STRUCTURAL AND MECHANICAL CHARACTERIZATION OF ALUMINIUM FOAMS

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ABSTRACT

Aluminium foam is a lightweight, porous material made by introducing gas bubbles into molten aluminium alloy. Aluminium foams are low-density, high-stiffness materials with excellent energy absorption, ideal for automotive, aerospace, and structural engineering applications. This study focuses on the structural and mechanical characterization of aluminium foams to better understand their behavior under various loading conditions. This research includes Al-Cu-TiB_2. A detailed analysis of the macrostructural parameters such as cell size and pore size distribution are done using ImageJ software. Mechanical Characterization is done by Uniaxial compression testing to evaluate the plateau stress, energy absorption capacity of the foams. Mean cell Diameter for the foam is 2.85mm. The Average Circularity is 0.83. The energy absorption is 9.3MJ/m^3. The foams have good energy absorption due to nano particles of TiB_2. Findings from this study are essential for optimizing the design and use of aluminium foams in engineering applications where weight reduction and impact resistance are critical.

Keywords:
Aluminium Foams, Cell Size, Pore Size Distribution, Plateau Stress, Energy Absorption Efficiency.

1. Introduction

The need for replacement of structural materials in the automotive, aerospace, and allied industries are increasingly adopting innovative materials like lightweight composites and advanced alloys to enhance safety, performance, and sustainability while reducing emissions. This shift, driven by evolving regulatory demands and consumer preferences, aims to improve fuel efficiency and durability. However, challenges like high costs, supply chain disruptions, and technical complexities persist. Despite these hurdles, the transition highlights the industry's commitment to balancing efficiency, cost, and environmental goals.

1.1 Why Metal Foams

Metal foams are lightweight, high-strength materials ideal for aerospace and automotive applications, offering excellent energy absorption during impacts. Their porous structure provides effective vibration damping, reducing noise and enhancing performance. Additionally, their high surface area improves heat transfer, making them valuable for radiators, heat exchangers, and thermal management systems.

1.2 Metal Foam

Metal foam is a material with a dispersed gaseous phase within a solid metallic matrix, formed by solidifying liquid metal with bubbles. The resulting pores create two types of foams: closed-cell, with isolated, non-connected cells, and open-cell, with interconnected pores. This study focuses on closed-cell foams. Each cell consists of thin walls, Plateau borders (junctions of three cell walls), and nodes (junctions of four borders), forming a unique porous structure.

1.3 Aluminium Foam

Aluminium foams are lightweight, porous materials created by introducing gas into molten aluminium, forming a sponge-like structure. They exhibit high strength-to-weight ratios, energy absorption, and thermal conductivity, making them ideal for automotive, aerospace, and construction applications. The foam's porous nature also supports sound absorption, impact resistance, and insulation. Tailoring pore size and distribution enhances their mechanical properties for diverse uses. Aluminium foam is corrosion-resistant, durable, and versatile, commonly used in crash protection, lightweight structures, insulation, and packaging. It is produced in sheets or blocks and customized for specific applications, making it invaluable in modern engineering.

1.4 Properties of Aluminium Foams:

Figure 1.1 represents the classification of Properties Aluminium foams such as Structural and Mechanical Properties. Aluminium foams are lightweight and have high energy absorption, making them excellent for impact protection and crashworthiness. They exhibit good thermal insulation and sound absorption due to their porous structure. Aluminium foams also have high plateau strength, which means they can withstand significant stress before collapsing. They are corrosion-resistant, enhancing their durability.

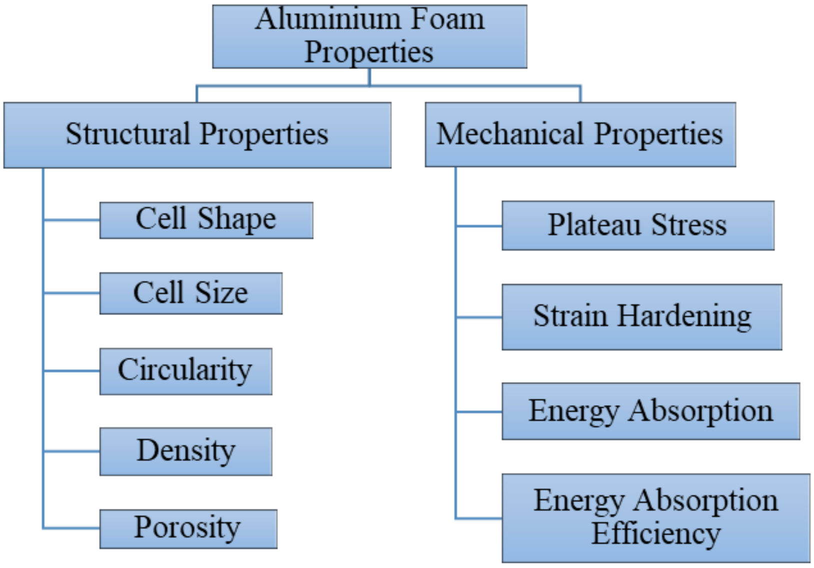

Figure 1.1: Classification of Properties of Aluminium foams

1.5 Advantages of Aluminium Foams

Aluminium foams are lightweight with a high strength-to-weight ratio, ideal for aerospace and automotive applications, improving fuel efficiency and crash absorption. They offer excellent thermal conductivity for cooling systems, strong corrosion resistance for marine environments, and effective sound and vibration damping for industrial machinery. Customizable and versatile, aluminium foams find use in structural components, insulation, and emerging foam panel technologies.

1.6 Disadvantages of Aluminium Foams

Aluminium foams are expensive to produce due to complex manufacturing processes, limiting their use in cost-sensitive industries. They offer lower structural strength and load-bearing capacity compared to solid metals, making them unsuitable for high-stress applications. Their porous structure complicates machining and can lead to material waste. Under extreme stress, aluminium foams may fail unpredictably, and variations in pore size and density result in inconsistent mechanical properties, posing challenges for reliable mass production.

1.7 Application of Aluminium Foams

Aluminium foams are used across industries for their unique properties. In automotive crash absorption systems, they dissipate energy effectively, making them ideal for bumpers, door panels, and crumple zones. Aerospace applications leverage their high strength-to-weight ratio for lightweight components like panels and beams, enhancing fuel efficiency and load capacity. Their porous structure aids in thermal management, dissipating heat efficiently in electronic devices. Aluminium foams also excel in soundproofing and vibration damping, reducing noise pollution in buildings and industrial equipment. In marine environments, they provide lightweight, corrosion-resistant solutions for ship hulls and other structures. Additionally, architectural uses include building facades for aesthetics, thermal insulation, and innovative lightweight designs.

2. Literature survey

Hui Zhou et al.,[1] studied the CFRP-FA-FW structure, reporting a 113.55% increase in energy absorption and a 60.73% increase in specific energy absorption over the CFRP-FA structure. Fiber lay-up angles [0°/90°] ns and [45°] ns optimized energy absorption, further enhanced by increased carbon fibre lay-up thickness. The relative density of aluminium foam minimally affected axial deformation, while finite element simulations validated the findings and explored parametric effects.

V.G. Belardi et al.,[2] introduced a beam finite element (FE) model for open-cell aluminium foams using Kelvin cells to simplify traditional 3D modelling. Elastic properties were calibrated via homogenization and optimization using the NSGA-II genetic algorithm. This approach accurately replicated the orthotropic elastic behaviour of aluminium foams with reduced computational effort, highlighting its efficiency and practicality.

Qiang Gao et al.,[3] enhanced aluminium foam sandwich (AFS) panels by incorporating copper-coated carbon fibres (Cf) using the packing rolling powder metallurgy method. Synchrotron X-ray imaging revealed that Cf improved nucleation rates, foaming stability, and minimized defects. Cf/AFS showed finer pores, better wettability, and reduced coalescence. Compression tests indicated a 40.6% increase in strength and 84.8% higher energy absorption compared to AFS.

E. Smyrna iOS et al.,[4] analysed the impact behaviour of metal foams, highlighting factors like velocity, strain rate, and micro-inertial effects. Realistic finite element method (FEM) models, incorporating macro- and micro-level characteristics, were developed to predict yield and energy absorption in closed-cell aluminium foams. Two approaches were a cell-based method using Voronoi tessellation and an isotropic, strain-hardening continuum model by Deshpande-Fleck. These models effectively reduce reliance on extensive experimental testing.

Zichen Zhang et al.,[5] examined the three-point bending behaviour of integral-forming aluminium foam sandwich (IFAFS) panels under flatwise and edgewise conditions, finding edgewise bending to be more stable. Varying span lengths revealed failure modes: oblique core shear, asymmetric surface fracture, and symmetrical surface fracture. Porosity mutations-initiated cracks, underscoring the need for homogeneous pores to enhance performance and predictability. Anisotropy and internal strain vortex effects influenced directional performance, while micropore connections during deformation contributed to failure. Optimizing pore distribution, structural symmetry, and pore wall thickness are key for improving bending performance.

S. Bhogi et al.,[6] highlighted the benefits of ultrasonic treatment in aluminium foams reinforced with in-situ $MgAl_2O_4$ particles. This treatment improves particle dispersion, refines the microstructure, and enhances foam stability and mechanical performance. Ultrasonically treated foams demonstrated higher compressive strength and energy absorption than conventional foams due to better particle distribution and smaller particle sizes. The in-situ formation of $MgAl_2O_4$ also improved wettability and foam stability. These findings confirm ultrasonic techniques effectively optimize foam properties for diverse applications.

S. Bhogi et al.,[7] studied metal matrix composite (MMC) foams containing TiB_2 nanoparticles, noting improved expansion, stability, and mechanical properties compared to those with micron-sized particles. Nanoparticles enhance uniform distribution, interfacial bonding, and microstructure, leading to higher compressive strength, better energy absorption, and improved oxidation and creep resistance. These properties make nanoparticle-stabilized MMC foams ideal for high-temperature aerospace, automotive, and biomedical applications. However, challenges like uniform nanoparticle dispersion and process control remain, with ongoing research aiming to optimize parameters and explore new reinforcements.

S. Bhogi et al.,[8] investigated the foaming behaviour of Al-Mg alloy melts, showing stable foams produced with or without a thickening step. Oxides like $MgAl_2O_4$ and MgO stabilize the foams, with $MgAl_2O_4$ being key to reducing drainage and enhancing stability. Foams from stirred alloys (S alloys) exhibited greater expansion and stability than unstirred ones (U alloys) due to higher $MgAl_2O_4$ content. Mg addition improves foam stability by lowering melt surface tension and increasing viscosity. The study also revealed MgO forms first in Al-Mg melts, converting into $MgAl_2O_4$ over time.

A. Salehi et al.,[9] reviewed the enhancement of nanocomposite foams reinforced with SiO_2 nanoparticles, showing improvements in hardness, strength, and energy absorption. Fabrication methods like ultrasonic and stir casting ensure uniform nanoparticle dispersion. Optimal SiO_2 content (around 0.75 wt.%) balances hardness and strength. TiH_2 as a foaming agent controls porosity, influencing compressive behaviour. Higher foam densities correlate with increased plateau stress, and microstructural analysis shows improved foam cell distribution, enhancing energy absorption.

Han Wang et al.,[10] studied the compressive properties and energy absorption of aluminium tubes filled with ordered aluminium cellular structures. The results showed that both uniform and graded structures significantly enhanced performance, with filling ratio and position being crucial factors. Tubes with vertically filled middle sections performed better than those with horizontally filled bottom sections. This research emphasizes optimizing filler configurations to improve structural performance and energy absorption efficiency.

P.J. Tan et al.,[11] introduced the dynamic compressive strength properties of closed-cell Hydro/Cyma aluminium foam. Part I presents experimental data on foam’s dynamic response at varying velocities, highlighting changes in plastic collapse strength and the roles of microinertia and shock formation. It also examines the effects of density gradients and compression rates on cell crushing. Part II focuses on modelling these phenomena for better understanding.

Ying Zhao et al.,[12] investigated aluminium foam sandwich structures under low-velocity impact, using drop-hammer testing and numerical analysis with ABAQUS. The study evaluated the effects of face sheet thickness, core height, and density on energy absorption. Results showed that these factors significantly influence impact resistance and the optimal design of energy-absorbing structures. This research aids in anti-collision design and evaluating foam structures' energy absorption.

Alexandra Kemeny et al.,[13] created high-performance bimodal composite metal foams (BCMFs) by infiltrating Al alloys into Al_2O_3 ceramic hollow spheres. Mechanical properties were assessed through quasi-static compressive tests, revealing that the properties largely depend on the filling rate, not sphere volume ratios. This highlights that the matrix material plays a key role in determining the performance of BCMFs, offering insights for optimizing foam design.

Imre Norbert Orbulov et al.,[14] developed low-cost metal matrix syntactic foams (MMSFs) using Al alloys and light expanded clay agglomerate particles (LECAPs). The foams showed densities ranging from 1.38 to 1.53 g/cm^3, and compressive tests revealed exponential relationships between fracture force, strength, and absorbed energy. These MMSFs demonstrated properties superior to top materials in the literature and exhibited plastic collapse failure.

Wen-Yea Jang et al.,[15] studied closed-cell aluminium foams like ALPORAS, focusing on their unique microstructure and mechanical properties. The foams’ anisotropic behaviour results from irregular polyhedral cells and varying wall thickness. Mechanical responses are influenced by specimen size, geometry, and loading direction, providing insights into how these factors affect foam performance under different conditions.

Guiquan Chai et al.,[16] improved the mechanical properties and corrosion resistance of Al foam using vacuum sintering and microarc oxidation (MAO). The MAO treatment enhanced wear resistance and provided stable friction coefficients. This process overcomes the limitations of porous metal foams by producing wear-resistant materials, making it a promising solution for improving their overall mechanical properties.

Xiongfei Liu et al.,[17] investigated gradient aluminium foam under impact loading using SHPB tests and numerical simulations. They found that strain rate positively correlated with mechanical properties, with negative gradient foams demonstrating superior energy absorption compared to homogeneous foams. A constitutive model was developed to predict impact stress-strain behaviour, providing insights for designing energy-absorbing materials.

Song Yan et al.,[18] introduced a novel aluminium foam-filled corrugated tube for better energy absorption and reduced compression force in thin-walled structures. Finite element analysis revealed that varying structure parameters like radius, wall thickness, and corrugation length significantly impacted axial compression. This innovative tube design offers valuable insights for optimizing energy-absorbing devices for improved crashworthiness.

Amarish Kumar Shukla et al.,[19] explored aluminium foam development using cenosphere as space holders via spray forming. They examined process variables such as current, gas pressure, and cenosphere weight fraction to optimize foam microstructure. Mechanical properties like microhardness, compressive strength, and tensile strength were evaluated, providing a deeper understanding of the process and its effect on material properties.

Sihang Xiao et al.,[20] studied the compressive behaviour of closed-cell Al foams at elevated temperatures using experiments and numerical simulations. A deep learning approach simplified CT-reconstructed models, and a temperature-dependent constitutive model was developed. These findings improve the understanding of Al foam behaviour in high-temperature environments, contributing to material design under such conditions.

Yue Zhang et al.,[21] investigated the initial yield behaviour of closed-cell aluminium foams under complex stress states. Through experiments, they observed isotropic yield behaviour across different stress states. A constitutive model was proposed that accounts for tension-compression strength asymmetry, enhancing the understanding of foam behaviour under various loading conditions.

M. Tavares et al.,[22] explored the thermo-mechanical behaviour of HS steel and PM aluminium foams under compressive loading at elevated temperatures. The study found that plastic buckling of cells is the key failure mechanism, with HS steel foam showing minor degradation at lower temperatures and PM aluminium foam degrading earlier. The research suggests that oxidation in HS steel foam could improve its quasi-elastic modulus and overall performance.

Anja Mauko et al.,[23] studied the high-strain rate mechanical properties of open-cell aluminium foam M-pore using a modified DIHB apparatus. The study found that loading rate strongly affects deformation behaviour, with X-ray MCT providing insights into the internal structure of specimens. The experimental and computational results were in good agreement, validating numerical models for simulating foam response at different loading rates.

Fateme Hassanli et al.,[24] examined the effect of structural design on aluminium foams fabricated with carbamide space holders. Modifying pore distribution significantly improved mechanical properties and energy absorption, compensating for density gradients caused by die wall friction. Introducing desired gradation in pore frequency increased plateau stress and energy absorption ability, making the foam more efficient.

Zichen Zhang et al.,[25] investigated composite aluminium foam tubes (CAFTs) produced by melt foaming. The study demonstrated improved stability and controllability of CAFT deformation, with increasing diameter ratio leading to higher specific energy absorption. Finite element simulations revealed that deformation initiated in the foam core and interface bonding played a crucial role, with high consistency between experimental and simulation results.

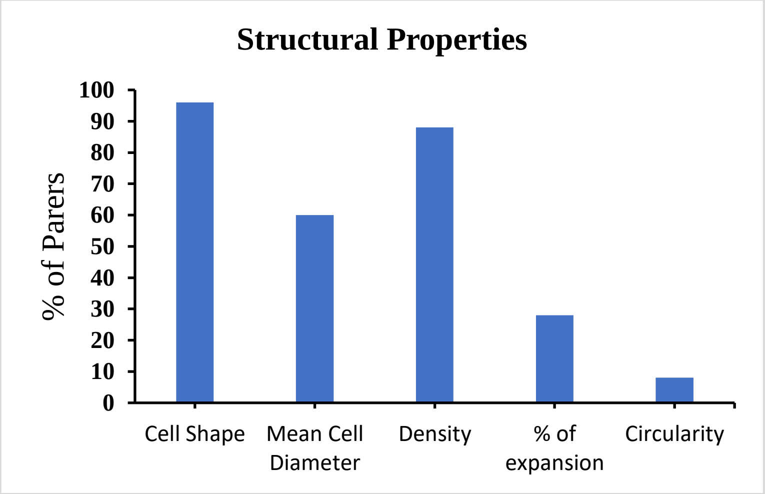

Figure 2.1: Graphical representation of % of Papers vs Structural Properties

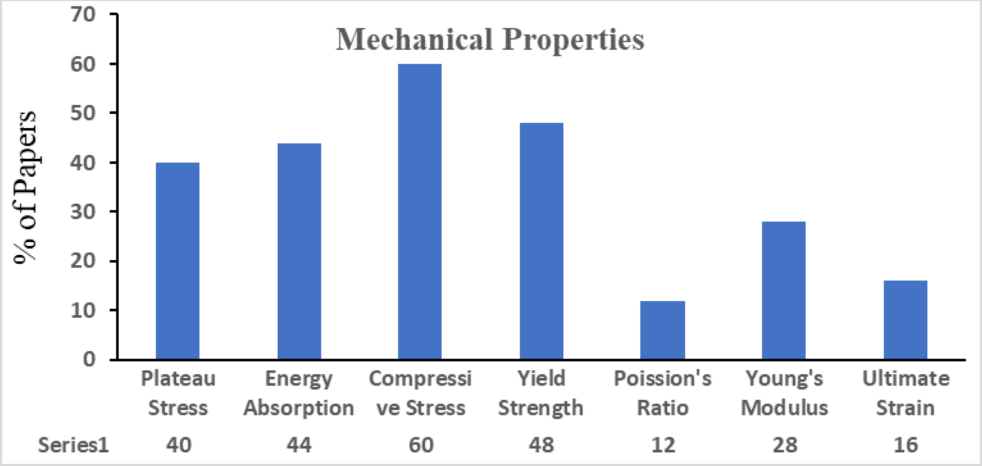

Figure 2.2: Graphical representation of % of Papers vs Mechanical Properties

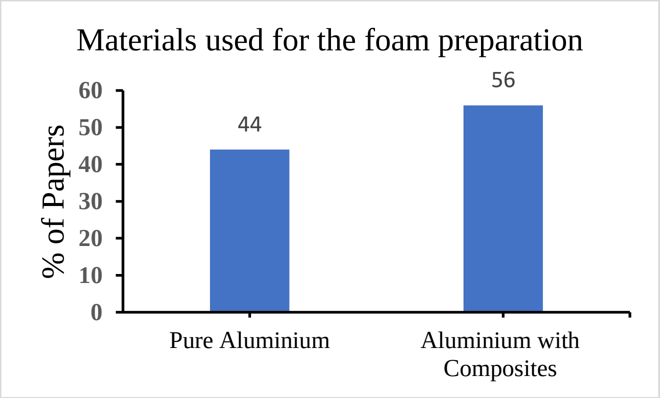

Figure 2.3: Graphical representation of Materials used for the foam preparation

Figure 2.1 shows the distribution of structural properties studied across 25 research papers on aluminium foams. Cell shape is the most studied property (96%), while circularity is the least explored (4%). Figure 2.2 illustrates the focus on mechanical properties, with compressive stress (60%) and yield strength (48%) being the most studied, followed by energy absorption (44%) and plateau stress (40%). Young's modulus (28%) and ultimate strain (16%) are moderately studied, while Poisson's ratio (12%) receives minimal attention. Figure 2.3 compares foam materials, showing that 44% of authors use pure aluminium, while 56% use composites like carbon fibre reinforced aluminium foams.

3. Methodology

Figure 3.1 gives the Detailed Flow-Chart for methodology of Structural and Mechanical Characterization of aluminium foams

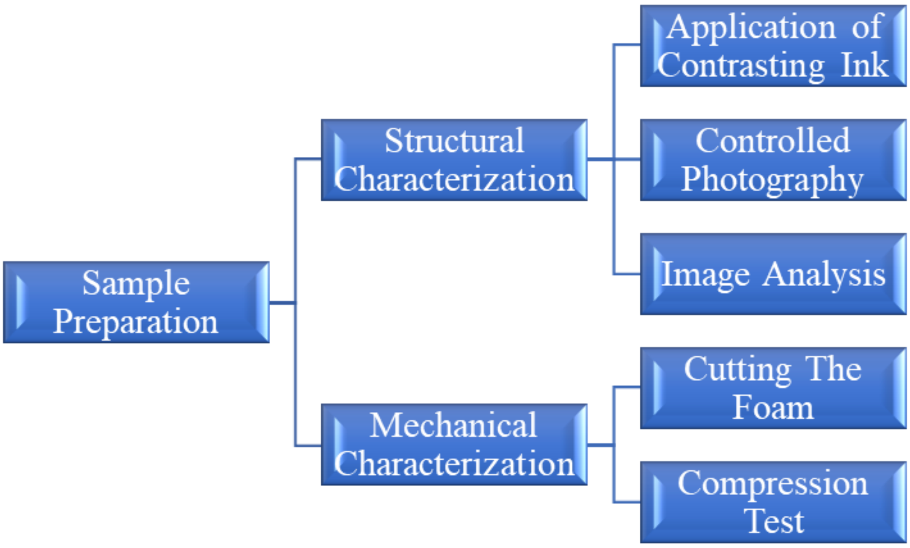

Figure 3.1: Detailed Flow-Chart of Methodology

3.1. Sample preparation

The aluminium foam samples analysed in this study were sourced from IIT Madras and included compositions: Al-Cu-TiB_2. To ensure consistency in mechanical testing, samples were prepared using Wire Electrical Discharge Machining (EDM). Despite the challenges posed by the foam's porosity, EDM was chosen for its ability to minimize thermal and mechanical stresses, thus preserving the delicate structure and ensuring dimensional accuracy. The samples were cut into cuboidal shapes with a length-to-width ratio of 2.5. This ratio was selected to reduce bending or buckling effects during testing while maintaining adequate material representation for structural analysis. Additionally, a minimum of 10 foam cells along the length of each sample was included to improve the statistical reliability of the results.

3.2. Structural characterization

Structural characterization focused on evaluating the foam's features, such as pore distribution, cell diameter, and circularity. To enhance the visibility of the foam structure, contrasting ink was applied to the samples, improving image clarity for subsequent analysis. Photographic imaging was performed under controlled lighting conditions to capture high-resolution images, minimizing shadows and ensuring consistency. The captured images were processed using ImageJ software, which involved converting the images to an 8-bit format, adjusting the contrast, and analysing particles to extract key parameters. These parameters included the mean cell diameter, cell surface area, and circularity, all critical to understanding the foam's structural properties. Nearly 7000 pores were assessed in Al-Cu-TiB_2 foams, as demonstrated in Figures 3.4 to 3.5.

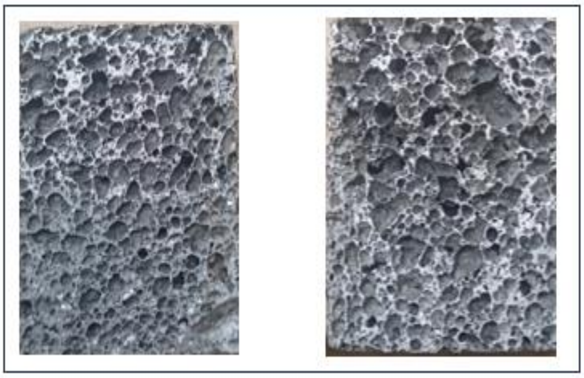

Figure 3.4: Original Aluminium Foam (Al-Cu-TiB_2)

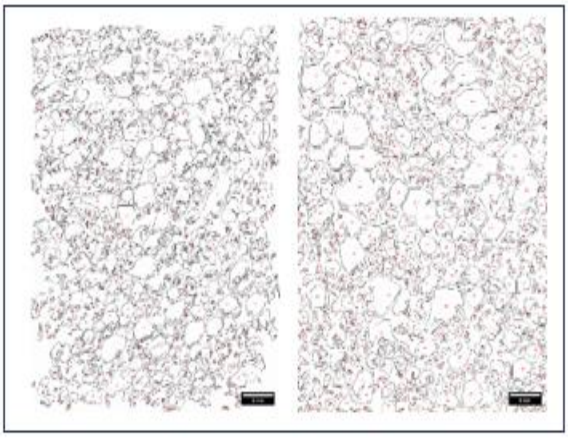

Figure 3.5: Extracted Images from ImageJ Software.

The processed data was further analysed using Origin-Pro software to plot relationships such as diameter versus circularity and pore size distribution. The cell size distribution was fitted to a log-normal curve, and area fractions were calculated using Equation 3.1, providing a detailed understanding of the foam’s microstructure.

$$\text{N area fraction of the cell with diameter } D_i = \frac{N_i \times \frac{1}{4}\pi D_i^2}{\sum_i N_i \times \frac{1}{4}\pi D_i^2} \qquad (3.1)$$

3.3. CHARACTERIZATION OF FOAMS

The macrostructural analysis utilized the extracted data to evaluate cell sizes and distributions. The mean cell diameter was calculated, and the area fraction for cells of varying diameters was determined, providing insights into the foam’s internal structure. Density measurements were performed by dividing the foam's weight by its volume, with relative density calculated by normalizing against the solid material's density. Table 3.1 summarizes the densities, showing Al-Cu-TiB_2 with 0.34 g/cm^3. These measurements were essential for understanding the lightweight nature and structural efficiency of the foams.

Table 3.1: Density of Foams

Sample	ρ (g/cm^3)
Al-Cu-TiB_2	0.34

3.4. Mechanical characterization

The mechanical behaviour of the aluminium foams was investigated through compression testing using the INSTRON-Servo Hydraulic Fatigue Testing System (Model 8801). Cuboidal samples, prepared with specific dimensions were subjected to uniaxial compression at a controlled displacement rate of 1 mm/min until reaching 80% of their original length. This approach provided valuable insights into the stress-strain behaviour of the foams under high strain levels. The resulting stress-strain curves revealed key mechanical properties such as plateau stress (σ_p), which indicates the onset of constant-rate deformation, and densification strain (ε_d), marking the point where the foam’s structure collapses. Additionally, energy absorption (W) was calculated to evaluate the foam’s ability to absorb mechanical energy, a critical factor for applications requiring impact resistance. These results, illustrated in Figure 4.6, highlight the structural and mechanical performance of the aluminium foams under compressive loads.

Figure 3.6: Instron-Servo Hydraulic Fatigue Testing System

4.Results and discussions

4.1 Structural Properties

4.1.1. Frequency of Small Pores:

Foam (Al-Cu-TiB_2) have the majority of their pores in the range of 0.5–1 mm as shown in Figure 4.1, contributing to structural integrity

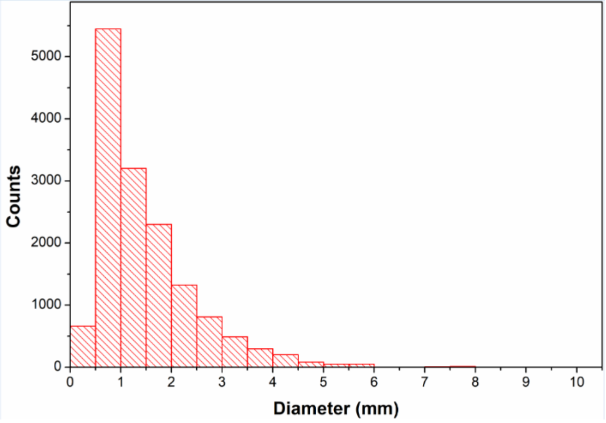

Figure 4.1 Counts vs Diameter of Al-Cu-TiB_2

4.1.2. Pore Size Distribution:

Al-Cu-TiB_2 foam has a mean pore diameter of 2.85 mm (standard deviation: 0.58 mm) with an R^2 value of 0.98, indicating a narrow size range, suggesting a denser and more uniform structure as shown in Figure 4.3.

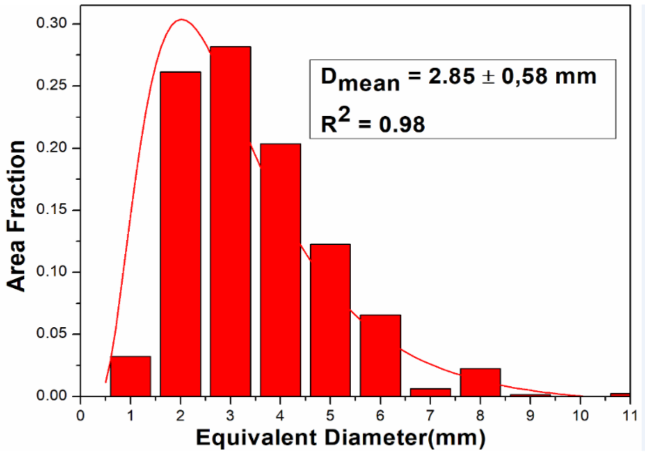

Figure 4.3: Pore size distribution of Al-Cu-TiB_2

4.1.3. Circularity of Pores:

Al-Cu-TiB_2 foam shows variability in circularity for small pores (<3 mm) and irregular shapes for larger pores (>5 mm), reflecting non-uniform growth, as shown in Figure 4.5 with more uniform and well-defined shapes, suggesting better geometric consistency.

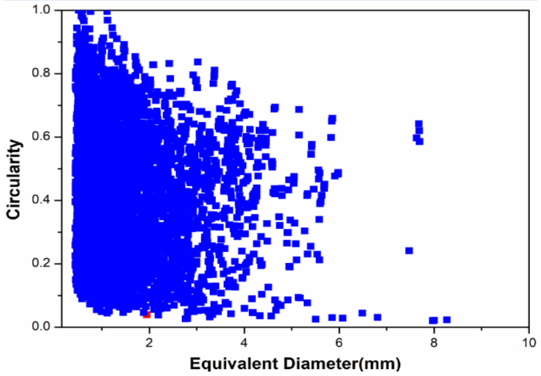

Figure 4.5 Circularity vs Diameter of Al-Cu-TiB_2

4.2 Mechanical Properties

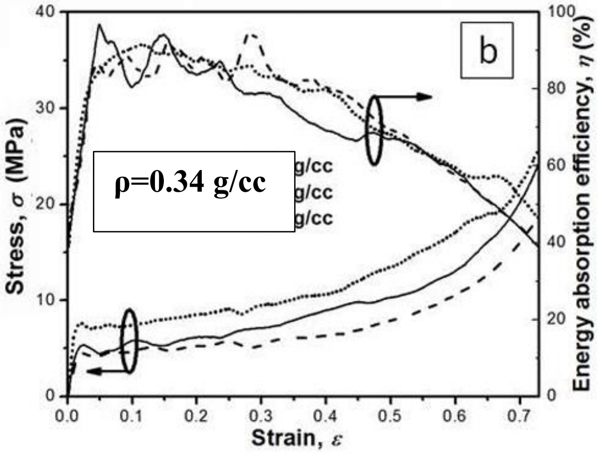

Figure 4.6: Compressive stress and energy absorption efficiency of Al-Cu-2TiB_2 foams vs strain

4.2.1. Plateau Stress (σ_p):

Al-Cu-TiB_2 foam has an average plateau stress of 5.56 ± 1.66 MPa, indicating moderate resistance to deformation

4.2.2. Energy Absorption(W):

Al-Cu-TiB_2 absorbs energy with an average of 9.3 ± 1.64 MJ/m^3, achieving peak efficiency (~90%) at ~40% strain as shown in Figure 4.6

4.2.3. Strain Hardening and Densification:

Foams exhibit an elastic region followed by a plateau phase for energy absorption. Al-Cu-TiB_2 foam shows gradual strain hardening and a higher resistance to deformation during densification, attributed to its smaller, denser pores.

4.2.4. Modulus of Elasticity:

Al-Cu-TiB_2 foam shows a relatively flexible structure suited for moderate energy absorption. aligning with its role in high-impact applications where flexibility is preferred over stiffness.

5.Conclusion

While foams are effective for structural and energy-absorbing applications, Al-Cu-TiB_2 in terms of compressive strength, pore uniformity, and resistance to deformation, making it more suitable for applications requiring high energy absorption and impact resistance. Al-Cu-TiB_2, with its slightly larger pore sizes and moderate mechanical properties, is better suited for applications requiring less rigidity and a balance of strength and flexibility.

For Al-Cu-TiB_2 foam, the average plateau stress is 8.5 MPa, with a standard deviation of ±1.66 MPa. Energy absorption is similarly impressive, averaging 9.3 MJ/m^3 with a standard deviation of ±1.64 MJ/m^3. The pore structure in this composite foam has a mean equivalent diameter of 2.85 mm and a standard deviation of ±0.58 mm. Circularity, which measures how closely the pores resemble a perfect circle, varies but remains relatively consistent, suggesting no strict correlation between pore diameter and shape.

These findings highlight the importance of tailoring pore size, distribution, and circularity to achieve specific mechanical properties in aluminium foams, emphasizing their adaptability for diverse engineering applications.

6.Future Scope

1. Advanced Applications in Lightweight Structures: With the continuous need for weight reduction in automotive, aerospace, and marine industries, aluminium foams are promising due to their high strength-to-weight ratio. Future research could focus on optimizing aluminium foam structures for lightweight applications while maximizing their energy absorption and mechanical resilience.
2. Enhancements in Energy Absorption for Crashworthiness: Aluminium foams are increasingly used in impact mitigation applications. Future studies could investigate design optimizations to enhance their energy absorption and crashworthiness in vehicle safety components, protective gear, and architectural designs that must withstand impact.

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