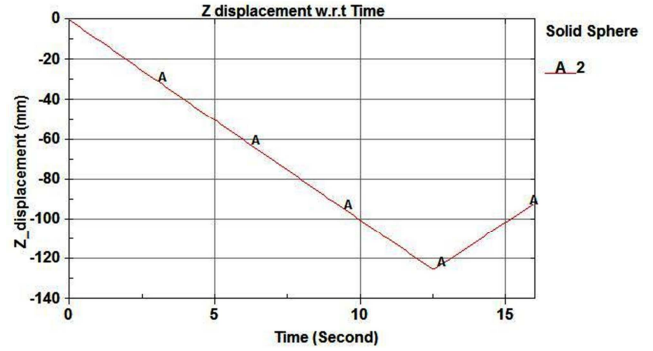


Figure 9. Curve of Z displacement of solid sphere w. r. t. Time.

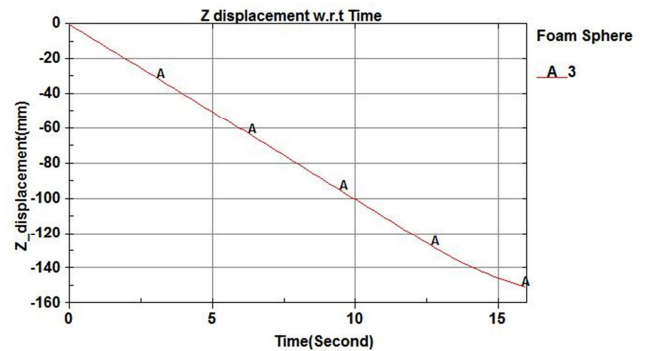


Figure 10. Curve of Z displacement of foam sphere w. r. t. Time.

From figure 9 the co-efficient of restitution of solid sphere can be found out as given below.

It is known that,

$$\text{Co-efficient of Restitution of solid sphere} = \sqrt{\frac{h_2}{h_1}}, \quad (1)$$

Where  $h_1$  = height of releasing the object from datum line,  $h_2$  = height from datum line up to which the object will bounce up after collision with bodies at datum line.

$$\text{So, the co-efficient of restitution of solid sphere} = \sqrt{\frac{91-15}{150-15}} = 0.7503$$

It is observed that the solid aluminium sphere is bouncing back from the rigid surface that means enough energy is absorbed to be used in automobile or packaging industries, thus does not fulfill the requirement. But the aluminium foam sphere is getting crushed and absorbing energies with more quantity comparatively with solid one. It can be also proven from the curve shown in figure 10. Thus the objective of this present work is successfully fulfilled.

### 3.4. Crashing Simulation

Aluminium foam is normally used in crash box which is placed in front of the chassis of a racing car. Crash box is a hollow extruded parts produced by aluminium or fabricated by aluminium sheet metals. The chance of survival of a driver in an accident is achieved by a combination of the crash resistance of the car and its ability to absorb energy. This has been achieved by providing a survival cell (the

chassis) which is extremely resistant to damage, around which energy absorbing devices are placed at strategic points on the vehicle. The energy absorbing devices operate to enable maximum deformation up to a specified limit. The devices used are designed to dissipate energy irreversibly during the impact, thereby reducing the force and momentum transferred to the survival cell and hence the driver. Since the late 1980s FIA has introduced a series of regulations to ensure that the cars conform to stringent safety requirements and build quality. Each vehicle must satisfy a list of requirements, in the form of officially witnessed tests, before it is allowed to race.

There are two groups of tests that must be passed for a frontal absorbing structure of a prototype. The first is a static load applied on a vertical and transversal plane passing 500 mm forward of the front wheel axle. A constant load of 2000 N must be applied to one side of the crash-box using a pad. After 30 seconds of application, there must be no failure of the structure or of any attachment between the crash-box and the chassis. The second test defines the effectiveness of the energy absorbing structure. The crash-box and the front part of the survival cell must be subjected to an impact test against a solid, vertical barrier. The front part of the chassis to be tested must be solidly attached to the trolley. The total weight of the trolley and test structures must be of 610 Kg and the velocity of impact of 12 m/s. During the test maximum average deceleration of the trolley must not exceed 25 g and the final deformation must be contained in the zone situated more than 100 mm ahead of the driver's feet. Prototype manufacturing and testing of each configuration would be too expensive in cost and time. For these reasons corresponding FE models are generated with a minor effort and are capable of predicting the structural behavior under dynamic loads.

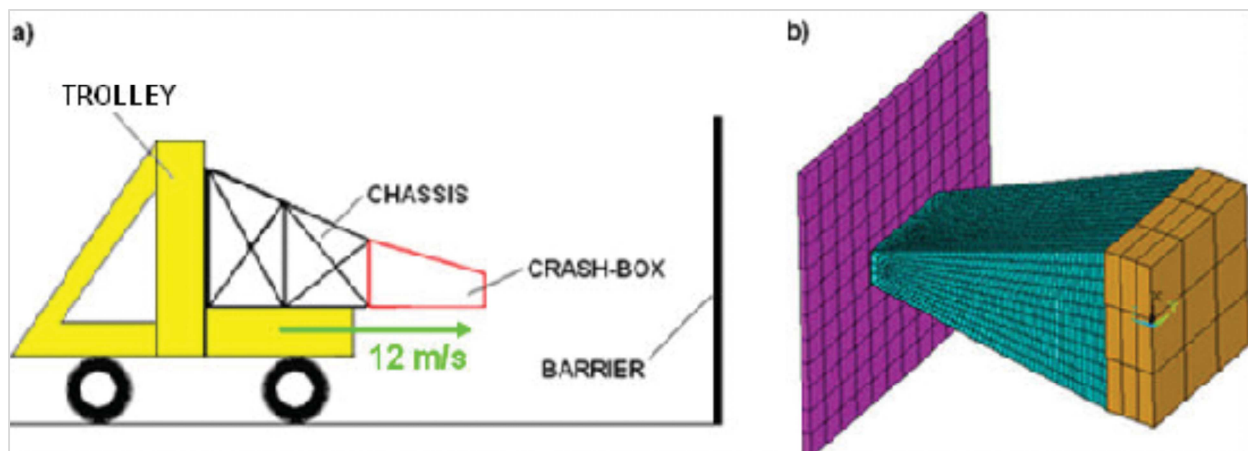
The finite element simulation of such structure was performed in the usual three typical steps:

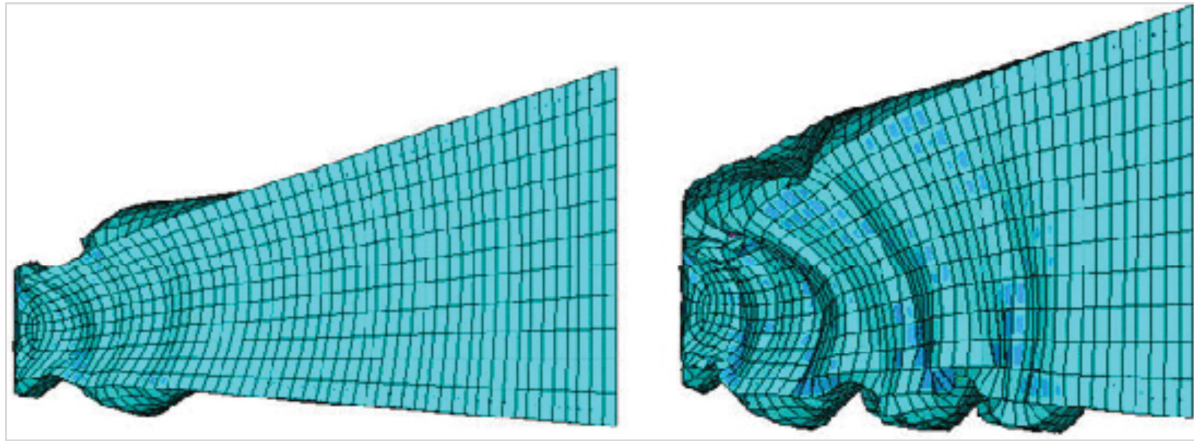
Building of a parametric model by means of the pre-processor ANSYS, non-linear dynamic analysis with LS-DYNA and post-processing using ANSYS for the interpretation and visualization of the results. The total

system was obtained by the right combination of a crash-box and a striking mass that impact a barrier (Figure 11). The material models verified by previous sandwich component test were incorporated into FE model of the crash-box. The barrier and the moving mass were meshed with the element type SOLID 164 and were also regarded as rigid body. The contact interface type 'nodes-to-surface' is used for the contact between the rigid barrier and the crash-box. This type is selected in order to prevent penetration of the specimen's internal nodes could be in contact with the rigid platen during the simulation procedure. In order to prevent sliding at the proximal ends, a coefficient of friction of 0.39 incorporated between the rigid body surface and the edges of the structure. Moreover any self-contacts of the inner and the outer surfaces of the crash-box are assumed frictionless. The boundary condition refers to the barrier and to the moving mass. The moving mass is modeled as a rigid body with five constraints. There are no displacements along the three global axes x and y, and no rotations about the three global basic axes. Therefore, displacement along the z axis is only permitted with a constant initial velocity of 12 m/s. The nonlinear analysis using the LS-DYNA code is performed setting the total duration of the modeled axial collapse process and other control's parameters. During the dynamic tests displacements (Fig. 13) and forces were recorded.

Above crash simulation has been done assuming the density aluminium foam is  $544.05 \text{ Kg/m}^3$  and its height is 12 mm. For reason of simplification, the cellular honeycomb core structure is treated as a homogeneous material using its effective orthotropic material properties. The honeycomb material directions are defined as the foaming-direction, and direction perpendicular to the foaming. The crash tests have been done by using the data generated by stress & strain under compression test, shear and bending diagram carried out under virtual environment.

Similar drop-tests were carried out for Aluminium foam (produced by using pre-treated  $\text{TiH}_2$  as a foaming agent along with  $\text{CaCO}_3$ ) filled cube made of thin aluminium sheet metals (Figure 12).



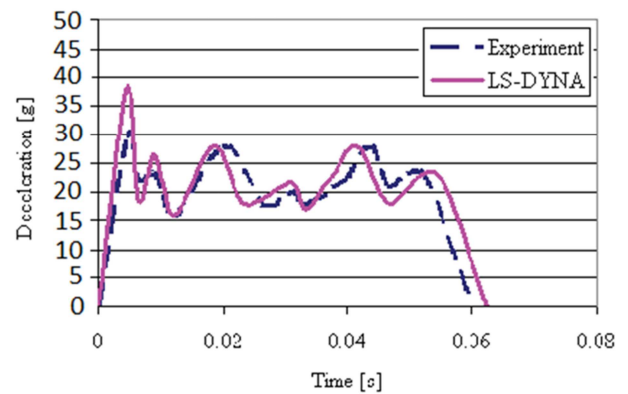


(c)

**Figure 11.** (a) schematic diagram of a racing car (b) Numerical model crash box at the time of Collision. (c) Modeling of deformed shape of crash-box during impact in two different times.



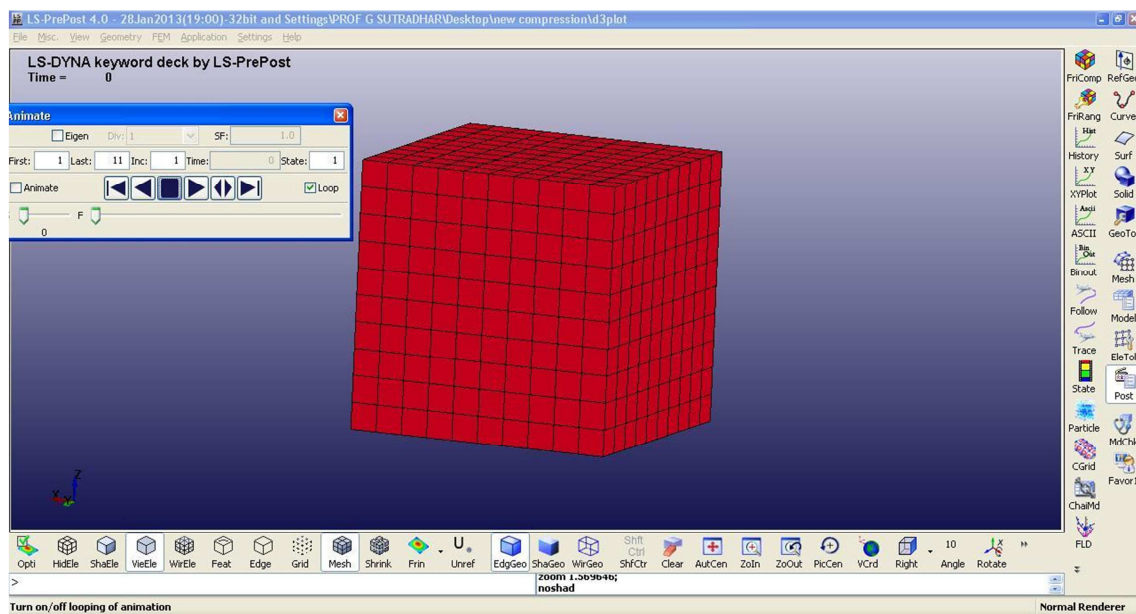
**Figure 12.** Experimental deformation.



**Figure 13.** Deceleration-time curve.

### 3.5. Compression Test Simulation

A cube of side 20 mm made of closed cell aluminium foam is modeled at first. Then load is applied on its upper surface and lower surface kept as fixed. The set up of the box before compression is shown in figure 14.



**Figure 14.** Cube before compression in LS-DYNA.



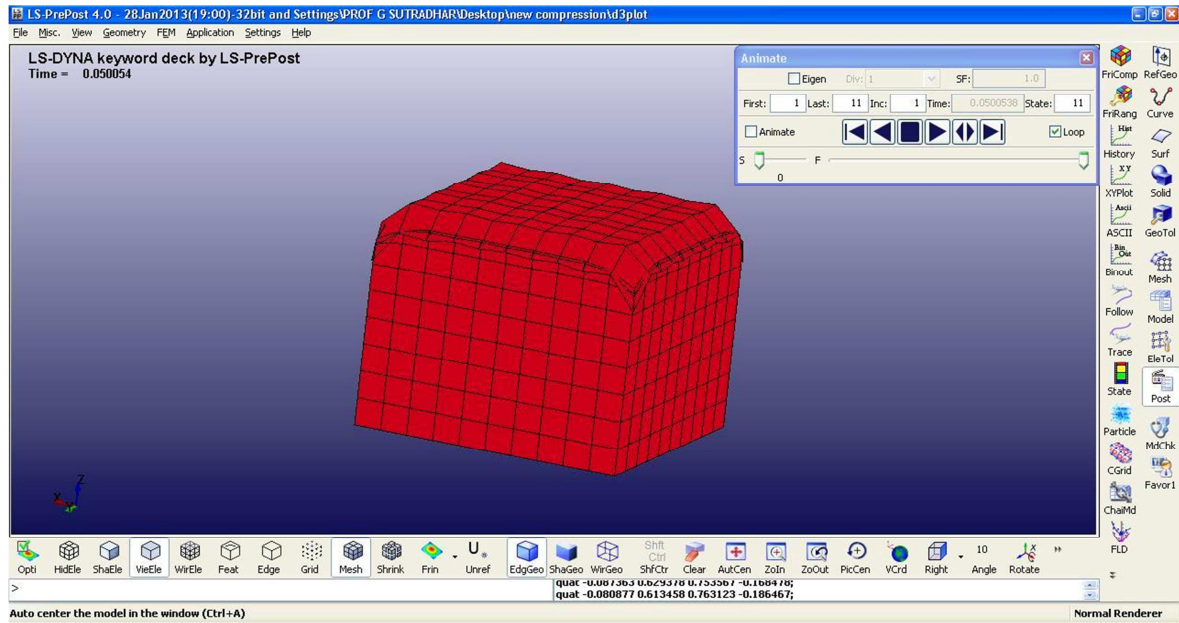


Figure 15. Cube after compression in LS-DYNA.

Now, 80N force is applied on its top surface which gives the deformation of the cube. The simulation is animated and recorded. The figure 15 is showing the cube after deformation.

Rate of change of energies are found and plotted. They are shown in figure 16.

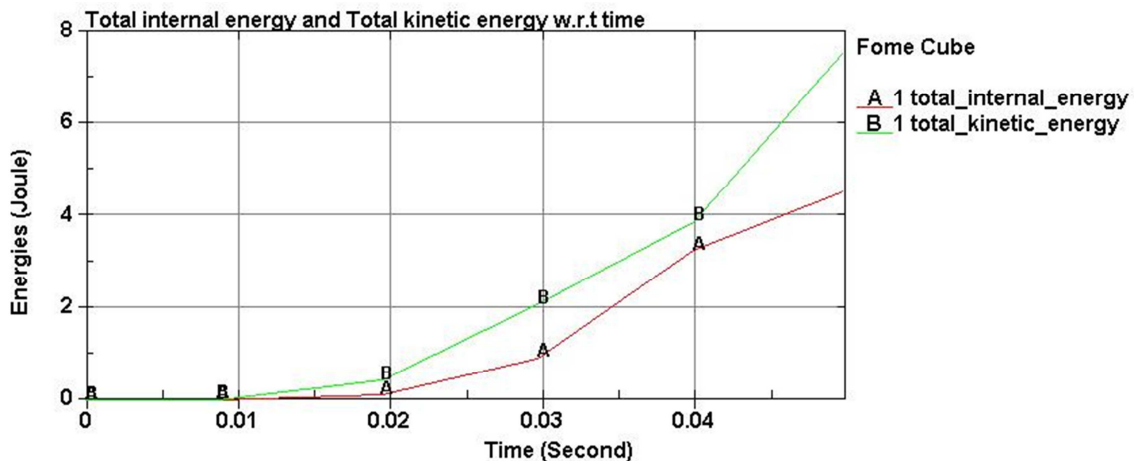


Figure 16. Curve of change of Total internal energy and Total kinetic energy w.r.t Time.

## 4. Conclusions

The best quality foam composition is found out and quality is further improved by preheat treatment of  $TiH_2$ . After producing samples the properties has been tested several times and average values are taken and they are used as input in simulation by the software LS-DYNA. The simulation results support the experimentally found outcome of the amount of absorbing energy by closed cell aluminium foam.

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