

Manufacturing and characterization of anisotropic syntactic foams

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Calliope Tulea

Abstract (In English):

Manufacturing and Characterization of Syntactic Metal Foams

Syntactic foams are composite materials made by embedding hollow or porous particles into a matrix material. Syntactic foams have significant potential in applications such as in the automotive, aerospace, and marine industries, where lightweight materials that can stand high loads are deeply important. They have been used in structural components such as in fuselage panels in aircraft and submarine hulls due to their structural integrity under high pressure.

Syntactic foams are usually isotropic, which means they respond to stress in the same manner from all directions. However, in some applications, anisotropic response can be advantageous. This research investigates the development of syntactic foams with anisotropic properties, specifically focusing on their fabrication and mechanical properties.

In this study, parallel hollow metal tubes were used as the reinforcement. During manufacturing, the hollow tubes were positioned parallel to each other and structured in sheets. In order to structure the tubes, paraffin wax was used as a temporary placeholder to keep the tubes in the specific orientation before being burned out at 250C. The ends of the tubes were fixed to the mold and were infiltrated with the matrix material, resulting in the syntactic foam. We investigated the compressive properties of this new type of material and compared its performance with different types of syntactic foams from the literature.

Abstract (In Hungarian)

Anizotróp szintaktikus fémhabok előállítása és mechanikai vizsgálata

A szintaktikus habok olyan kompozit anyagok, amelyeket üreges vagy porózus részecskék mátrixanyagba való beágyazásával állítanak elő. A szintaktikus habok alkalmazhatók az autópárhuzamosban, a repülőgépiparban és a tengerészetnél, ahol a könnyű, de nagy terhelést bíró anyagok kulcsfontosságúak. Jelenleg szerkezeti elemekben használnak ilyen anyagot, például repülőgép törzs paneljeiben és tengeralattjárók törzsében is megtalálhatók, mivel képesek nagy nyomás alatt is megőrizni szerkezeti integritásukat.

A szintaktikus habok általában izotróp anyagok, azaz a fizikai tulajdonságok iránytól függetlenek. Azonban bizonyos alkalmazásokban az anizotróp viselkedés előnyös lehet. Ez a kutatás olyan szintaktikus habok fejlesztését vizsgálja, amelyek anizotróp tulajdonságokkal rendelkeznek. Ehhez párhuzamos csöveket használtunk erősítésként. A gyártás során az üreges rudakat párhuzamosan helyeztük el és ezekből rétegeket készítettünk. A rudak térbeli elhelyezkedésének kialakításához paraffin viaszt használtunk.

Ezek biztosították, hogy a rudakat a kívánt irányba álljanak, mielőtt 250°C -on kiégettük volna. A csövek végeit rögzítettük, majd a csövek közti üreget mátrixanyaggal töltöttük fel őket, így jött létre a szintaktikus hab. Ennek az új típusú anyagnak vizsgáltuk a mechanikai tulajdonságait is, és összehasonlítottuk a szakirodalomban szereplő szintaktikus habok mechanikai tulajdonságaival.

1. Introduction

In the status quo, industries like automotive, aerospace, and construction display a constant need for materials that offer strength but are simultaneously lightweight in order to improve efficiency and reduce energy consumption. For example, by reducing the weight of aircraft while improving specific strength, less fuel is necessary for aircraft functionality, thus resulting in the lowering of costs for airlines and substantial reductions in greenhouse gas emissions. Ultimately, the purpose of lightweight materials is to ensure the practicability of cost-effective environmentalism, encouraging corporations to willingly pursue environmental policies and production methods.

In the previous decades, syntactic foams (SFs) have become increasingly investigated for their mechanical properties, high specific strength, and damage-tolerance. SFs are lightweight materials, where porous or hollow particles are incorporated into a matrix material and similar to naturally occurring porous materials such as sea sponges, wood, and bones. These SFs have been used in the automotive, aerospace, and marine industries for their compressive properties, as they can withstand high pressure environments. Scarcely known applications of polymer syntactic foams include boat decks, ribs, hulls, and floatation modules, as well as deep sea applications like underwater pipelines and submarines [1].

1.1 Background of Syntactic Foams

Syntactic foams are composite materials made of hollow or porous materials. In nature, we find similar structures in various forms, such as coral reefs, sea sponges, and even wood. These natural examples can be classified as cellular materials, distinguished by their intricate, porous configurations. The porous architecture of these natural materials has sparked considerable interest in the development of syntactic foams, as researchers seek to manufacture materials that possess a higher specific strength while remaining lightweight. SFs are mostly reinforced with microspheres, e.g. glass microballoons, cenospheres etc. By altering the distribution or positioning of reinforcement material, the mechanical properties can be changed. In this study, the reinforcement material used are aluminum metal tubes.

Generally, foams can be closed-cell or open-cell. Open-cell syntactic foams have connections between pores, forming a continuous pore throughout the material. Contrastingly, closed-cell foams have pores that are separated and discrete, which will be the topic of this investigation. Closed-cell foams tend to have better mechanical properties due to increased stability [2].

1.2 What is Anisotropy in Materials?

Anisotropy refers to the directional dependence of a material's physical properties. In an anisotropic material, characteristics such as strength vary depending on the direction in which they are measured. This is in contrast to isotropy, where a material exhibits the same properties in all directions.

Anisotropy is common in many natural and engineered materials and arises from the internal structure of the material. In the case of syntactic foams, anisotropy may result from the non-uniform distribution of reinforcing particles (such as microspheres) or from specific manufacturing techniques that align the material's components in certain directions. This

means that the material may exhibit different mechanical properties—such as higher strength or stiffness—along one axis compared to others. In this investigation, the use of tubes positioned in one direction serves to achieve the desired anisotropic effects.

1.3 Research Objectives

Despite the extensive research into polymer syntactic foams with resin matrix and microspheres, there has been no investigation of manufacturing syntactic foams with anisotropic properties. Therefore, the topic of this study is partially the investigation of how to produce anisotropic syntactic foams and to investigate the anisotropic compressive properties in these syntactic foams. Additionally, this study will investigate the effect of the aluminum tubes, which was used as a possible way to incorporate “pores” into the matrix material, on the compressive properties.

2. Literature Review on Syntactic Foams:

This section explains the various terminology and concepts which are relevant to this work, as well as previous studies and results. Firstly, different manufacturing processes and their resulting syntactic foams will be discussed, followed by a discussion of the current applications of syntactic foams. Then, there will be a discussion of compressive properties of syntactic foams and the impact of the addition of reinforcement. Lastly, I will mention the current gaps in research and the way in which this preliminary study aims to begin investigating the research objectives outlined earlier.

2.1 Manufacturing Processes

Polymer and metal matrix syntactic foams (PMSFs and MMSFs) have been a topic of interest in recent decades. Several studies have investigated syntactic foams with matrices such as epoxy resin or aluminum, with hollow microparticles or microspheres embedded, often called microballoons [3]. There are several manufacturing methods for SFs, yielding different results of foam structure.

Polymer matrices used in the manufacturing of SFs are classified into thermosetting and thermoplastic. Some examples of thermosetting polymers are the epoxy, unsaturated polyester, phenolic resin, polyurethane, silicone, and polyamides [4]. One example of a manufacturing process for thermosetting polymers is an in-situ polymerization process. In this method, hollow microspheres are dispersed within a liquid resin. Then, it is mixed with a hardener substance. The curing process allows the resin to solidify, thus trapping the microspheres in the polymer matrix to form a rigid syntactic foam structure. This process is commonly used due to its simplicity and the uniform distribution of microspheres that it can achieve [5].

Other methods include casting and compression molding, which differ based on the heating and pressure applied. Compression molding involves placing a pre-mixed polymer and microsphere mixture into a mold, where heat and pressure are applied to shape and cure the material, thus creating a stable sample [6,7].

Manufacturing metal matrix syntactic foams (MMSFs) can involve embedding hollow microspheres in a metal matrix, often using metals like aluminum, magnesium, or titanium for their lightweight properties. One common method is powder metallurgy, where metal powders are mixed with hollow microspheres along with a binder material to help keep them in place. The mixture is then compacted and sintered at high temperatures to fuse the metal particles around the microspheres. This process allows for accurate manipulation of the foam's density and porosity, making it useful in applications requiring specific structural properties [8].

Casting is also used to manufacture MMSFs. In this method, microspheres are added to molten metal and poured into molds where they solidify together. While casting is straightforward, it requires careful control to ensure even distribution of the microspheres, as they can sometimes shift within the metal matrix during cooling [9].

Another technique is infiltration, used in this study with a polymer matrix, which involves first creating a structure or arrangement of hollow microspheres. Molten metal is then forced into this structure by pressure or gravity, filling in the spaces between the microspheres. Infiltration allows for uniform distribution, resulting in a stable, consistent foam structure [10]. As we decided to use hollow aluminum tubes for introducing anisotropy to the SF, the uniform

parallelism of the hollow aluminum tubes is deeply significant in this study. Thus, infiltration was used as the manufacturing technique, yielding control over the arrangement of the tubes.

2.2 Current Applications of Syntactic Foams

Applications of MMSFs and PMSFs are especially significant in the automotive, aerospace, and marine industries due to the necessity of lightweight, high-specific-strength materials. As aforementioned, SFs exhibit high specific strength and can withstand high-pressure environments. Therefore, these industries have begun incorporating SFs into e.g. vehicles to lower the cost of fuel and the emission of greenhouse gases to ensure compliance with regulations in the respective jurisdiction.

SFs are significant in the marine industry for example through their use in remotely operated vehicles (ROVs) and human-operated vehicles (HOVs), as well as structural components for construction of underwater pipelines, underwater vehicles, deep water moorings, torpedo targets, and sonar arrays, thermal insulation for undersea pipelines and high depth applications [11]. Due to their high specific compressive strength, SFs are deeply useful in the marine industry.

The lightweight characteristics of SFs are equally significant for innovative designs while minimizing weight. In the automotive industry, these materials are employed in various structural components, leading to enhanced safety and fuel efficiency. Similarly, in the aerospace industry, SFs have been used in fuselages and other structural components [11].

2.3 Compressive Properties of Syntactic Foams and Reinforcement Impact

Figure 1 shows a typical compressive stress-strain curve of a foam. The graph can be divided into three stages: a quasi-linear elastic region, a plateau region, and a densification region. Depending on the matrix material, SFs show similar compressive behavior. The quasi-linear elastic region represents the initial, mostly reversible deformation of the material. Then, in the case of SFs, the compressive curve often reaches a peak value of stress as strain increases. This peak is the compressive strength – the maximum stress a material can withstand before the plateau region begins. After this local peak in stress values, the stress slightly drops due to the “failure initiation” of the material [12]. In the case of plastically deforming matrix material, the stress values stabilize as microspheres or reinforcements collapse. This plateau is often responsible for the foam’s energy absorption properties, making it useful in applications that require protection against impact. Lastly, as void spaces in the material close up and there is less empty space, stress values sharply increase because the material is being compacted, as there is no space for further deformation [13].

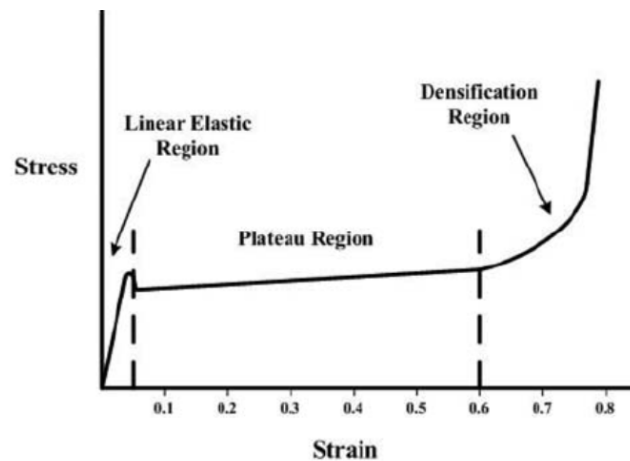


Figure 1. Typical compressive stress-strain curve of a foam [17]

Several other factors can also influence the mechanical properties of syntactic foams such as the microsphere volume fraction, material composition, and reinforcement type. Microsphere volume fraction refers to the proportion of the total volume of the syntactic foam that is occupied by hollow microspheres (typically made of materials like glass or ceramic). Gupta et al. investigated the effect of altering microsphere volume fraction and discovered that a high-volume fraction generally led to an increase in energy absorption characteristic, however, a decrease in compressive strength due to the increased number of “weak points” in the structure [14]. Secondly, the material composition itself will alter mechanical properties, depending on which matrix is used (e.g. polymer or metal) as well as the material of microspheres. Yousaf et al. also investigated the use of glass microspheres – showing distinct results in mechanical compressive properties in the foam [15]. The use of polymer and metal matrices also alters compressive properties. PMSFs and MMSFs have different mechanical properties and the altering of both reinforcements and matrices has an impact on these properties. Kadhimi Al-Sahlaní investigated the effect of the matrix material, as well as the effect of different reinforcement types, finding that cost-effective expanded glass particles are favorable due to their low density and high crushing strength [16].

2.4 Current Gaps in Research and Goals

SFs are isotropic by nature as they use porous particles or hollow spheres as the reinforcement, thus, according to our knowledge, there is no paper on anisotropic syntactic foams. The effect of the material of the reinforcement and the matrix is not clear for SFs. Due to the complex geometry of the structure, it is difficult to ascertain these effects.

Thus, within this study we investigate the followings:

1. How can be manufactured an anisotropic SF.
2. The compressive properties of the manufactured anisotropic syntactic foam, formed from hollow aluminum tubes as the reinforcement and epoxy as a matrix material.
3. We also produced a foam with a similar “pore” arrangement to investigate the effect of the reinforcement material on the stiffness and the strength of the SF. Comparing the

mechanical properties of a foam with and without aluminum reinforcement, we produced in the epoxy matrix holes by drilling. This encompassed a manufacturing process where the creation of the parallel tube-structure is possible.

3. Materials and Methods

3.1 Materials

During the manufacturing process, several materials were used for the construction of the tube arrangement and for infiltration with the matrix material. Generally, syntactic foams are manufactured using a matrix material such as resin or epoxy and reinforcement material such as hollow spheres. Within this study, the reinforcement materials used were aluminum alloy tubes and epoxy as a matrix material. However, several other materials such as paraffin wax were used as temporary binders during the manufacturing process.

The following materials were used within this study:

Epoxy



Figure 2. (a) Epoxy

Ipox MR 3012 epoxy resin with Ipox MH 3122 hardener (mixing ratio 100:40) was chosen as the matrix material for syntactic foams due to its combination of mechanical strength, lightweight properties, and excellent bonding capabilities with various reinforcements such as hollow microspheres and metal tubes. Epoxy resins provide superior stiffness and durability, which are essential for applications requiring long-term performance under mechanical stress, such as in the aerospace and marine industries.

Aluminum Tubes

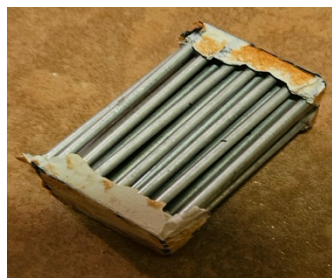


Figure 2. (b) Tube arrangement fixed with gypsum

Aluminum tubes were used as reinforcement material due to their low density and corrosion resistance. The aluminum alloy (Al2521) tubes were 2.5 mm in diameter with the wall thickness of 0.2 mm and 1 m in length. I cut them into small 49 mm tubes and then arranged

them in the parallel structure (Figure 2(b)). Parallelism was highly important for us to ensure enhanced anisotropic properties during their manufacture.

Paraffin Wax



Figure 2. (c) Molten paraffin wax

I chose paraffin wax as a temporary binder to construct the parallel, layered tube arrangement before it is infiltrated with the matrix material. Paraffin wax was used because of its quick drying properties and wide availability. The wax is also chemically inert, non-corrosive, and adhesive to reinforcements when molten, however non-stick as it cools. Therefore, the use of paraffin wax improves the ease of use within the manufacturing process. Lastly, paraffin wax has a low melting point of 48 °C to 66 °C, thus ensuring ease of removal by heating.

Gypsum



Figure 2. (d) Gypsum

I used gypsum to secure the aluminum tubes before the paraffin wax is melted off in order to maintain the parallel tube arrangement. Gypsum was used due to having a higher melting point than paraffin wax as well as its wide availability. Additionally, gypsum is relatively quick to dry and is sufficiently hard to secure the tubes in place.

3.2 Manufacturing Process

In this investigation, a parallel structure of tubes must be achieved in order to ensure anisotropic properties which will be created through the use of paraffin wax as a temporary binder and the use of a stamp to maintain parallelism. Figure 3. displays the desired structure for the final syntactic foam.

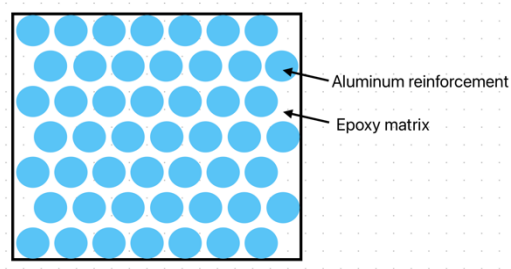


Figure 3. Plan for tube arrangement

3.2.1 Preparation of parallel tube arrangement using paraffin wax

The first step of the manufacturing process involves the construction of the tube arrangement using paraffin wax. This was the initial issue to resolve in order to create the tube arrangement in relatively quick manner while ensuring the parallelism of the tubes once the sample is infiltrated with epoxy. As previously mentioned, the parallelism of the tubes was incredibly significant to ensure anisotropic properties in the final foam.



Figure 4. (a) Molten paraffin wax

Firstly, the paraffin wax is melted into a paste – stirring is required to achieve a uniform consistency. The paraffin wax is then used as a temporary binder for the tubes. Secondly, an aluminum foil which is cut to the correct size is used. In Figure 4(b) the sizing used is 24mm*24mm*49mm.



Figure 4. (b) Initial layer of wax on aluminum foil

I placed an approximately 1mm layer of paraffin wax onto the size of the aluminum foil, ensuring there is enough wax to keep the tubes in place but simultaneously leaving the ends of the tubes without wax.

As the tubes are placed onto the first wax layer, the issue of maintaining parallelism becomes acutely apparent. Therefore, I designed a 3D-printable PLA stamp to ensure the appropriate 1 mm spacing between tubes as well as parallelism as the stamp was applied perpendicularly to the wax.

The stamp can be observed in Figure 4(c) and should be modelled based on the necessary spacing between tubes and size of tubes. The stamp was designed for 2mm tubes with 1mm spacing in between.



Figure 4. (c) 3D-printed stamp

For further assurance of parallelism, a paper box was used to secure the tubes and minimize shifting during the placement of the wax. This process was repeated to create approximately a square prism. The sample in Figure 4(d) has 7 layers of 7 tubes with 1mm spacing in between. Thus, the initial tube arrangement is prepared.



Figure 4. (d) Tube arrangement bound by paraffin wax

3.2.2 Securing structure using gypsum material

The next problem arose when attempting to secure the tube arrangement without the temporary wax. To achieve this, the tube arrangement was first fixed on both sides with gypsum. In Figure 5(a), a depth of 5 mm of gypsum was used to secure the tube arrangement in its parallel position.



Figure 5. (a) Tube arrangement bound by paraffin wax and fixed with gypsum

At first, the fixation was tested with only one side secured with gypsum at a depth of 5 mm. However, it was noted that the tubes were less secure in the gypsum and would shift and/or bend downwards.



Figure 5. (b) Tube arrangement secured with gypsum after wax was burned out. Bottom left is fixed only on one side while top right is fixed on both ends modelled with toothpicks.

After the fixation of the tube arrangement in gypsum, the paraffin wax was burned out at a temperature higher than its melting point, being 48 °C to 66 °C. For the preservation of the oven or furnace used, the wax was collected in a metal container, and heatproof gloves are recommended upon removing the sample from the oven or furnace.

3.2.3 Silicon casting and epoxy infiltration

Once the preparation of the secured tube arrangement was complete, the last step was to infiltrate the tube arrangement with the matrix material – epoxy resin. This is in order to create the final sample in preparation for compression testing.

First, a mold was created for the epoxy infiltration using silicon casting. Silicon casting is a method utilizing a silicon compound to create a mold based on a requires shape. In order to create the mold, a block of gypsum (as muster) was procured by the construction of a paper box with gypsum poured into it. The box was constructed in the dimensions $[L_0 + 10\text{mm} \times L_0$

+ 10mm x L_0 + 20mm] with L_0 being the length of the side of the tube arrangement sample. The added length, width, and height were to ensure there was extra space.

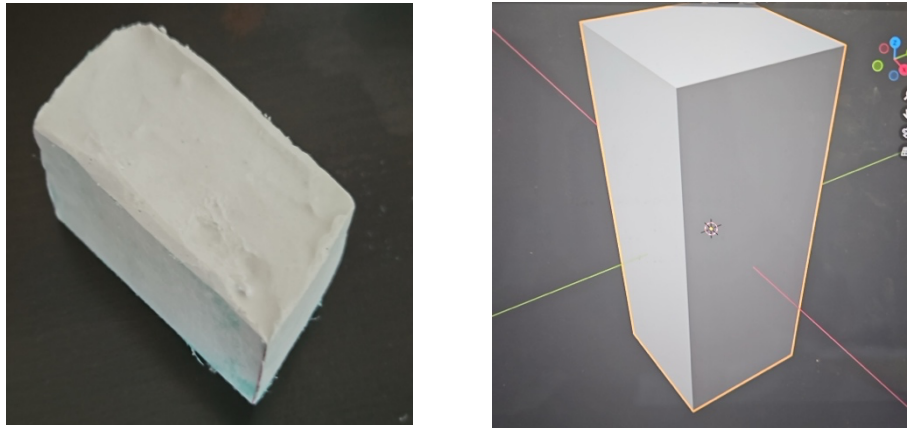


Figure 6. (a) The gypsum block. (b) The 3D model of the block.

In order to create the mold, a frame was created out of building blocks – aiming at a 20 mm space around the gypsum. The gypsum was fixed to the glass underneath the frame. Plasticine was used to then secure the frame and gypsum block to the glass. Ideally, the block would have been more precise had it been 3D printed using PLA, as the perpendicularity of the sides could have been ensured, reducing the time taken for grinding the infiltrated sample for testing.



Figure 6. (c, d) Block construction for silicon casting with 20 mm space around the gypsum in all directions

The substance silicon (OXAM S1, T-Silox, Hungary) and silicon catalyst (OXAM, T-Silox, Hungary) were mixed in a ratioed amount 40 ml catalyst to 1000 g silicon - in this case being 300g and 12 g, resulting in the necessary silicon compound. Then, the substance was poured over the gypsum block from a distance of 10 cm, in order to reduce the radius of the pouring substance. This reduces the risk of air bubbles within the mold. The mold is left to cure for 1-2 days in room temperature. Once the mold is hardened, the gypsum block can be removed.



Figure 6. (e) Mixing of silicon with silicon catalyst (f) Hardened silicon mold (g) Pouring of earlier mixture into block construction

For the epoxy infiltration, the tube arrangement can be placed inside the mold and the epoxy was poured over the tube arrangement from 10 cm to reduce air bubbles. To further remove air bubbles, the sample can be placed in a vacuum chamber. Lastly, the tube arrangement could easily move in the epoxy resin, so it was fixed with aluminum plate. The epoxy requires 1 day for full curing.



Figure 6. (h) Epoxy mixture (i, j) Tube arrangement infiltrated with epoxy

Furthermore, alongside two samples of tube arrangements, a purely epoxy sample was made in order to compare the compressive properties of the sample with aluminum tube reinforcement with no-reinforcement samples. The block was cut into the same size as the SF samples and 2 mm holes were drilled in the exact arrangement of the tubes. Figure 6(k) displays the pure epoxy sample.

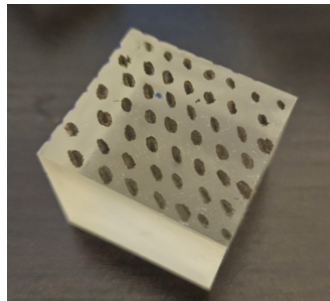


Figure 6. (k) Epoxy block to be drilled in shown markings

4. Results Evaluation and Improvements

4.1 Results of Compression Testing

In the first area of investigation, investigating the properties of anisotropic syntactic foams, the difference in stiffness was measured between the two orientations of the tubes. Two samples of each type were constructed in order to test both orientations. Figure 7. displays the first sample of epoxy matrix reinforced by aluminum tubes. The grid arrangement of the tubes was not perfectly maintained, which is a factor of improvement for further investigations.

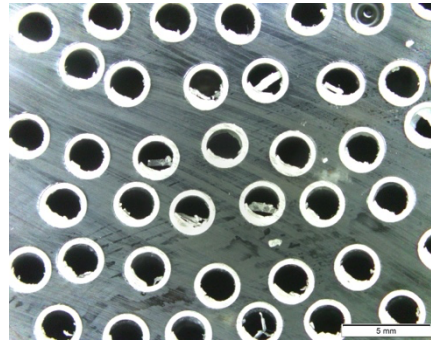


Figure 7. Top view of tube arrangement under microscope

The final size of the SF samples was approximately $30 \times 30 \times 30 \text{ mm}^3$. The compression test was done with an MTS810 testing machine, with a constant crosshead velocity of 3 mm/min. A compression test was performed on each sample in different orientations. Figure 8. shows the engineering stress – engineering strain curve. This result was from a compression test performed on each sample in the vertical and horizontal direction.

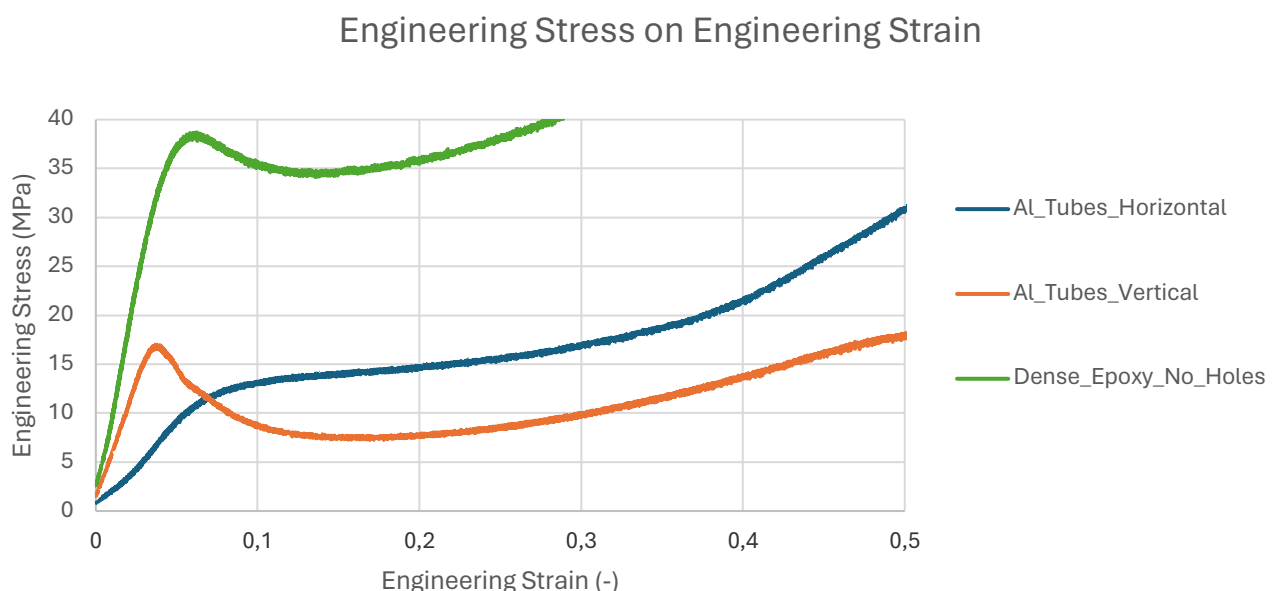


Figure 8. Engineering stress on engineering strain graph for aluminum reinforced epoxy matrix syntactic foams in vertical and horizontal orientation and dense epoxy

The vertical arrangement had a steeper initial linear stage, signifying a higher Young's modulus when compressed vertically. A higher Young's modulus is indicative of higher stiffness of the material, thus showing a higher resistance to elastic deformation under load. In the horizontal direction, the initial stress-strain curve is less steep, signifying a lower Young's modulus. In comparison to the vertically positioned sample, this sample is less stiff, suggesting that the material is stiffer when the strain acts longitudinally. However, during the plateau and densification regions, the horizontal position seems to require more stress to deform.

The second area of investigation was regarding the use of aluminum reinforcement to strengthen the syntactic foam. In order to test the effect of aluminum reinforcement, four samples were prepared for the compression test: two syntactic foams of epoxy matrix reinforced with aluminum tubes positioned parallelly in the foam, and two epoxy samples with holes drilled. Figure 9. displays the drilled epoxy arrangement. (The size of the sample was 25x25x25 mm³.)

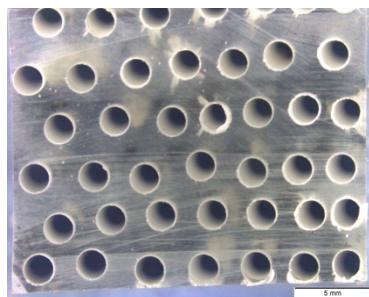


Figure 9. Drilled epoxy arrangement under microscope

Figure 10. shows the comparison of syntactic foams with the drilled samples.

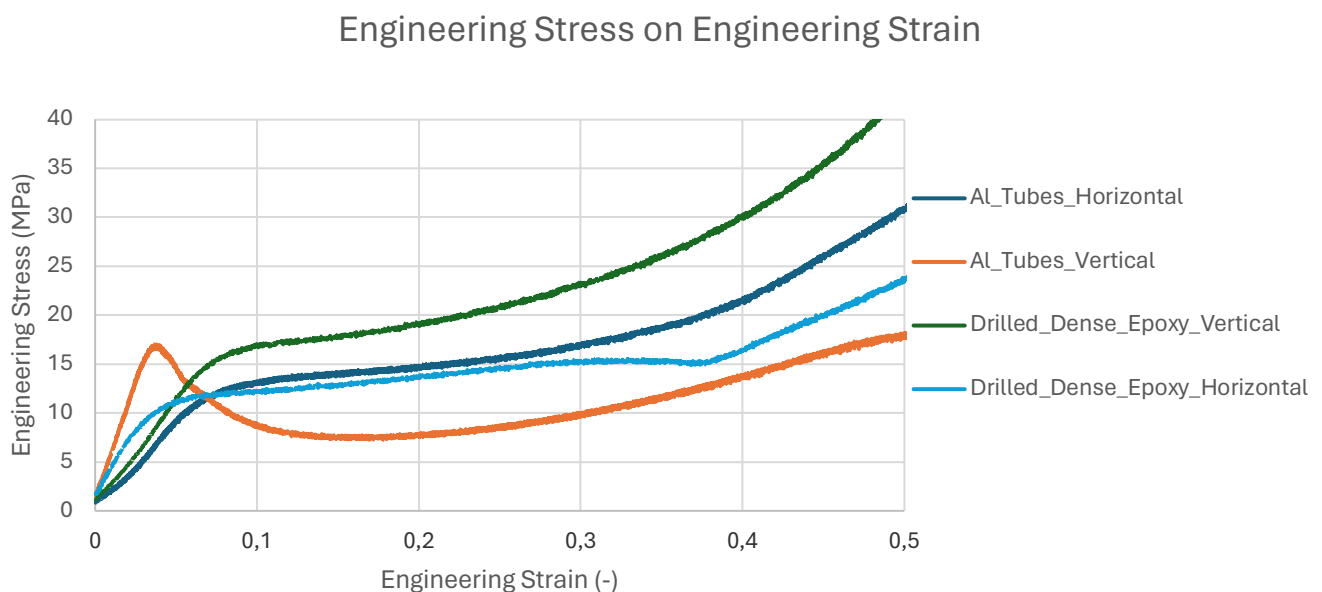


Figure 10. Engineering stress - engineering strain graph for aluminum reinforced epoxy matrix syntactic foams and the drilled epoxy samples in vertical and horizontal orientations

In order to evaluate the structures constructed in this study, two parameters were determined: the proof stress and the Young's Modulus. The proof stress shows the load per unit area these structures can withstand without being permanently deformed, while the Young's modulus is a measure of stiffness, describing the ease with which a material will deform. In Table 1, the proof stress and Young's modulus are shown for each individual sample.

Identifier	Measured Young's Modulus (MPa)	Measured Proof Stress (MPa)
aluminum reinforcement; epoxy matrix; horizontal	181	15
aluminum reinforcement; epoxy matrix; vertical	470	9
drilled holes; epoxy matrix; horizontal	272	12
drilled holes; epoxy matrix; vertical	224	18
epoxy;	570	38

Table 1. The Young's modulus and proof stress values for all the measured samples

For the aluminum-reinforced epoxy composites, the vertical orientation shows a significantly higher measured Young's modulus (470 MPa) compared to the horizontal orientation (181 MPa). This suggests that the load-bearing capacity is higher when the reinforcement is aligned vertically relative to the loading direction, as the tubes are better able to resist deformation along their length.

The measured proof stress is also slightly lower for the vertical orientation (9 MPa) compared to the horizontal (15 MPa), which may indicate that the vertical arrangement of reinforcement provides better stiffness but slightly less resistance to plastic deformation under stress.

The drilled holes in the epoxy matrix significantly reduce the measured Young's modulus compared to the plain epoxy. For example, in the horizontal drilled-hole orientation, the modulus is measured at 272 MPa, while for the dense epoxy, it is 570 MPa. This drop indicates that the holes in the material significantly reduce its stiffness, as expected.

An upper bound for the Young's modulus of the drilled epoxy can be obtained by the rule of mixture [18]:

$$E_{cl} = E_r V_r + E_m V_m. \quad (1)$$

Here E_{cl} , E_r and E_m are the Young's modulus of composite, the reinforcement and the matrix material, respectively, and V_r and V_m are the volume fraction of the reinforcement and matrix material, respectively.

Similarly, the proof stress was calculated using the equation below. The σ_{cl} , σ_r , and σ_m are proof stress values of the composite, reinforcement, and matrix material, while V_r and V_m are the volume fraction of the reinforcement and matrix material, respectively.

$$\sigma_{cl} = \sigma_r V_r + \sigma_m V_m \quad (2)$$

Using Eq. 1 the calculated upper limit for Young's modulus of the drilled epoxy samples is 427 MPa, which is much higher than the measured 224 MPa. Similarly, Eq. 2 was used to calculate the proof stress of the drilled epoxy samples, yielding a value of 28MPa, similarly higher than the measured proof stress of 18 MPa.

In summary, the data suggests the following conclusions:

- Vertical orientation is stiffer and has higher Young's modulus than horizontal orientation in aluminum-reinforced epoxy.
- Aluminum reinforcement leads to increased stiffness in the vertical direction while having no effect or even decreasing stiffness in the horizontal orientation.

4.2 Improvements

The initial issue faced during this investigation was a method of arranging the tubes in a relatively quick manner while still maintaining parallelism. The most logical initial idea is to secure the tubes through holes on two opposing sheets of metal or paper and slide the tubes through them one by one. However, this process can be time-consuming, especially when faced with large number of tubes. Figure 12. displays the initial idea of manufacturing the tube arrangement.

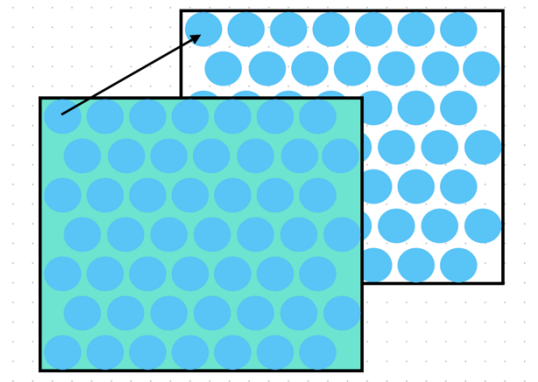


Figure 12. Initial idea for manufacturing of tube arrangement

Therefore, the idea of a more automatic placement of the tubes was used through molds with already-made grooves for the tubes to slip into. This would ensure there is less manual work in the placement of the tubes. Figure 13. displays the initial idea of using a rigid structure to hold the order of the tubes.

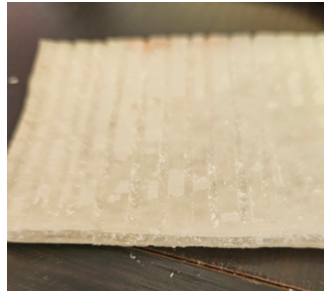


Figure 13. Initial idea of using an already hardened mold for fitting the tubes

Furthermore, due to the impracticality of making several molds of this sort, the investigation arrived at the idea of having a stamp to engrave the grooves in any layer of wax. Thus, to ensure parallelism of the grooves and uniformity when creating the desired grooves, a stamp was 3D printed which would be placed onto the paraffin wax and mark the position of the tubes. Figure 14. displays the stamp.



Figure 14. 3D printed stamp

The next issue encountered involved the material to be used as a temporary binder. The initial trials involved the use of a type of wax due to its adhesiveness and its low melting point. The wax could easily be molten off in the process to create the mold. At first, the wax used was beeswax as can be seen in Figure 15.



Figure 15. Use of beeswax as binder

However, the beeswax was far too adhesive and brittle for plausible usage. It also did not fully harden and remained malleable long after initial placement. Thus, it could not be used to create

a rigid arrangement of tubes. Instead, paraffin wax was used due to its quick drying speed and lack of adhesiveness to materials other than itself.

Subsequently, an issue encountered was the material of the adhesive securing the end of the tubes. Several materials were tested, including heat resistant glue and gypsum. Tubes were infiltrated into each respective material and their resistance to temperature and strength were investigated. Ultimately, gypsum was chosen due to its wide availability and sufficient stability it provided.

Next, the parallelism of the tubes itself became an issue due to the lack of borders around the mold. This meant there were often several outliers that shifted, thus skewing the parallelism of the whole tube arrangement. Figure 16. is an example of the skewed tube arrangement.



Figure 16. Skewed tube arrangement

To combat this, a paper box was used, and the sample construction was done inside the paper box. This meant the stamp could be applied in a parallel manner, while simultaneously keeping the tubes parallel due to box's fitting to the length of the tubes. The use of this method can be seen in Figure 17.



Figure 17. Use of box to maintain parallelism

Lastly, the final issue encountered was of the heat from the furnace which led to a skewing of the aluminum tubes. In order to resolve this issue, instead of using a furnace when melting the wax off, a candle or lighter would be used instead, thus reducing contact of the flame with the actual gypsum and aluminum tubes. Thus, this resolved the skewing issue. Figure 18(a) displays the initial skewing while Figure 18(b) displays the parallelism of the final product.

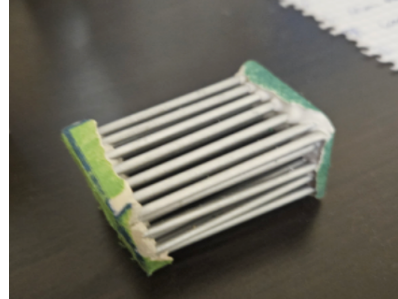


Figure 18. (a) skewed arrangement (b) straight arrangement

5. Conclusion

Epoxy matrix syntactic foams with aluminum tube reinforcements present with anisotropic properties, yielding distinct compressive properties under uniaxial compression test. The vertical orientation of the aluminum-reinforced foam shows a marked increase in Young's modulus (from 138 MPa in the horizontal aluminum-reinforced sample to 470 MPa) indicating a substantial improvement in load-bearing capacity. Aluminum reinforcement appears to lead to increased stiffness in the vertical direction while having no effect or even decreasing stiffness in the horizontal orientation. However, this increased stiffness comes at the cost of reduced proof stress, with the vertical aluminum-reinforced sample exhibiting a proof stress of 9 MPa, lower than the 15 MPa proof stress observed in the horizontal aluminum-reinforced sample and significantly lower than the 18 MPa proof stress of the vertical drilled hole epoxy matrix. This could be due to the poor interface between the epoxy matrix and the aluminum tubes, which appeared to easily fall out after the compression test.

Due to the status of this investigation as a preliminary study to a wider investigation regarding the use of steel tube reinforcement in aluminum matrix syntactic foams, only one repeat was done under these conditions as opposed to the standard three. In the further investigation, a similar process will be undergone as has been detailed in this paper, however, with metal as a matrix material. This could also improve the interface between the matrix and reinforcement material, potentially leading to improved mechanical properties. However, research avenues will begin with an assessment of the minimum required temperature for infiltration of aluminum matrix as to maintain parallelism of the tubes and prevent the tubes from dissolving.

Outlook

In further investigation, it would be beneficial to repeat the experiment several times with at least 3 syntactic foams per orientation. As this was a preliminary study, it was largely concerned with the practicality of its fruition. In further investigations, repeats of these findings would be recommended, as well as the expansion into MMSFs and other methods of characterization such as metallography and comparisons of specific strength. Furthermore, the arrangement of the tubes could be improved as was previously suggested in the "Improvements" section, potentially yielding more definitive results.

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