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FABRICATION AND CHARACTERIZATION OF HYBRID COMPOSITE ALUMINUM FOAM FOR STRUCTURAL APPLICATIONS

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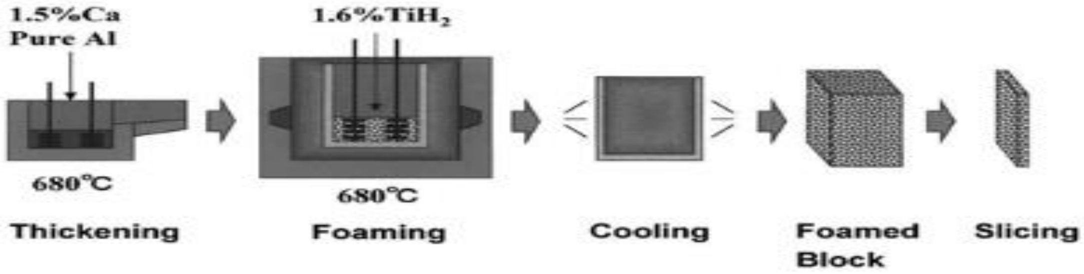
ABSTRACT
The mechanical behaviour of an aluminium metal matrix composite foam structure under quasi-static uniaxial compressive loading (compressive strength, energy absorption behaviour, stress-strain characteristic behaviour) has been studied in this work. The aluminium alloy Al 7075 is used in the foam structure, and it is reinforced with weight SiC (1%, 2%, 3%, 4%, 5%), B_4C (5%, 4%, 3%, 2%, 1%) particles. Using a high-resolution optical zoom microscope image, the microstructural surface morphology of the manufactured metallic foam samples was also examined for the aforementioned composition. The analysis included pore size, porosity percentage, and distribution, as well as cell wall thickness. For all characterisation investigations, wire EDM was used to cut samples with dimensions of 3 cm x 2 cm x 2 cm from the As-cast ingot, which had a diameter of 5 cm and a length of 10 cm.

Keywords: Aluminium, Metal Matrix Composite, Foam Structure, Compressive Loading, Microstructural Analysis, Wire EDM

INTRODUCTION
Aluminium metal foams, characterized by a high porosity range of 75–95%, are emerging lightweight materials ideal for applications requiring energy absorption, thermal insulation, and structural integrity. Their unique cellular structure—achieved by methods such as powder processing, melt-route foaming, and infiltration—makes them suitable for automotive, aerospace, military, and acoustic uses. Among these, the ALPORAS process stands out for producing uniform pore structures using blowing agents like $CaCO_3$ and TiH_2. In this study, AA 7075 alloy was selected due to its high strength and relevance in load-bearing applications. Foams were synthesized via the liquid metallurgy route with varying $CaCO_3$ weight fractions to evaluate pore distribution and mechanical performance. The results aim to advance the application of aluminium sandwich foams in dynamic environments such as defense and transportation.



Direct foaming of melts with blowing agents ("Alporas"-process).

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OBJECTIVES

The primary aim of this project is to fabricate hybrid aluminum foam and characterize its properties for structural applications. This involves using aluminum alloy Al 7075, reinforced with varying weight percentages of SiC and B_4C particles. The project seeks to analyze the mechanical behavior of the resulting composite foam structure under compressive loading, assessing compressive strength, energy absorption, and stress-strain characteristics. A key component of this analysis includes examining the microstructural surface morphology to evaluate pore size, porosity, and cell wall thickness. The overall goal is to develop a hybrid aluminum foam with enhanced properties suitable for structural applications.

LITERATURE REVIEW

1. **Ashby et al.** were pioneers in the field of cellular solids, offering a comprehensive classification of metal foams based on their physical structure. Their work emphasized the multifunctional capabilities of aluminium metal foams (AMFs), particularly their high stiffness-to-weight ratios, damping capacity, and energy absorption, making them suitable for aerospace and automotive industries.
2. Researchers have extensively explored the mechanical and thermal behavior of open-cell and closed-cell foams. Open-cell foams provide better acoustic and thermal insulation, while closed-cell foams offer superior mechanical strength and energy absorption, making them ideal for impact-resistance applications.
3. **Banhart** introduced the ALPORAS method, a widely adopted liquid metallurgy process, for producing aluminium foams using titanium hydride (TiH_2) as a blowing agent. While effective, TiH_2 has limitations due to its relatively low decomposition temperature, making it unsuitable for high-melting-point aluminium alloys and economically less viable.
4. To overcome the limitations of TiH_2, recent studies have investigated alternative, cost-effective blowing agents like calcium carbonate ($CaCO_3$). **Doege et al.** demonstrated that $CaCO_3$ decomposes at around 723 °C, producing finer, more uniform pores and making it a promising alternative for use in aluminium foam production.
5. **Singh and Pandey** showed that $CaCO_3$-based foaming results in aluminium foams with improved structural homogeneity, better control over porosity, and enhanced energy absorption, making them suitable for load-bearing applications and crash protection systems.
6. The melt-route method (liquid metallurgy technique) has remained the most feasible and scalable method for producing aluminium foams. However, it is prone to challenges like achieving uniform pore distribution and preventing gas bubble coalescence, necessitating process control mechanisms like efficient stirring and melt stabilization.
7. **Miyoshi et al.** examined the thermodynamic and kinetic factors influencing gas bubble formation during the foaming process. They emphasized that a stable and uniform foam structure can be obtained by controlling the temperature and achieving near-equilibrium conditions before blowing agent addition.
8. Several aluminium alloys have been explored for foam production, including AA5083, A356, LM13, and Al-Zn-Mg series, each chosen for their mechanical and thermal compatibility with foaming processes. However, alloys like AA7075 are gaining popularity due to their high strength and lightweight nature.
9. **Zhu et al.** found that AA7075 aluminium alloy foams exhibit superior impact resistance and energy absorption, particularly useful in high-stress applications such as defense, rail, and aerospace sectors. Their findings suggest that AA7075 is an ideal candidate for Aluminium Sandwich Foam (ASF) panels used in crash-resistant vehicle structures.
10. The present study builds upon these findings by exploring AA7075 aluminium foams synthesized using $CaCO_3$ as a blowing agent through the melt-route process. The goal is to determine the optimal weight fraction of $CaCO_3$ that produces foams with the best combination of pore uniformity, density reduction, and mechanical strength.

METHODOLOGY

The experimental work was conducted using AA7075 aluminum alloy as the matrix material. Reinforcements such as silicon carbide (SiC), boron carbide (B_4C), and graphene (Gr) were selected to improve the mechanical and microstructural characteristics of the final foam. Calcium carbonate ($CaCO_3$) was used as the blowing agent due to its effective gas-releasing property upon decomposition.

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A stir casting technique was employed to fabricate the hybrid aluminum foam. The aluminum alloy was melted at approximately 750°C in a graphite crucible. Reinforcements and $CaCO_3$ were preheated and then added to the molten metal while stirring at 450 RPM to ensure homogeneous dispersion. The mixture was held for 5 minutes before rapid solidification using compressed air cooling.

Process parameters included:

- **Base Alloy**: AA7075
- **Reinforcements**: SiC and B_4C (1–5 wt.%), Graphene (0.5 wt.%)
- **Blowing Agent**: $CaCO_3$ (1%, 2%, and 3% by weight)
- **Stirring Speed**: 450 RPM
- **Foaming Temperature**: ~750°C
- **Holding Time**: 5 minutes

After fabrication, the samples were subjected to various tests:

- **Mechanical Testing**: Compression testing was performed using a 100 KN UTM to determine compressive strength, modulus of elasticity, and energy absorption capacity.
- **Thermogravimetric Analysis (TGA)**: Conducted to determine the decomposition range of $CaCO_3$ (~600–740°C).
- **Microstructural Characterization**: Carried out using optical microscopy and SEM to evaluate pore morphology, reinforcement distribution, and cell wall integrity.

Experimental Procedures

Ingredients:

The project uses Al 7075 alloy reinforced with varying weight percentages of SiC (1%-5%) and B_4C (5%-1%) particles to fabricate the foam structure.

ELEMENT (AA 7075)	Mg	Si	Cu	Fe	Ti	Cr	Zn	Mn	Al
Weight %	2.1	0.4	0.25	0.12	0.2	0.18	5.1	0.2	Balance

Density (r_s)	2.8 g.cm^{-3}
Compressive Elastic Modulus (E_s)	72 Gpa
Compressive Yield strength (s_s)	105 Mpa

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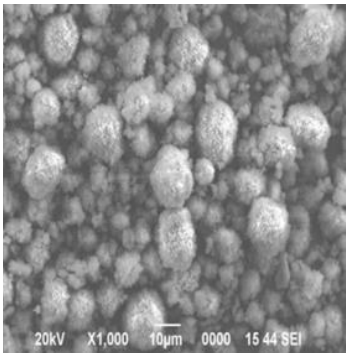
Determination of particle size of $CaCO_3$ by SEM

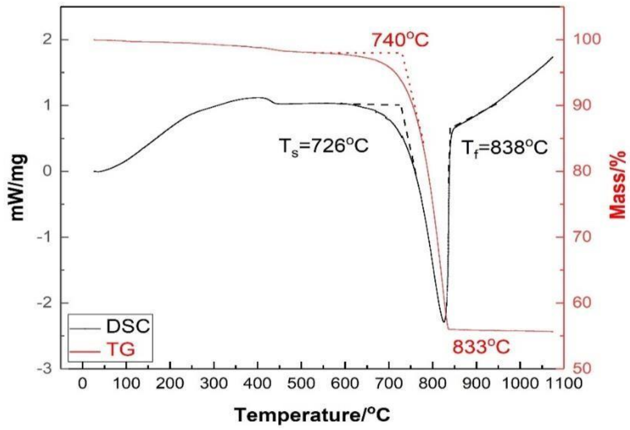
The particle size of $CaCO_3$ was determined by Scanning Electron Microscopy (SEM).



Scan Electron image of $CaCO_3$ particles.

Thermogravimetric analysis of $CaCO_3$

The Thermogravimetric Analysis was used to analyze the decomposition temperature of the blowing agent



Calcium carbonate thermogravimetric curve.

Aluminum foam samples preparation

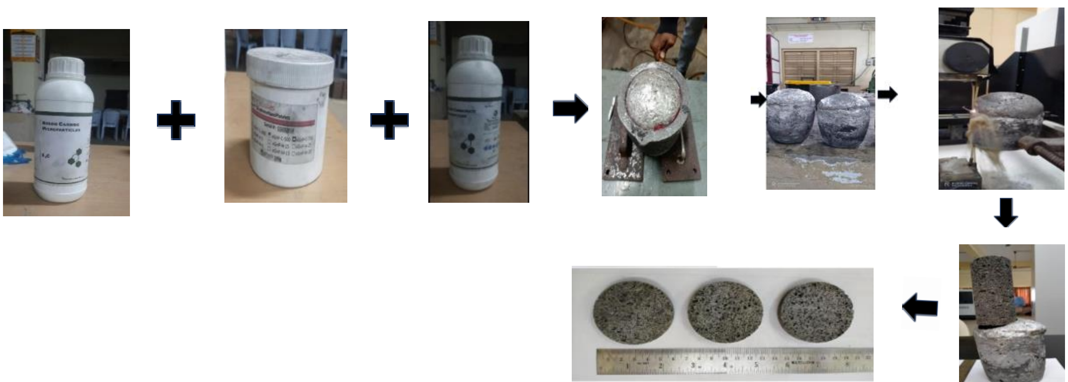


Figure 5: Foam Preparation Procedure

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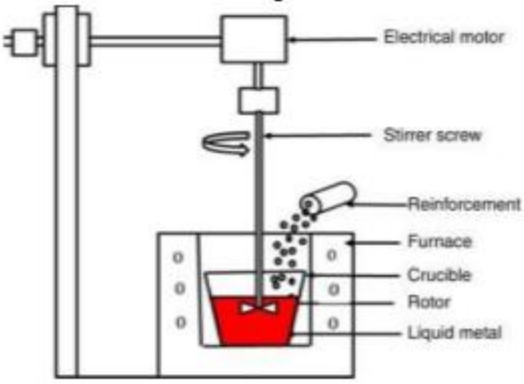
Stir casting machine



Wire cut EDM

Rectangular specimen

RESULTS AND DISCUSSION

Characterization of physical and mechanical properties

Physical Properties:

- Relative density of aluminum foam produced
  The relative density of aluminum foam produced was determined by the mass to volume ratio
- Measurement of density by the mass to volume ratio
  Density was measured by taking the mass to volume ratio.
- Microscopy of aluminum foam
  Microscopy of aluminum foam helps in analyzing the structure, pore size and distribution.

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Micrograph of AA 7075 with different weight ratio of $CaCO_3$

The samples with high content of B_4C and SiC did not give any proper expansion due to the increase in the melt pool viscosity.

Mechanical Properties:

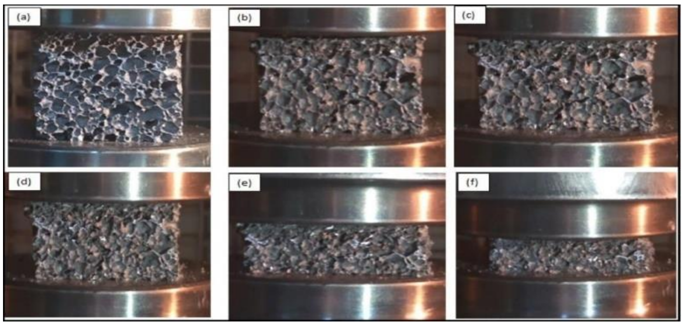
- Uniaxial Compression
  Mechanical properties are important properties to determine the behavior of prepared foam structures. For all the mechanical properties compression tests were conducted as per ASTM standards. The prepared samples are subjected to quasi-static uniaxial compression

- Experimental determination of compressive properties

Compression Testing Machine

This is the UTM used to test the compression strength of the sample.

The universal testing machine is used for the testing of the samples with a 10kN load cell. The machine is displacement controlled with a constant speed of 2mm/min.



Foam structure at different strains up to 70% (aluminum foam relative density=0.14)
(a) Strain 0% (b) Strain 20% (c) Strain 30% (d) Strain 40% (e) Strain 50% (f) Strain 70%

This figure shows the foam at different compression strains and also shows the deformation of the specimen in the UTM. It shows that the deformation happens layer by layer.

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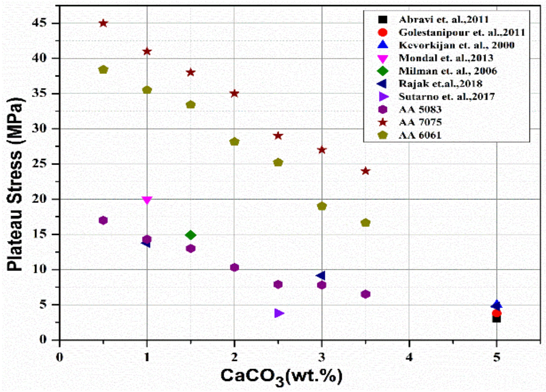
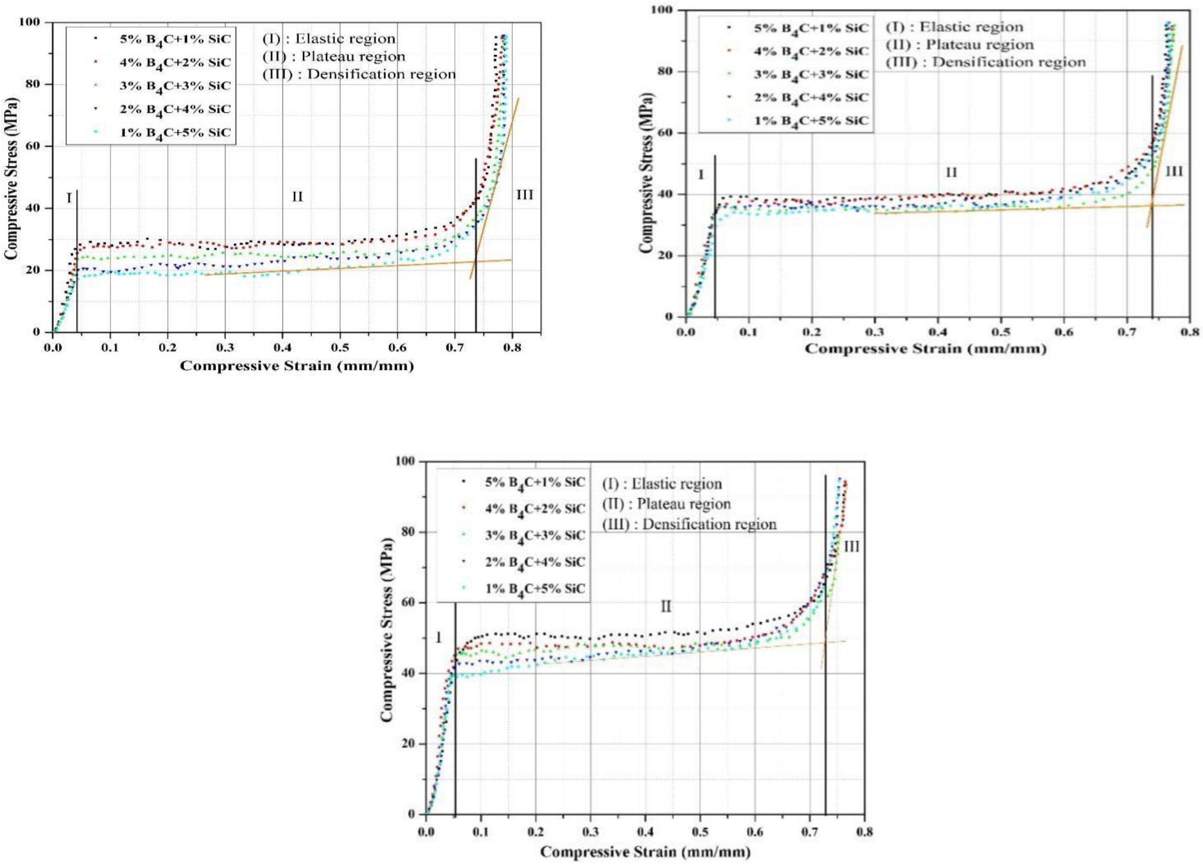


Comparison of plateau stress ~ wt. % of $CaCO_3$ for present investigation with previous studies;



(c) Compressive stress and strain plot of AA 7075 foam with 1, 2, 3 wt. % of $CaCO_3$ blowing agent.

From the above graph it is evident that the aluminum foam shows the mechanical nature towards the various loads applied.

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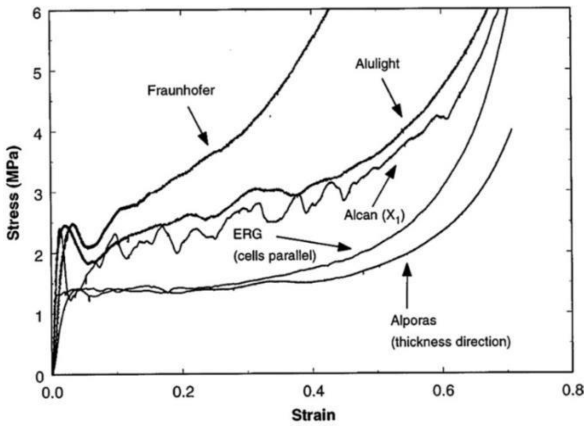
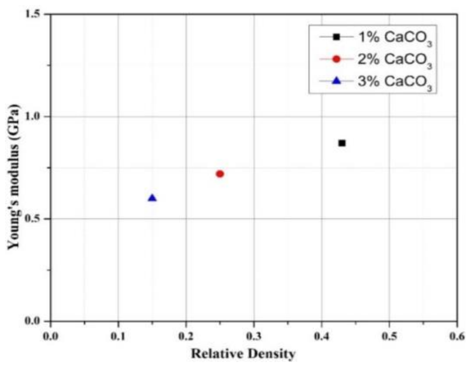
Compressive stress–strain curves of typical aluminum foams

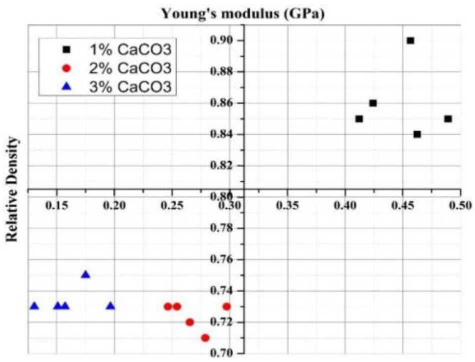
This figure illustrates stress-strain curves of the typical aluminum foams, which reveals different stages of deformation.



Young's modulus against relative density for foamed aluminum 6061

This graph plots Young's modulus as a function of relative density, showcasing the relationship between these properties.





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Investigated by	**$CaCO_3$ wt. %**						
Present work hybrid composite AA 7075		1		2		3	
Youngs's Modulus (GPa)		0.87		0.72		0.60	
Plateau stress (MPa)		46.8		37.38		24.78	
Densification strain (%)		0.7		0.73		0.74	
AA 5083	0.5	1	1.5	2	2.5	3	3.5
Youngs's Modulus (GPa)	0.31	0.41	0.27	0.17	0.20	0.18	0.17
Plateau stress (MPa)	16.3	14.3	12.5	10.5	8.2	7.5	6.5
Densification strain (%)	0.51	0.53	0.55	0.56	0.58	0.63	0.65
AA 7075	0.5	1	1.5	2	2.5	3	3.5
Youngs's Modulus (GPa)	1.18	1.03	1.00	0.88	0.74	0.63	0.56
Plateau stress (MPa)	45	41	38	35	29	27	24
Densification strain (%)	0.52	0.54	0.57	0.61	0.64	0.65	0.67
Present work AA 6061	0.5	1	1.5	2	2.5	3	3.5
Youngs's Modulus (GPa)	1.25	1.1	0.84	0.74	0.61	0.52	0.49
Plateau stress (MPa)	38.41	35.49	33.40	28.15	25.21	19.01	16.64
Densification strain (%)	0.58	0.62	0.65	0.66	0.66	0.66	0.66
Abravi et al.,2011 [25]	1	3	5	-	-	-	-
Youngs's Modulus (GPa)	0.48	0.36	0.12	-	-	-	-
Plateau stress (MPa)	12.5	10	3.9	-	-	-	-
Densification strain (mm/mm)	0.42	0.40	0.58	-	-	-	-
Rajak et al., 2019 [31]	1	3	5	-	-	-	-
Youngs's Modulus (GPa)	0.43	0.25	0.17	-	-	-	-
Plateau stress (MPa)	13.2	11.4	5.6	-	-	-	-

Table-1:Mechanical Properties of AA7075 Aluminum Foam Composites

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AA 7075 + wt. % $CaCO_3$	Relative density	Density ($g.cm^{-3}$)	Elastic modulus (GPa)
5% B_4C+1% SiC + 0.5 Gr	0.4626	1.3	0.84
4% B_4C+2% SiC + 0.5 Gr	0.4567	1.2833	0.97
3% B_4C+3% SiC + 0.5 Gr	0.4893	1.375	0.85
2% B4C+4% SiC + 0.5 Gr	0.4122	1.1583	0.85
1% B_4C+4% SiC + 0.5 Gr	0.4241	1.1917	0.86
5% B_4C+1% SiC + 0.5 Gr	0.2788	0.7833	0.71
4% B_4C+2% SiC + 0.5 Gr	0.2654	0.7458	0.72

Table-2:Elastic modulus of foamed aluminum with wt.% $CaCO_3$ to the base AA 7075 alloy

Table(1) and Table(2) show the various result of the compression test. The aluminum 7075 is more preferable in comparing with the other aluminum alloy. The different composition gives rise to the varying mechanical strength.

CONCLUSION

This project successfully fabricated and characterized hybrid composite aluminum foam for structural applications. The mechanical behavior of the aluminum metal matrix composite foam structure under quasi-static uniaxial compressive loading was studied with Al 7075 alloy reinforced with weight SiC and B_4C particles. Microstructural surface morphology was also examined. The project has yielded valuable insights into the relationship between the material composition, processing techniques, and the resulting physical and mechanical properties of the foam. These findings contribute to the broader understanding of aluminum foam technology and offer a foundation for future research and development in this field.

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