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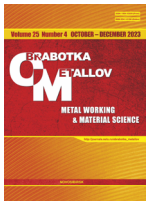

A synergistic approach to the development of lightweight aluminium-based porous metallic foam using stir casting method

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ABSTRACT

Introduction. A synergetic approach to the development of lightweight aluminium metal foam by stir casting process is presented and various mechanical properties and microstructure are tested. **The purpose of this study** is due to the constant industrial demand for lightweight materials and increased research interest in porous substrates, mainly due to its unique properties. **Materials and method.**. The method used for developing metallic aluminium foam was stir casting with calcium carbonate as a foaming agent to achieve a target interconnected porous microenvironment on a metal foam substrate. **Results and Discussion.** A set of physical properties, such as apparent density (1.8 g/cm^3), relative density (0.67 g/cm^3) and porosity (30 %) of the developed aluminium-based metal foams, is stated as the result. The developed metal foam has a strength-to-weight ratio 67 % higher than that of the base material. In addition, the results of field emission scanning electron microscopy of the developed metal foam confirm the presence of a porous network with a pore size from 0.075 mm to 1.43 mm. Energy dispersive spectroscopy confirmed the presence of the desired elements with minimal contamination in the developed aluminium foam substrates. Metal foam demonstrates a higher compressive strength (607 kN) compared to the base metal (497 kN). The mechanical characteristics of the developed metal foam substrate (hardness, compressive strength and impact energy) show the expected results compared to the base material. In general, the developed aluminium foam substrate established a promising route to the development of highly performance lightweight metal foam for shock absorber and acoustic applications.

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Introduction

Natural materials with a cellular structure, such as wood, bone, pumice stone and leaf structure, have historically found use due to its unique properties. Polymer foamed material, which is also called “man-made foam”, has a wide application and gives the object a unique structure. It is also used as a protective casing in various equipment, such as bicycle helmets, refrigerator enclosures, etc. [1]. The unique properties of natural cellular materials prompted researchers to develop a metal foam. The first metal foamed material was reported by *De Moeller* in 1925, but many authors referred to a patent dated from 1960 to 1970 [2]. The 2-D honeycomb structure has many of the metal foam’s mechanical properties. Compared to metal foam, honeycomb structures have a simple structure, although very similar; the cost of manufacturing metallic foam is high and, and its manufacturing technology is quite complicated. Among the methods of obtaining metal foam, casting and powder metallurgy are the most common. A large amount of metal foam is made from various materials such as steel, aluminium and titanium. Methods of electrodeposition, chemical vapor

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deposition and physical vapor deposition have also been used to produce more exotic foam [3]. Foam can be defined as a uniform diffusion of the gas phase in a liquid, while the cells and pores formed in the liquid, characterized by very thin films separating it. This structure provides relatively high stiffness and strength with low density and is used where it is necessary to significantly reduce the weight of the structure. The shape and size of the cells depend on the function of the structure and determine the effectiveness of the latter. Metal foam with an open structure absorbs the energy of compression strain well compared to metal foam with closed pores. The structure also resists sudden fracture well. Metallic foams can be divided into two categories: with closed pores and with open pores. For the production of the first category, the melting method or the powder metallurgy method is used. Generally, the melting method is a casting method that is used to produce metal foam with closed pores, whereas powder metallurgy is used to produce metal foam with open pores. Metal foam with closed pores can be obtained by three methods: by adding a blowing agent, by injecting an inert gas into the molten metal, and by a gas-eutectic reaction [4]. These processes require high initial investments. In powder metallurgy, a space holder technique and a foaming agent are added to the metal powder. The purpose of the development of metal foam is to obtain unique properties such as high stiffness, low specific weight, high gas permeability, low thermal conductivity, high impact absorption capacity, and electrical insulation. Various metal foams are developed from metals and alloys such as *Al*, *Al-Si*, *Al-Mg*, *Cu*, *Pb*, *Fe*, *Steel*, Ni_3A1, *Zn*, *Mg*, *Ti*, *Al-Cu*, *MMC*, metal glasses, etc. Among them, aluminium foam has received a tremendous development in industrial production.

Aluminium metal foam was developed using calcium carbonate as a foaming agent. The amount of calcium carbonate added to the composition for the formation of metal foam was 2.5 wt. % [6]. The density of the obtained material was 848 kg/m^3, the relative density was 0.342 [5].

The zinc content in aluminium foam with closed cell and the study of the effect of zinc on aluminium foam material.

The results showed that aluminium foam, which contains 4 wt. % *Zn*, has a better yield strength and a longer plateau section than aluminium foam, which does not contain zinc. Aluminium foam is fabricated by foaming the melt [7]. Two aluminium foam materials were fabricated by powder metallurgy using calcium carbonate and TiH_2. Calcium carbonate as a foaming agent demonstrates greater stability compared to TiH_2, therefore calcium carbonate is an expensive and effective gas-generating agent [8]. Zinc-aluminium alloy foam was obtained by stir casting method, and calcium hydride (CaH_2) was used as a foaming agent. The density of the resulting material varies from 0.25 g/cm^3 to 0.45 g/cm^3, and the porosity of 94 % is achieved in aluminium alloy foam metal by stir casting [9]. The melt route method is superior to other methods in terms of the required amount of capital and various requirements for the desired final form [10].

Improving the stabilization of aluminium foam and its cellular structure in the production process through the use of coated calcium carbonate as a foaming agent.

It is not necessary to additionally introduce a stabilizer into the molten metal, since a material that increases viscosity is formed during decomposition [11]. Based on the thermal decomposition and cellular structure, a foaming agent is added to the material [12]. It is noted that the temperature and mixing speed are the dominant parameters determining the ability of energy absorption by aluminium foam [13]. Aluminium metal foam is fabricated by the melt foaming method, and exhibits its mechanical properties under repeated impact load. The test results showed that the degree of damage to aluminium foam increases with an increase in the number of impacts [14].

Metal aluminium foam with open cells was developed using a steel mesh structure. In this study, the arrangement of cells is considered an important parameter for controlling mechanical properties [15].

For the manufacture of aluminium syntactic foams, the method of cold chamber die casting was used. The density of such foam material varied from 1.17 to 1.5 g/cm^3 and it was found that the foam material subjected to heat treatment becomes more brittle [16].

The open-pore material is made of biodegradable magnesium alloy through infiltration technique. Its porous structure is similar to that of a gyroid. Tests have shown that the Young's modulus of the obtained open-pore material is similar to the Young's modulus of the human trabecular bone [17].

The effect of cell size, partition thickness, and pore circulation on the compressive strength of aluminium foam was investigated using the *FEM* method. Aluminium foam is obtained by stir casting with the addition of titanium hydride (foaming agent) to the molten metal [18]. The purpose of this research paper is to successfully develop aluminium metal foam by stir casting and calculate the porosity of metal foam with various mechanical properties such as hardness, compressive strength, impact energy and these mechanical properties should be commensurate with the original aluminium material.

The methods of investigation

Materials

In this study, aluminium with medium strength and corrosion resistance is used as the main material. It is widely used in the automotive and aerospace industries. It has also found mechanical application, for example, in water-cooled manifolds, road transport fitting, etc. The chemical composition of commercial pure aluminium in weight percentages: *Si* (0.096), *Fe* (0.356), *Cu* (0.009), *Mn* (0.002), *Mg* (0.001), *Zn* (0.003), *Ti* (0.008), *V* (0.006) and *Al* (99.52). To create a metal foam, 500 g of aluminium with a density of 2.65 g/cm^3 and a melting point of 800 °C. were taken.

Calcium carbonate was used as a foaming agent, its density is 2.93 g/cm^3, the melting point is 825 °C. The optimal amount of foaming agent is 2.5 % of the weight of the aluminium material [6]. Calcium carbonate is an anhydrous and stable compound shown in fig. 1. Its advantages are that it decomposes slowly and therefore gives a better porous structure to the solidified metal.

Fig. 1. General view of calcium carbonate particles used as a foaming agent

Calcium carbonate decomposes into calcium oxide and carbon dioxide. Decomposition occurs when this foaming agent is added to molten aluminium. The aluminium obtained has a porous structure due to the release of carbon dioxide. Using these materials, a metal foam material with closed porosity was developed.

Method

Stir casting method

During the implementation of the stir casting process, the foaming agent and the base metal are evenly mixed and best wettability is achieved. A lower rotation speed of the stirrer and a short mixing time can lead to non-uniform mixing of calcium carbonate in molten aluminium, because of this, powder accumulation may occur in different places and as a result large voids will form in the final material. The mixing time is

an important factor for obtaining uniform porosity on the inner surface of the cast metal. Therefore, it is necessary to choose the optimal rotation speed of the non-stirrer and the mixing time. The graphite stirrer `used in this study is equipped with an electric motor and a speed controller, as shown in fig. 2. A clay pot mould, shown in fig. 3, was used to pour the molten metal.

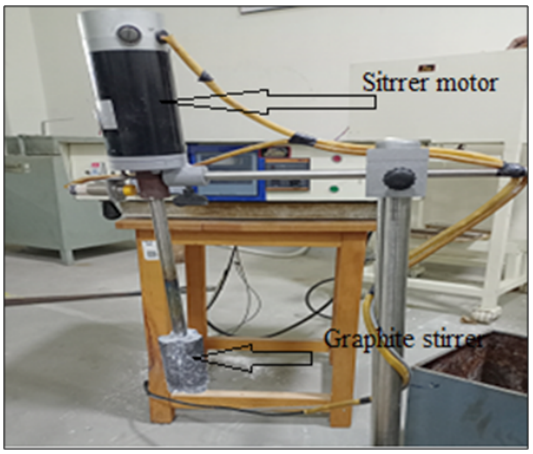


Fig. 2. Stir casting setup

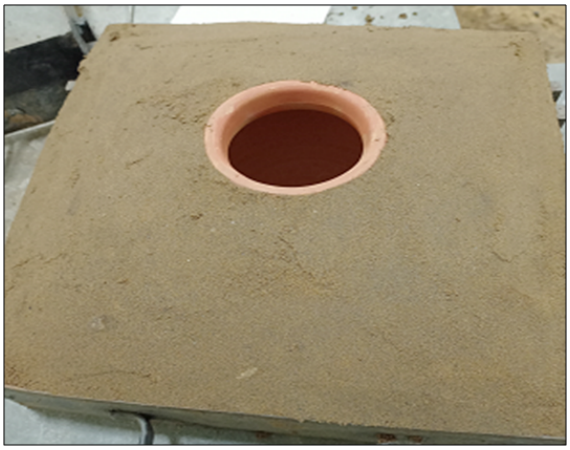


Fig. 3. Clay pot mould

Aluminium melt preparation

Aluminium was cut into small pieces and weight calculations were carried out. The pieces of aluminium were then placed in the crucible of an induction furnace for melting. The melting process was completed in 2.5 hours. Before pouring the molten aluminium into the mold, the slag was first removed from the molten metal, since it does not allow the foaming agent to mix thoroughly.

Pouring

Before pouring, the mold was preheated to about 300 °C in order to prevent instant solidification. After preheating, molten aluminium is poured into the mold. A mechanized stirrer was used to form metal foam, as shown in fig. 4. Calcium carbonate powder was added in three stages. At the first stage, 40 % of calcium carbonate was dispersed into the mold.

After that, molten metal was poured into the mold from the crucible. After pouring into the molten metal at a temperature of 750 °C, 30 % calcium carbonate was added again. After that, they started mixing. After a few minutes, a third part was added to the molten metal, that is, 30 % of the calcium carbonate powder. Aluminium molten metal was mixed for 4–5 minutes at 460 rpm. As a result of mixing, the calcium carbonate powder was uniformly distributed or thoroughly mixed with molten aluminium. After that, the mixture was left to decompose calcium carbonate inside the molten metal. During the decomposition of calcium carbonate, carbon dioxide is released, which should linger inside the molten metal. The metal foam covering the mouth of the pot is formed without the use of an agent that increases the viscosity, since it is formed during decomposition. The decomposition process is explained by the following reactions.

$$CaCO_3 = CaO + CO_2$$

$$2Al + 3CO_2 = Al_2O_3 + 3CO$$

$$8Al + 3CO_2 = 2Al_2O_3 + Al_4C_3$$

$$Mg + CO_2 = MgO + CO$$

$$2Al + Mg + 4CO_2 = MgAl_2O_4 + 4CO$$

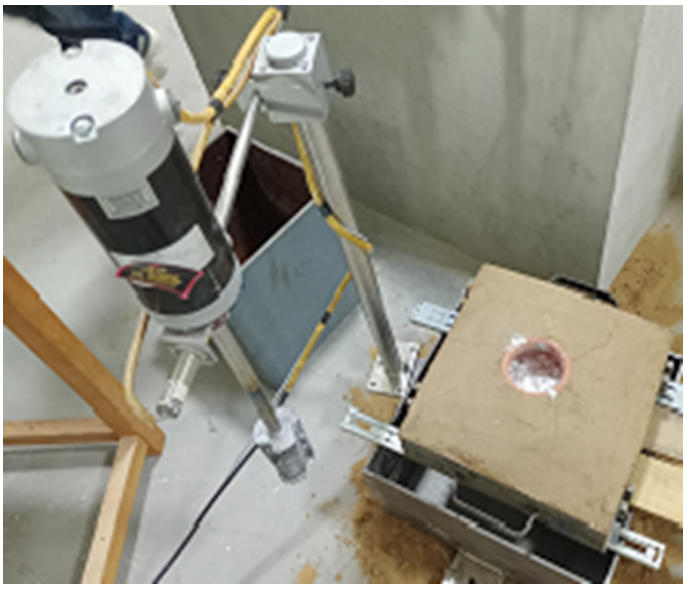


Fig. 4. Aluminium melt poured into the mould

Al_2O_3, Al_4C_3, and MgO increase the viscosity of the molten metal, which makes it difficult for the bubbles of gases released during the decomposition of calcium carbonate to rise. These gas bubbles create a porous structure of semi-solidified material. After an hour, the molten metal completely solidifies. The result is aluminium foam, as shown in fig. 5 and fig. 6. To analyse the inner surface of the resulting casting, it was cut into two parts using *EDM*.

Fig. 5. Solidified aluminium foam

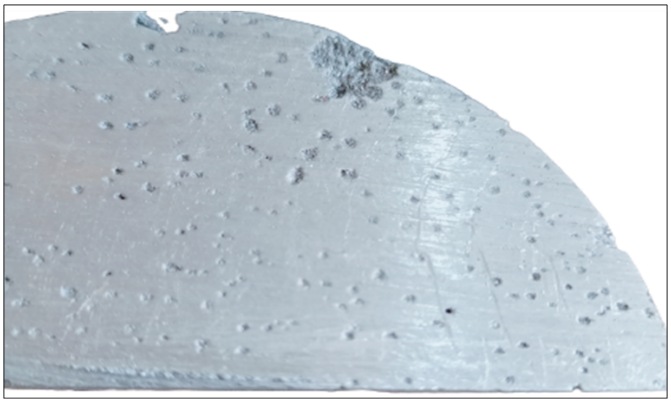


Fig. 6. Aluminium foam cut

Results and Discussions

After obtaining aluminium foam, its properties such as density, porosity percentage and microstructure were analysed.

Density and porosity

Density and porosity are crucial factors in the quality of the foam metal. If the foam density decreases, the porosity increases. In this study, the density was calculated.

- The mass of the specimen was measured using an electronic balance.
- The volume of the specimen was calculated.
- Relative density.

Density of aluminium metallic foam (ρ_{Alf})

$$\text{Density } (\rho_{Alf}) = \frac{\text{mass of aluminium foam}}{\text{volume of aluminium foam}}$$

Mass of aluminium foam (m_f) = 130 g
Dimension of specimen (aluminium foam) = 50×40×35 mm
The volume of specimen aluminium foam (V_f) = 70 cm^3
The density of aluminium foam (ρ_f) = 130/70

$$\rho_{Alf} = 1.8 \text{ g/cm}^3.$$

The density of the parent aluminium material from which the aluminium foam was formed (ρ_{Al})
The mass of the initial aluminium material (specimen) = 143.59 g.
Specimen size (initial aluminium material) = 60×41×22 mm.
The volume of the initial aluminium specimen = 54.12 cm^3.
The density of the base metal = 143.59/54.12.

$$\rho_{al} = 2.65\text{g/cm}^3.$$

Percentage porosity ($P_{\%}$)

$$\text{Percentage Porosity } (P_{\%}) = \frac{(\text{Density of parent aluminium}) - (\text{Density of aluminium foam})}{\text{Density of parent aluminium}};$$

$$\text{Percentage of porosity } (\text{P}_{\%}) = \frac{(2.65\text{-}1.8)}{2.65};$$

$$P_{\%} = 32\ \%.$$

Relative density (ρ_R)

$$\text{Relative density } (\text{R}) \quad \frac{\text{Density of aluminium foam material}}{\text{Density of parent aluminium material}};$$

$$(\rho_R) = 1.8/2.65 = 0.67.$$

The relative density is an important parameter characterizing the foamed material from the parent solid aluminium material. This is a comparison parameter that shows how much heavier a substance is than a standard substance. The estimated relative density is 0.67. This means that the weight of aluminium foam is 32 % less than that of parent solid aluminium. If aluminium foam is used instead of a solid aluminium part of the vehicle structure, then the weight of this part is reduced by 32 %. This type of material is necessary in the automotive and aerospace industries. Table 1 shows the various properties calculated for the developed aluminium foam.

Microstructure analysis

Field Emission Scanning Electron Microscope (*FE-SEM*) has been done to study the microstructure of aluminium foam produced with $CaCO_3$. Standard size specimen (8×8×4) was prepared for the microstructural analysis and its microstructure image is presented in fig. 7.

Table 1

Properties of Developed Metallic Foam

No.	Volume of Aluminium foam, cm^3	Mass of Aluminium foam, gm	Density, gm/cm^3	Percentage of Porosity, %	Relative Density
1	70	130	1.8	32	0.67

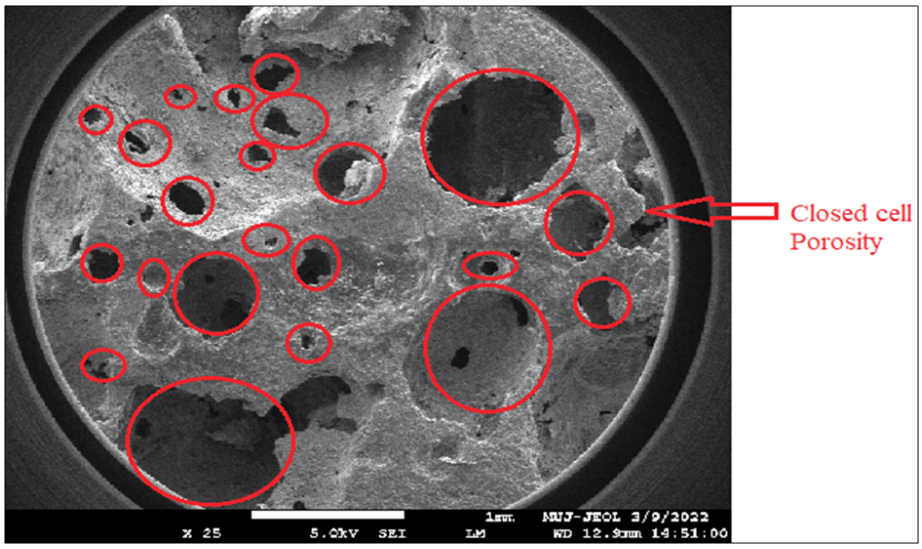
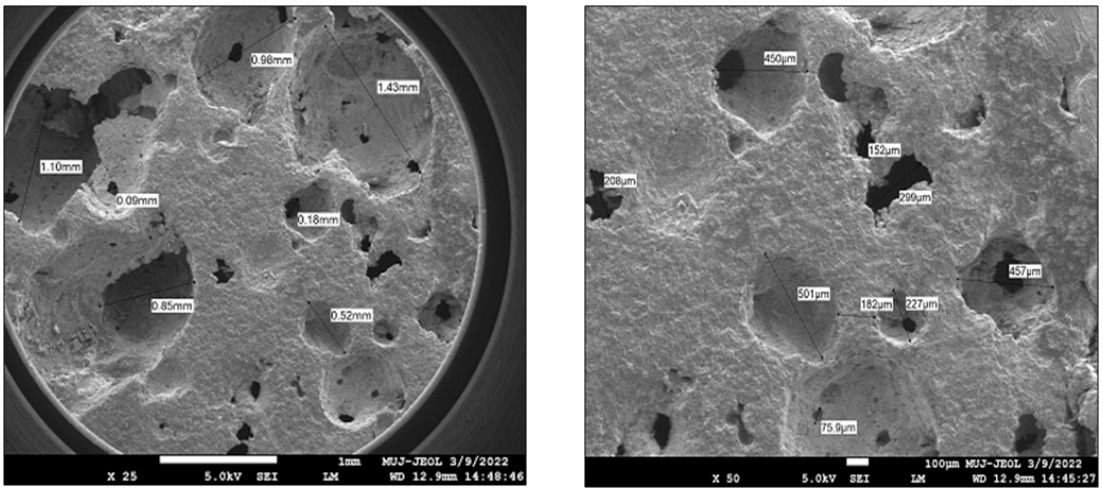


Fig. 7. Surface morphology of closed-cell aluminium foam (2.5 % calcium carbonate), observed using *FE-SEM*, is characterized by interconnected pores

The *FE-SEM* study allows us to estimate the value of the pore size and wall thickness. Pores of different sizes were formed in the resulting aluminium foam, as shown in fig. 8a, b. The largest pore size is 1.43 mm, and the smallest is 0.075 mm. One of the reasons for obtaining an uneven pore size is the non-uniform distribution of the foaming agent in molten aluminium. The uneven porosity of the aluminium foam has led to high internal strength. The distance between the pores varies from 0.40 mm to 1.97 mm. In fig. 8, *a*, *b* the resulting wall thickness varies from 0.182 mm to 0.40 mm.

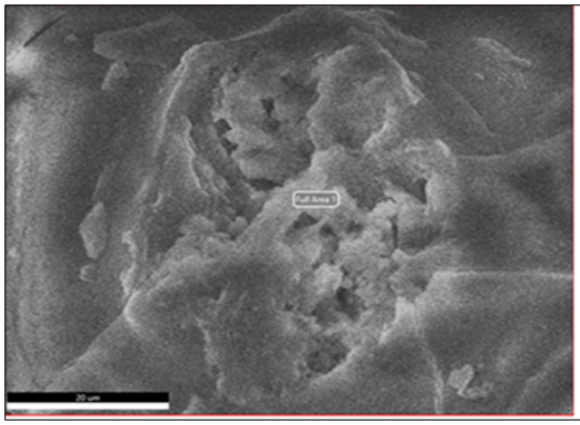


a *b*

Fig. 8. Pore size distribution of aluminium foam (*a*) 25× and (*б*) 50×

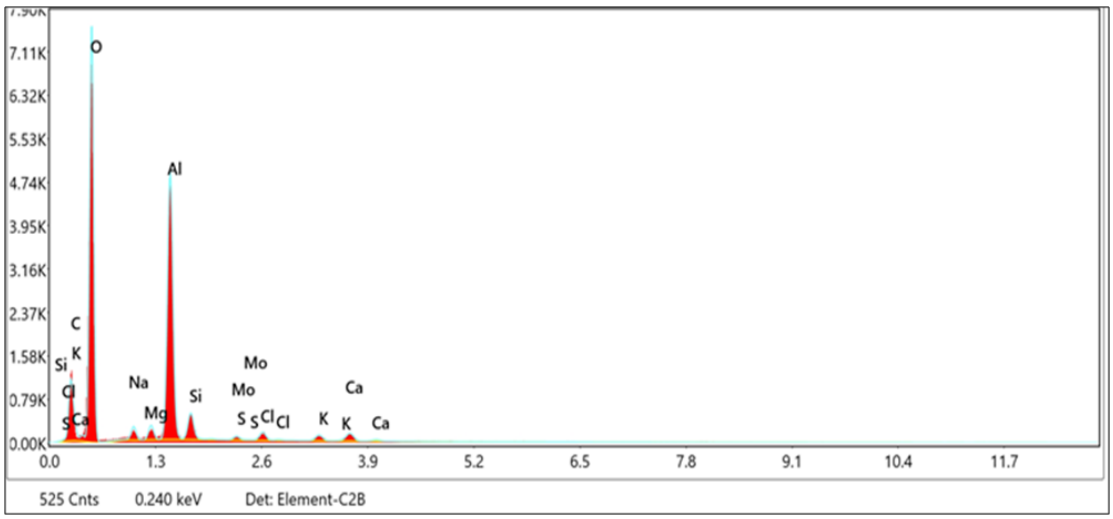
Energy dispersive spectroscopy (EDS) of Aluminium foam

To observe the presence of constituent element in the developed metallic foam EDS analysis was performed. Fig. 9, *a* shows the area focus consider for obtained the peaks within the specimen. While fig. 9, *b* shows the weight % of constituent elements with 3-sigma% error. Additionally, fig. 9, *c* shows the EDS spectra of also constituent elements with their respective intensities.



Element	Weight %	Atomic %	Error %
C K	20.4	27.9	10
O K	56.8	58.4	8.7
NaK	1.7	1.2	12.9
MgK	1.1	0.7	9.9
AlK	16.1	9.8	5.5
SiK	1.7	1	8.7
MoL	0.2	0	37.5
S K	0.2	0.1	24.5
ClK	0.6	0.3	12
K K	0.5	0.2	12.6
CaK	0.8	0.3	8.2

a *b*



c

Fig. 9. Elemental analysis of aluminium foam (*a*) mapping area, (*b*) weight %, (*c*) elemental spectra

Calcium, silicon, molybdenum and magnesium can be seen on the *EDS* pattern of the specimen. The amount of aluminium, oxygen, silicon and magnesium is 16.1; 56.8; 1.7 and 1.1, respectively. Silicon, magnesium and molybdenum are alloying elements of aluminium, but oxygen is not an alloying element. This EDS pattern indicates that aluminium foam has a high percentage of oxygen by weight. It is important that aluminium foam has a high level of porosity, since more gases are trapped inside the pores.

Mechanical properties of aluminium foam material

Charpy impact test

The *Charpy* impact test is used to test the strength of the material. It measures the energy absorbed by a V-notch specimen until the moment of destruction under impact load. The standard sample size is 55×10×10 mm and it has a notch of 45° across one of the dimensions [21]. The test results are presented in table 2. The impact energy absorbed by foamed aluminium is very close in values to the similar characteristic of the parent aluminium.

Table 2

Impact Test Results

No.	Specimen	Joules
1	Aluminium foam	4
2	Solid Aluminium	6

Rockwell hardness test

For the Rockwell hardness test, a rectangular sample was cut out of aluminium foam. A ball indenter made of high-carbon steel (1/16”) was chosen for testing. Initially, a minor load of 10 kgf was applied to the surface of the material, this minor load does not depend on the material. After that, the main load of 100 kgf was applied to the surface of the material for 30 seconds. The hardness value was measured in three tests, the corresponding hardness values are shown in table 3. It was observed that the resulting aluminium foam has a high hardness compared to the parent aluminium material. Specimen 1 is the aluminium foam obtained in the work, and Specimen 2 is the parent solid aluminium.

Table 3

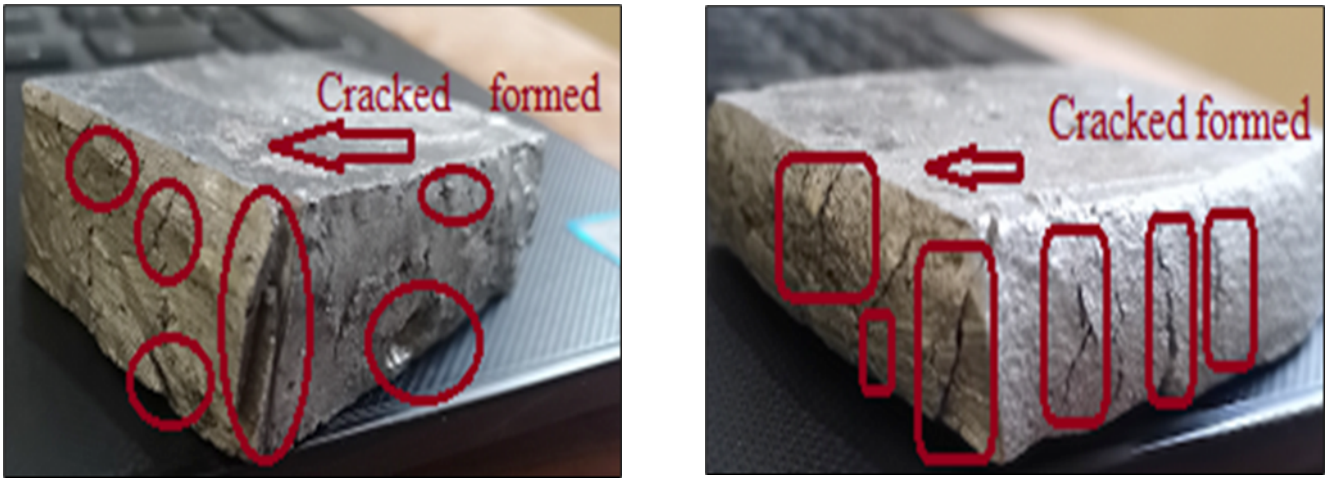
***Rockwell* Hardness test results (HRB)**

Specimen	Trail 1	Trail 2	Trail 3	Average
Specimen 1	77	76	80	77.6
Specimen 2	24	28	25	25.6

Compression test

The compressive strength of the aluminium foam material was determined on a compression-testing machine (C.T.M). To do this, rectangular specimens were cut out of aluminium foam material and parent solid aluminium, after which the specimens were placed on the C.T.M table and a load was applied to it.

After applying a compressive load, both specimens were deformed, and its size changed, as shown in fig. 10, *a*, *b*. The resulting compressive strength for aluminium foam and the parent aluminium material is 607 kN and 493 kN, respectively.



a *b*

Fig. 10. Deformed aluminium foam (*a*), parent material (*b*)

Fig. 11 shows the deformation of aluminium foam. The displacement of the specimen is directly proportional to the applied load up to 700 KN. When a load is applied, the specimen can be broken into pieces, while the porous structure is damaged. The maximum observed compressive load is 760 KN, and the maximum displacemrnt is 17 mm. The offset percentage is 51 %.

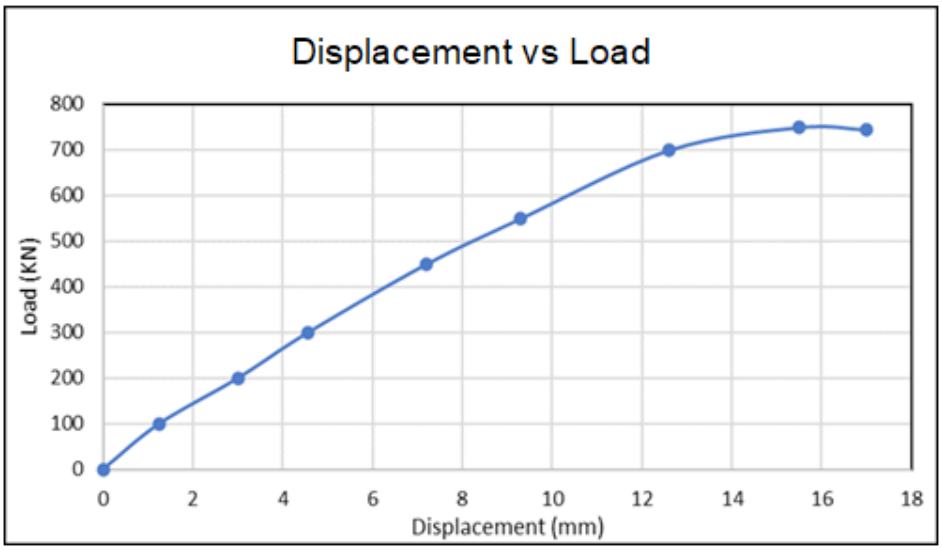


Fig. 11. Graph for dependency of displacement (mm) on load (kN) of the foam aluminium material specimen

Conclusions

An aluminium foam material was developed using calcium carbonate as a foaming agent. It was not necessary to additionally introduce a stabilizer into the molten metal, since a material that increases viscosity is formed during decomposition. A mechanized stirrer was used to form metal foam. The developed foam material has a higher compressive and impact strength compared to the parent solid material. For the developed foam material, the following can be noted:

- The developed metal foam has a strength-to-weight ratio 67 % higher than that of the parent material.
- The pore size ranges from 0.075 mm to 1.43 mm, which allows the metal foam to better absorb impact energy.
- The hardness of the foam material is 52 HRB higher than that of the parent solid material.
- The foam material demonstrates higher compressive strength (607 kN) compared to the parent metal (497 kN).
- Due to its low density and high compressive strength, the developed foam material will be useful in the automotive industry, where a lightweight material with high strength is required.

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Conflicts of Interest

The authors declare no conflict of interest.