

STRUCTURAL ANALYSIS AND ITS STATISTICAL EVALUATION OF A CLOSED-CELL METAL FOAM

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The development of an efficient procedure for 3d modeling and finite element simulation of metal foams is one of the greatest challenges for engineer researchers nowadays. Creating 3d CAD model is alone a demanding engineering task due to its extremely complex geometry, and the proper finite element analysis process is still in the center of the research. The increasingly widespread application of the metal foams, e.g. in vehicle and medical industry, requires this knowledge in the design phase. A closed-cell metal foam is studied using different analyzing methods where the aim is to collect information about the composition and geometry (structure) that is satisfactory for the later research. Using statistical methods microscopic, X-ray and surface analyzing studies on the specimens produced according to the concerning standard are evaluated. The main goal of this part of the project is to obtain structural information and to determine the homogeneity or the in-homogeneity property of the metal foam specimens taken from different locations.

Keywords: metal foam, quantitative image analysis, composition analysis, statistical evaluation

1. Introduction

Metal foams are relatively new and advanced materials with high stiffness to weight ratio, good thermal conductivity, good acoustic insulation and excellent energy absorption capability which make them ideal materials for a variety of applications [1–3]. Therefore, they have increasingly been employed for a wide range of applications, such as structural elements, automotive parts, sound and vibration absorbers or even biomedical implants [4–9]. Basically, the mechanical properties of metal foams are influenced by three dominating factors, namely the property of the solid phase, the relative density of the solid phase and the spatial arrangement, that is, the structure of the metal foam (cell distribution, cell shape). To understand the structure property correlations in metal foams is required

for optimizing its mechanical performance for a given application [10].

Although metal foams are popular, they are still not sufficiently characterized thanks to its extremely complex structure which is highly stochastic in nature. In the last few years, several researchers focused on the finite element modeling of metal foams with more or less success, but it is still one of the greatest challenges. Instead of modeling the complex internal structure directly, idealized structural approaches (unit cell, statistical models, etc.) are often used where the cells are represented by miscellaneous two- or three dimensional models according to the structure behavior [11–15]. A 3d model created by the help of X-ray tomography (beam model, voxel and tetrahedral element methods) [16, 17] is another possibility. In detail, different numerical approach-

es for the simulation of metal foams were proposed [11–17].

To be able to prepare for the numerical simulation, extensive information is needed from the applied solid phase (density, Young's modulus) and from the metal foam structure (relative density, cell distribution, cell shape).

In this paper a closed-cell aluminum foam is investigated. The aim of this research is the preparation for the finite element simulation of the metal foam under compression using 3d CAD model. In order to reach this target, firstly the applied solid aluminum was studied and the density and the Young's modulus were determined. Then a microscopic analysis of the metal foam is investigated to determine the average cell size for obtaining the required size of the specimens according to the ISO 13314 [18]. Statistical analyses are done to select from the specimens with the same material properties for the further investigation. To provide information from the cell distribution manual and digital quantitative image analyses were performed using macroscopic records from the specimen's surfaces. The results of the two image analyses were evaluated and compared.

2. Investigation of the solid phase

The examined metal foam was manufactured from Duralcan F3S.20S Metal Matrix Composite. Considering the later investigations, the relevant physical and mechanical properties of the solid phase are measured and also the composition which can be compared with

the available commercial and literature [19] data. It is important to classify our material because it is indispensable to the finite element analysis.

The density of the investigated material is determined by the well-known technique, the modulus of elasticity is determined by a compression test using INSTRON 8874.

The material composition is evaluated with EDX analysis, see Fig. 1.

For control analysis the SiC median particle size is also determined by a microscopic analysis, see Fig. 2. The average particle size of the SiC at $\times 500$ enlargement is $13.245\ \mu\text{m}$.

The comparison of the commercial and the measured data can be seen in Table 1.

3. Metal foam specimens

The experiments were performed with closed-cell aluminum foam (Metal Matrix Composite Duralcan F3S.20S), see Fig. 3. According to the ISO 13314 standard, all spatial dimensions of the specimen have to be at least 10 times the average cell size. The investigated faces of the specimens were ground and polished by a STRUERS LaboPol-5 machine to avoid artifacts in acquired image data. The determination of the average cell size in the cut section using Hitachi Tabletop 3030 SEM microscope was done, see Fig. 4.

The average cell size analysis is studied at 9 different locations at $\times 30$ enlargement and the results are recorded and evaluated, see Table 2.

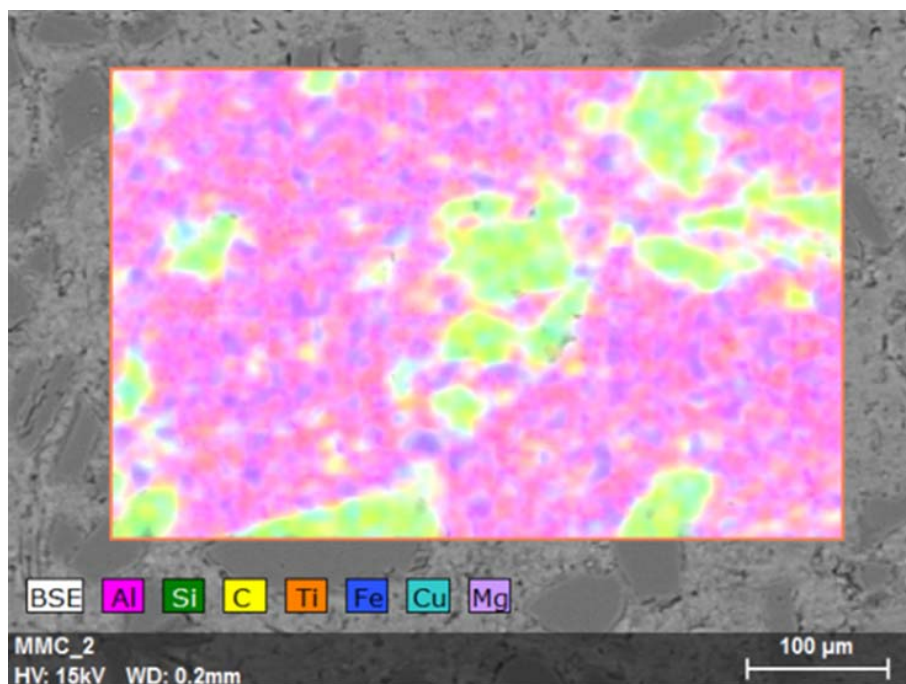


Fig. 1. Composition analysis of the Duralcan F3S.20S MMC

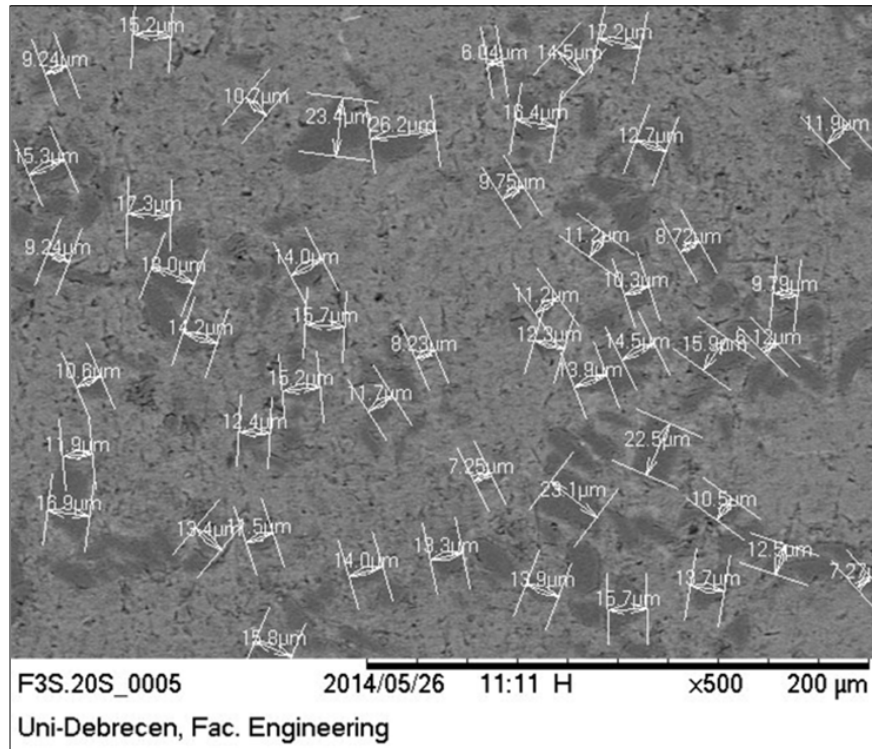


Fig. 2. SiC median particle size determination

Table 1. Properties of the F3S.20S Metal Matrix Composite Duralcan

Properties	Commercial data [19]	Measurement
Density (kg/m ³)	2850.00	2875.12
Modulus of elasticity (GPa)	98.60	97.20
Si content (%)	9.30	9.21
Mg content (%)	0.55	0.53
Fe content (%)	0.11	0.11
Ti content (%)	0.10	0.98
Cu content (%)	0.01	0.01
SiC median particle size (mm)	12.80	13.24



Fig. 3. Closed-cell aluminum foam

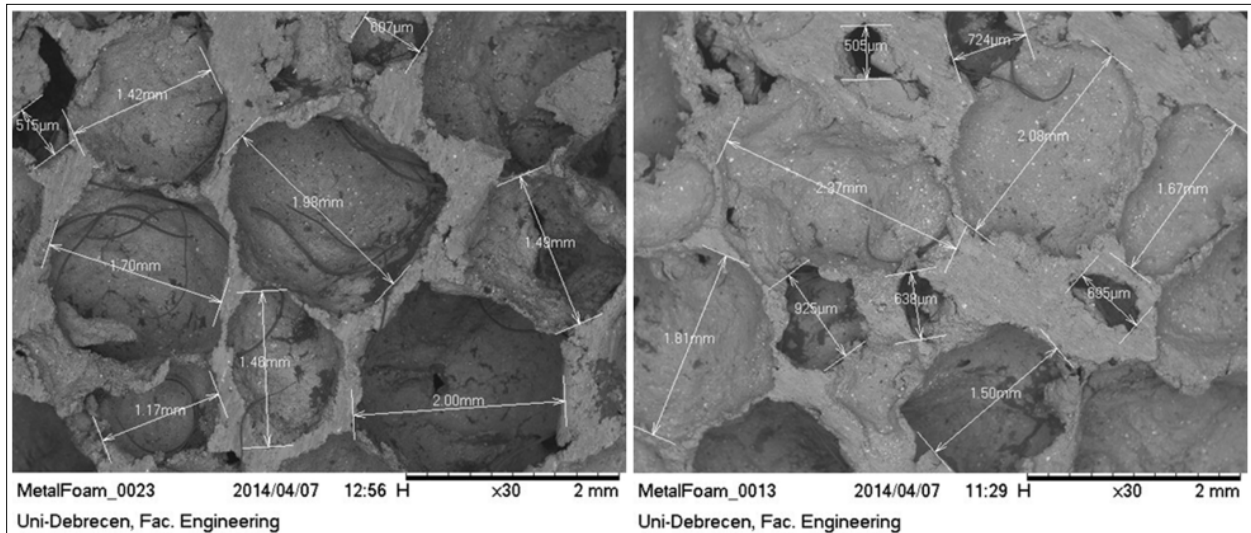


Fig. 4. Measurement of the average cell size

Table 2. Measurement results on average cell size determination

Measurement No.	1	2	3	4	5	6	7	8	9
1	1.01	2.09	1.51	0.50	1.02	1.44	0.65	0.51	1.52
2	1.30	1.94	1.05	0.72	0.68	1.13	1.59	1.42	0.59
3	1.19	0.88	1.78	2.37	1.77	1.34	1.34	0.61	1.34
4	0.85	1.16	1.49	2.08	1.95	1.59	1.48	1.98	1.18
5	1.20	1.75	0.89	1.67	1.45	2.44	1.15	1.70	1.52
6	1.14	0.71	1.75	0.69	1.71	1.52	1.64	1.49	0.86
7	0.74	0.88		0.64	1.69	0.67	2.24	1.46	1.25
8		0.99		1.50	1.48	1.43	1.76	1.17	1.67
9		0.62		0.92	1.69	1.98	1.05	2.00	0.78
10		1.91		1.81	0.77	1.44			1.52
11					1.32	1.05			1.42
Average cell size by location (mm)	1.06	1.29	1.41	1.29	1.41	1.46	1.43	1.37	1.24
Average cell size (mm)	1.33								

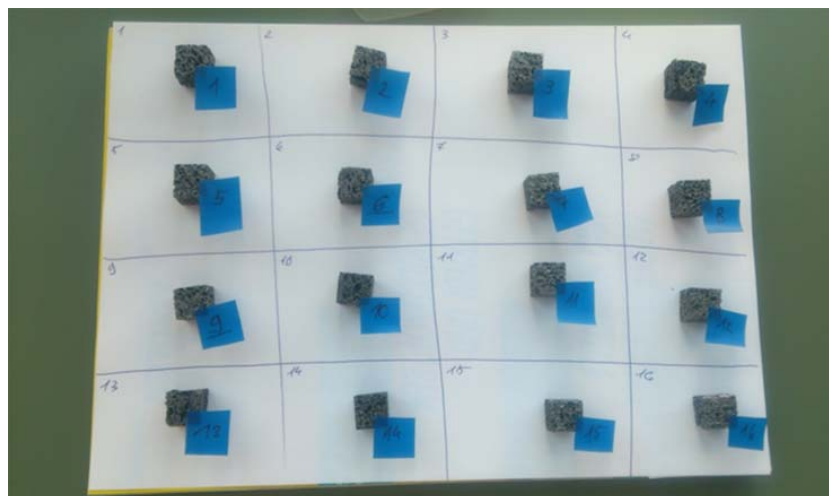


Fig. 5. Test specimens

The measured average cell size is 1.33 mm, so according to the ISO standard, the chosen size of the specimen is 14.5 mm × 14.5 mm × 14.5 mm.

The specimen cut is carried out by a STRUERS Labotom-15. 16 pieces of test specimen are manufactured, see Fig. 5.

While the required accuracy is difficult to achieve, the measurement of the specimens are needed. To be able to decide which specimen has the same physical properties, the weight and the relative density of the specimen are determined. The relative density (*r.d.*) can be calculated by

$$r.d. = \rho_F / \rho_S = m_F / m_S, \quad (1)$$

where ρ_F , ρ_S , m_F and m_S are the relative density of the metal foam and the solid phase, the mass of the metal foam and the solid phase, respectively.

Table 3 and Fig. 6 show the edge lengths of the specimens. There are only four specimens where at least one the edge lengths is out of the range 14.5 mm ± 1 mm = [13.5 mm, 15.5 mm]; specimen 6: $a = 13.38$ mm, specimen 9: $a = 13.45$ mm, specimen 13: $c = 15.66$ mm, specimen 15: $a = 13.24$ mm.

According to the chi-squared test, the edge length of the specimens (on the basis of the sample of 48 edge lengths) is normally distributed (at the significance level of 5% $\chi^2 = 2.18 < 7.81 = \chi^2_{\text{critical}}$ obtained), $m = 14.39$ mm, $\sigma = 0.52$ mm (Fig. 7).

Volume of the specimens was proved to be normally distributed as well (at the significance level of 5% we have $\chi^2 = 1.79 < 7.81 = \chi^2_{\text{critical}}$ obtained in the chi-squared test), $m = 2982$ mm³, $\sigma = 223$ mm³ (Fig. 8).

Unlike the geometrical data of the specimens, the parameters depending on the cell distribution (e.g. the mass and the density) are not normally distributed. The density histogram of the mass can be seen in Fig. 9).

Table 3. Edge length of the specimens

Specimen No.	a (mm)	b (mm)	c (mm)
1	14.87	14.26	15.17
2	14.28	15.05	14.50
3	14.22	14.53	15.14
4	14.98	15.33	14.14
5	14.89	14.60	13.94
6	13.38	14.24	14.72
7	14.08	14.05	14.10
8	14.93	14.17	15.08
9	13.45	13.98	14.41
10	13.74	14.80	14.49
11	14.26	13.93	13.67
12	14.13	14.27	14.03
13	14.62	14.94	15.66
14	14.64	14.22	13.81
15	13.24	14.22	14.24
16	14.44	14.03	14.82

4. Quantitative image analysis of the specimens

The volume ratio V_v , one of the most important parameters of the quantitative fractography, is very useful in the construction the 3d CAD model of the metal foam. For the determination of the V_{cell} volume of the second phase located in the solid phase – in the case of the metal foams the cells are filled with air – a number of methods are known. Here, the volume ratio derived by the investigation of the sides of the specimen, namely 6 different plane segments of the metal foam. Area fraction analysis is applied for the determination of the area occupied by the second phase. Another method is the so-called line analysis where the lengths of the line segments passing through the second phase are meas-

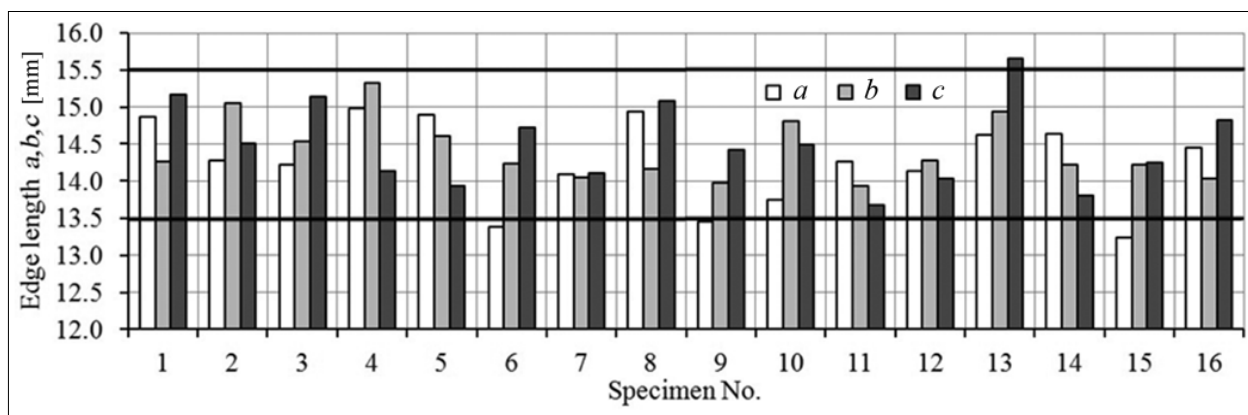


Fig. 6. Edge lengths (a , b , c) of the specimens

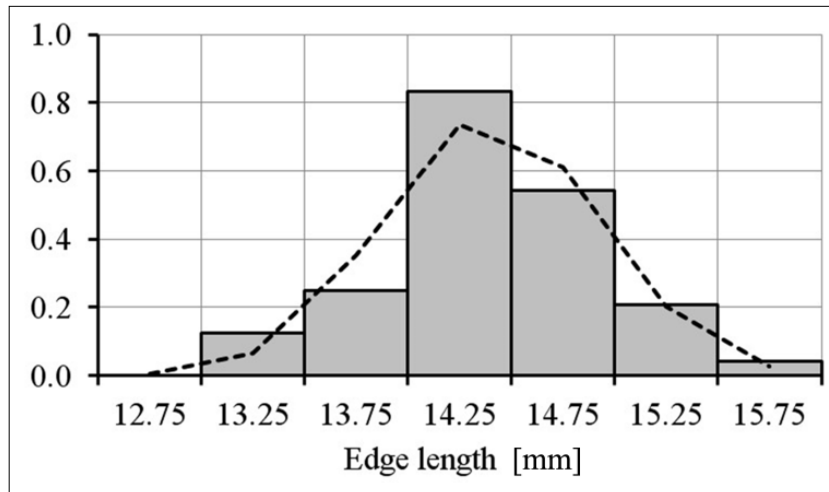


Fig. 7. Density histogram of the edge length

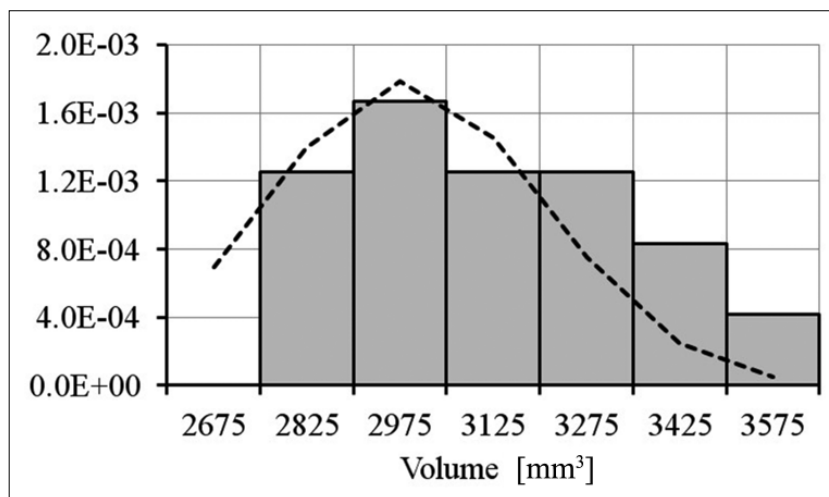


Fig. 8. Density histogram of the volume

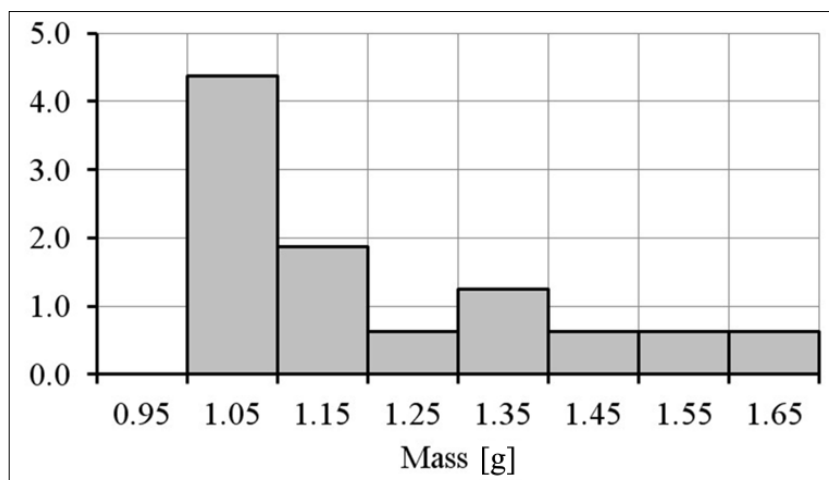


Fig. 9. Density histogram of the mass

ured and added up to determine the total line length belonging to the second phase [20]. The investigations are done using macroscopic pictures taken from the plane segments of the metal foams, see Fig. 10.

The volume ratio can be derived equally based on the surface area ratio and the line length ratio. These two quantities are equivalent [20]. The volume ratio can be described by

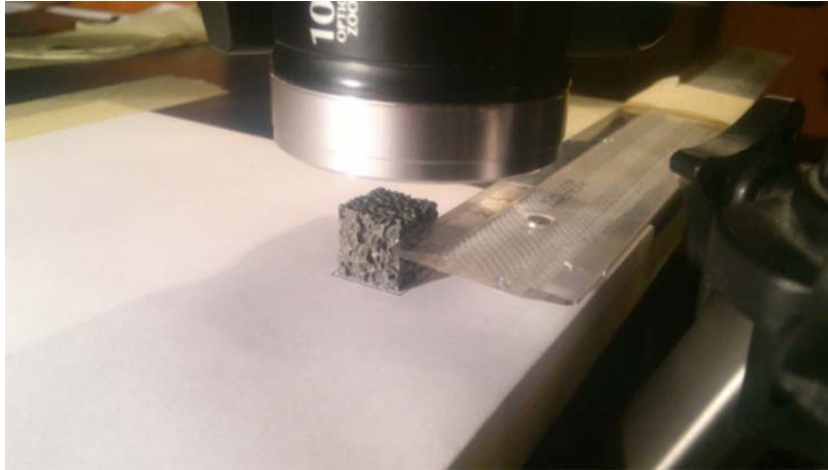


Fig. 10. Preparing macroscopic picture for the area fraction and line analysis

$$V_V = (V_{\text{cell}}/V_0) \cdot 100 = [V_{\text{cell}} / (V_S + V_{\text{cell}})] \cdot 100 \quad (2)$$

where V_0 is the volume of the metal foam specimen, V_S is the volume of the solid phase in the specimen.

4.1. Area fraction analysis

The A_A^j surface area ratio on the j th plane segment is defined by

$$A_A^j = \frac{1}{A_0^j} \sum_{i=1}^n A_{\text{cell},i}^j \cdot 100, \quad j=1, \dots, 6, \quad (3)$$

where A_A^j is the area of the j th plane segment, n is the number of cells, and $A_{\text{cell},i}^j$ is the area of the i th cell on plane segment considered.

The average surface area ratio specified for the metal foam is

$$\bar{A}_A = \frac{1}{6} \sum_{j=1}^6 A_A^j. \quad (4)$$

According to [21], the volume ratio is theoretically equal to the average surface area ratio in the case of statistically even structures.

The analysis is based on macroscopic pictures. The steps of the process can be seen in Fig. 11.

4.2. Line analysis

In addition to the surface analysis, the line analysis is a useful tool for deriving the volume ratio. With the help

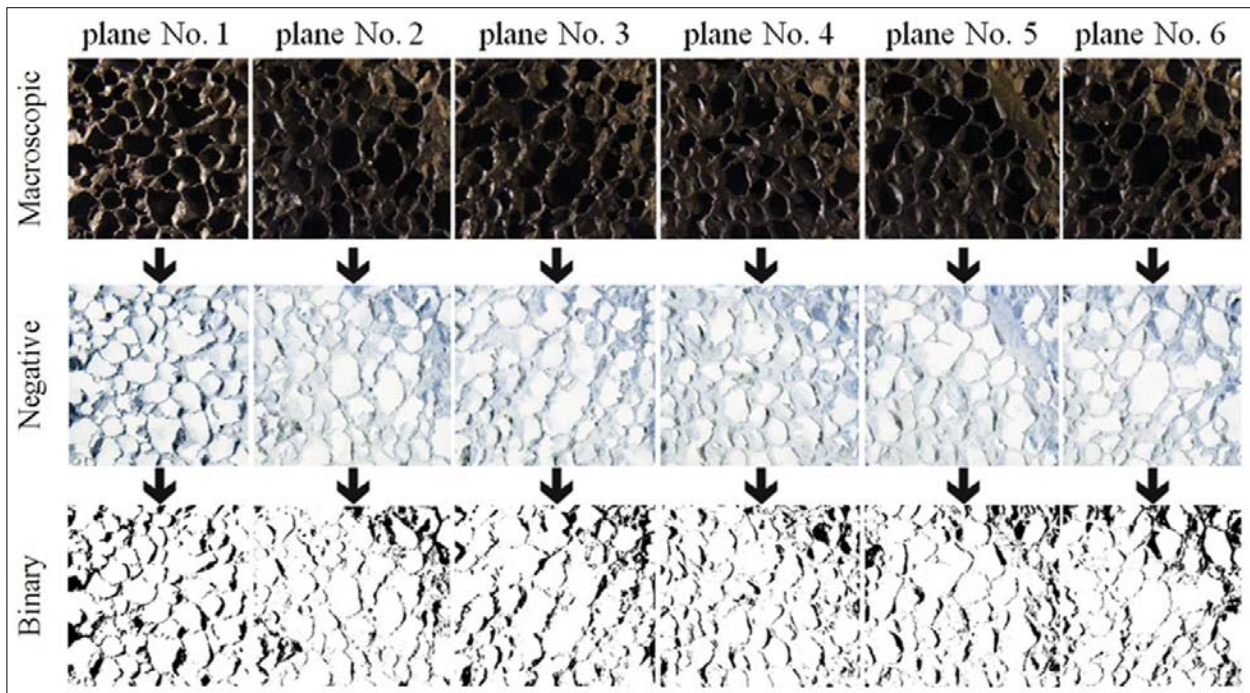


Fig. 11. Process of the surface analysis

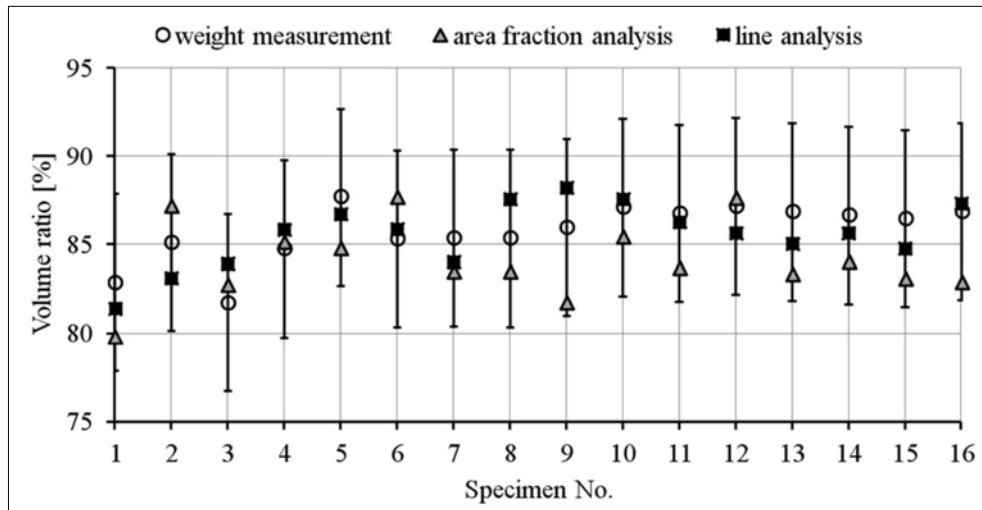


Fig. 12. Volume ratio determined by the three methods

of a grid (net of lines) placed on the screen of the microscope the total length of the line segments belonging to the second phase can be determined.

The line length ratio on the j th plane segment is defined by

$$L_L^j = \frac{1}{L_0^j} \sum_{i=1}^n L_{\text{cell},i}^j \cdot 100, \quad j = 1, \dots, 6, \quad (5)$$

where L_0^j is the total lengths of the line segments in the j th plane, n is the number of line sections belonging to the second phase, and $L_{\text{cell},i}^j$ is the length of the i th line section passing through the second phase in the j th plane.

The average line length ratio specified for the metal foam is

$$\bar{L}_A = \frac{1}{6} \sum_{j=1}^6 L_L^j. \quad (6)$$

According to [22], the volume ratio is theoretically equal to the average line length ratio in case of statistically even structures.

4.3. Comparison of the methods

In case of the metal foams the second phase is air, so the volume ratio can be directly determined by weight measurement. This fact gives the opportunity to control the applied methods. The results of the weight measurement, the area fraction analysis and the line analysis can be seen in Fig. 12.

5. Results and conclusion

In this paper a closed-cell aluminum foam was investigated. Considering the later finite element simulations, the relevant physical and mechanical properties of the solid phase were measured and also the composition which was compared with the available commercial

and literature data. The specimens cut from the metal foam were classified on the basis of the geometrical parameters.

Quantitative image analysis has also been done which gives detailed information about the structure of the metal foam. The image analysis is also a useful tool for the determination of the volume ratio. The volume ratio, the specific quantity of foam materials were derived by area fraction and line analysis as well. The two applied methods were compared. Although the line analysis is more accurate, it is much more time-consuming than the area fraction analysis. The results showed that the easily and rapidly performable area fraction analysis is sufficiently proper.

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