Géza Pattantyús-Ábrahám Doctoral School of Mechanical Engineering

Budapest University of Technology and Economics, Faculty of Mechanical Engineering
Department of Materials Science and Engineering

Attila Szlancsik

MSc in mechanical engineering

Metal matrix syntactic foams: elastic and compressive mechanical properties and their modelling

Thesis Booklet

Supervisor:
Imre Norbert Orbulov
professor, PhD, dr. habil, DSc

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1. INTRODUCTION

In this thesis booklet, I review my doctoral thesis and I give a summary of the most important contents. This summary contains the outcome of the literature research, the objectives of my scientific research and also the description and evaluation of the research tasks defined by the objectives. In this theses booklet, according to the formal requirements of a doctoral thesis, I present my scientific results in a uniform, self-explanatory system.

In this summary, I intend to introduce, explain, justify and outline, within their domain of validity, the results of my scholarly research work, which can be considered as independent initiations, formulated in thesis statements. This thesis booklet structure makes it possible to formulate the thesis statements clearly and as briefly as possible.

In today's modern world, the pursuit of energy efficiency is an increasing compulsion. In this connection, there are two important development directions for materials: one is to make the load-bearing capacity of the material in the main direction or directions of the load as high as possible, and the other is weight reduction, which can improve the specific (density-specific) properties. In both cases, hybrid materials can provide an effective solution.

Metal matrix syntactic foams have low density, so their specific properties are outstanding. Conventional metal foams, in which the porosity is created not by a reinforcing material but by some gas-forming process, have lower densities, but in most cases metal matrix syntactic foams, have a much higher specific strength (conventional metal foam: 10 MPa/(g/cm^3) [1], syntactic metal foam: 126 MPa/(g/cm^3) [2]), and their specific mechanical energy absorption capacity is also higher (conventional metal foam: 1-2.5 J/g [3], syntactic metal foam: 12-16 J/g [4, 5]). As foams, it is advisable to use them in compression based applications, accordingly, their compressive characteristics are widely studied (the test method has also been standardized [6]). In terms of macrostructure, the spatial distribution and volume fraction of the reinforcing material are the most important. The issue to be clarified in relation to the microstructure is the adequacy of the relationship between the hollow spheres and the matrix material. This boundary layer, or transition layer, is responsible for the load transfer in the metal matrix syntactic foams between the reinforcing material and the matrix.

Polymer matrix syntactic foams were first developed, mainly for deep sea applications. Examples are the HOV Alvin or the REMUS 6000 diving equipment, which can dive to a depth of up to 6500 meters [7]. Metal matrix syntactic foams may play a significant role in deep-sea research, the aerospace industry and even the automotive industry in the future. Nowadays, traditional metal foams are already being installed in luxury and series cars, such as the Ferrari Spider 360 or Audi Q7 [8].

In the course of the literature search, I came across questions in the field of mechanical properties of metal matrix syntactic foams, to which there are only relatively few scientific results and answers. In the following, I will also mention these shortcomings and initial results, and then, after describing the objective, I will turn to the basic details of my research work.

2. MAIN RESULTS OF LITERATURE RESEARCH

Metal matrix syntactic foams were developed on the model of polymer matrix syntactic foams published in the late 1960s [9]. The first publications on metal matrix syntactic foams appeared in the early to mid-1990s. The field of metal matrix syntactic foams is active, as its application possibilities are partly undiscovered even 60 years after the development of the discipline, thanks to the fact that, like many other materials, syntactic foams are products of military development (submarines, radar cross-section reduction, and projectile absorption).

2.1. Compressive properties of metal matrix syntactic foams

The main field of application of metal matrix syntactic foams is the impacting elements, therefore its most important property is the mechanical energy absorption, which can be best determined by compression tests.

Anbuchezhiyan et al. [10] produced glass microsphere shell reinforced metal foams with a magnesium matrix alloy with 9 wt% aluminum. During production, 10, 15 and 20% by volume of microsphere shells were added to the melt and then molded into the mold under vacuum, thus helping to improve the quality of production and avoid micro cavities. By optimizing the production parameters, they managed to achieve a 5% improvement in compressive strength. The compressive strength value thus obtained was 280 MPa.

Broxtermann et al. [11] produced zinc matrix metal foam containing 27 wt% aluminum and 2 wt% copper using expanded perlite and expanded glass. The density of the expanded perlite-reinforced metal foam was 2.05 g/cm^3, while that of the expanded glass was 1.84 g/cm^3. As expected, quasi-static compression tests showed that expanded perlite-reinforced metal foams had higher mechanical properties. The compressive strength of perlite and glass-reinforced metal foams was 57 and 53 MPa, while the plateau stress was 67 and 57 MPa, respectively.

Vendra and Rabiei [12] produced metal matrix syntactic foams with low carbon steel as well as AlSi7 matrix reinforced with stainless steel spheres by gravity casting. 35×40×50 mm samples were machined from the produced blocks. The samples were quasi-statically compressed and then standard mechanical properties were determined. The metal foam reinforced with stainless steel hollow spheres outperformed the metal foams with low carbon hollow spheres in all respects, while their densities were nearly the same (2.46 g/cm^3 and 2.41 g/cm^3, respectively). The plateau stress was 80 MPa for the stainless steel hollow sphere reinforced samples, while it was only 58 MPa for the low carbon steel hollow sphere reinforced samples. The values of energy absorbed up to 50% deformation were 40 J/cm^3 and 30 J/cm^3, respectively. Compared to a conventional - ie without reinforcement - aluminum matrix foam, the energy absorption capacity increased more than tenfold, as, for example, the conventional metal foam studied by Ruan et al. [13] was able to absorb 2.6 J/cm^3 at 50% deformation.

2.2. Modeling of metal matrix syntactic foams

Computer-aided modeling of metal matrix syntactic foams has only recently begun. Few articles deal with the modeling and finite element analysis of closed-cell metal foams.

Bardella et al. [14] created their models using the Ansys program, in which they created metal foams with different space fillings. Six different space fillings were used, with increments of 10% from 10-60%. 10-node tetrahedral elements were used for modeling. Compression test was modeled and determined the shear modulus from it. The results were compared with theories based on different analytical calculations. It was found that the results from the simulations were halfway between the analytical calculations results of the different theories, and that the results of three theories were close together, namely the Mori-Tanaka estimate (MT), the classical self-consistent estimate (CSC), and the differential self-consistent estimate (DSC).

I highlight the work of Nian et al. [15] because they have changed the diameter of the hollow spheres in their 3D model, so there were spheres of different diameters within one model, which approximates reality well (that the reinforcement particles are not perfectly the same, but their diameter shows standard deviation). From their results, it was found that the shape has no particular effect on the effective Young's modulus, whereas the Poisson's ratio is reduced by the decrease in the slenderness of the reinforcement.

2.3. Determination of the effective Young's modulus of metal matrix syntactic foams by measurement

Structural stiffness is a size-dependent property that cannot be generalized to specimens of other sizes. In contrast, the effective Young's modulus, as defined by Bardella et al. [14], is a size-independent material property that can even serve as a basis for design.

The procedure which was examined was modal analysis [16]. Majkut [17] studied the beam theories of Timoshenko and Euler-Bernoulli. Both theories are suitable for determining the Young's modulus based on Eigen frequencies. He compared the Young's modulus values converted from the measurement with the results of a finite element model, from which he concluded that Timoshenko's beam theory gave a good approximation to the simulated results in all cases. The great advantage of this theory is that the Young's modulus of the tested specimen can be determined from it in such a way that only the geometrical dimensions, density and the values of the first and second Eigen frequencies are required.

2.4. Radially constrained compression

Radially constrained compression can provide a lot of additional information compared to conventional compression. However, due to its more difficult feasibility, few studies currently address this topic.

Duarte et al. [18] produced AlSi7 aluminum-alloy closed-cell metal foam. Free and radially constrained compression tests were performed with two different speed. There was no detectable difference between the quasi-static and dynamic (284 mm/s) tests, however, due to the differences in density, the higher density specimens had more favorable mechanical properties. There was a significant difference between free and radially constrained compression, not only did the value of compressive strength increase, but the compaction deformation also decreased. In addition, the slope of the plateau section increased significantly.

Li et al. [19] also investigated an open-cell aluminum foam for free and radially constrained compression. The compressive strength was 4.8 MPa for free compaction and 17.4 MPa for constrained. A 68% increase in plateau stress was observed, from 22 MPa to 37 MPa.

Radially constrained compression also allows the determination of the parameters of a material model from it. Shima and Oyane [20, 21] have developed a material model for powder metallurgy materials that takes into account that these materials do not have volume constancy, but only mass constancy.

3. REFERENCES FOR CHAPTERS 1. AND 2.

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4. RESEARCH OBJECTIVES

The values defined by the existing ISO 13314 standard [7] for the compression testing of porous materials are not generally used, which makes it almost impossible to compare different studies. Because of these, the effect of the matrix material on the values required by the standard cannot be determined on the basis of literature data, which would be important during design and use.

Modeling of syntactic metal foams is also key for design, as this step can reduce the number of prototypes and specimens. Currently, only models with 5-10 hollow spheres are available in the literature that are capable of simulating plastic deformation, however, this does not reach the size required by the standard, so the results provided by them are unreliable. Models with multiple hollow spheres are currently only suitable for the study of elastic properties, however, elastic properties cannot be supported by any measurement. There is currently no measurement method in the literature suitable for measuring the effective Young's modulus of metal matrix syntactic foams, so it is not possible to validate these models.

Radially constrained compression is an undiscovered area of metal foam research, although it can be used to investigate a possible failure mode for energy absorbing applications.

It would be very important for design purposes to have a material model for the metal matrix syntactic foams that allows for size- and load-independent description of these materials. There is currently no example of this in the literature, so the values specified there can always be said to be true only for materials of a given size and composition. Based on my previous research and literature search, I set the following objectives:

- To investigate the effect of matrix material, heat treatment condition and specimen size on the compressive strength properties of syntactic metal foams.
- Finite element modeling of syntactic metal foams so that it can be validated by measurements, thus providing a model that can be used during design.
- Determination of the effective modulus of elasticity of syntactic metal foams by a measurement method suitable for the validation of models found in the literature.
- Validation of a material model that is suitable for modeling syntactic metal foams, thus being able to describe these materials regardless of specimen size and stress state.

5. OVERVIEW OF THE RESEARCH

In line with the objectives, I divided my research into four major topics, which are:

1) Production and compression testing of metal matrix syntactic foam specimens with different matrix materials and heat treatments;
2) creating a finite element model that fully depicts a compression test;
3) to determine the effective Young's modulus of the metal matrix syntactic foams I have studied using modal analysis, analytical methods and finite element simulation, and
4) performing radially constrained compression, which allows the fitting of Shima-Oyane material model parameters.

In the following, I summarize the experimental and material testing work for each topic, as well as the results of analysis and evaluation, by topic, specifically in such a way that these summaries provide a sufficient basis and justification for the short formulation of the theses.

5.1. Effect of matrix material and heat treatment on the mechanical properties of metal matrix syntactic foams reinforced with globomet hollow spheres

In my experiments four types of matrix materials were used (Al99.5, AlSi12, AlMgSi1, AlCu5), which were reinforced in each case with a globomet (GM) grade pure iron hollow spheres from Hollomet GmbH. For the production, low-pressure infiltration was used, after which three specimens were machined of different sizes from the block. Each specimen was 14 mm in diameter and 14, 21, and 28 mm in height, respectively. After production, an annealing (O) heat treatment was performed, during which all the specimens were kept at 520°C for 1 hour and then cooled in water. The two alloys (AlMgSi1 and AlCu5) which can be hardened by precipitation were then subjected to artificial aging (T6) at 170°C for 14 h. The labeling scheme is as follows: matrix material – filler material – heat treatment.

Subsequently, the compression tests were performed on the MTS 810 universal material testing equipment with a deformation rate of 0.01 1/s. Figure 1 shows the values which was evaluated according to the standard.

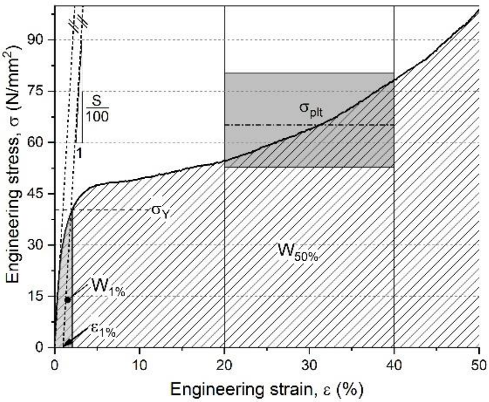

Figure 1. Interpretation of the examined standard measurement values.

The standard measurement values which were examined: the initial slope, i.e. the structural stiffness – S (MPa) – a straight line was fitted to the initial section, and then divided the slope of the resulting line by 100 (due to the percentage representation). The fit was made between 6 and 18 MPa in each case. It should be noted that the structural stiffness is identical to the effective Young's modulus of the sample (i.e., the Young's modulus of the homogeneous isotropic body replacing the metal foam). In the next step, a parallel to this line was drew for the deformation ε = 1% in order to determine the conventional yield strength (σ_Y (MPa)) and absorbed energy for the 1% residual deformation. This work – $W_{1\%}$ (J/cm^3) – was obtained by finding the value of ε for σ_Y and then numerically integrating the curve up to this value. The next value is the plateau stress - σ_{plt} (MPa) - which would belong to the near horizontal part of the curve. My curves show that there is no horizontal part, but the stress value is constantly increasing, so the plateau stress was determined (according to the recommendation of ISO 13314 [7]) by averaging the stress in the section up to ε = 20-40%. The next value to be calculated for the energy absorption related to the total strain – $W_{50\%}$ (J/cm^3) – was obtained by numerically integrating the total area under the curve up to 50% deformation. In addition, the energy absorption efficiency – W_h (%) – was determined which should be calculated by the following formula:

$$W_h = \frac{W}{\sigma_0 \varepsilon_0} 10^4 \quad (1)$$

Where W_h is the energy absorption efficiency, W is the energy absorbed up to 50% deformation in my case, σ_0 is the stress measured at 50% deformation and ε_0 is the upper limit of the deformation, which was 50% in my case.

In the case of structural stiffness, in order to have an even more accurate picture of the size dependence, the values were normalized with the value corresponding to H/D=2. Taking the standard deviation into account, a line was fitted passing through the origin, the slope of which was 0.473 and the square of the standard deviation of the fit was 0.996. Based on these, it can be stated that there is a linear relationship between the dimensions of the specimen and the structural stiffness. Figure 2 shows the normalized structural stiffness, while Figure 3 shows the energy absorption efficiency.

During the compression tests of the metal matrix syntactic foams reinforced with iron hollow spheres, it was observed that they behaved plastically during the whole deformation, so no pieces broke out of the specimens, but the whole specimen remained together and deformed with the appearance of small barreling. After complete compaction, the specimens were dissected and subjected to a microstructural examination in order to examine whether cracks appeared inside the material during the deformation. The hollow spheres were partially separated from the matrix material, however, they did not create cracks, and as the matrix material deformed, the hollow spheres also deformed. Based on these, it can be stated that iron hollow spheres are plastically deformed, and metal matrix syntactic foams reinforced with iron hollow spheres are also plastically deformed in compaction tests. The fact that the energy absorption efficiency does not depend on either the matrix material or the H/D ratio may be due to this mode of failure, however, this cannot be expressed with absolute certainty due to the large deviation fields.

My 1st thesis statement was defined on the base of those summarized conditions of the measurements and experimental details of my research, which are seen in the Chapter 5.1.

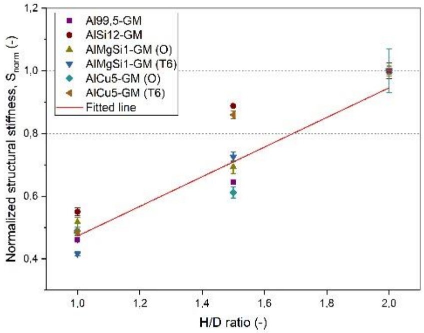

Figure 2. Dependence of normalized structural stiffness on the H/D ratio of the specimen.

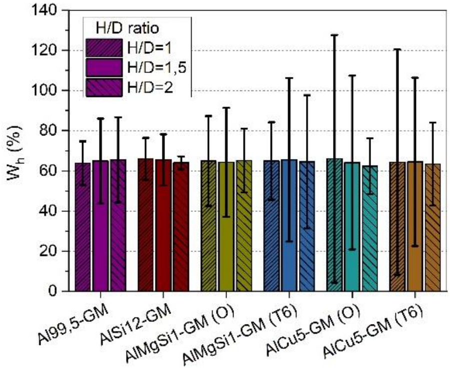

Figure 3. The efficiency of the energy absorption per matrix and H/D ratio.

5.2. Modeling of metal matrix syntactic foams compression test

This chapter presents a 3D model of an H=14 mm height, D=14 mm diameter compression specimen (H/D=1), from its creation to the finite element simulation. The matrix material is Al99.5, while the reinforcing material is an iron spherical shell (GM type).

The first step in creating the model begins with the random placement of the hollow spheres. As a first step, I wrote a Matlab program that divides a volume with a 1 μm mesh in the x, y, and z directions as well. Where these networks intersect, nodes form, and these nodes can be possible centers of the spheres. In the next step, the distance of how far a newly deposited sphere is from the other sphere was set. A range has to be specified, which is necessary because if the spheres are too far apart, the desired space filling will not be achieved, whereas if the spherical shells come into contact, the model cannot be meshed due to singular points. Experience (experimental runs of the program) has shown that a minimum distance of 10 μm should be left between the spheres. The smaller the value of the maximum distance, the higher the space fill, however, as this value decreases, the running time of the program increases exponentially, so that the optimal maximum distance is 50 μm. This is how the 10-50 μm band in which the spheres can be placed was formed. However, this criterion would also be few, because if the newly placed spheres were always so close to only one sphere, it is easy to imagine a case where a proper space fill as not reached, because the program places the next sphere exactly so that it does not fit between the already placed spheres. There is another criterion in the program to eliminate this. This criterion states how many of the already placed spheres should be close enough to the new sphere to be placed. It was found that the best space fill was achieved while minimizing computation time if this value was chosen as three.

To reduce the computation time, the program was modified to fill the space per lane. In order to avoid the formation of bad surfaces when shifting the strips, a 2 mm overlap was created. So if the bar was moved in the z direction and say 10 mm high, the next bar will last from 8 to 18 mm. With this system, any sample size can be created without increasing the computation time, it will only change linearly with the sample size, which is a big step forward. To make it as realistic as possible, the spheres diameter values are randomly called from a file. This file contains 700 sphere diameter values measured with an Olympus SZX16 stereomicroscope. As a result, the program returns a text file containing the x, y, and z coordinates of the center of the spheres and the corresponding diameter value.

Using this text file, the 3D model was created in PTC Creo software. After that, it was meshed in ANSA and created the finite element model in MSC Marc Mentat software. The parameters of the simulation were the same as the parameters of the real measurement. The obtained engineering stress-engineering strain curve approximated within 5% accuracy. The result of the validated finite element simulation was examined in detail. The great advantage of simulation is that one can “look inside” the material at any time. Taking advantage of this possibility, it was found that the stress will be the highest in the thin walls formed between the hollow spheres, so here it first reaches the yield point and then the plastic deformation begins. During failure, failure planes are formed at an angle of 30-45 ° to the axis of compression.

My 2nd thesis statement was defined on the base of those summarized conditions of the measurements and experimental details of my research, which are seen in the Chapter 5.2.

5.3. Effective Young’s modulus of metal matrix syntactic foams

As shown in Chapter 5.1. the structural stiffness determined by the compression test depends on the size of the specimen. As a result, it cannot be material characteristic. In this chapter, this section and question was examined. Unlike before, not only iron hollow sphere-reinforced metal foams was investigated, but also metal matrix syntactic foams reinforced with globocer ceramic hollow spheres, in order to broaden the experience. The matrix material was Al99.5 and AlSi12. The production method is the same as in Chapter 5.1. Three different approaches were used: (i) modal analysis, (ii) finite element simulation, and (iii) analytical methods.

During the modal analysis, the size of the specimens was 170×25×15 mm. Rectangular cross section was chosen because in this case the Eigen frequencies in the x and y directions would be different, while if I a square cross section would have been chosen, these values would have fallen very close to each other and could not be separated from each other. From the obtained first and second Eigen frequency values, I calculated the effective Young’s modulus using the Timoshenko beam theory. Using this model, I assume that it is a homogeneous beam with a constant cross-section and density.

I made two types of finite element simulations. One was a modal analysis while the other was a purely elastic compression. With the help of the Matlab program presented in Chapter 5.2., the distance between the hollow spheres could be changed in any way, thus indirectly the space filling. Thus, unlike the measurements, I had the opportunity to study the elastic properties of metal matrix syntactic foams in the case of different space fillings as well.

I have dealt with three of the analytical methods in more detail, these are the Mori-Tanaka estimate, the classical self-consistent estimate (CSC), and the differential self-consistent estimate (DSC). For the first two, a short Maple program was written that ran the calculation, with different space fillings, and wrote the results to a text file. Thus, as a result, the effective Young’s modulus values were obtained as a function of space filling. For the DSC estimation, a Matlab program was written that also the space filling and solved the differential equation numerically in each case using the explicit Euler method.

The input parameters used in the finite element simulations and analytical calculations are the Young's moduli of the matrix materials and reinforcements, which are included in Table 1.

Table 1. The Young's moduli of materials used in simulations and analytical calculations.

	Al99,5	AlSi12	Globomet	Globocer
Young's modulus (GPa)	70	78	200	93

The results obtained from the three approaches for metal matrix syntactic foams reinforced with ceramic hollow spheres are shown in Figures 4 and 5.

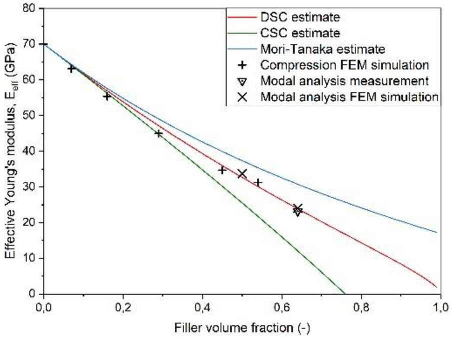

Figure 4. Results of measurement, simulation and analytical models for the effective Young's modulus as a function of space filling for Al99.5-GC.

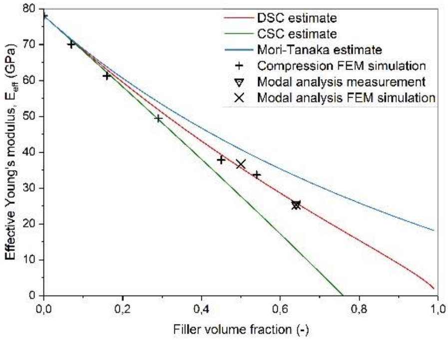

Figure 5. Results of measurement, simulation and analytical models for the effective Young's modulus as a function of space filling for AlSi12-GC.

My 3rd thesis statement was defined on the base of those summarized conditions of the measurements and experimental details of my research, which are seen in the Chapter 5.3.

5.4. Radially constrained compression

For the studies presented in this chapter, three types of matrix materials (Al995, AlSi12 and AlSi10MnMg) and two types of reinforcing materials (iron hollow spheres (GM) and lightweight expanded clay particles (LECAP)) were used. For this measurement the MTS 810 type hydraulic universal material testing machine was used. The test specimens were placed in a die with an inner diameter of 30 mm, an outer diameter of 90 mm and a height of 50 mm. The samples measurements were Ø30 × 30 mm. The test was performed with a deformation speed of 1 mm/min, and the force - displacement data were recorded. In addition, the tool was fitted with strain gauges on three sides. They were located at a 120° offset from each other on the outside of the die. The measurement set-up is shown in Figure 6.

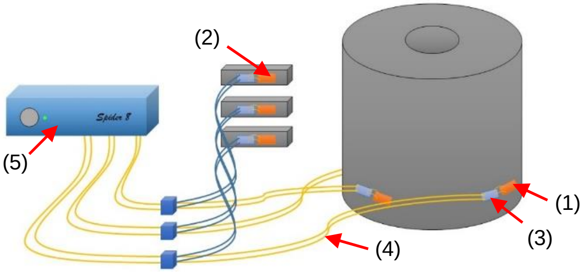

Figure 6. Schematic diagram of the measurement set-up for radially constrained compression. (1) strain gauge, (2) compensator strain gauge, (3) solder point, (4) cable to data logger, (5) data logger.

From the strain gauge measurement, signals with μm/m dimension were determined, which can be calculated as mechanical stress by dividing by 10^6 and multiplying by 210,000 - since the elastic modulus of the tool is 210,000 MPa - after which the stress values were obtained in MPa. The signals of the force - displacement and the strain gauge measurement were matched based on the time, as both data loggers recorded the time since the start of the measurement. Thus, the force required for deformation as a function of the stress in the tool could be plotted.

The measurements were evaluated similarly to the evaluation method presented in Chapter 5.2. There is a big difference in the investigated mechanical properties between metal foams made with LECAP and GM reinforcement, which is mainly due to the fact that while GMs are hollow, the structure of LECAP is porous, thus containing much more materials. From the results, it can be concluded that neither matrix material nor reinforcement material dependence can be observed between the energies absorbed up to a load level of 200 kN.

Then the parameters of the Shima-Oyane material model were determined. For this, the stress state of the metal foam was needed, which could be calculated from the data of the strain gauges using the thick-walled pipe theory. Since this theory assumes an infinitely long tube that is uniformly loaded from the inside over an infinite length, a preliminary simulation was performed to determine the deviation between the simulated and calculated results based on this theory. It was found that there was a maximum difference of 5% between the values obtained by the simulation and those calculated by the theory, which allows me to use this theory. Using this information, the parameters were determined and then performed a finite element simulation for validation.

With the results of the simulation, it was proved that the Shima-Oyane material model is suitable for modeling metal matrix syntactic foams with an aluminum matrix and GM or LECAP reinforcement. This is a very important step because it allows to use not only the results obtained from specimens of a given size and stress state in the design, but also the components that are already larger and loaded with complex stress state. In addition, the simulation requirements are greatly reduced by this method, since the metal foams in this case can be treated as a bulk material.

My 4th and 5th thesis statements were defined on the base of those summarized conditions of the measurements and experimental details of my research, which are seen in the Chapter 5.4.

6. RESULTS OF THE RESEARCH IN THESIS POINTS

In Chapter 1-5. I summarized my research results in a unified, self-explanatory system, which I achieved in the course of my research work and described in detail in my doctoral dissertation. This thesis booklet structure makes it possible to formulate my thesis statements in a genre-specific (i.e. clear and as short as possible) manner.

Thesis 1: [S1-S5]

A linear relationship exists between the structural stiffness values (determined along ISO 13314: 2011 standard) and the and the height values of Al99.5, AlSi12, AlMgSi1 and AlCu5 matrix iron hollow sphere reinforced metal matrix syntactic foam samples.

Thesis 2: [S6]

I developed a computational method that is able to estimate the plateau stress and the value of the absorbed mechanical energy in the case of Al99.5 matrix iron hollow sphere reinforced metal matrix syntactic foams within 5% accuracy. With this validated procedure, I showed that failure begins in the thin walls between the hollow spheres.

Thesis 3: [S7-S9]

Using modal analysis, I validated that the differential self-consistent estimation gives the best approximation, and the finite element simulation is able to determine the effective Young’s modulus of Al99.5 and AlSi12 matrix iron or ceramic hollow sphere reinforced metal matrix syntactic foams within 5% error.

Thesis 4: [S10]

From the radially constrained compression of aluminum matrix (Al995, AlSi12 and AlSi10MnMg) syntactic foams reinforced with iron hollow spheres (Globomet) or lightweight expanded clay particles (LECAP), I determined the energy-absorption values and it was found that this value is dependent on the matrix and filler material until 40% strain, however it is nearly the same up to the same (283 MPa) stress level.

Thesis 5: [S10]

I determined the parameters of the Shima-Oyane material model with radially constrained compression tests. I proved that the Shima-Oyane material model is suitable for modeling iron hollow sphere (Globomet) and lightweight expanded clay particles (LECAP) reinforced aluminum matrix (Al995, AlSi12 and AlSi10MnMg) syntactic foams.

7. OWN PUBLICATIONS FOR THE THESIS STATEMENTS

[S1] **Szlancsik A**, Katona B, Bobor K, Májlinger K, Orbulov IN, Compressive behaviour of aluminium matrix syntactic foams reinforced by iron hollow spheres, Materials & Design 83, (2015) 230-237; IF: 3,997

[S2] Bálint A, Májlinger K, **Szlancsik A**, Fém gömbhéj erősítésű szintaktikus fémhabok mechanikai tulajdonságai, Bányászati és Kohászati Lapok, Kohászat 147 (2014:3) 39-44.

[S3] Bálint A, Kovács Zs, **Szlancsik A**, Vas gömbhéj erősítésű szintaktikus fémhabok nyomószilárdsági tulajdonságai (Compressive characteristics of iron hollow sphere reinforced metal matrix syntactic foams), OGÉT 2013 XXI Nemzetközi Gépészeti Találkozó. Konferencia helye, ideje: Arad, Románia, 2013.04.25-2013.04.28. Szerkesztő: Dr. Csibi Vencel-József, Kiadja: Erdélyi Magyar Műszaki Tudományos Társaság (EMT), Kolozsvár Románia pp. 32-35.

[S4] Bálint A, **Szlancsik A**, Mechanical Properties of Iron Hollow Sphere Reinforced Metal Matrix Syntactic Foams, Materials Science Forum 812 (2015) 3-8.

[S5] **Szlancsik A**, Katona B, Májlinger K, Orbulov IN, Compressive behavior and microstructural characteristics of iron hollow sphere filled aluminum matrix syntactic foams, Materials 8 (11), (2015) 7926-7937; IF: 2,728

[S6] Katona B, **Szlancsik A**, Tábi T, Orbulov IN, Compressive characteristics and low frequency damping of aluminium matrix syntactic foams, Materials Science and Engineering: A 739, 140-148; IF: 4,081

[S7] **Szlancsik A**, Katona B, Dombóvári Z, Orbulov IN, On the effective Young's modulus of metal matrix syntactic foams, Materials Science and Technology 33 (18), 2283-2289; IF: 1,008

[S8] Kádár Cs, **Szlancsik A**, Dombóvári Z, Orbulov IN, Monitoring the failure states of a metal matrix syntactic foam by modal analysis, MATERIALS LETTERS 257 p. 126733 Paper: 126733 (2019)

[S9] **Szlancsik A**, Dombóvári Z, Katona B, Orbulov IN, Szintaktikus fémhabok mechanikai tulajdonságainak becslése és mérése (Measurement and estimation of mechanical properties of metal matrix syntactic foams), OGÉT 2017 XXI Nemzetközi Gépészeti Találkozó. Szerkesztő: Dr. Csibi Vencel-József, Kiadja: Erdélyi Magyar Műszaki Tudományos Társaság (EMT), Kolozsvár Románia pp. 396-399

[S10] **Szlancsik A**, Orbulov IN, Compressive properties of metal matrix syntactic foams in uni- and triaxial compression, Composites Part B: Engineering; Bírálat alatt, „major revision"