

BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS

Faculty of Mechanical Engineering

Department of Materials Science and Engineering



# **A Study of Grid Reinforcement and Unwanted Pores in Syntactic Foams on Compressive Properties**

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## DECLARATIONS

### *Declaration of acceptance*

This thesis fully complies with the requirements of the Faculty of Mechanical Engineering of the Budapest University of Technology and Economics for the Scientific Student Conference in terms of content and form, as well as with the objectives. I consider this thesis to be suitable for public evaluation and public presentation.

Date of submission: 07.11.2022.

.....  
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**Güneri Mehmet Sinan**

## **Abstract (In Hungarian)**

### **Rácsszerkezettel Történő Erősítés és Nem Kívánt Pórusok Hatása Szintaktikus Habok Zömítési Tulajdonságaira**

Napjainkban sok olyan alkalmazási terület van, amelynél nagy fajlagos szilárdságú anyagra van szükség. Ilyen például a repülőgépipar, az építőipar és a járműipar. Az Ashby-féle anyagválasztási térkép alapján a fémhabok is alkalmazhatók ezeken a területeken, nagy fajlagos szilárdságuk miatt.

A fémhabok alapvetően cellás szerkezetű, gázzal töltött üregekkel rendelkező fém anyagok. A porózus szerkezet miatt a mátrix anyagának és a hab porozitásának változtatásával a habszerkezet fajlagos szilárdsága változtatható. Az utóbbi néhány évben megjelent egy új típusú fémhab, az úgynevezett kompozit fémhab, ahol porózus részecskék vagy üreges gömbök adják az anyag pórusait és celluláris szerkezetét.

Dolgozatunkban először acélrács erősítésének hatását vizsgáltuk alumínium mátrixú szintaktikus fémhab zömítési tulajdonságaira. A mintákat duzzasztott agyagkavics kis nyomású infiltrációjával állítottuk elő. A szintaktikus fémhab mintákban a vízszintes és függőleges irányban elhelyezett acélrácsok hatását zömítéssel vizsgáltuk. Ezután megvizsgáltuk a mintában lévő nagy, nem kívánt pórusok hatását a zömítési tulajdonságokra. Néztük mind a méret, mind az elhelyezkedés hatását a mechanikai és deformációs tulajdonságokra.

Mindkét esetben az anyag mechanikai tulajdonságait a módosítás nélküli kompozit fémhab tulajdonságaival vetettük össze.

## **Abstract (In English)**

### **A Study of Grid Reinforcement and Unwanted Pores in Syntactic Foams on Compressive Properties**

Materials used in the industries such as aerospace, construction, and vehicle manufacturing, should exhibit high strength and durability on one hand, and also have to be light weighted on the other hand. According to the Ashby material selection charts, metal foams are good candidates for this purpose.

Metal foams are cellular materials composed of solid metal and gas-filled pores. Due to the porous structure, by changing the material and the porosity of the foam, the specific strength of the foam structure can be set. In the last few years, a new type of metal foam has emerged, where the pores are introduced into the matrix by adding porous particles or hollow spheres. These metal foams are called syntactic foams.

In this study first, we investigated the effect of a steel grid reinforcement on the compressive properties of an aluminum matrix syntactic foam. Lightweight expanded clay aggregates were used to form the pores. For manufacturing, low-pressure infiltration was applied. The final material was tested in compression. The effect of steel grids in horizontal and vertical orientation in the structure has been evaluated. Next, we investigated the effect of big unwanted pores in the structure on the compressive properties. The effect of the size of the unintentional pores and the location was studied.

In both cases, the mechanical properties of the material were compared to that of the unmodified syntactic foam.

**Keywords:** *Compression test, Syntactic Foam*

## 1. Introduction

In our modern world, production, research, and development sectors do not only focus on the results, but they need to care about environmental issues. This is caused by fossil fuel usage around the world which is the main reason for global warming and pollution nowadays, also, with the decreasing amount of natural energy sources, global warming seems to become a bigger problem. As a result, research and projects started to focus on solutions that could help to protect the environment and provide the same quality products within the expectations. Aerospace and automotive industries are being involved in such research and projects.

In the aerospace and automotive industries, one of the biggest problems in environment and finance topics is the CO<sub>2</sub> emissions of vehicles. They are obliged within some standards, below the permitted quota, to protect the environment while they still would like to provide high-performance vehicles to be competitive in their sectors. The main expectations in the automotive and aerospace area are high-speed vehicles with low fuel consumption. These expectations had become the need for reducing fuel consumption and reducing the harm to the environment by using less fuel. Many research and projects were carried out to find a solution to these challenges. A good solution for this problem is to use lightweight materials with high strength. In this manner, also according to the Ashby material selection charts, syntactic foams had become a potential candidate of materials that could be used in this area.

Syntactic foams, in basic, are composite materials formed of two constituent materials called matrix and hollow spheres or particles with high porosity like expanded aggravated clay particles [1]. Matrix materials are usually metal, ceramic, or polymer while hollow spheres are usually made of glass microspheres, polymers, or metals [2]. In the case of metal matrix syntactic foams (MMSFs), the matrix material is metal, and the foam structure is caused by gas-filled hollow spheres or by adding porous particles in the metal matrix material. Metal foams can be produced by adding porous particles or hollow spheres in the metal matrix material. The properties of the MMSFs can be changed by using different matrix and hollow sphere materials. Also, by changing the porosity, metal foams' specific strength values can be set. Due to these advantages of syntactic foams, lightweight materials with high strength can be obtained, which can be used as structural materials in industries. When it comes to strength, most of the time the compressive properties of the material should be investigated. Even though their compressive properties and porosity effects have been investigated before, there are still not

enough data about the effect of unwanted pore on the whole structure. It is also crucial to find new ways to increase the strength of the materials without increasing the weight; steel-grid reinforcement in metal foams can be a good solution. The main purpose of this research is to investigate two things. 1. By adding a steel-grid to the MMSF samples, can we increase some of the compressive properties (like the plateau stress or the stiffness modulus) of MMSFs? We also investigated the effect of the orientation of the grid. 2. What are the effects of the not perfect infiltration of the porous spheres on the compressive properties? Due to imperfect infiltration, a set of unwanted pores appears in the matrix, changing the properties of the MMFs. We investigated the effect of these unwanted pores by adding pores of different sizes and putting them in different places. Moreover, for more accurate results, the samples created to study were compared with the unmodified syntactic foam samples.

## 2. Syntactic Foams Literature Review

This section explains the concepts that might be relevant to this work. The explanations start with the terminology and general information. The first two topics are about the common and distinguishing properties of metal foams and metal matrix syntactic foams. The history of metal foams and applications is mentioned to show the potential application areas in the next sections. Manufacturing methods were also provided to detail their effect on mechanical properties and the final structure of the material.

Additionally, the effect of reinforcement and pore size on such structures is discussed as this work investigates the possibility of reinforcing syntactic foams with a steel grid. General and compressive mechanical properties are also considered, as this work analyses these features (especially the compressive ones). Literature on metal matrix syntactic foams is reviewed about relevant subjects to this research.

### 2.1 What is “Syntactic Foam”

Metal foams (MF) are materials with lightweight characteristics. They are inspired by natural cellular structures like sea sponges, bones, and wood. MFs are frequently made of aluminium but there are other often-used metals like nickel, copper, zinc etc. MFs offer very good stiffness-to-weight ratio. To provide this, the materials are usually produced with 75-95 porosity. The pores can be both open or closed thus, according to the structure, we can distinguish open-cell and closed-cell metal foams. The structures may determine the application area, open-cell structures are mostly used as heat exchangers and filters, while closed-cell structures are used against impact loads due to their high impact energy absorption capacity [3] [4].

Syntactic foam is a type of composite material with two different components called "matrix" and "particles containing pore(s)". Depending on the matrix material, we can distinguish e.g., syntactic polymer foams and syntactic metal foams or also called as metal matrix syntactic foams (MMSFs). The matrix material can be metal, ceramic, or polymer [5]. The particles in the matrix can be hollow spheres of various materials; they can be made from glass, carbon, ceramics, and polymers [2]. In our case, lightweight expanded clay aggregate particles (LECAP) were used in the MMSFs.

The most significant advantage of syntactic foams is that their mechanical properties are adjustable. The properties, like damping, thermal, physical, and mechanical properties might be engineered by adjusting the porosity and choosing appropriate materials for both the matrix and the porous particles. All these structure properties might be advanced by changing the volume fraction of porous particles in the matrix and the size of the LECAPs or by using reinforcements or tougheners [5].

Another remarkable property of the syntactic foams is their compressive behaviour. Tensile and compressive strength might also be adjusted by changing particle orientation and the matrix material. The tensile properties primarily depend on matrix material while the compressive strength depends on both the matrix material and the properties of the hollow spheres/porous particles. This tailorability of the syntactic foams makes them usable in many areas, such as aerospace, marine, military, and automotive industries [6]. These industries require high-strength, lightweight materials most of the time.

Due to their tailorability and high specific strength, syntactic foams are considered as desirable structural materials with outstanding properties [7].

## **2.2 Metal Syntactic Foam**

Metal matrix syntactic foams (MMSFs) are specific types of syntactic foams where the matrix material is metal. MMSFs are competitive in selection in terms of structural materials by their outstanding mechanical properties, such as being light and having high specific energy absorption capacity [8]. As mentioned in general information about the syntactic foams, the properties of MMSFs can also be varied in a large range [3].

When it comes to metal syntactic foams, the important properties to investigate are the compressive properties due to their high specific energy absorption capacity [9]. The Young's modulus of MMSFs can only be calculated with the help of e.g. finite element model analysis or other computational methods or by modal analysis since local plastic deformation takes place even at very low strain [10].

## 2.3 History of Metal Foams

The history of metal foams started with a French patent published in 1925 about how to make high-porosity metal [11].

Even though the first publication about metal foams was in the 1920s, the first manufacturing techniques were applied in the 1950s. Some of these processing methods are still being used [12].

In the early 1960s, these metal foams were developed for marine applications. In the marine industry, they were used as buoyancy materials [13].

The interest in syntactic foams increased because of the development of aviation and automotive industries in the mid-1990s. Nowadays, the interest in syntactic metal foams is still increasing.

## 2.4 Applications of Metal Foams

Syntactic metal foams can be used in various applications. The main possible application is for MMSFs where lightweight materials with high strength are needed, such as the aviation and automotive industries.

For the automotive industry, MMSFs are desirable materials because of their mechanical properties. As mentioned before, syntactic metal foams have outstanding damping capacity, which makes them a good material candidate for the automotive industry, which usually has a problem with vibrative effects. Moreover, due to the lightweight structure of the foams, the CO<sub>2</sub> gas emission can be reduced by reducing the fuel consumption. Also, it may increase the accelerating feature of the cars [14].

For the aerospace industry, MMSFs can be advantageous due to their strength, damping capacity and durability. In this industry's activities, inertial forces might become a problem, but it can be reduced by having a lightweight structure [15].

In addition, there are some other areas that open-cell metal foams could be used, such as heat exchangers and fuel cells:

- The optimized design of metal foam can be used in heat exchangers, as a replacement for finned-tube in air-cooled condensers [16].
- Metal foams can be used in high temperature PEM fuel cells as flow fields. The metal foam cells' performance is 20% better than normal cells [17].

## **2.5 Manufacturing Methods and Their Effects on Metal Foams**

Manufacturing methods can change the properties of metal foams. For example, if the structure is open-cell, it can be used in the biomedical industry, while if the structure is closed-cell, it is mostly used in structural elements [19] [20] [18]. MMSFs can be considered as closed-cell foams.

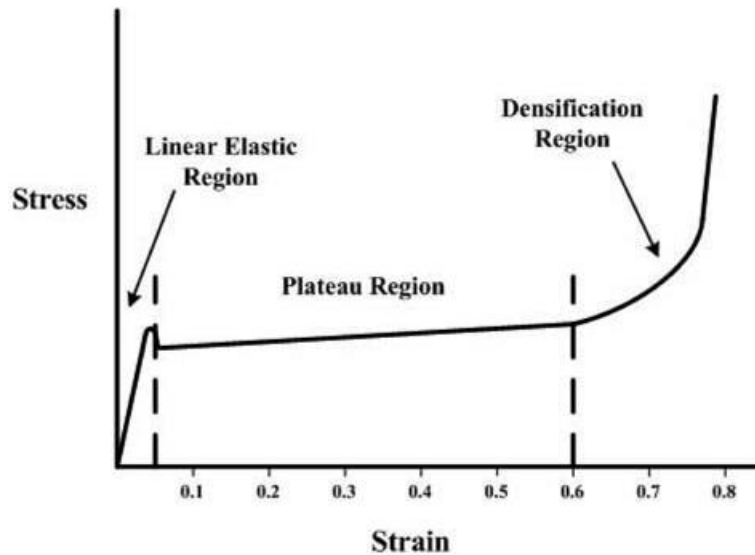
The compression tests applied on the metal foams show that their strength and Young's modulus primarily depend on the properties of the matrix material and the volume fraction of the pores. In the case of MMSFs, the volume fraction of the included porous particles also affect the MMSFs' properties [21].

The buoyancy effect can also be examined during the manufacturing process by setting the density of the material while producing it [12] [22]. Therefore, in the marine industry, the applicability may depend on manufacturing processes [20].

One of the ways to manufacture MMSFs is infiltration. In this method, the molten metal is squeezed into the space between the porous particles with gas pressure [21]. Additionally, this is the method we used in our sample preparation [23].

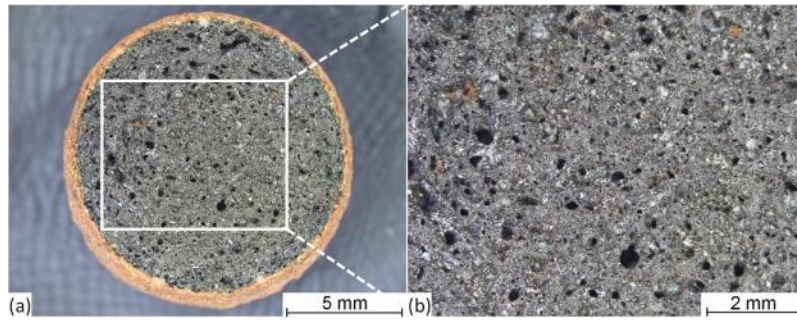
## **2.6 Mechanical Properties of Syntactic Metal Foams**

According to the literature, the compressive stress-strain curve of MMSFs consists of 3 stages. First, the stress increases as the linear function of the strain, this is the so-called quasi-linear stage can be seen in Figure 1. [24]



**Figure 1.** Typical stress-strain curve of a MMSF [30]

In the case of a ductile metal matrix, the second stage is the plateau stage, where the hollow spheres or porous particles crush, resulting in almost constant stress. By using e.g., ceramic hollow spheres, the energy absorption capacity can be increased. By changing the mechanical properties of the hollow spheres, the mechanical and energy absorption properties can be also changed [24]. Gupta, in his research, found another way to change the mechanical and energy absorption properties of MMSFs by changing the volume fraction of the incorporated hollow spheres [25]. He found that by increasing the amount of HSs, the strength of the material is decreasing, but material with high specific strength can be achieved. In another investigation about the strength which was done by Bibin John et al., he has resulted that the mechanical properties were dependent also on the volume fraction of the hollow spheres and the density of the material. While the pore amount was increased in the structure and the mechanical strength values decreased at the same time as the density [26]. Heat treatment was also mentioned to be effective in research conducted by Taherishargh et al. on the strength, the plateau stress, and the absorbed energy of the MMSF if the matrix material is heat treatable [27]. Mechanical properties can also be enhanced by the choice of the porous particle inside the MMSFs. One of the porous particle types which are also used as a construction material is lightweight expanded clay agglomerate particles (LECAPs). These particles are continuous at the surface and porous at the inner part as can be seen in Figure 2. According to the research held by Orbulov et al., the MMSFs with LECAPs had equal or better mechanical properties in comparison with the equivalent materials in this area [28].

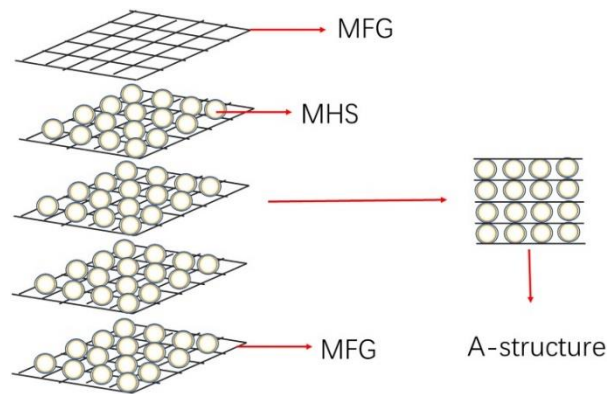


**Figure 2.** a) Cross section of a LECAP b) Inner structure in a magnified scale [28]

When it comes to material selection of the matrix in MMSFs in terms of mechanical properties (yield strength), Nikhil Gupta resulted in his research that magnesium matrixed syntactic metal foams had the highest if the samples were compared within the same density values form of different matrix material [30]. Moreover, another research was held on infiltration parameters' effects on the compressive properties. Orbulov resulted that the infiltration with high pressure in a short time may offer more desirable mechanical properties [31]. Two different pieces of research supported the idea that the energy absorption capabilities were also adjustable. According to Pradeep K. Rohatgi et al., the wall size thickness of the hollow spheres may set the compressive energy absorption while research done by Mingming Su resulted that the energy absorption is dependent on the density of the samples. The material density was enhanced by decreasing the size of the hollow spheres and this modification also improved the mechanical properties [32].

### **Reinforcement in metal matrix syntactic foams**

According to the research done by Nima Movahedi et al. integration of metal syntactic foams into an aluminum tube has a great reinforcement effect by increasing the mechanical properties [33]. Different reinforcing effects can be taken into consideration in different physical aspects. For example, according to M. Durante et al. in their research, with the help of steel wire mesh-grid reinforcement in an aluminum foam, they could overcome the problems of mold processes cost-effectively and flexibly. Also, in terms of mechanical properties, they observed that the bending load-carrying capacity of the samples was significantly improved [34]. In another research effects of steel grid reinforcement were investigated. Wang et al. constructed the structure according to Figure 3. They found that the layered structure can greatly improve the compression performance of the CMF [35].



**Figure 3.** Plan of the layered structure [35]

Some authors had remarks regarding the effect of unwanted pores in passing, but none of them investigated them systematically.

According to Orbulov et al., the unwanted voids in the matrix have a considerable effect on the elastic moduli of the structure [36]. Gupta et al. emphasized in their research about magnesium matrix composite foams that the unwanted pores might result in undesirable effects on the strength and the modulus. Also, the research indicates that unwanted pores can be useful in the production of low-density foams [30]. Orbulov provides results about the relationship between the infiltration parameters and imperfections and unwanted void formation. He stated that the unwanted pores worsen the overall cohesion of the composite [31].

### **3. Purposes of Research**

There are two different investigation areas in this research.

The first one is to investigate the effect of one steel grid on the compression properties of a syntactic metal foam. Adding only one grid does not influence the density relevantly. We also investigated the effect of the orientation of the steel grid in the syntactic metal foams (horizontal – vertical orientations).

And the second one is to investigate unwanted pore effects on the stiffness modulus and strength of syntactic metal foams. We investigated how important the location and the size of an unwanted pore are.

These effects were tried to be shown visually by real-time experimental photographs and data-based graphs.

## **4. Report of Research**

In this part, the whole process from the preparation to the testing step will be explained in detail.

The main steps in the completion of this report are:

- Designing the particles' arrangement for the "effect of unwanted pores" experiment
- Preparation of the steel grid case
- Arrangement of the LECAP for the unwanted pores experiment
- Arrangement and preparation of the steel grid reinforcement experiment
- Solution for arrangement stability problem
- Low-pressure infiltration
- Cutting the molds
- Machining the samples
- Compression test

### **4.1 Designing the particles' arrangement for the effect of unwanted pores experiment**

At the beginning of the experiment, the first important step was to find a solution to the problem "how to arrange the LECAP identically?". The problem was that the LECAP should have been put in the mold in a well-ordered way. The mold in Figure 4. was too high to directly put the hollow spheres on its bottom (approx. 15 centimeters). The arrangement of the particles had great importance; therefore, our first idea was to put the particles with a tweezers-like tool to place them into the mold, but it was too short to do that (around 7 centimeters).



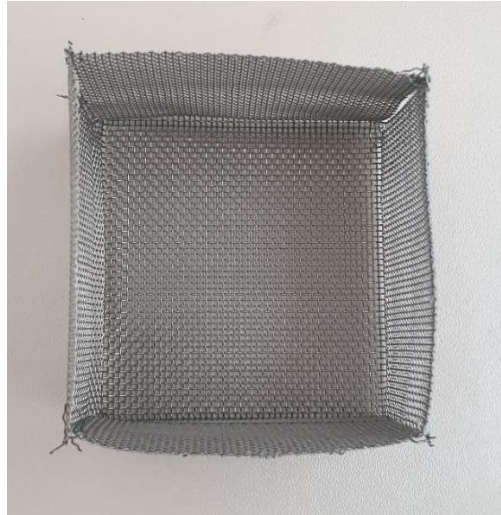
**Figure 4.** Mould used in the experiment

The best alternative solution to overcome this problem was to use a case to arrange the spheres in it and then put the case into the mold directly. The case should have been created with a material that would have been more resistant to the heat so that it wouldn't melt during the infiltration process, but it should have also been shapable. We decided to use a steel-grid material to prepare the case. The steel is resistant to the heat of the melting temperature of the matrix material we used (aluminum) and was easy to shape, while it could be used like a mold when it comes to the arrangement of the particles.

## **4.2 Preparation of the steel grid case**

The first step in preparing the steel grid was to measure the mold's width and length to mark it on the steel grid. The sizes were pointed on the steel grid and the edges were created by cutting the 2D open-top cube-like shape from the grid.

For cutting, clippers were used. The final shape was given to them by flattening the surface with a hammer, and the edges were interlaced using steel wires. The cut steel grid was put between clamps and tightened during the flattening. In the interlacing process, the edges were connected with two wires from the top and the bottom. The final shape can be seen in Figure 5. The sizes related to these steel grids were about 10x10x8 centimeters (width x length x height).



**Figure 5.** Steel grid case

### **4.3 Arrangement of the LECAP for the unwanted pores experiment**

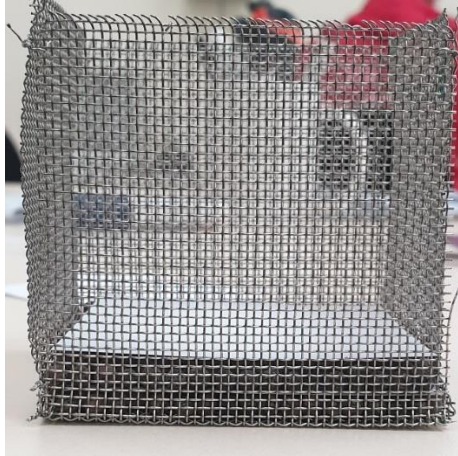
In this experiment, the arrangement of LECAP was one of the most important factors as unwanted pores should be positioned in the structure well. Therefore, the following methods were tried to position the extra pore.

For the preparation, the steel grid cases were placed at the top part of the molds, and by forcing them a bit inside, they were fastened. LECAPs of 3.54 mm diameter were put into these steel cases (Figure 6.) with the help of a tweezers-like tool to keep the particles in a nice order.



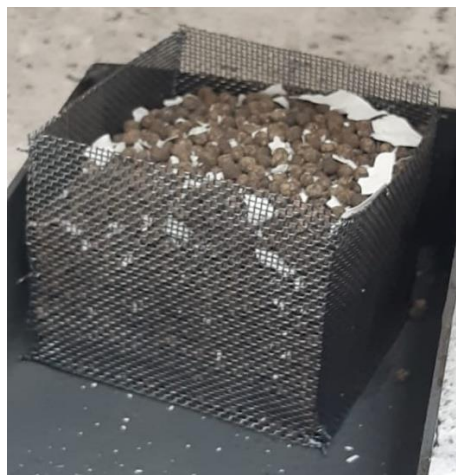
**Figure 6.** LECAPs in steel grid case

After the bottom layer of the steel case was full of particles, a new layer of particles started to be built. To keep these layers in a nice order and to easily separate them, a rectangular piece of paper (later a piece of a napkin) was used to separate the layers. The structure can be seen in Figure 7.



**Figure 7.** LECAPs in the case and a paper separator at the top

By using a separator, the layers were easily separated, and the order of the particles seemed well too. The paper separators were expected to be burnt out in the furnace without any problem and to become dust mixed into the structure during the infiltration process. The result was not as good as we expected because the paper separators deformed during the heating and ruined the well-ordered structure so that the infiltration could not be applied. The ruined structure can be seen in Figure 8.

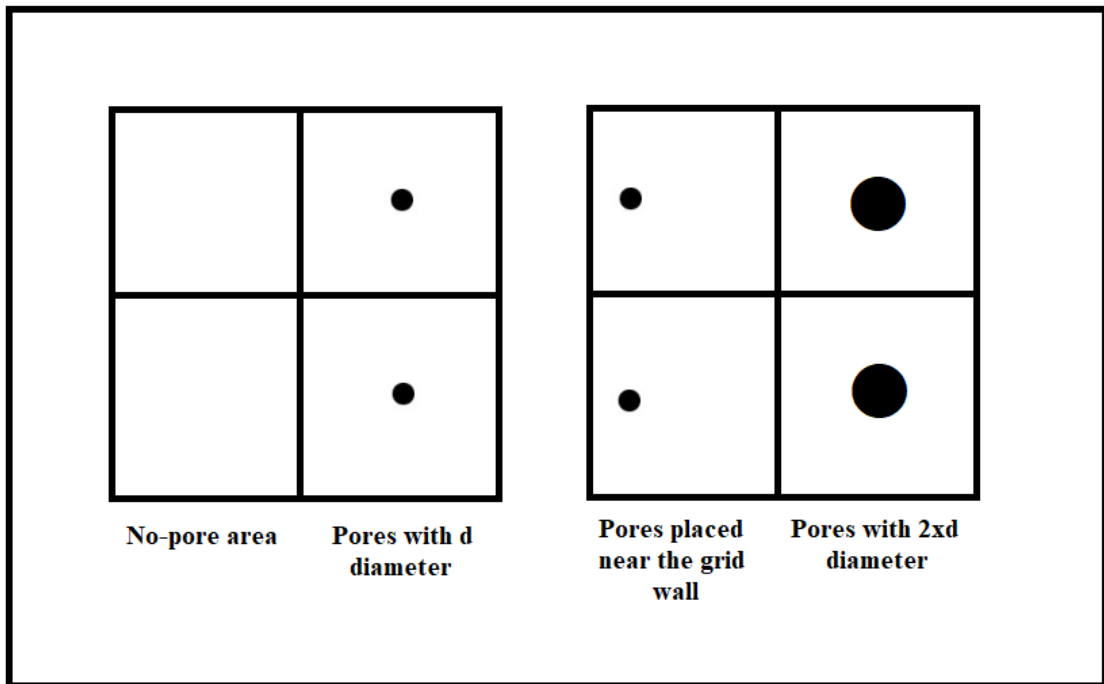


**Figure 8.** Ruined structure after heating

As an alternative way, the layer numbers were recorded by taking photos of each layer, and the LECAPs were put directly onto each other sensitively and carefully to keep the well-order in between. The final height aim (about 7 cm) was reached after 16 layers. Some more layers were added to the top to ensure the appropriate size of the sample even after cutting it for compression specimens.

The investigated parameters in this experiment were,

- Having a pore in size of  $d$  (diameter of the LECAPs) in the middle of the sample (2 specimens with this arrangement); the other half of the material in the mold contained well-ordered particles to have 2 samples without unwanted pores
- Having a pore in size of  $2d$  in the middle of the sample (2 specimens with this arrangement) to investigate the size effect of the unwanted pores; the other half of the material in the mold contained again a  $d$  size pore, but the location of the pore was close to the rear part of the mould to investigate the effect of the position of the pores. The arrangements can be seen in Figure 9.



**Figure 9.** Orientation plan of the unwanted pores experiment

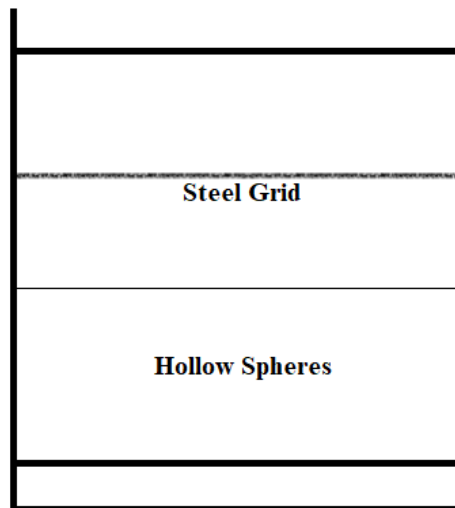
These pores were placed in the middle of the samples at the 8th layer. After the arrangement was done, the steel grid case was fully pushed into the mold onto an alumina layer. To keep the well-ordered structure for the whole production process, a steel grid was placed at the top of

the particles to prevent their displacement during the infiltration, when the order can be ceased due to the molten metal's flowing.

#### **4.4 Arrangement and preparation for the steel grid reinforcement experiment**

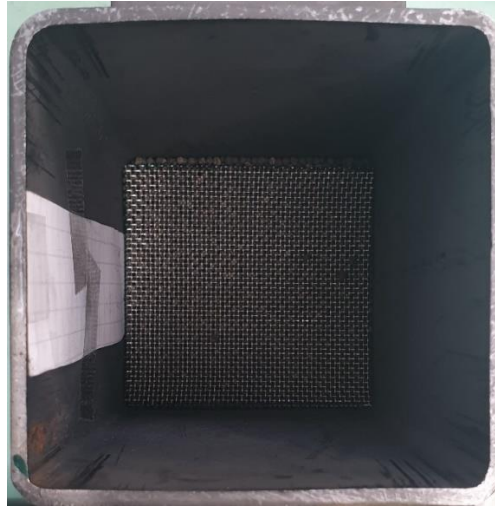
In this experiment, the LECAPs were not needed to be put in a well-ordered way because we investigated the effect of a steel grid inside the structure. The spheres were 2 mm in diameter.

For preparation, the spheres were put directly into the mold since now the arrangement of the particles was not important. We planned to have samples containing a grid in the middle and samples without a grid to be able to compare the mechanical behavior. The planned structure can be seen in Figure 10.



**Figure 10.** The mould with one steel grid

The LECAPs were put in the mold directly and randomly. Steel grids in the size of the molds' base area were cut to be placed on a 50 mm height particle layer. The planned structure was 7 centimeters in height. A paper with some lines indicating the desired heights was attached to the molds. These structures can be seen in Figure 11.



**Figure 11.** The mould with paper indicator

First, 50 mm height of LECAPs were put in the mold randomly. Then, a steel grid was added and after the steel grid, 20 mm more height of randomly put hollow spheres were added. The reason for this design was to obtain samples with steel grids in it with 30 mm height, and 30 mm height samples without grid reinforcement. Additionally, the rest of the height (5 mm from the bottom and 5 mm from the top) was going to be kept for the cutting process.

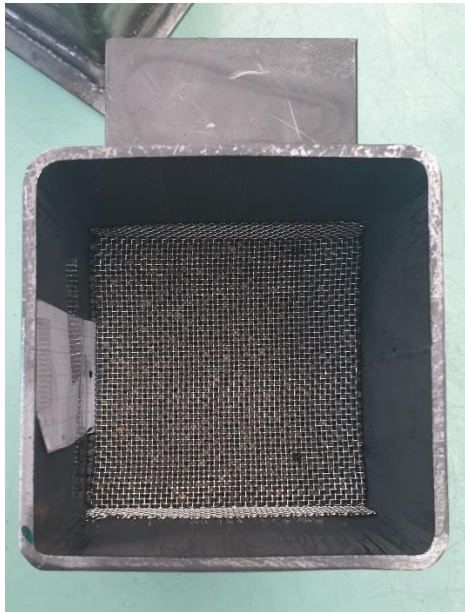
After the arrangement was made, another steel grid was added to prevent the movement of the particles. The preparation of the arrangement can be seen in Figure 12.



**Figure 12.** Arrangement in steel grid experiment

#### 4.5 Solution for the arrangement stability problem

Keeping the arranged hollow spheres and reinforcements was as important as building them. This problem could be solved by applying a compressive force to the layers from the top. Therefore, a steel grid of a little bit bigger size compared to the base area of the mold was cut for the samples. This grid was folded from the rear parts and pushed into the mold by force. The grid, with the help of the friction, was slightly squeezing the layers enough to keep the layers in a well-order. The pusher grid can be seen in Figure 13.



**Figure 13.** Steel-grid at the top to prevent the movement of the particles.

#### 4.6 Low-pressure infiltration

In the infiltration process, the first step was to prepare the molten aluminum in the furnace. The furnace temperature was set at about 750°C, and the aluminum rods were put into the induction furnace to melt. This process can be seen in Figure 14.



**Figure 14.** Aluminium being melted in a pot

After the melting of the aluminum, the preheated particles in the mold were taken into the pouring area. The molten metal was poured onto the particles in the mold and low pressure was applied on the mold to help the infiltration of the molten metal. The processes can be seen in Figure 15.



**Figure 15.** Low pressure being applied after pouring the molten aluminium into the mould

The mold was cooled down with running water until the mold became holdable by bare hand. This process can also be seen in Figure 16. After all these steps, the final samples were ready in the molds. Cutting needed to be applied to take out the material from the mold.



**Figure 16.** Cold water was poured onto the mould after the infiltration to cool it down

#### 4.7 Cutting the moulds

After preparing the samples in the molds, the samples needed to be taken out from the molds. For this, the bottom and crossing corners of the mold needed to be removed by cutting. During this process, a disk grinder was used. The molds were put and fixed between table clamps, cutting was applied after clamping and, protective equipment was used during the process. The cutting process can be seen in Figure 17. By the end of this process, the final samples were ready to be machined.



**Figure 17.** Mould cutting

## 4.8 Machining the samples

The samples were prepared for the compression test. For that, the material was cut into smaller pieces according to the ISO 13314:2011(E) standard. The reason for machining to be applied instead of directly cutting was to ensure the right angles of the adjacent faces of the samples. These parameters are important for compression tests. During this process, machining techniques were used.

## 4.9 Compression Test

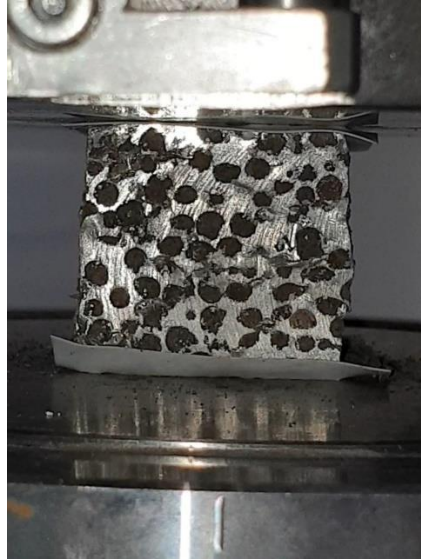
Before the compression test, the weight and dimensions of the specimens were registered to calculate the density. The compression tests were executed with an MTS 810 testing machine (Figure 18).



**Figure 18.** The sample placed in the compression test machine

The test was started with 500 N preload to avoid correction of the deformation curve at low strain. The initial strain rate was 0.001 s<sup>-1</sup>. During the compression, the surface deformation

was recorded with a mobile phone for analysis later. A computer recorded the displacement and the applied force. The material being compressed can be seen in Figure 19.



**Figure 19.** The sample under compressive load

The final materials were nearly compressed up to 50% deformation. An example of the compressed sample can be seen in Figure 20.

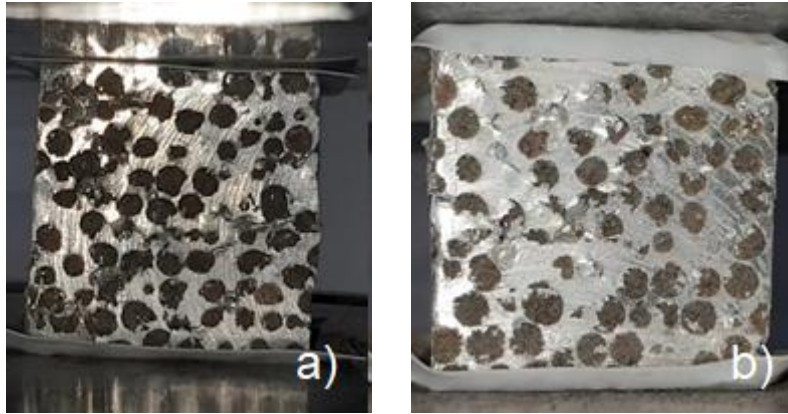


**Figure 20.** Compressed material after compression test

## 5. Results and Discussion

### Results for the experiment “Unwanted Pores”

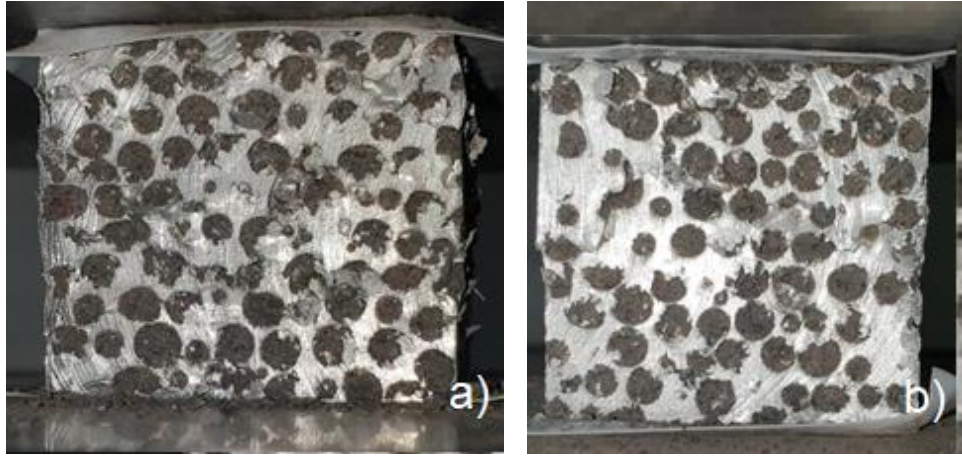
In the unwanted pores experiment, as it was mentioned before, two samples were without any unwanted pores and two with  $d$  size diameter pores. The deformed surface of the samples can be seen in Figure 21.



**Figure 21.** Sample (a) without pore (b) with  $d$  size diameter unwanted pore, under compression

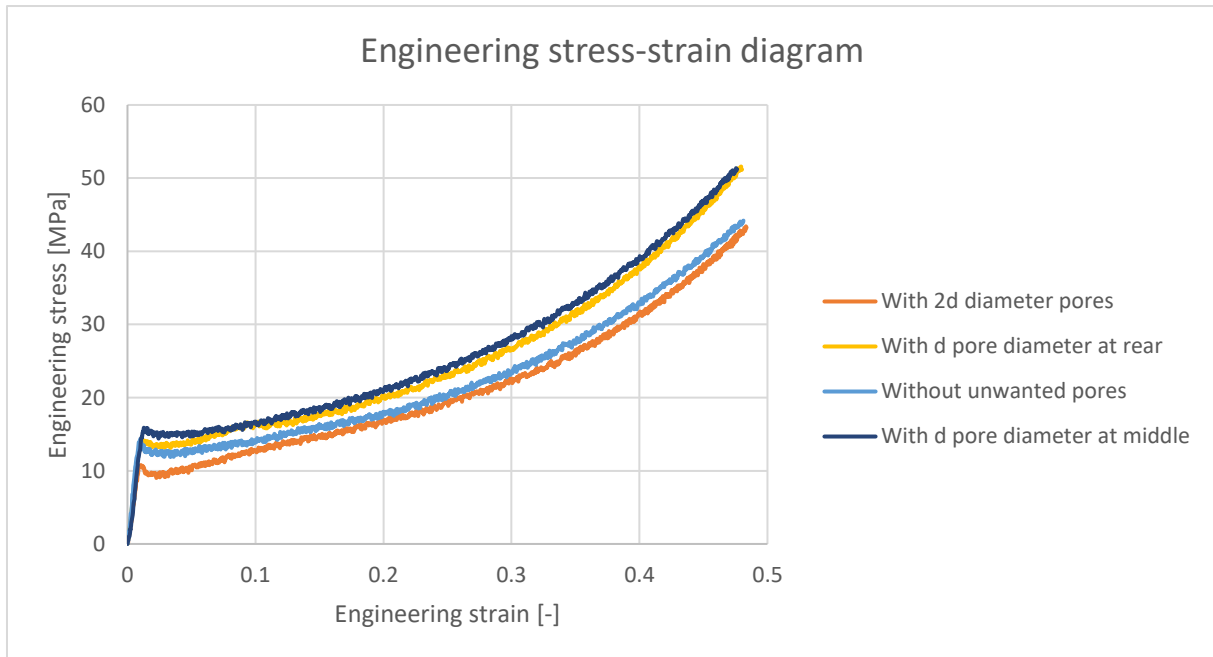
Deformation bands on the samples' surface can be seen in Figure 19. for both types of foam. In the sample, without unwanted pores, the first deformation band appears in the middle of the sample, almost horizontally. In the sample with  $d$  diameter unwanted pore, there are many bands, most of them do not go through the whole sample like in the previous case.

The next four samples contained a  $d$  size unwanted pore close to the surface and a  $2d$  diameter size pore in the middle of the sample. The deformed surface of these samples can be seen in Figure 22.



**Figure 22.** Sample with (a)  $d$  size pore near the surface and (b)  $2\cdot d$  diameter size pore in the middle of the sample

The difference between deformation bands due to the location of the pores inside the samples can be seen in the figures. The deformation band goes through the middle part of the sample with a bigger pore size while for the other sample the bands are close to the rear part because of the location of the pore.



**Figure 23.** Typical stress-strain curves of the samples for unwanted pores experiment

In Figure 23. the engineering stress and strain values of the different samples can be compared up to 0.5 deformations. Table 1 shows the stiffness modulus, which is the slope of the stress-strain curve in the first, quasi-linear stage, and the yield strength of the foams. According to

Table 1. the samples without unwanted pores had the highest stiffness modulus. The lowest stiffness modulus value was obtained with the sample, which had 2d sized pore diameter. According to the data, the position of the unwanted pore does not influence the stiffness of the sample. The difference in yield strength is not that pronounced. The samples containing 2d pores have the lowest yield strength and stiffness modulus. The yield strength of the other samples is approximately the same; only one of the “d size pore, near the surface” samples, shows lower yield stress. The difference is most probably not due to the introduced pores. This suggests that unwanted pores have a larger effect on the stiffness of the samples than on the yield strength. However, by increasing the pore size, both the stiffness and the yield strength are affected by the presence of the “big” pore.

**Table 1.** Stiffness modulus and yield strength for the Samples

| Sample                        | Stiffness Modulus<br>[MPa] | Yield Strength<br>[MPa] |
|-------------------------------|----------------------------|-------------------------|
| without unintentional pore    | 1663                       | 17.09                   |
| without unintentional pore    | 1932                       | 16.84                   |
| d size pore, in the middle    | 1438                       | 17.18                   |
| d size pore, in the middle    | 1342                       | 16.68                   |
| d size pore, near the surface | 1403                       | 12.88                   |
| 2d size pore, in the middle   | 1208                       | 12.65                   |
| 2d size pore, in the middle   | 1095                       | 9.73                    |
| d size pore, near the surface | 1490                       | 16.57                   |

### Results for the experiment “Steel Grid Reinforcement”

In this experiment, a steel grid was put in a metal syntactic foam structure in vertical and horizontal directions to investigate its strengthening effect. Again, reference samples that are not modified were also used during the experiment to compare the results. The unmodified sample under compression can be seen in Figure 24.



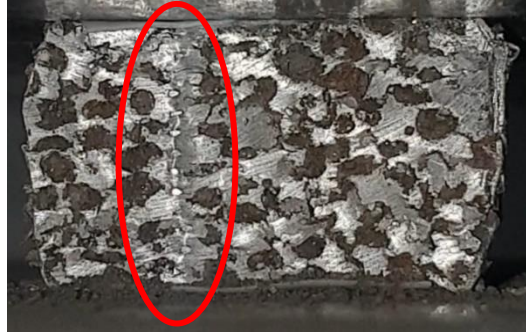
**Figure 24.** Unmodified sample

The surface of a “horizontally located grid” sample under the compression can be seen in Figure 25. It can be seen that at large deformation, the steel grid ends come out from the sample, and they become even more visible.



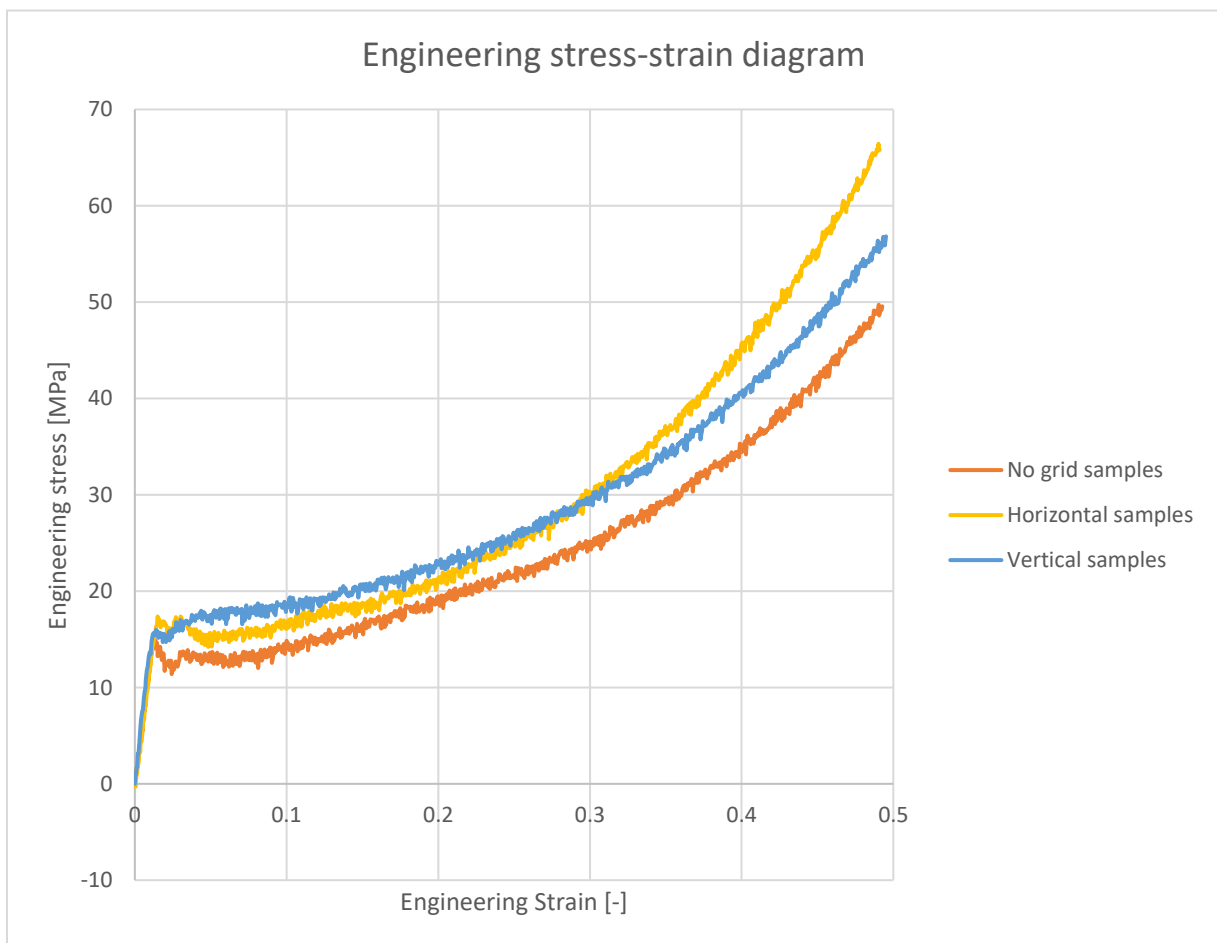
**Figure 25.** Sample with horizontally located steel grid

The “Vertically oriented grid” sample under compression can be seen in Figure 26. The same behavior mentioned in the “horizontal grid” sample is valid for vertical ones during the compression.



**Figure 26.** Sample with vertically oriented steel grid

Figures 24., 25. and 26. show that the grid affects the appearance of the deformation for the samples. It is because around the steel grid, the samples are less deformed compared to the other parts of the sample as the sample is denser around the steel grid.



**Figure 27.** Typical sample diagrams for steel grid reinforcement experiment

In Figure 27. the engineering stress and strain curves can be compared for the whole compression process, about up to 0.5 deformations.

We determined different mechanical parameters, like the stiffness modulus, the yield strength, the plateau strength, and the absorbed energy of the samples until 0.45 deformation according to ISO 13314:2011 international standard. These data can be found in Table 2.

**Table 2.** Samples and their Properties

| Sample name                 | E [MPa] | $\sigma_y$ [MPa] | $\sigma_{pl}$ [MPa] | $\rho$ [kg/m <sup>3</sup> ] |
|-----------------------------|---------|------------------|---------------------|-----------------------------|
| With grid, vertical, S_1    | 1605.2  | 24.29            | 23.35               | 1529.66                     |
| With grid, vertical, S_5    | 1452.7  | 20.47            | 24.56               | 1565.09                     |
| With grid, vertical, S_10   | 1185.2  | 18.05            | 27.02               | 1627.16                     |
| With grid, vertical, S_30   | 1395.7  | 20.67            | 23.26               | 1547.20                     |
| Without grid, S_14          | 1035.5  | 18.14            | 18.04               | 1398.12                     |
| Without grid, S_16          | 1254.9  | 20.24            | 19.98               | 1461.99                     |
| With grid, horizontal, S_3  | 1269.2  | 23.19            | 22.06               | 1640.46                     |
| With grid, horizontal, S_7  | 1337    | 24.22            | 25.63               | 1666.07                     |
| With grid, horizontal, S_8  | 1288.6  | 21.88            | 23.83               | 1684.21                     |
| With grid, horizontal, S_33 | 1334    | 21.51            | 23.69               | 1566.22                     |

As we mainly investigate the effect of the direction of the steel grids, the results are collected as average values in Table 3. The specific values that are data divided by the density were also determined as the density of the sample varies because of the grids. The scatter in these data is wide but still evaluable. These data are shown in Table 3.

**Table 3.** Average data of the different types of syntactic foams

| Type of sample    | Average<br>( $E \pm \delta E$ )/ $\rho$<br>[ $10^6 \text{m}^2/\text{s}^2$ ] | Average<br>( $\sigma_y + \delta \sigma_y$ )/ $\rho$<br>[ $10^3 \text{m}^2/\text{s}^2$ ] | Average<br>( $\sigma_{pl} + \delta \sigma_{pl}$ )/ $\rho$<br>[ $10^3 \text{m}^2/\text{s}^2$ ] | Average $\rho$ [kg/m <sup>3</sup> ] |
|-------------------|-----------------------------------------------------------------------------|-----------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|-------------------------------------|
| Vertical-Grided   | $1.02 \pm 0.03$                                                             | $15.8 \pm 0.4$                                                                          | $14.8 \pm 0.4$                                                                                | $1567.3 \pm 42.5$                   |
| Horizontal-Grided | $0.98 \pm 0.03$                                                             | $15 \pm 0.5$                                                                            | $14.2 \pm 0.5$                                                                                | $1639.2 \pm 45.2$                   |
| Non-Grided        | $1.12 \pm 0.04$                                                             | $17 \pm 0.5$                                                                            | $16.5 \pm 0.5$                                                                                | $1430.1 \pm 51.9$                   |

It can be seen; that, however, the yield strength and the plateau strength of the reinforced foams are higher, but the specific values of the non-modified foams are better than the reinforced ones. Still, between the modified ones, vertically oriented grids had a slightly better performance in terms of properties per density.

Lastly, as the density increased in these materials, the energy absorption until 0.45 deformation was investigated. The results can be seen in Table 4.

**Table 4.** Average Energy Absorption of the Orientations

| Sample            | Average absorbed energy<br>in unit volume [J/cm <sup>3</sup> ] |
|-------------------|----------------------------------------------------------------|
| Vertical Grided   | 11.60                                                          |
| Horizontal Grided | 11.83                                                          |
| No Grided         | 9.09                                                           |

It is clear from the table that the absorbed energy was higher in steel-graded samples. Between horizontal and vertical samples, the difference was not significant. Figure 25. also shows this tendency: the deformation curve of the no-grid sample is under the deformation curves of the reinforced samples.

## 6. Summary and Conclusion

To summarize our investigations, we first investigated the effect of the unwanted pores on the stiffness modulus and yield strength in aluminum matrix syntactic foams. We have found that the existence and size of the unwanted pores affect the mechanical properties of the samples. The pores with two times the porous particles' diameter caused the highest decrease in the strength and stiffness of the syntactic foams. The location of the unwanted pore did not have a significant effect on the same properties.

Next, we investigated the mechanical properties of steel grid-reinforced aluminum matrix syntactic foams. We found that syntactic foams without grids have a lower density, but also lower strength and stiffness modulus values compared to the samples with grids. The samples with a grid also had better energy absorption properties caused by the increased density. However, the specific mechanical values are lower for the reinforced samples.

### Outlook

Further research recommendations: the number of steel grids can be increased in further works on this subject. So, the effect of the number of steel grids on the mechanical properties of the syntactic foam can be studied. For the unwanted pores research, the unwanted pore location's effect on larger samples can be studied to understand its effect on the formation of deformation bands.

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