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ENCLOSURES:

1. ABSTRACT
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ABSTRACT

Aluminium foams have high specific strength and higher stiffness than other contemporary packaging materials. They have important application as packaging material for critical applications that needs highest safety standards. Commercially, established processes for manufacturing of metal foam include Hydro/Alcan Process, Alporas Process, Gasar/Lotus process, Alulight/Foaminal process, Formgrip Process, ALUHAB and Powder Metallurgy route. In the above methods, control of the shape and size of pores is difficult. In these techniques significant changes in the chemistry of the melt is carried out to foam the metals. The Gap area of the above commercial processes is minimised by "Hollow sphere technique". This process overcomes the limitations in achieving the cell wall thickness, shape of the pores, non-uniformity of pore size and its distribution in comparison to existing commercial established process. Moreover, it is easy to fabricate foams, with desired/tunable mechanical properties. This thesis discusses, the fabrication technique of hollow spheres using a special die by successive pressing of hollow tube through a series of ten die cavities. The fabricated hollow spheres are cured in the required shape using suitable bonding material (resin based or metal binder). The advantage of this process being, any asymmetrical shape is easier to fabricate and mechanical properties can be controlled by using spheres with different diameters and varying wall thickness. This process does not require any additional alloy nor does it require huge experimental facilities for fabrication. This mechanical processing method of hollow sphere technique can fabricate different diameter spheres with varying wall thickness. By arranging spheres in desired pattern, "graded foams" which is a new concept exhibiting peculiar properties is introduced. This work includes assessment of mechanical properties and its comparison with respect to commercially available foams. The main properties under consideration were yield strength, Young's modulus, plateau stress, densification strain and energy absorption evaluation. This thesis also, discusses practical application of developed product in the field of engineering as base isolators, which is novel.

The thesis concludes by highlighting advantages of this technique over the other existing commercially established fabrication routes:

- Desired/tunable Mechanical properties can be achieved on case-to-case basis with ease and can be supported by impact simulations using finite element analysis.
- It is the fastest and easiest way for production of High purity aluminium foam and in achieving any asymmetrical shapes.
- Relative Densities of the order of 10%, 20%, 30%, 40%, 50 % and higher can be achieved by varying only the hollow sphere diameter or wall thickness of the sphere.
- Cost effective and Environment/Eco-friendly and Recyclable

This route of hollow spheres fabrication and the final product is different from the prevalent commercially established routes of metal foam fabrication using hollow sphere technique.

SYNOPSIS

Aluminium foams have wide range of applications for strength and functional requirements, due to their varied properties related to various mechanical, thermal, acoustic & electrical fields. They have great potential for lightweight structures, especially, for energy absorption in packaging during impact at high velocities. Metal foam structures have relative density fraction of that of a solid structure and have high specific strength and higher stiffness than other contemporary packaging materials. Therefore, the metal foam in particular “Aluminium Foam” has an important application as packaging material for critical applications that needs highest safety standards. Metal foams can play a key role in providing cushion for absorption of shock and impact.

Chapter –I gives in detail the present status in the fabrication and characterisation of metal foams and sets out the motivation for the present work. There are different ways in which foam fabrication of various metals can be carried out. The established processes for manufacturing of metal foam include Hydro/Alcan Process, Alporas Process, Gasar / Lotus process, Alulight / Foaminal process, Formgrip Process, ALUHAB and Powder Metallurgy route.

In the Hydro/Alcan Process, metals foams are fabricated by injecting gas. About 20% SiC is commonly added to the melt to stabilize it. Foam can be continuously drawn on conveyor belt in slabs of 100x400 mm^2 from the surface of the melt, and can be produced up to a length of 16m. The foam produced by his process has a density in the range of 0.07 to 0.54 g/cc with average bubble size 3 to 25 mm. The advantage being that, the capability for continuous production of a large volume of foam at relatively low density is possible. The disadvantage being eventual cutting of foam, results in the opening of cells and non-uniformity of pore size.

The Alporas process foams are developed by adding TiH_2 as the blowing agent in a pool of aluminium. The Al melt viscosity increased with the addition of Ca metal. The Shinko Wire Company has produced blocks of 2050x650x450 mm^3 using the above process. The major disadvantage being that, the control of process parameters becomes difficult, like viscosity, uniform mixing of TiH_2 in the molten pool, maintaining the uniform process temperature etc.

The Gasar/Lotus process foams a metal by supersaturating a liquid with H_2 gas under high pressure and temperature after the liquid solidifies. Gasar stands for gas reinforced in Russian language. The disadvantage of this process being that Handling of H_2 gas is difficult. Being highly flammable, storage and handling are very difficult.

Alulight foaming process uses the powder route in which a compacted mixture of metal (Al) and blowing agent (TiH_2) powders are used.. Re-melting the precursor results in release of H_2 gas from the blowing agent within the metal. The greatest advantage with this process is that closed moulds can be filled with foam and structural foam parts of complex shapes can be fabricated. The disadvantage being that the maximum size of the billet is limited with the diameter of extruded billet.

Foamgrip process starts from the melt in which the blowing agent is finely dispersed in the matrix. The melt is solidified to form a solid precursor that can be foamed by re-melting. The disadvantage being that the process parameters are difficult to control. In addition, the uniform dispersion is poor.

ALUHAB is one of the new closed metal foam manufacturing techniques, which satisfies the present state of art. The advantage is that the process generates porosity of desired sizes along the length of the foam sample but the disadvantage, being that the size of the pores may not be spherical and uniform throughout.

In all of the above methods, control of the shape and size of pores in the foam is difficult. Further getting near net shape of irregular shapes is difficult. In, many of the above techniques significant changes in the properties of the melt are required which is achieved by changing the chemistry of the melt. For ex., Silicon when added increases the viscosity whereas blowing agents such as titanium hydride, calcium carbonate, etc., when added increases the impurity in base material. Also, one of the issues that have limited the use of foams is the cost of production.

Precise control of process parameters is critical for formation of foams by blowing methods. The route in which process parameters control is lesser is by Hollow sphere technique.

Recycling of materials used in any product is also something that is desirable. The recycling becomes easier if the product is free from additives. Thus, a minimum change in the composition of the base material is preferred during the recycling process.

The Gap area of the above commercial processes is minimised by "Hollow sphere technique". This process has the advantage of overcoming non-uniformity of pore size and is free from issues like control of viscosity of the melt, uniform mixing of Titanium hydride (TiH_2) in the melt, maintaining uniform process temperature of melt, handling of Hydrogen gas, requirement of extrusion equipment or cold isostatic press etc..

The cell wall thickness, shape of the pores, the size of the pores and its distribution, which control the properties of foam, is generally difficult to control in the above-mentioned processes.

A process that can control all these variables would be desirable /ideal. A technique that can achieve all of the above is the “Hollow sphere technique”. In this technique, it is easy to fabricate foams, with desired/tunable mechanical properties. Further, processing of any desired shape is achievable by this technique.

This chapter gives the different established commercial routes of metal foam and its properties as available from open literature.

This chapter also, discusses the fabrication technique. A special die design was evolved to manufacture these hollow spheres. The specialty of this die is to fabricate the hollow spheres using successive pressing of hollow tube through a series of ten die cavities. The process evolved in a phased manner.

The amount of force required during the crimping process and number of sequential successive pressing is the key for die design in the fabrication of hollow spheres. The design evolved by overcoming the drawbacks of alternate route for sphere fabrication.

The fabricated hollow spheres are cured in the required shape using suitable bonding material (resin based or metal binder). The advantage of this process being, any asymmetrical shape is easier to fabricate. This process can fabricate spheres with different diameters and varying wall thickness.

Chapter-II discusses the fabrication route for hollow sphere metal foams. It explains in details the proposed process for development of metal foams using the novel way of hollow spheres fabrication by mechanical means and subsequently curing procedure.

Hollow sphere technique is the only process by which aluminium foams 1S grade (99.9% pure) can be manufactured. This feature makes the process ahead of others, as all other processes use a composition of different alloying agents for the production of metal foam. Thus, it can be said that this is the only process by which pure Aluminium 1S Grade Material Foams can be fabricated. **However, aluminium of any grade or any other metals can also be used for the fabrication of hollow spheres and in turn metal foam**.

The metal foam fabrication by this route is with desired tunable mechanical properties. This process does not require any additional alloy nor does it require huge experimental facilities for fabrication. However, this process requires a hollow sphere fabrication machine, binder (resin based or metal based) and a furnace. The prime concern in the international scientific research community with Metal foams is achieving the important primary properties such as:

- Controlled pore size (porosity) with controlled wall thickness
- Controlled distribution of porosity

Hollow sphere technique can fabricate different diameter spheres with varying wall thickness. By arranging spheres in desired pattern, “graded foams” which is a new concept exhibiting peculiar properties has been introduced.

Review of literature reveals the formation of graded foams by powder metallurgy route, melting and casting and ALUHAB. However, this thesis highlights that the “Hollow Sphere Technique” has minimised major disadvantages in foam production with the controlled distribution of porosity across the cross section, in comparison to other processes.

By Hollow sphere technique, closed cell metal foam is fabricated. Researchers all over the world are planning to get variation in porosity distribution along the length of the sample. ALUHAB researchers have introduced the porosity variation concept along the cross section of the fabricated samples. However, in ALUHAB process, uniformity of pore size distribution as quoted is difficult to achieve as the spherocity of the inner pores varies. **In addition, some researchers have shown their work using the concept of hollow spheres with uniformity of pore size, but uniform distribution along the cross section is yet to be made achievable.**

Chapter-III discusses the characterisation of closed cell Aluminium foam carried out in terms of density, microstructure for finding the wall thickness, porosity content, correlation of hardness with yield strength, etc. This thesis focuses on the assessment of mechanical properties like yield strength, tensile strength, Young’s modulus, plateau stress, densification strain and energy absorbed. The observation made from the data is as under:

- The average density of the fabricated foam can be varied with changing the following parameters:
    - Hollow sphere diameter
    - Wall thickness of the hollow sphere
    - Binder (resin base or metal base)
- Introduction of graded foam concept, i.e. by using different sphere diameters along the length of the sample
- Introduction of similar hollow sphere material and binding matrix.
- Due to introduction of aluminium hollow spheres of various diameters, the density of the aluminium foam can be in the range of 10 to 60 % of the theoretical density of solid aluminium.
- Introduction of dissimilar materials of hollow spheres and binding matrix has the advantage of combined strength benefits
- The length of the specimen decides the plateau stress. The larger the length of the sample more is the plateau stress and in turn, increases the energy absorption. Young’s modulus varies in the range of 0.1 – 0.50 GPa for the foams developed by hollow spheres technique.

- Foams with 5mm diameter hollow spheres and 0.5mm wall thickness have shown density in the range of 0.8 g/cc to 1.2 g/cc. The binder used is aluminium metal.
- The different densities achieved using this hollow sphere technique can be varied from 0.48g/cc to 0.639 g/cc for aluminium spheres of 7mm diameter with 0.2mm wall thickness depending upon the content of binder resin or metal base. As density of foam varies value of Young's modulus changes and energy absorption increases for aluminium foam
    - Porosity distribution in Hollow sphere technique
    - Uniformity in porosity distribution in the fabricated sample
    - Uniformity in cell wall thickness
    - Density repeatability of foam samples within ±3%
- Hardness studies carried out to compare with the yield stress evaluated from the developed foams.
- The X-ray radiographs before and after the compression studies reveal the pore failure pattern similar to the other developed standard foams.

Chapter-IV focuses on the characterisation of metal foam using Finite Element analysis with actual experimental results tabulated for the different types of foams as mentioned in **Chapter –I of the published literature by the researcher in a group**. As a part of analysis commercially available foam such as "ALPORAS" (closed-cell Alporas foam imported from GLEICH Aluminium werk GmbH & Co, Germany) is used to evaluate and characterize the properties which serve as a bench mark for the indigenously developed metal foam developed using powder metallurgy route and Hollow sphere technique.

For high strain rate experiments, feasibility of using Split Hopkinson pressure bar system for evaluating mechanical properties of metal foams was considered. Nevertheless, studies confirmed that, Split Hopkinson Pressure Bar System might not be practical for characterisation of metal foam samples. The small porosity which would normally be required for testing would have very few cells (generally of 3 mm to 8 mm in size) in them. Also, **the effect of outer surface (referred to as scale) would be predominant, which concluded that split Hopkinson pressure bar system cannot be used for the small sample sizes of metal foams for characterisation.**

In order to overcome the deficiency of conventional high strain rate tests for mechanical characterisation, a new approach is developed by combining low strain rate tests using a servo-hydraulic UTM, drop tests at medium strain tests, ballistic impact testing using a gas gun-based device, and advanced numerical simulation using LS-DYNA for quantifying the dependence of strength for developed metal foams. The methodology adopted for properties evaluation for Alporas foams helped in the characterisation of hollow spheres.

Chapter-V discusses practical application of developed product in the field of engineering as case study:

- Hybrid shock isolation device i.e., as base isolators

Chapter-VI concludes by highlighting advantages of Hollow sphere foams, its fabrication technique over the other existing fabrication routes. In addition, it highlights the future scope of work:

- Desired/tunable Mechanical properties can be achieved on case-to-case basis with ease and supported by impact simulations.
- It is the fastest and easiest way for production of High purity aluminium foam.
- Choice of the Hollow Spheres technique helps in achieving any asymmetrical shapes.
- Relative Densities of the order of 10%, 20%, 30%, 40%, 50 % and higher can be achieved by varying only the hollow sphere diameter or wall thickness of the sphere.
- Cost effective
- Environment/Eco-friendly and Recyclable

This thesis explains in detail the foam production by hollow sphere technique, its characterisation and techniques to fabricate controlled porosity foams using the same.

Also, it shows the comparison of experimental results with finite element analysis for prediction of properties. It introduces the concept of graded foams in the real sense. In general, researchers fabricate hollow spheres by synthesis routes using chemicals.

However, this thesis deals with the mechanical processing techniques for fabrication of hollow spheres. This technique is fast, reliable, precise and more accurate in hollow spheres generation. The route of hollow spheres fabrication and the final product is different from the prevalent established routes of hollow sphere technique.