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Design and Development of Manufacturing System Design for Producing Metallic Foam

Shyam Sunder Sharma

Abstract

This chapter involves the development of a new metal foam composite material using casting techniques. This work included the design and the development of a process to produce the metal foam and control it. The materials used to produce the foam consisted of aluminum. Using prefabricated hollow spheres assures a uniform pore size and cell wall thickness. Casting a metal into the interstitial space provides a solid medium to add a structural support to the foam. The experimental setup was designed and fabricated. By the use of the developed setup, aluminum metallic foam was developed from the raw aluminum. Some characteristics were studied to verify the findings with the published data.

Keywords: metallic foam, pores, honeycomb, foaming

1. Introduction

The development of the metal foam starts in the late 1940s. Many patents were registered in the 1950s and 1970s. The popularity of metal foam arises in the 1980s, and the old techniques are modified and re-established. Researchers are trying to mechanize the foaming method to minimize the production cost and increase the productivity [1–3]. For the development of complex shapes and large quantities, powder metallurgy and casting techniques were used. For refractory metals electro-deposition method was used. The metal foam has a better strength-to-weight ratio, higher stiffness, increased energy absorption and high temperature tolerance. It gives higher stiffness than a solid metal [4, 5]. The metal foam can be classified according to the foam structure. It has an open structure, close structure and combination of open and closed structures [6, 7]. The properties of metal foam are lightweight, energy absorption, high stiffness and higher compression strength [8, 9].

There are various methods for developing metallic foam. These production methods are classified according to the state of the material and process followed. Metallic foam was categorized into four groups as given in **Figure 1**:

- i. Casting method (liquid metal): In this method a liquid metal is poured into the mold, and a foaming agent is added which creates a metal foam around the solid filler metal.
- ii. Powder metallurgy (solid metal in powdered form): In this process metals are converted into a powdered form, and then a foaming agent is added

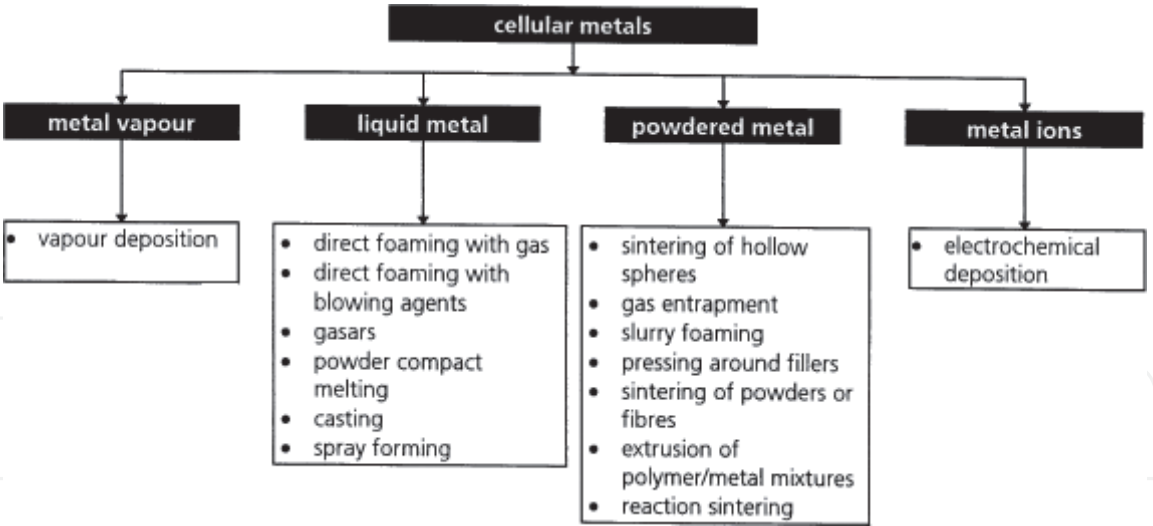


Figure 1.
Production methods of metallic foam [10].

with the metal powder; after that the blend is compressed to yield a dense. In this method, compaction can be performed by any technique that ensures that the foaming agent is embedded in the metal matrix without any residual open porosity.

- iii. Metal vapor: A metal foam is commonly produced by injection of foaming gas into the liquid metal or by adding a foaming agent into the metal powder. In this method melts can be foamed by creating gas bubbles in the material. Normally, bubbles in the molten metal are highly buoyant in the high-density liquid and rise quickly to the surface.
- iv. Metal ion solution: The alkali metal ions in the solution electrostatically adsorb onto the many bubbles by bubbling ionic surfactant solution, and they transfer to the air/water interface. These bubbles change to the foam state that is removed using a long glass tube.

2. Design and fabrication

For producing metallic foam liquid state, a casting processing technique was used. In this process calcium carbonate was added into the liquid aluminum and was stirred. When aluminum liquid was stirred, calcium carbonate released gases, and these gases are entrapped in aluminum and created porosity. For producing metallic foam, a setup was required, and this was fabricated in the production engineering department. For design and fabrication, the resources which are available in the department are used. This was the first setup fabricated for producing metallic foam. According to the resources, different elements have been designed and fabricated.

For fabricated setup different elements were required, and these were designed according to the requirement. Some elements are available in the lab and they are directly taken according to the requirement, and others were fabricated. Fabricated setup resources were used that were available in lab, because this was the first setup and after the successful of that setup go for the standardization. The process sheets of fabrication are given in the appendix. The design given in **Figure 2** was taken as the reference design. The elements that were required are given below:

1. Induction motor.
2. Shaft.
3. Selection of bearing and bearing socket.
4. Driver and driven pulley.
5. Milling socket.

2.1 Specification of induction motor

An induction motor was used for a rotate stirrer that was placed in the end of the shaft. When the setup will be standardized, a standard motor will be used. The speed of the motor was constant. Driver and driven pulleys were connected by a rope. The specifications of the motor are given below:

1. Power = 1 HP.
2. rpm = 1380.
3. Efficiency = 72%.
4. Machine no. = 88A615–204.
5. Diameter of the shaft = 19.19 mm.

2.2 Design of the shaft

A shaft was a rotating element which is used for a rotate stirrer and produces metallic foam.

2.2.1 Calculation

Material of shaft = Mild steel, it has tough material and it was absorbing vibration that was caused by the motor.

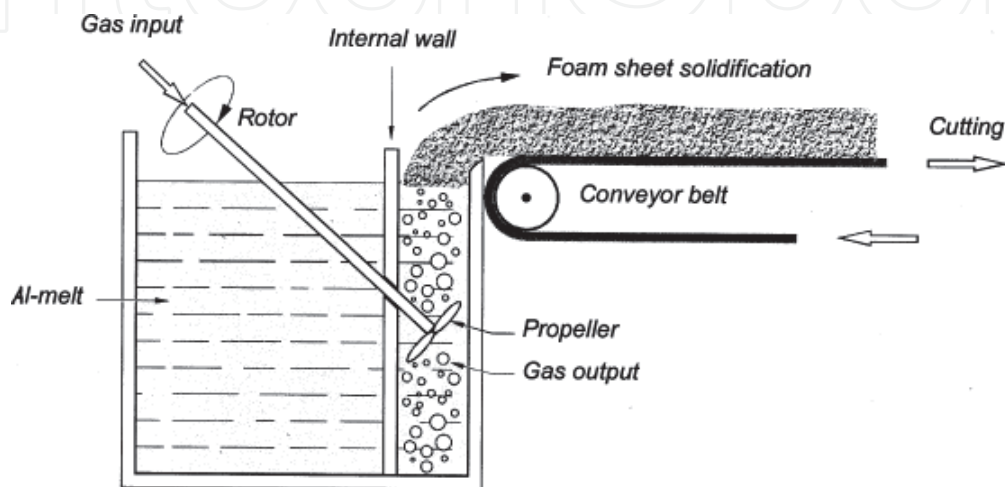


Figure 2.
Basic design for producing foam [10].

Length of the shaft = 315 mm.

Diameter of the shaft from top 225 mm = 20 mm.

Diameter of the shaft at lower 80 mm length = 19.98 mm.

Dimension of thread = 10 × 1.5 mm.

Considering the load at the top, i.e. load of the pulley mounted on the shaft.

$$\begin{aligned}\text{Slenderness ratio of the shaft} &= \frac{L}{K} \\ &= \frac{315}{10} \\ &= 31.5\end{aligned}\quad (1)$$

Thus, the shaft is a medium type (**Figure 3**).

2.2.2 Rankine formula for calculating the crippling load

$$W_{cr} = \frac{\sigma_c \times A}{1 + \frac{\sigma_c \times A \times L^2}{\pi^2 \times E \times I}} \quad (2)$$

where W_{cr} = crippling load, σ_c = crushing stress or yield stress, A = cross-sectional area, L = length of the shaft, E = modulus of elasticity, I = moment of inertia.

$$W_{cr} = \frac{\sigma_c \times A}{1 + a \left(\frac{L}{K}\right)^2} \quad (3)$$

$$a = \text{Rankine's constant} = \frac{\sigma_c}{\pi^2 E} \quad (4)$$

$$a = \frac{1}{7500}$$

For one end fixed and another end free.

$$\begin{aligned}L &= 2L \\ &= 2 \times 315 \\ &= 630 \text{ mm}\end{aligned}$$

$$K = 10 \text{ mm}$$

$$\frac{L}{K} = \frac{630}{10} = 63$$

$$W_{cr} = \frac{320 \times \frac{\pi}{4} (20)^2}{1 + \frac{1}{7500} (63)^2}$$

$$\sigma_c = 320.$$

$$W_{cr} = 65.707 \text{ N}$$

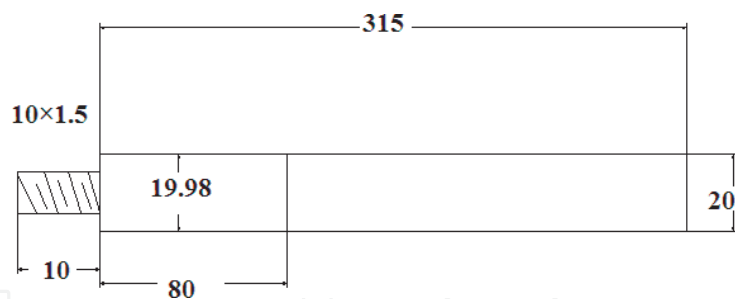


Figure 3.
Shaft.

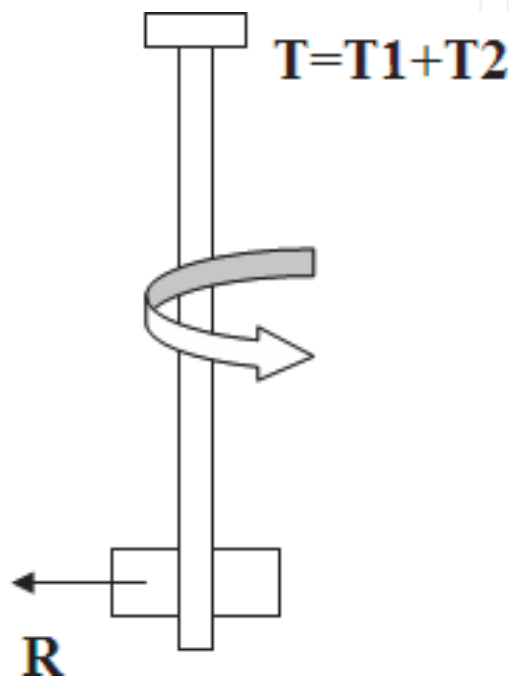


Figure 4.
Shaft in vertical position.

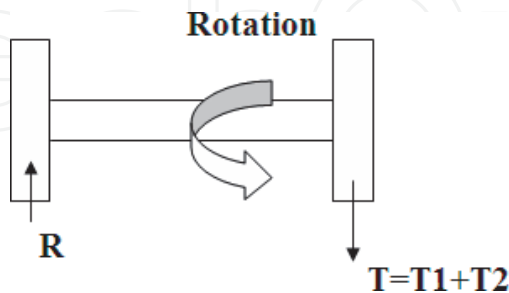


Figure 5.
Shaft in horizontal position.

2.2.3 Considering the weight of pulley

Figure 4 shows the vertical position of the shaft, and **Figure 5** shows the horizontal position of the shaft. In **Figure 6** power is transmitted from the driver pulley to driven pulley. For designing a shaft and pulley, the following calculations are required.

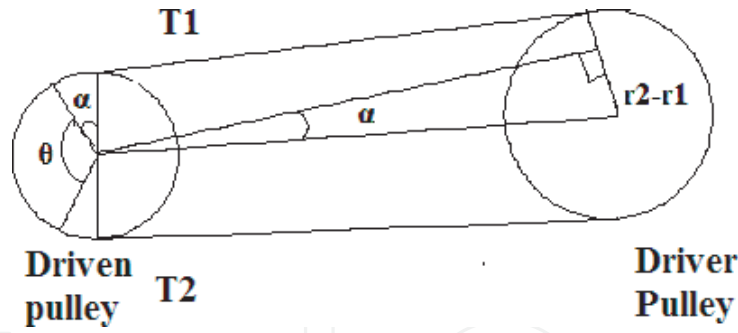


Figure 6.
Power transmitted by rope.

$$\begin{aligned} \text{weight of the pulley} &= 400 \text{ g} \\ &= \frac{400 \times 9.81}{1000} \\ W_p &= 3.9 \text{ N} \end{aligned}$$

The shaft bears more load; hence, the design is safe.

2.2.3.1 Power of motor

$$P = \frac{2\pi NT_0}{60} \quad (5)$$

T_0 = Torque.

$$\begin{aligned} 746 &= \frac{2 \times \pi \times 1380 \times T_0 \times .72}{60} \\ T_0 &= 7.18 \text{ N mm.} \\ T &= (T_1 - T_2) \times 44. \end{aligned}$$

$$\frac{T_1}{T_2} = e^{\mu\theta} \quad (6)$$

T_1 = Tension in the tight side.

T_2 = Tension in the slack side.

μ = Coefficient of friction.

The distance between the driven and driven pulley is 330 mm:

$\theta = 180 - 2\alpha$.

θ = Angle of contact.

$$\sin \alpha = \frac{r_2 - r_1}{330} = \frac{60 - 44}{330} = 0.484 \quad (7)$$

r_1 & r_2 = radii of the driving and driven pulley.

$\alpha = 2.778^\circ$.

$\theta = 180 - 5.55$.

$\theta = 174.44^\circ = 3.03 \text{ rad.}$

$\mu = 0.25$.

$$\frac{T_1}{T_2} = e^{0.25 \times 3.02}$$

$T_1 = 2.12 T_2$.

$(2.12 - 1)T_2 \times 44 = 7.18$.

$T_2 = 0.159 \text{ N mm.}$

$$\begin{aligned}T_1 &= 0.33 \text{ N mm.} \\R &= T_1 + T_2. \\R &= 0.489 \text{ N mm.} \\M_b &= T \times L = 0.489 \times 315 = 154.03 \text{ N mm.} \\M_t &= T_0 = 7.18 \text{ N mm.}\end{aligned}$$

Load is steady hence.

$$\begin{aligned}K_m &= 1.5. \\K_t &= 1.0. \\K_m &= \text{Combined shock and fatigue factor for bending.} \\K_t &= \text{Combined shock and fatigue factor for torsion.}\end{aligned}$$

2.2.4 Equivalent bending moment

$$M_e = \frac{1}{2} \left[K_m \times M_b + \sqrt{(K_m \times M_b)^2 + (K_t \times T)^2} \right] \quad (8)$$

$$M_e = \frac{1}{2} \left[1.5 \times 154.035 + \sqrt{(1.5 \times 154.035)^2 + (7.18)^2} \right]$$

$$M_e = 231.108 \text{ N mm.}$$

Determine the equivalent bending moment:

$$231.108 = \frac{\pi}{32} \sigma_b \times d^3.$$

$$\sigma_b = \frac{231.108 \times 32}{\pi \times (20)^2}.$$

$$\sigma_b = 0.294 \text{ N/mm}^2.$$

This was very less than the allowable tensile or compressive stress. Hence the design was safe.

2.3 Selection of bearing

In order to select a most suitable ball bearing, first, the basic dynamic load was calculated. It was multiplied by the service factor to get the basic dynamic load capacity. After finding the basic dynamic load capacity, the selection of bearing was made from the catalog of a manufacturer (**Figure 7**).

2.3.1 Striebeck formula for the strength of a single ball in compression

$$F_e = Kd^2 \quad (9)$$

$$\begin{aligned}K &= 7200. \\d &= \text{diameter of ball.} \\F_e &= 7200 \times 7^2. \\F_e &= 352,800 \text{ N/mm}^2.\end{aligned}$$

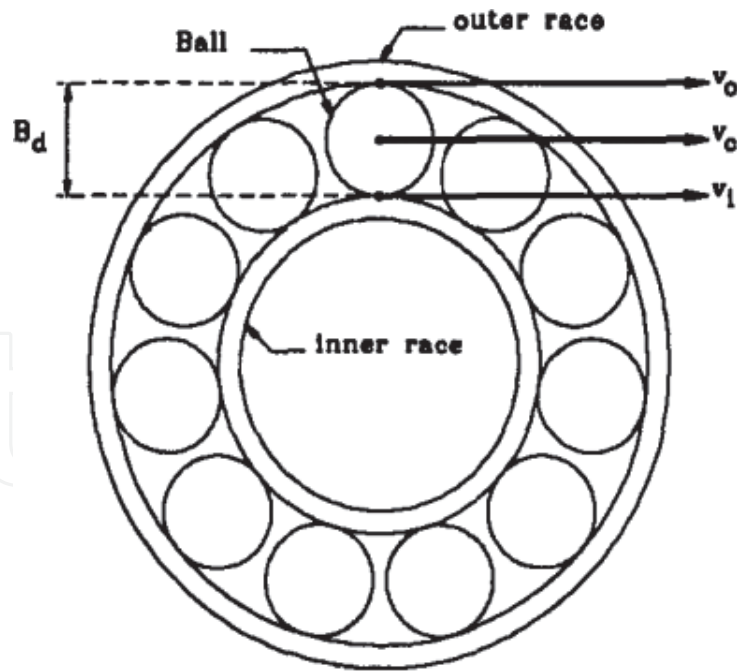


Figure 7.
Axial view of ball bearing.

2.3.2 The maximum load per ball

$$F_c = \frac{4.37}{n} \times C \quad (10)$$

$$C = \frac{F_c \times n}{4.37} = \frac{Knd^2}{4.37} \quad (11)$$

n = no. of balls.

C = capacity of the bearing.

$$C = \frac{7200 \times 8 \times .007^2}{4.37}.$$

$$C = 6.45 \text{ kg.}$$

$$F_c = \frac{4.37}{8} \times 6.45$$

$$\text{Torque} = \frac{9550 \times \text{H.P}}{N} = \frac{9550 \times .75}{1380}.$$

$$T = 5.19 \text{ N m.}$$

where HP in kW, N in rpm.

2.3.3 Basic dynamic load of bearing

$$C_d = F_c \times (n \cos \alpha)^{0.7} Z^{\frac{2}{3}} D^{1.8} \quad (12)$$

$$= 3.46 \times (8 \cos 15)^{0.7} \times 47^{1.8}.$$

$$C_d = 14807.3 \text{ N.}$$

$$C_d = 14.8 \text{ kN.}$$

α = nominal angle of contact.
D = diameter of outer race.

2.3.4 Life of bearing in revolutions

The life of an individual ball bearing may be defined as the number of revolutions which the bearing runs before the first evidence of fatigue develops in the material of one of the rings or any of the rolling elements.

The rating life of a group of apparently identical ball bearing as the number of revolutions that 90% of a group of bearings will complete or exceed before the first evidence of fatigue develops:

$$L_n = \left(\frac{C_d}{P} \right)^{\frac{14.8}{2}} = 12.3 \quad (13)$$

P = weight of pulley + weight of shaft.
P = total load (.400 + .800) = 1.2 kg.
Life of bearing = 1800 million revolution.

2.3.5 Bearing number

Bore diameter = 20 mm.
Outer race diameter = 47 mm.
ISI no. = 20BC02.
Bearing of basic design no. = 04.
Basic capacity of dynamic load = 1000 kg.

2.3.6 Bearing socket

The outer diameter of the bearing race is 47 mm.
The diameter of the socket bore is 47 mm (**Figure 8**).

2.4 Design of driver and driven pulleys

The pulley was used to transmit power from one shaft to another by means of a flat belt, V-belt or rope.

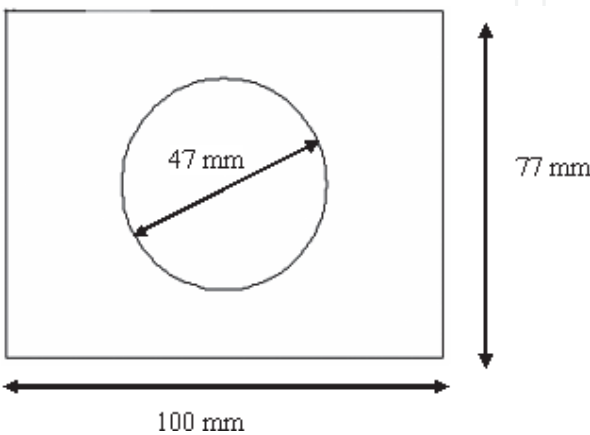


Figure 8.
Bearing socket.

2.4.1 Diameter of driver pulley

$$D = (110-113) \times \sqrt[3]{\frac{P(KW)}{2\pi N_{\max}}} \quad (14)$$

$$D = 113 \times \sqrt[3]{\frac{.75}{2 \times \pi \times 1380}}$$

$D = 5.3 \text{ cm.}$

$D = 6 \text{ cm (consider)} = 60 \text{ mm (Figure 9).}$

2.4.2 Diameter of driven pulley

The velocity of driven pulley is increased by 1.4 times (Figure 10):

$$\text{velocity ratio} = \frac{N_2}{N_1} = 1.4 \quad (15)$$

$$\text{Diameter of driven pulley} = \frac{60}{1.4} = 43 \text{ mm.}$$

2.4.3 Thickness of web and depth of groove

$$T = 0.252\sqrt{D} + 1.6 \text{ mm (for light duty pulley)} \quad (16)$$

$$T = 0.252\sqrt{60} + 1.6 = 3.55$$

$$T \approx 4 \text{ mm.}$$

Depth of groove on driver and driven pulley, where the rope is bounded = 3 mm.

Angle of taper on groove = 5° .

2.4.4 Dimension of collar

A collar is used for locking of pulley on the shaft. The pulley is locked on the shaft by bolt. So, the pulley is not coming out when the shaft is rotating.

Diameter of shaft of driver pulley = 19.19 mm.

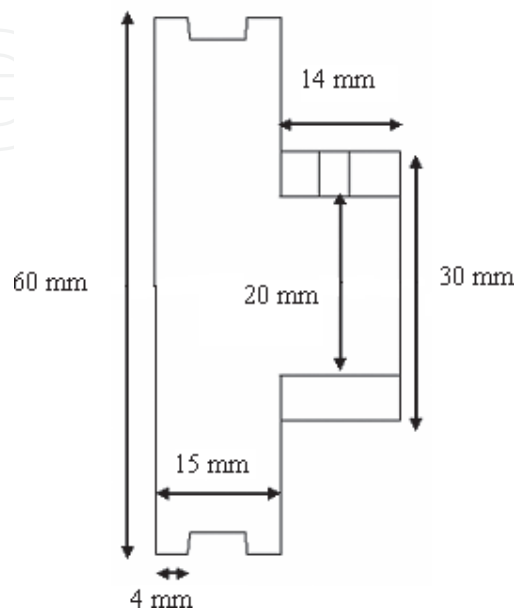


Figure 9.
Driver pulley.

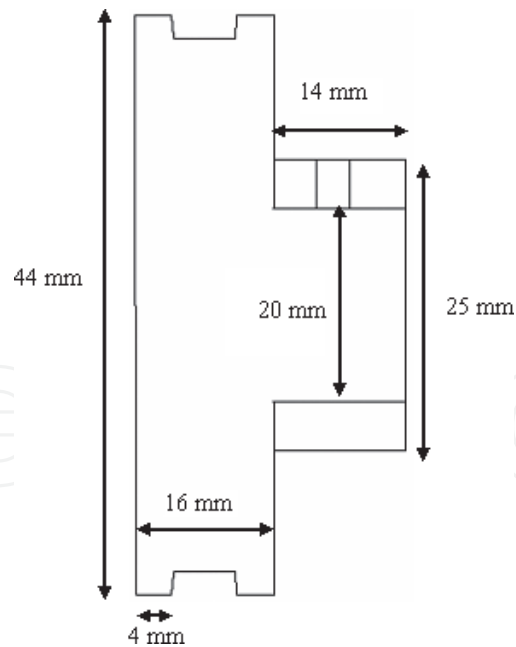


Figure 10.
Driven pulley.

Diameter of shaft of driven pulley = 20.00 mm.

Then,

Diameter of bore of collar of driver pulley = 20 mm.

Diameter of bore of collar of driven pulley = 20.02.

Length of collar of driver pulley = 14 mm.

Length of collar of driven pulley = 14 mm.

Diameter of tap = 4 mm (for both).

2.5 Design of milling socket

Material of socket = G.I.

Diameter of pipe = 27 mm.

Wall thickness of pipe = 3 mm.

Length of socket = 130 mm.

Morse taper = 1.5° .

Length of morse taper = 100 mm.

Material of inserted piece = M.S.

Length of inserted piece = 30 mm.

Diameter of through hole in inserted piece = 21 mm.

Internal threading = M10 \times 1.5.

Length of thread = 15 mm (**Figure 11**).

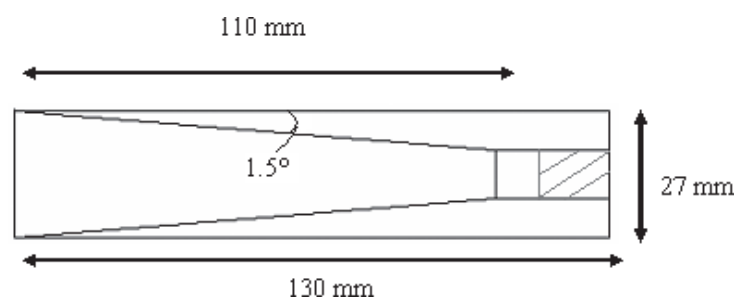


Figure 11.
Milling socket.

3. Experiment

The setup that was fabricated, with the use of this setup metallic foam, has been produced. For producing metallic foam, calcium carbonate is added into liquid aluminum and was stirred. Gases are formed at the time of stirring, and gas is entrapped into the liquid aluminum, and holes (porosity) are created into the aluminum. The foam that was formed can be cooled down, and after cooling the metallic foam can be taken out from the mold. Six experiments were done, and how much amount of aluminum and calcium carbonate can be taken is given below.

3.1 Experiment no. 1

Weight of aluminum = 887 g.
Amount of CaCO_3 = 50 g (approximate).

This was the first experiment and the amount of aluminum was 887 g. The amount of calcium carbonate added was 50 g (approximate), and after liquid aluminum was stirred and foam was developed. The foam was cooled down, and after cooling metallic foam was taken out from the mold. The porosity of foam was very low, so it was improved in the next experiments.

3.2 Experiment no. 2

Weight of aluminum = 900 g.
Amount of CaCO_3 = 30 g.

In first experiment, a satisfactory result was not obtained, so a second experiment will be performed. In this experiment the amount of aluminum was 900 g. The amount of calcium carbonate that was added was 30 g. It was added in three parts. The first part of calcium carbonate was in the mold before pouring aluminum. The second part of calcium carbonate was added when molten aluminum was poured into the mold. The remaining 10 g of aluminum was added at the time of stirring. The stirring time of a molten metal was 67 s. When calcium carbonate was added into molten aluminum, viscosity of aluminum was increased. After stirring, the stirrer was taken out from the mold and was cooled down. After cooling the foam was taken out from the mold. Metallic foam can be cut into pieces with the

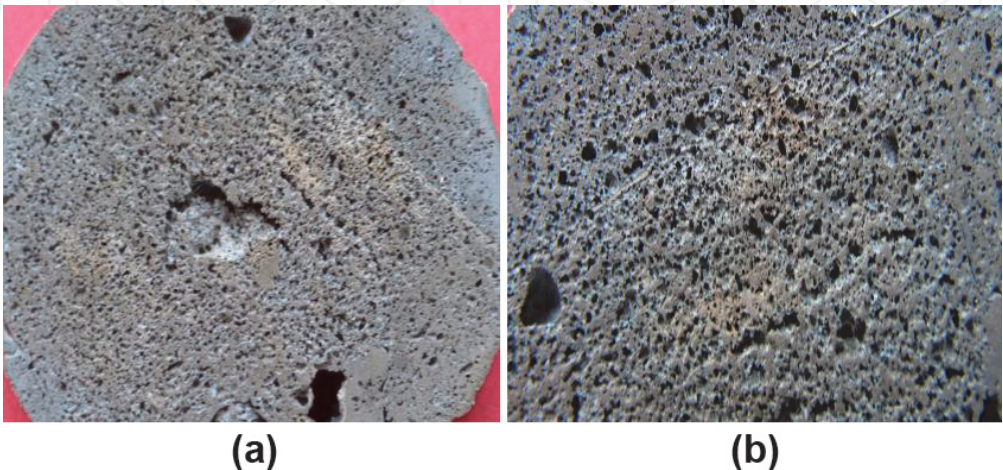


Figure 12.
Microstructure of metallic foam sample 2. (a) Microstructure of metallic foam; (b) section of metallic foam.

help of a wire cut electric discharge machining. The microstructure of metallic foam is given in **Figure 12a** and **b**.

3.3 Experiment no. 3

Weight of aluminum = 665 g.
Amount of CaCO_3 = 30 g.

Experiment 3 was not successful because calcium carbonate was directly added into the molten metal at the time of melting. All gases were escaped, and foam was not produced.

3.4 Experiment no. 4

Weight of aluminum = 969 g.
Amount of CaCO_3 = 20 g.

This was the fourth experiment. In the previous experiments, some ideas are obtained, and some standardization step was taken. The amount of aluminum was 969 g and the amount of calcium carbonate was 20 g (2% of weight). The process of producing metallic foam was shown in **Figures 13–19**. In **Figure 13** the setup is shown, which was used for producing metallic foam. In **Figure 14** aluminum metal was melt in a pit furnace. When aluminum melted, a slag was formed due to the impurities in the metal. In **Figure 15** mold was there in which molten metal was pouring. The mold was preheated with the help of a torch of gas welding. Preheating was required to reduce the temperature difference. In the mold there was one hole in the bottom. It was taken out molten metal after the foam was produced. In **Figure 16** the molten metal was poured into the mold. 20 g of calcium carbonate is divided into three parts. One part of 6 g was drawn before the molten metal is poured into the mold. When half of molten metal was poured, 7 g of calcium carbonate was added. In **Figure 17** the molten metal was stirred and the remaining amount of calcium carbonate was added. The stirring time was 60 s. After stirring, the stirrer was taken out. In **Figure 18** foam was generated due to the formation of gases, and these gases were entrapped in the aluminum. When the



Figure 13.
Setup for making a foam.



Figure 14.
Aluminum melted in a pit furnace.

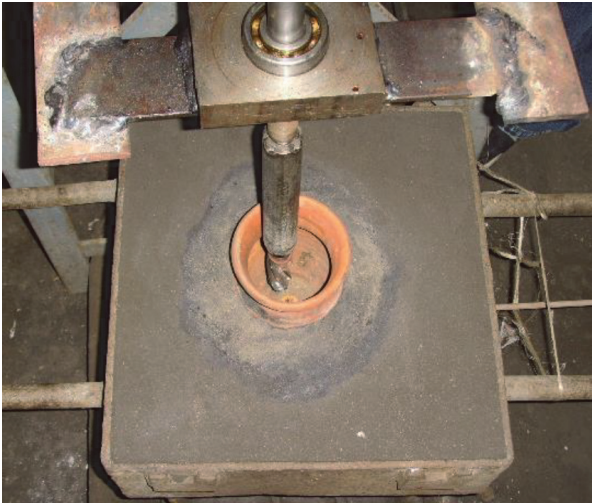


Figure 15.
Mold.



Figure 16.
Aluminum poured into the mold.



Figure 17.
Add calcium carbonate and stir it.



Figure 18.
Metallic foam.

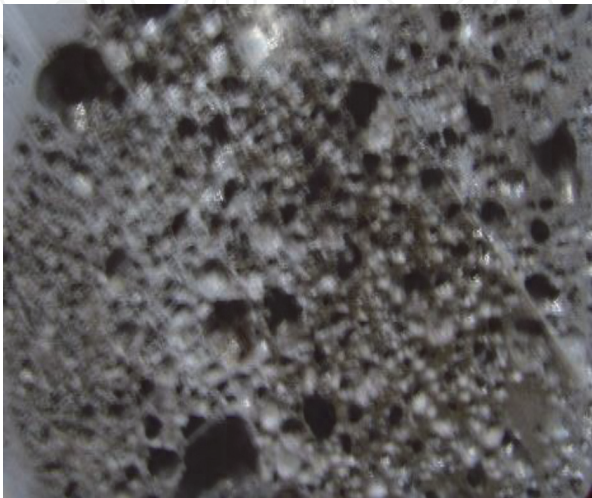


Figure 19.
Microstructure of metallic foam sample 4.

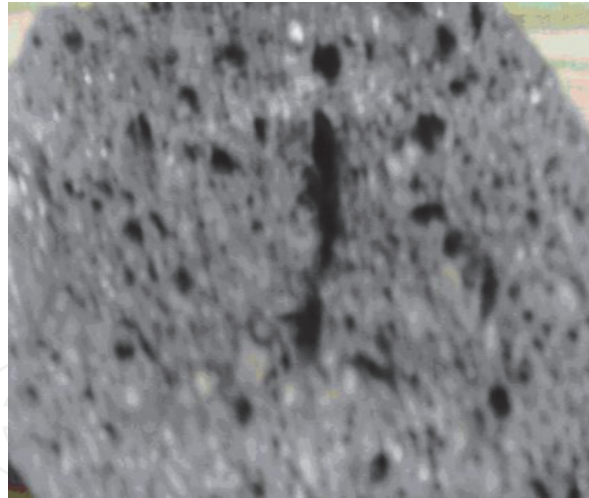


Figure 20.
Microstructure of metallic foam sample 4.

aluminum was cooled down, casting can be taken out from the mold. In **Figure 19** the microstructure of metallic foam that was produced was shown.

3.5 Experiment no. 5

Weight of aluminum = 776 g.
Amount of CaCO_3 = ?

Experiment 5 was not completed because the molten metal was drained out from the hole.

3.6 Experiment no. 6

Weight of aluminum = 330 g.
Amount of CaCO_3 = 6 g.

This was the sixth experiment in which the amount of aluminum was 330 g and amount of calcium was 6 g (2% of weight). The stirring time was 60 s. All procedure was the same as described above. The drainage time of the molten metal from the bottom hole was 60 s. The microstructure was shown in **Figure 20**.

4. Result

Test the aluminum that was used is pure or not, Archimedes' principle was used. In Archimedes' principle water taken in a bucket and that bucket was full of water at the top level. Then a piece of aluminum that was used for producing metallic foam was dipped into the water, and the water that was coming out from the bucket was collected into the next bucket. The weight of water was calculated and calculations that are given below are performed:

Weight of aluminum piece = 85 g.
Weight of water displaced out = 35 g.

$$\text{Density of water } \rho_w = \frac{m_w}{V_w} \quad (17)$$

$$v_w = \frac{m_w}{\rho_w} = 3.5 \times 10^{-5} \text{ m}^3.$$

The volume of water was equal to the volume of the aluminum piece:

$$\text{Density of aluminum: } \rho_{Al} = \frac{m_{Al}}{v_{Al}}.$$

$$\rho_{Al} = 2.42 \times 10^3 \text{ kg/m}^3.$$

The density of pure aluminum was $2.319 \times 10^3 \text{ kg/m}^3$.

So, there were some impurities in the aluminum that are used in this research.

5. Density of metallic foam

Cut a rectangular piece of metallic foam and take the weight of that piece.
Calculate the dimensions of piece also and find the volume of that piece:

$$\text{Dimension of piece} = 65 \times 20 \times 15 \text{ mm.}$$

$$\text{Volume of piece} = 1.9500 \times 10^{-5} \text{ m}^3.$$

$$\text{Weight of metallic foam piece} = 8.25 \text{ g} = 0.00825 \text{ kg.}$$

$$\rho_f = 0.4230 \times 10^3 \text{ kg/m}^3.$$

6. Conclusion

There is a large potential for metal foam applications. However, there are several deficiencies with the current technology. With these opportunities for the improvement identified, research objectives were set to design a new foam product and develop a new method of production to overcome the present shortcomings. Given the current results of this research work, it is evident that these areas for improvement have been addressed, and the knowledge gained from this work lends valuable information to plan future actions for further improvement to this product.

The system was designed, fabricated and controlled for aluminum foam generation. The obtained foam was tested, and the density of metallic foam was $0.4230 \times 10^3 \text{ kg/m}^3$.


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