

## Analysis and Assessment of Aluminum and Aluminum-Ceramic Foams Structure

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### ABSTRACT

The paper presents an analysis of the aluminum porous structure serving as a structural material used in the automotive or marine industry. The subject of the research is the analysis of the mechanical properties of the aluminum porous structure, in particular its ability to absorb energy in comparison with quality of manufactured porous structures. The paper presents a description of the manufacturing process, quality control in the form of a statistical capture of geometric parameters of the foam made, as well as an X-ray microanalysis of the chemical composition of EPMA-EDS and the dispersion of components within the structure. In addition, results of static axial compression analysis of aluminum and composite foam specimens are presented.

**Keywords:** metallic foam, composite foam, statistics analysis, microscope

### INTRODUCTION

Nowadays, the costs and strength of engineering structures are very important aspects of their design. Due to the increasing demands placed on structures by stringent standards, it has become commonplace to use numerical analysis in the design process [1, 2]. Technological advancements have made it possible to upgrade commonly used “traditional” construction materials such as steel and aluminum alloys. The development of the production process allowed the improvement of the built machines, mainly due to the use of lightweight materials, while maintaining high strength and safety [3, 4]. Over the years, porous structures of metals, which are much lighter than solid material while maintaining high strength, have found their application. The quality of the produced foams is very important. They should

have a homogeneous, repeatable structure, i.e.: the size and shape of the pores. The quality of their structure is reflected in selected properties, e.g.: strength. We can maintain such a structure in foams produced by casting.

The casting of metal foams is carried out in several ways, e.g.: by full molding, infiltration of granules, foaming in a liquid state, or gas blowing. When comparing the cost intensity of the process with the quality of the obtained product, the gas-infiltration method is the most advantageous [5, 6]. It allows achieving a structure with even pores at a low material cost used in the production process. Currently, aluminum foams have found their widespread use as mechanical energy-absorbing structures. The arrangement of pores results in specific properties where the structure, with low density and stiffness in relation to solid material, retains good energy-absorbing properties.

Scientific research has confirmed the influence of the porous structure on the crush load efficiency index [7], which is important in the passive safety testing of motor vehicles [8, 9]. Researchers have found the use of porous metals in the crush analysis of thin-walled passive absorbers. Originally, the structures were filled with additional walls inside [10, 11]. However, due to the high stiffness in the impact direction, the multi-cell structures were replaced with metal foams [12–14]. The foams of metals compared to the foams of polymers have different characteristics of damage to the structure, consequently, they absorb mechanical energy to a different extent [15]. Porous materials have found their application in the marine industry as filling of hull coating elements. Due to the high restrictions, the materials used for the construction of the vessel are subjected to flammability tests [3], which is a very big advantage of metal foams in comparison with materials ones. Cast metal foams are used in the production of sandwich-type structure. Their high stiffness compared to the low weight of the product is an excellent filler [16–18]. Due to the multiple uses of foams, neural networks are often used to analyze them to determine the relationships between various parameters [19–23].

Aluminum-ceramic foams are characterized by very good fire-resistant properties, hence their dedicated use as insulation between batteries and the structure in electric cars and maritime transport of electric cars on ro-ro ships. For fire protection reasons, it is advantageous, that aluminum ceramic foams (when melted at temperatures even much higher than the melting point) have the structure of a discontinuous suspension of solid inclusions in liquid metal that does not have a liquid consistency. This paper is an excerpt from the authors' work focused on comparing the properties and structure of aluminum and aluminum-ceramic foams in order to select the best combination of performance properties of these materials. In addition, it is very difficult to produce aluminum foams by the gas blowing method. This technology requires a great deal of experience. Paradoxically, it is easier to produce an aluminum-ceramic composite, where SiC particles are a causing factor of pore formation and growth. In practice, aluminum foams produced by foaming in the liquid state method are most often used. However, this method is very expensive, because it is based on introducing a foaming agent, usually in the form of TiH<sub>2</sub> compound,

into the liquid metal, e.g.: calcium-densified aluminum. Therefore, the authors of this paper proposed a cheaper way to produce foams and evaluate their quality.

The authors made a comparison of the structures of aluminum and aluminum-ceramic foams in order to assess their chemical composition, described in selected sections, and the quality of their structure, i.e.: the uniformity of size, and shape of pores with the use of descriptive statistics.

Geometric parameters, the shape of pores, and their distribution are related to the production process of casting metal foams. The effect of the above-mentioned defects of the product is the decreased strength and increased susceptibility to damage. The subject of the research is also the analysis of the mechanical properties of the aluminum porous structure, in particular its ability to absorb energy. In the international literature, static loading is used as the primary test to determine the energy absorption capacity of structures [24–26], therefore the authors have chosen to use this type of test for porous structures. An analysis performed in this manner will not reflect the behavior of a structure in the case of a dynamic impact, however, it provides an indication of its ability to absorb energy.

The purpose of this study is to analyze aluminum and aluminum-ceramic foams, produced by themselves and then evaluate the quality of their structure, i.e. homogeneity of size, shape and distribution of pores using descriptive statistics. As well as analyzing and testing whether the homogeneity of the structure of the manufactured foams affects the compressive strength. In addition, the evaluation of their chemical composition is described in selected chapters.

## MATERIALS AND METHODOLOGY

The research material was produced aluminum and aluminum-ceramic foams. The foam used in the experimental study was produced ex-situ. It was manufactured using the method of gas blowing into the liquid metal. The foaming gas was air. The manufacturing process took place at the Maritime University of Szczecin, according to the patented technology of manufacturing this type of metal structure (P211439). In the case of composite foam, the feedstock was aluminum alloy (Al) doped with silicon carbide (SiC) in the amount of 10% by mass, and their size is 20 μm.

The first stage of production was mixing, which was done mechanically. This was followed by melting the metal-ceramic charge until a stable temperature of 720°C was achieved (Figure 1.). Once the temperature was stabilized, the liquid material was transported to the frothing chamber, with an agitator running continuously at 150 rpm and a simultaneous outflow of frothing gas(air) at 8 dm<sup>3</sup>/min. The foamed material was transported using a belt feeder, at the same time the process of cooling and stabilizing the structure of the foamed metal-ceramic composite was carried out. For aluminum foam without composite doping, the process was conducted in the same way except for the addition of SiC particles.

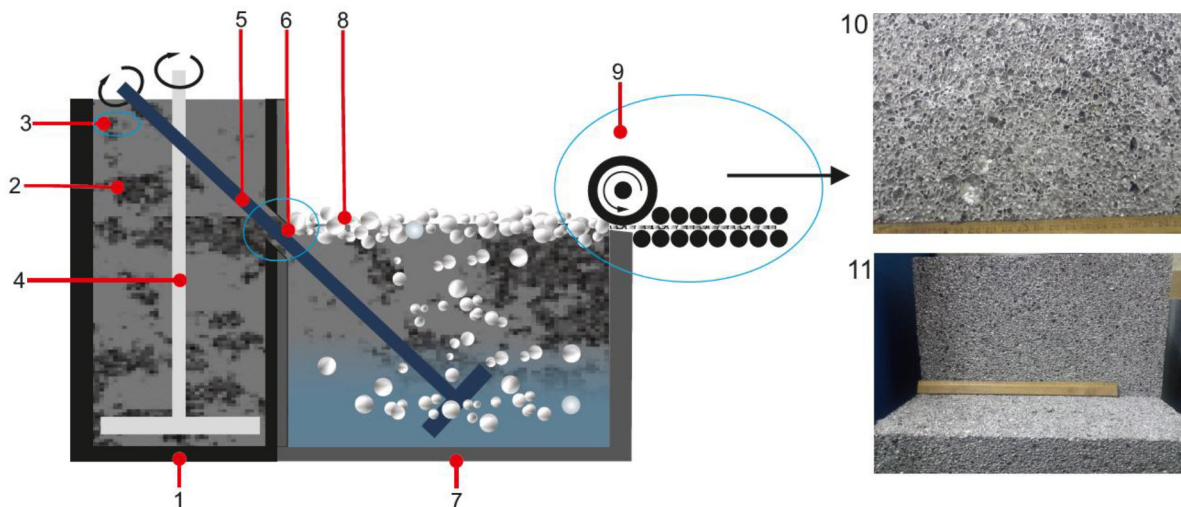
Spot analysis of the chemical composition was presented in the paper to assess the structural quality of the foams. The authors presented randomly selected fragments of the foam structure to indicate to the reader the differences between a foam made of “monolithic material” and a composite in an illustrative way. Elements were indicated using a Hitachi SU70 scanning electron microscope along with a Thermo Scientific EDS X-ray micro analyzer with NORAN 7 system. The image of the structure was subjected to microscopic analysis, on the basis of which the quality of the produced foam was statistically determined. To the controlled parameters belonged: to pore area, circumference, and circularity. Based on the cross-sectional view of the foam, it is possible to graphically determine the quality of the pores produced, i.e.: their shape and distribution. The structure characteristics (area, average

diameter, circumference, compactness) of pores of aluminum and aluminum-ceramic foams were compared by statistical methods using Excel, with Analysis ToolPak add-in. The mean, maximum, minimum values and standard deviation for each test were indicated. The data were checked for conformance with a normal distribution.

As part of the comparative analysis of the porous metals, 40x40x20mm samples were subjected to an axial static compression test. The obtained crush characteristics show the susceptibility of the structure and its failure mechanism. The test was conducted on a Comatech uniaxial testing machine with a load range up to 2.5kN. The sample was placed on a test table and the feed rate of the top table was set to 2 mm/min to obtain accurate characterization. Three samples from each type of foam were tested and the results were averaged.

### SPOT ANALYSIS OF CHEMICAL COMPOSITION

EPMA – EDS microanalysis (EPMA – Electron Probe Microanalysis, EDS – Energy Dispersive X-ray Spectroscopy) enables qualitative and quantitative analysis of the chemical elements being part of the tested material. The method of X-ray microanalysis with an energy dispersion spectrometer uses the spectrum of the characteristic X-rays, emitted by the material bombarded by a focused electron beam to determine the chemical composition in the micro-regions[27–29].



**Fig. 1.** Schematic diagram of foam manufacturing 1 – kiln crucible, 2 – metal bath, 3 –SiC reinforcing compounds, 4 – the stirrer, 5 – lance with gas dispersion rotor, 6 – culvert, 7 – frothing tank, 8 – metal-ceramic foam, 9 – foam reception via conveyor belt, 10,11 –the final product

The main problem with using the X-ray microanalysis method to assess the chemical composition of aluminum and aluminum-ceramic foams is the quantitative analysis of light elements, i.e.: carbon and oxygen. Determination of the content of these elements in the presence of elements with an atomic number above sodium is beyond the possibilities of this method, therefore their presence was marked in the tables with the “+” sign and was not taken into account in the quantitative analysis. Trace amounts of different elements, determined by chemical analysis (Table 1–2), may be present in the composition of foams, as they are formed during the casting process, which consists of melting and foaming operations of the metal (or composite). These impurities enter by diffusion into the suspension from the crucible or chamber in which the process takes place.

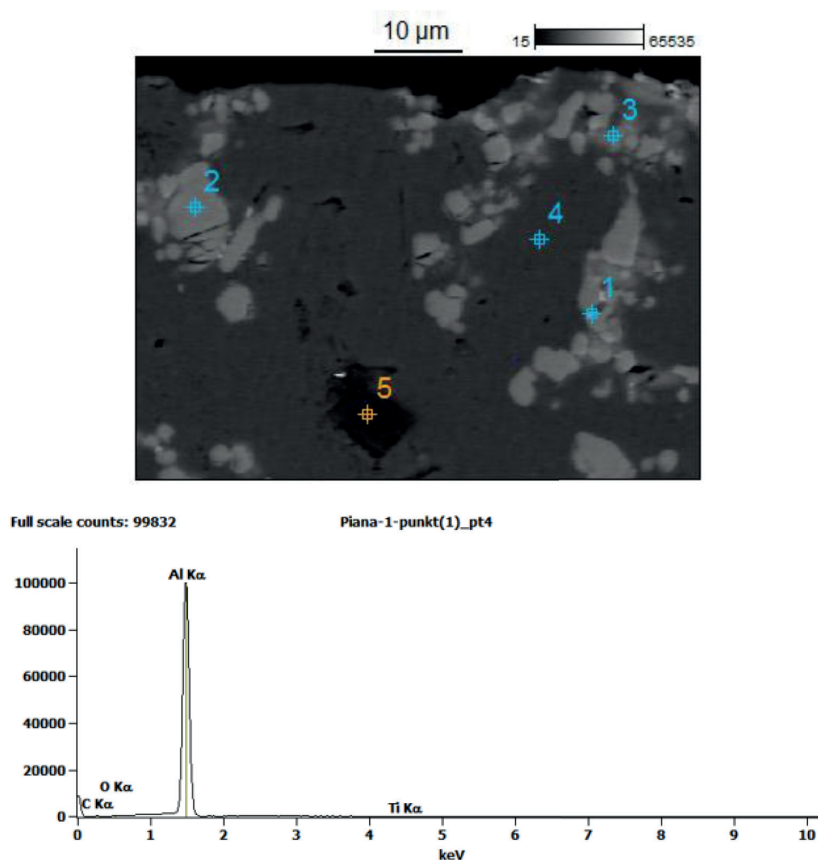
Figures 2 and 3 show the images indicating the points (point analysis), where the chemical elements of the tested foams (aluminum and aluminum-ceramic) were identified, along with the spectrum characteristic for one of the

points. Tables 1–2 show the percentage of chemical elements present in the analyzed points of these foams.

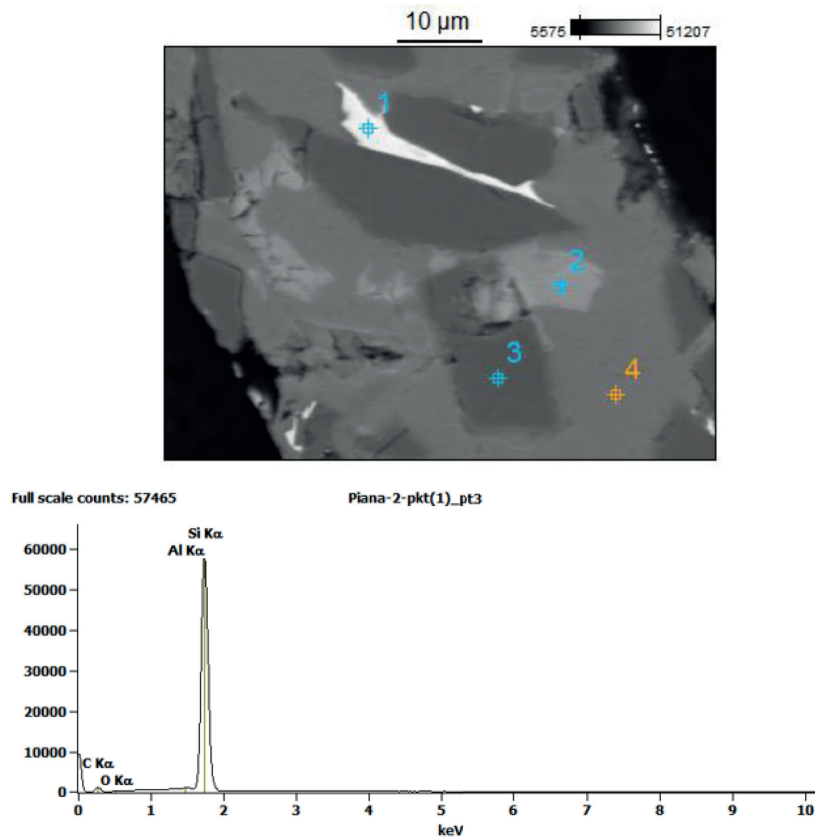
## RESULTS OF MICROSCOPIC ANALYSIS

The surface analysis of the porous structure was carried out using Metilo software. Based on the appropriately processed graphical image, the results of geometrical parameters responsible for the shape of the formed pores as well as their surface were obtained. Proper analysis of the foam structure is necessary to determine the quality of the final product. Three areas each were selected for analysis (Table 3), based on which selected geometric indices were determined.

After analyzing the images shown in the table above, data were obtained for three samples, which were collected statistically and presented both in Tables 4–5 as well as in histograms (Figures 4–6.). The statistical presentation shows four geometric quantities that are characteristic of



**Fig. 2.** Microstructure (Scanning Electron Microscopy-SEM) of the sides of the aluminum foam skeleton with marked EDS microanalysis points and the spectrum for point 4 in the SEM image



**Figure 3.** Microstructure (Scanning Electron Microscopy-SEM) of the sides of the aluminum-ceramic foam skeleton with marked EDS microanalysis points and the spectrum for point 3 in the SEM image

the structure of the porous structure and indicate the quality of the product obtained. The quality, shape, and size of the pores can change during the casting process depending on alloy additives and the technological process. The present results are intended to compare aluminum foam with aluminum-ceramic (composite) foam. Based on the following data, it is possible to determine the influence of the silicon carbide additive both on the casting quality of the product and its comparison with the mechanical properties of the product achieved.

Figures 4–6 show a histogram of the geometric parameters tested, which includes dozens to

hundreds of cases. The distributions of all studied parameters have a similar shape for aluminum and aluminum-ceramic foam. The results of the porous structure study show that the composite foam (Al-SiC) has significantly smaller pores both in terms of pore diameter and circumference. The compactness index is a little bit higher for the composite foam than the average value (Table 4). This indicates that the pores have a more circular shape.

The above histograms (Figures 4–6) show the values in micrometers (μm). The presented distributions are not normal distributions indicating homogeneity of the examined structure’s features.

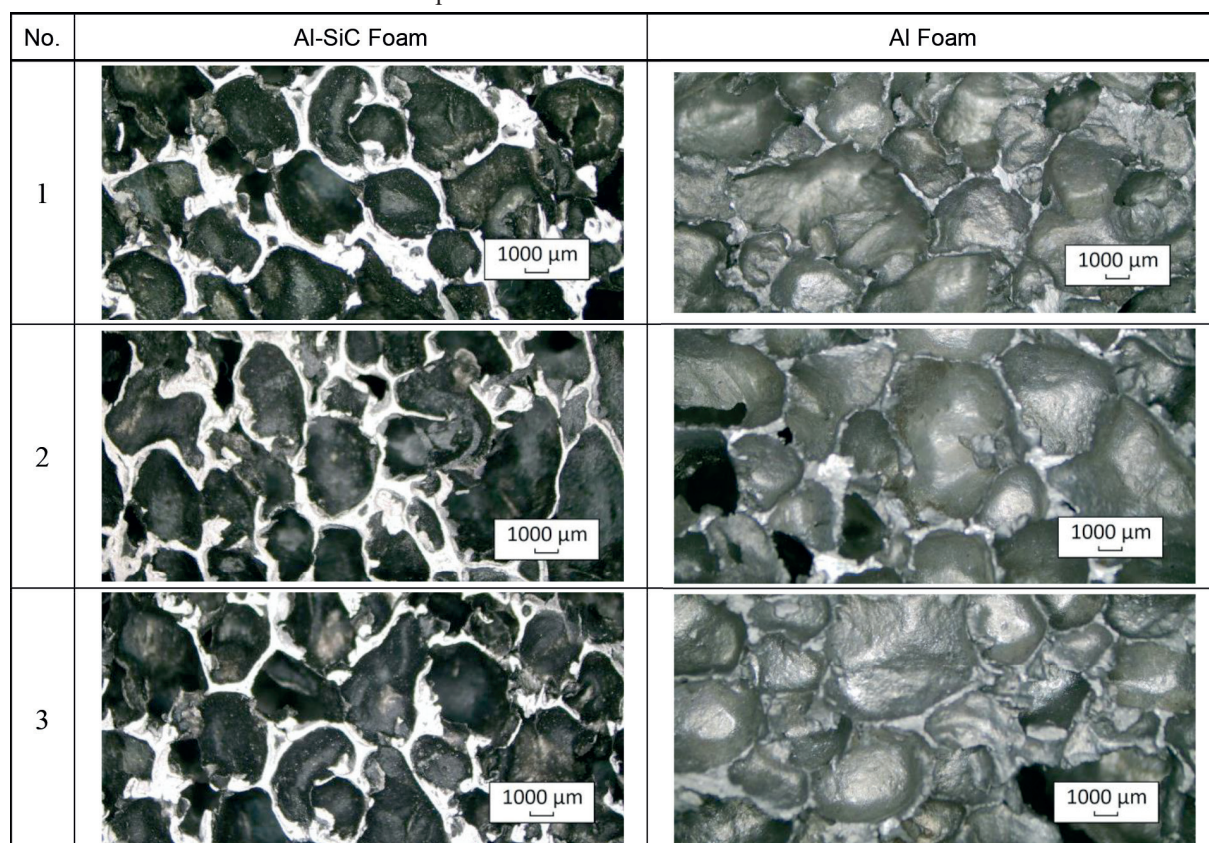
**Table 1.** Percentage (mass share) of elements in the tested area of the aluminum foam in points as shown in Figure 2 (EDS)

Point	C	O	Al	Si	Ca	Ti	Fe	Ni	Ga
Foam1-pt1	+		81.2		4.1	6.3	8.0	0.4	
Foam1-pt2	+		79.0		6.0	14.9			
Foam1-pt3	+	+	78.2		11.2	10.1			0.5
Foam1-pt4	+	+	99.9			0.1			
Foam1-pt5	+	+	1.9	98.1					

**Table 2.** Percentage (mass share) of elements in the tested area of the aluminum-ceramic foam in points as shown in Figure 3 (EDS)

Point	C	O	Mg	Al	Si	Fe	Ni	Cu
Foam2-pt1	+	+		39.3	0.6	0.6	37.4	22.1
Foam2-pt2	+	+	17.4	44.5	26.8	5.8	5.5	
Foam2-pt3	+	+		0.6	99.4			
Foam2-pt4	+	+		99.1	0.9			

**Table 3.** General view of the tested samples



This proves the diversity of size, shape, and distribution of pores in the examined aluminum and aluminum-ceramic foams. The description of statistical pore circumference for aluminum foam is an exception. This distribution is normal distribution, which means, that the described feature is within the given range of normality and is repeatable.

Slightly divergent distribution characteristics can be observed for the pore circumference (Figure 6), where the magnitudes for the aluminum-ceramic foam are much smaller. This indicates a change in pore shape caused by the feed additive in the form of silicon carbide particles. The graphs presented in Figure 6, showing how similar the shape of a single pore is to a circle,

**Table 4.** Aluminum foam statistic data

Parameter	N valid	Average	Minimum	Maximum	Standard deviation
Area [ $\mu\text{m}^2$ ]	50	5114160	76409.40	18953000	4606173
Average diameter [ $\mu\text{m}$ ]	33	2295	431.50	4912	1130
Circumference [ $\mu\text{m}$ ]	33	8391	1455.21	17385	3870
Compactness	50	0.6945	0.2782	0.9203	0.1780

**Table 5.** Aluminum-ceramic foam statistic data

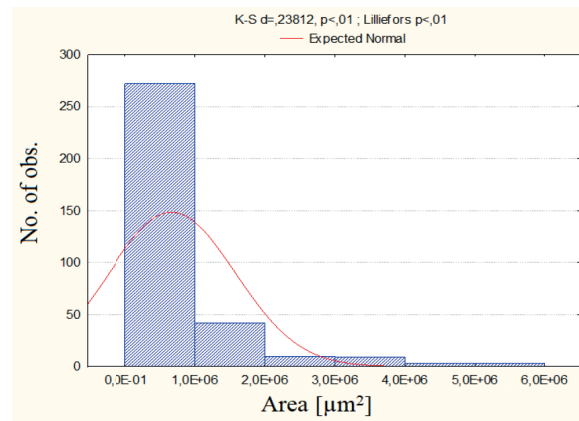
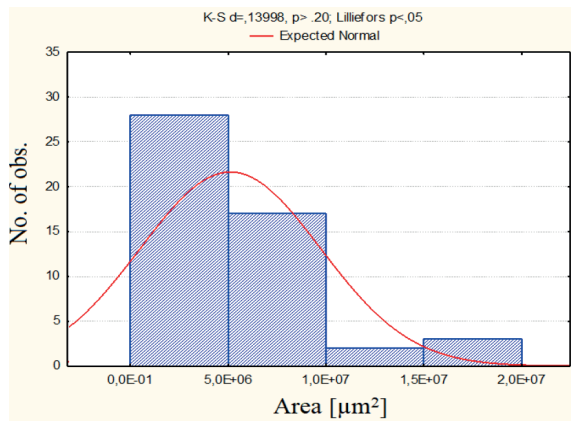
Parameter	N valid	Average	Minimum	Maximum	Standard deviation
Area [ $\mu\text{m}^2$ ]	339	665987.5	16630.20	5888120	911572.4
Average diameter [ $\mu\text{m}$ ]	339	784.6	145.51	2738	482.7
Circumference [ $\mu\text{m}$ ]	339	2980.0	573.27	13750	2038.7
Compactness	339	0.7435	0.2301	0.9898	0.1673

have a comparable range of values as well as their distribution. This indicator is presented as a dimensionless value.

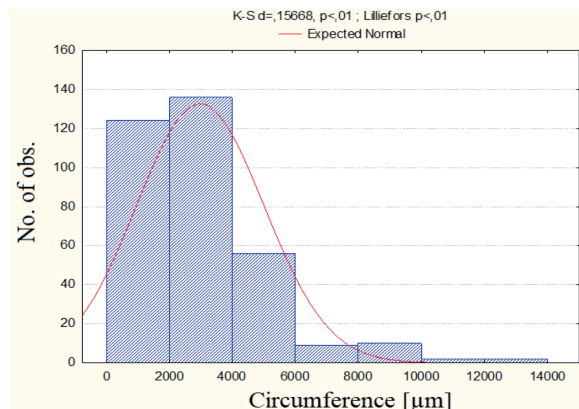
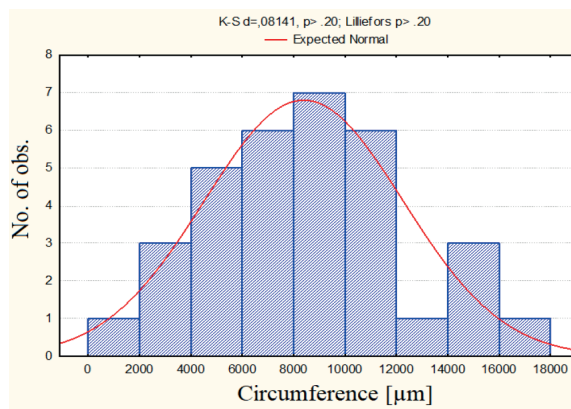
The statistical analysis shows that the aluminum foam and the aluminum-ceramic foam do not follow a normal distribution (apart from one aforementioned characteristic – pore circuit, Figure 5), so a random variable causes its amount, shape, and area. Discrepancies between described characteristics are large, which is proved by standard deviation, informing, how wide the values of a given size e.g.: average diameter, area, compactness, are scattered around its mean. The smaller the value of deviation, the more observations are concentrated around the mean (Table 5). On this

basis, it can be concluded, that the used method of foam manufacturing does not ensure the dimensional and geometric repeatability of the pores in both the aluminum and composite foam.

The above figures 7–9 show the conformity of the obtained values to the normal distribution, the figures refer to the indicators shown in Figures 4–6 respectively. Analyzing the obtained distributions, we can see quite a high agreement with the normal distribution of some parameters. In particular, the perimeter and compactness index for aluminum foam. Other cases show agreement with the normal distribution only to some range. A large discrepancy can be observed for very small pores, it may be due to the inaccuracy



**Figure 4.** Histogram, showing pore area for aluminum and aluminum-ceramic foam, respectively



**Figure 5.** Histogram, showing pores circumference for aluminum and aluminum-ceramic foam, respectively

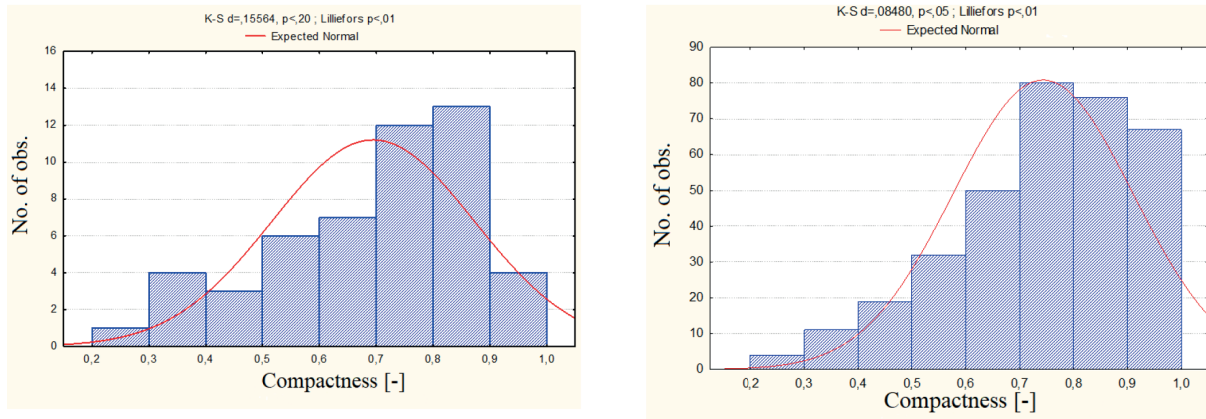


Figure 6. Histogram, showing pore compactness indicator for aluminum and aluminum-ceramic foam, respectively

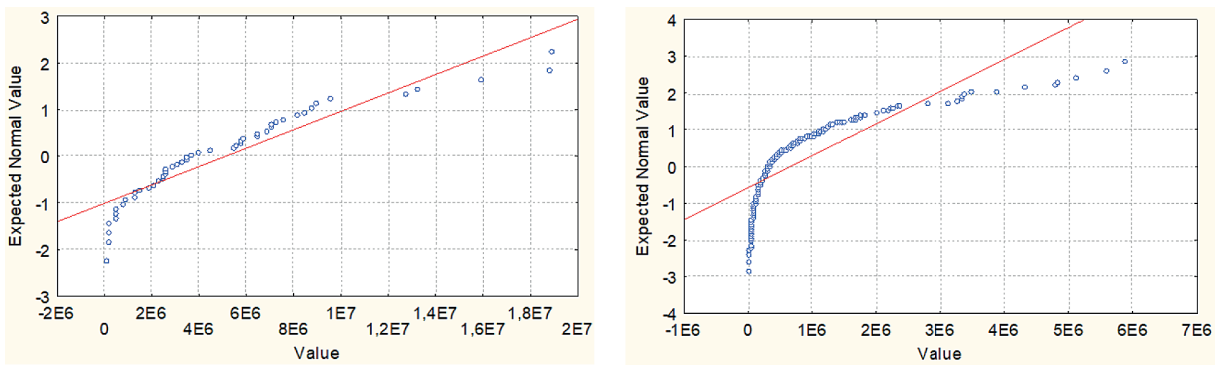


Figure 7. Analysis of normal distribution pores area for aluminum and aluminum-ceramic foam, respectively

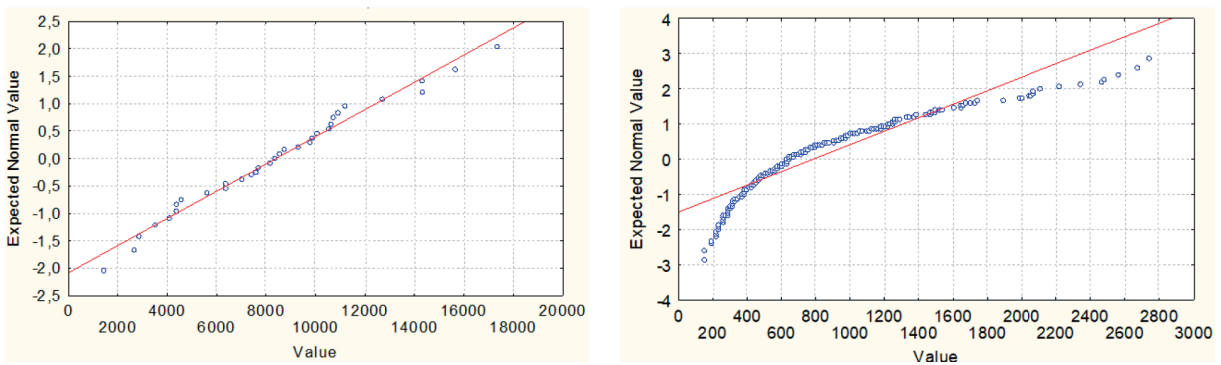


Figure 8. Analysis of normal distribution pores circumference for aluminum and aluminum-ceramic foam, respectively

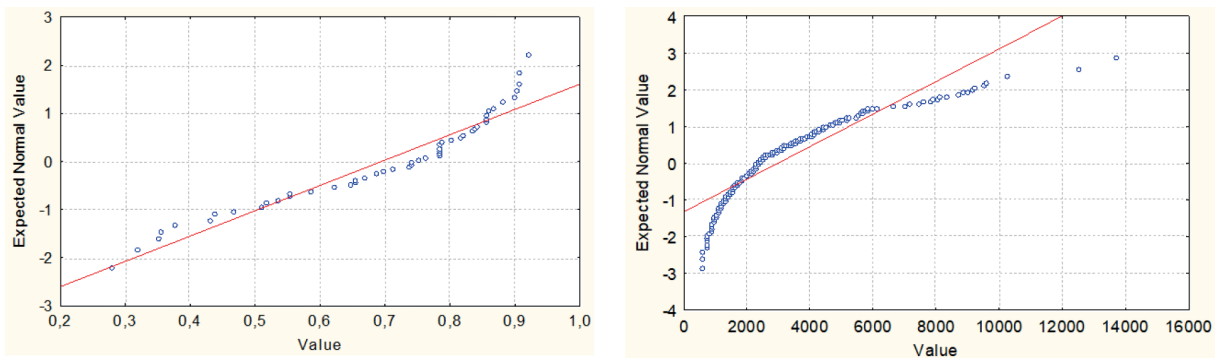


Figure 9. Analysis of normal distribution pores compactness indicator for aluminum and aluminum-ceramic foam, respectively



of the software erroneously detecting pores of small diameter or multiplication of incompletely formed pores with low geometric parameters.

## RESULTS OF STATIC TEST

The test subject was a cuboid with dimensions of 40x40x20 mm (Figure 10). The dimensions of the sample are due to the limitations of the testing machine as well as the cost of manufacturing the cast metal foams.

The force values obtained during the test were converted to engineering stresses, which are shown in Figure 11. Both characteristics are shown up to the point, where complete crushing of the foam occurs just before the point when the force begins to peak. The graph shows the higher strength of the aluminum foam, which is due to the higher ductility of the foam without the addition of ceramic particles. Composite foam, in contrast to aluminum foam, is much more brittle in the axial compression test. The sides of the composite foam are much more susceptible and their failure is sudden. The course of both characteristics is similar, however, the aluminum foam reaches values higher by about 100%. Due to this feature, the aluminum foam is a better energy absorber.

The use of static compression analysis in assessing the crashworthiness ability of thin-walled structures is common in research [30, 31]. The static tests carried out and the data obtained (Fig. 12) show that both foams, in spite of their different crush character, exhibit good energy absorption properties. In the case of aluminum foam, it shows a large plastic range in which it absorbs energy, while the composite foam is prone to cracking (more brittle).

## CONCLUSIONS

The aim of the study was to produce aluminum and aluminum-ceramic foams by the gas (air) blowing method, which has been achieved. The chemical composition at selected points of both foams has been determined, thus confirming the monolith nature of the first and the compositeness of the second foam. An analysis and assessment of the quality of the structure i.e.: homogeneity of size, shape, circumference, and pore distribution, using descriptive statistics, was carried

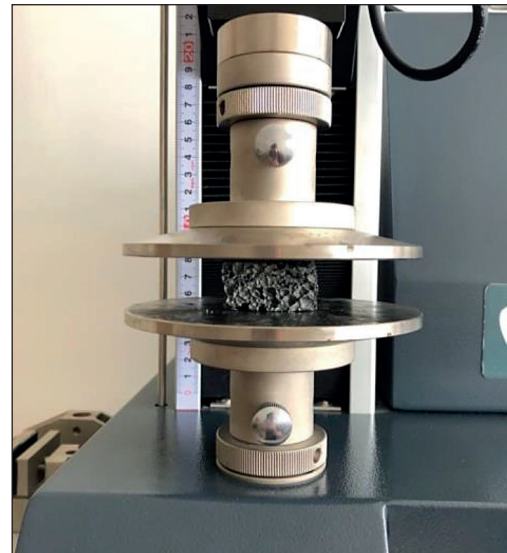


Figure 10. Static compression testing station

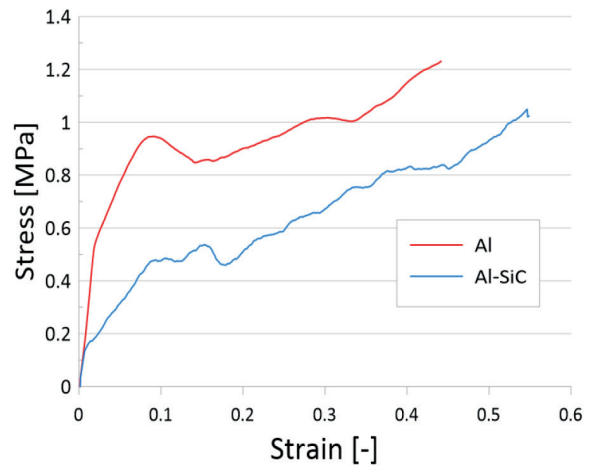


Figure 11. Stress-strain curve of aluminum (Al) and composite foam (Al-SiC) and energy absorbed from the uniaxial compression test

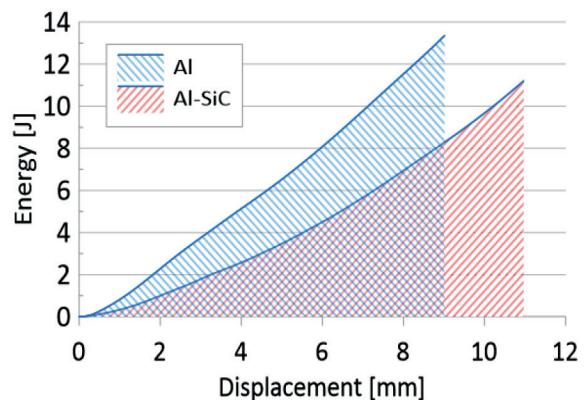


Figure 12. The energy absorption capacity of aluminum (Al) and composite foam (Al-SiC) based on the uniaxial compression test

out. It was also verified, whether the homogeneity of the structure of the produced foams affects the compressive strength.

The conducted research shows that:

- Using the epma-eds x-ray analysis, it is possible to describe the chemical composition of the tested aluminum and aluminum-ceramic foams (especially the determination of the reinforcing phase in the form of sic). This test allows to clearly indicate the distribution of elements in the studied area and identify the type of foam;
- The conducted analysis of the foam structure shows the pore structure and the shape distribution. The study showed that the addition of ceramic particles in the form of silicon carbide powder caused a decrease in the pore formation (approx. 13%) While maintaining the same technological parameters during foam casting;
- In addition, it was noted from the static compression test, that the composite foam is brittle, which causes that the strength of the foam is a half of aluminum foam, the latter exhibiting much greater ductility;
- In the case of closed pore foam, the constructability is related to the distribution of the pores, as well as their shape, hence the compactness index, which indicates the circularity of the pores, was determined in the study.
- Studies have shown that both foams are good energy absorbers which, combined with their structure, allows the foams to be used as a construction material

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## REFERENCES

1. Tarlochan F, Hamouda AMS, Mahdi E, Sahari BB (2007) Composite sandwich structures for crashworthiness applications. *Proc Inst Mech Eng Part L J Mater Des Appl* 221:121–130
2. Zhu F, Lu G, Ruan D, Wang Z (2010) Plastic deformation, failure and energy absorption of sandwich

- structures with metallic cellular cores. *Int J Prot Struct* 1:507–541
3. Kaczyński P, Ptak M, Gawdzińska K (2020) Energy absorption of cast metal and composite foams tested in extremely low and high-temperatures. *Mater Des*. <https://doi.org/10.1016/j.matdes.2020.109114>
4. Kulshreshtha A, Dhakad SK (2020) Preparation of metal foam by different methods: A review. *Mater Today Proc*. <https://doi.org/10.1016/j.matpr.2020.02.375>
5. Czarnecka-Komorowska D, Grześkowiak K, Popielarski P, Barczewski M, Gawdzińska K, Poplawski M (2020) Polyethylene Wax Modified by Organoclay Bentonite Used in the Lost-Wax Casting Process: Processing–Structure–Property Relationships. *Materials (Basel)* 13:2255
6. Bejger A, Gawdzińska K (2011) Identification of Structural Defects of Metal Composite Castings with The Use of Elastic Waves. *Arch Metall Mater*. <https://doi.org/10.2478/v10172-011-0014-z>
7. Rogala M, Ferdynus M, Gawdzińska K, Kochmański P (2021) The Influence of Different Length Aluminum Foam Filling on Mechanical Behavior of a Square Thin-Walled Column. *Materials (Basel)* 14:3630
8. Macaulay M (1987) Introduction to Impact Engineering. *Mater Des*. <https://doi.org/10.1007/978-94-009-3159-6>
9. Koczyński A, Rusiński E (2010) Passive safety. Energy absorption by thin-walled profiles. Publishing House of the Wrocław University of Technology, Wrocław
10. Pirmohammad S, Esmaili Marzdashti S (2018) Crashworthiness optimization of combined straight-tapered tubes using genetic algorithm and neural networks. *Thin-Walled Struct* 127:318–332
11. Pang T, Zheng G, Fang J, Ruan D, Sun G (2019) Energy absorption mechanism of axially-varying thickness (AVT) multicell thin-walled structures under out-of-plane loading. *Eng Struct* 196:109130
12. Hanssen AG, Langseth M, Hopperstad OS (1999) Static crushing of square aluminium extrusions with aluminium foam filler. *Int J Mech Sci* 41:967–993
13. Hanssen AG, Langseth M, Hopperstad OS (2000) Static and dynamic crushing of square aluminum extrusions with aluminum foam filler. *Int J Impact Eng* 24:347–383
14. Ferdynus M, Rogala M (2019) Numerical Crush Analysis of Thin-Walled Aluminium Columns with Square Cross-Section and a Partial Foam Filling. *Adv Sci Technol Res J* 13:144–151
15. Kinzl M, Wolfram U, Pahr DH (2013) Identification of a crushable foam material model and application to strength and damage prediction of human femur and vertebral body. *J Mech Behav Biomed*

- Mater 26:136–147
16. Sika R, Rogalewicz M, Popielarski P, Czarnecka-Komorowska D, Przystacki D, Gawdzińska K, Szymański P (2020) Decision support system in the field of defects assessment in the metal matrix composites castings. *Materials (Basel)* 13:4–12
  17. Dunaj P, Berczyński S, Chodźko M (2020) Method of modeling steel-polymer concrete frames for machine tools. *Compos Struct* 242:112197
  18. Dunaj P, Berczyński S, Chodźko M, Niesterowicz B (2020) Finite Element Modeling of the Dynamic Properties of Composite Steel–Polymer Concrete Beams. *Materials (Basel)* 13:1630
  19. Rogala M, Gajewski J, Ferdynus M (2020) The Effect of Geometrical Non-Linearity on the Crashworthiness of Thin-Walled Conical Energy-Absorbers. *Materials (Basel)* 13:4857
  20. Rogala M (2020) Neural Networks in Crashworthiness Analysis of Thin-Walled Profile with Foam Filling. *Adv Sci Technol Res J* 14:93–99
  21. Szabelski J, Karpiński R, Krakowski P, Jonak J (2021) The impact of contaminating poly (Methyl methacrylate) (pmma) bone cements on their compressive strength. *Materials (Basel)* 14:0–9
  22. Karpiński R, Jaworski, Łukasz, Jonak J, Krakowski P (2019) Stress distribution in the knee joint in relation to tibiofemoral angle using the finite element method. *MATEC Web Conf* 252:07007
  23. Jonak J, Karpiński R, Wójcik A (2021) Influence of the Undercut Anchor Head Angle on the Propagation of the Failure Zone of the Rock Medium–Part II. *Materials (Basel)* 14:3880
  24. Lakes RS (1989) Cellular solids. *J Biomech* 22:397
  25. Hu D, Wang Y, Song B, Wang Y (2018) Energy absorption characteristics of a foam-filled tri-tube under axial quasi-static loading: experiment and numerical simulation. *Int J Crashworthiness* 23:417–432
  26. Rogala M, Gajewski J (2021) Numerical analysis of porous materials subjected to oblique crushing force Numerical analysis of porous materials subjected to oblique crushing force. *J Phys Conf Ser.* <https://doi.org/10.1088/1742-6596/1736/1/012025>
  27. Goldstein JI, Newbury DE, Michael JR, Ritchie NWM, Scott JHJ, Joy DC (2018) Scanning Electron Microscopy and X-Ray Microanalysis. <https://doi.org/10.1007/978-1-4939-6676-9>
  28. Saito K, Hangai Y, Utsunomiya T, Kuwazuru O, Kitahara S, Yoshikawa N (2013) Compression Properties of Al/Al-Mg-Si/Al-Si-Cu Alloy Three-Layered Functionally Graded Aluminum Foam. *J Japan Inst Met Mater* 77:430–434
  29. Topin F, Bonnet J-P, Madani B, Tadrist L (2006) Experimental Analysis of Multiphase Flow in Metallic foam: Flow Laws, Heat Transfer and Convective Boiling. *Adv Eng Mater* 8:890–899
  30. Jandaghi Shahi V, Marzbanrad J (2012) Analytical and experimental studies on quasi-static axial crush behavior of thin-walled tailor-made aluminum tubes. *Thin-Walled Struct* 60:24–37
  31. Ling C, Ivens J, Cardiff P, Gilchrist MD (2018) Deformation response of EPS foam under combined compression-shear loading. Part I: Experimental design and quasi-static tests. *Int J Mech Sci.* <https://doi.org/10.1016/j.ijmecsci.2018.06.014>