

# METHOD OF DETERMINING THE ESSENTIAL GEOMETRIC CHARACTERISTICS OF THE METAL FOAM STRUCTURE

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The paper deals with the description of method, proposed by authors, that determining the essential geometric characteristics of the metal foam structure with using of the analytical imaging software. Method use economically available technical apparatus and software with emphasis on maximum consideration of the measurement uncertainty by Kline-McClintock method. The image analysis used three kinds of metal foams with a pore density of 10 to 40 pores per inch. The most important parameter - the size of a metal foam cell ranged from 1,165 mm (for 40 PPI) through a 2,262 mm (for 20 PPI) to 5,660 mm (for 10 PPI).

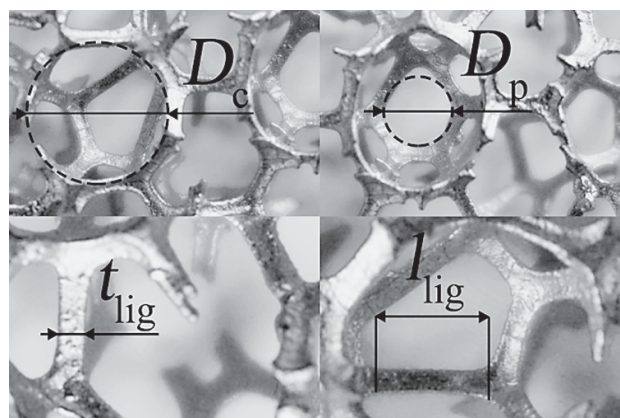
**Keywords:** metal foam properties, optical analysis, metal foam structure, cell diameter,

## INTRODUCTION

Foamed metals due to its unique properties finds use in a wide range of technical applications - impact energy absorbers, heat exchangers, chemical mixers [1,2], but most promised application can be found in dynamically developing renewable energy sector [3-6]. The unique properties are dependent not only on the base material (metal), but also on the geometric properties of the structure, which fundamental building element is cell. This cell is formed by interconnected ligaments (fibers) of the metal foam, in the form of tetrakaidehedrons (polyhedron with fourteen walls) that create a complex internal structure. Figure 1 depicted essential geometric characteristics and shapes of metal foam structure:

- cell diameter -  $D_c$
- pore diameter -  $D_p$
- ligament length -  $l_{lig}$
- ligament thickness -  $t_{lig}$

Possibility to correctly identify and quantify geometric characteristic of ligaments (shape in cross-section, diameter, length), pores and cells (shape, diameter) for different types of metal foams is crucial for further development leading to effective design of various technical applications based on metal foams (e.g. calculation of specific surface of metal foam, which forms the interface between the solid and fluid phase, mathematical modeling of the selected properties or inputs for finite element modeling, etc.). Determining of the geometric characteristics of metal foams has been previously carried out by two groups of authors. One group of authors [7,8], mainly used scanning electron microscopy or other types of



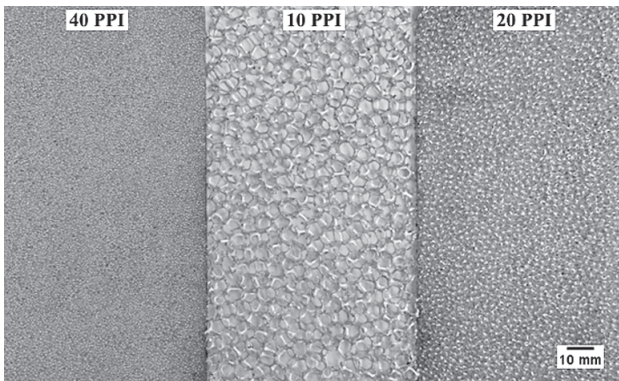
**Figure 1** Essential geometric characteristics and shapes of metal foam structure

highly specialized imaging devices that are not widely available on standard research institutions. These authors have achieved relatively consistent results unloaded with significant measurement errors. The disadvantage of the presented methods is the low availability of used devices for a wider range of researchers. The second group of up technically aimed authors [9,10] used in determining the essential geometric characteristics of the metal foam structure simple photo cameras and various graphic software. In this case, the authors did not reflect the possible optical distortion of devices, as well as did not address possible errors in the process of measurement and evaluation of data.

## METHODOLOGY

Within the described method of determining the essential geometric characteristics of metal foam structure were used freeware image analysis software ImageJ and economically feasible imaging devices (optical micro-

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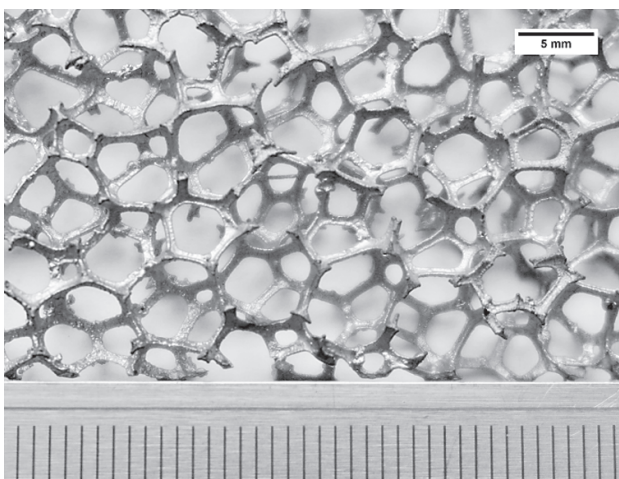


**Figure 2** Overview of used samples

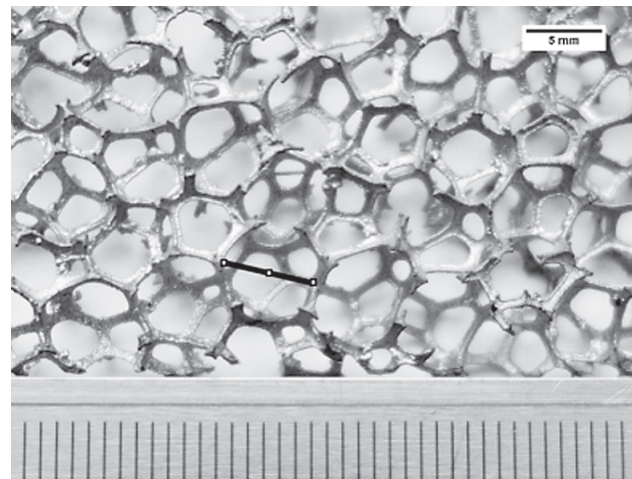
scope, macro lenses and photo cameras) with emphasis on maintaining a low level of measurement error. Geometric characteristics were determined for the three types of metal foam with a pore density from 10 to 40 PPI (pores per inch) and a density of  $300 \text{ kg}\cdot\text{m}^{-3}$ . The basic material was copper. Dimension of samples were modified to  $150 \times 300 \times 5 \text{ mm}$ . Overview of used samples is depicted in Figure 2.

Two-dimensional image of metal foams has been captured with 50 mm (F2.5) macro lens in combination with the body of the camera with an effective resolution of 18 megapixels (4,3 micron on pixel). The front lens element was located at a distance of 50 mm from the shooting area, the camera output was in uncompressed 14-bit RAW format with a resolution of  $5184 \times 3456$  pixels, which was later modified in the graphical editor. Task of the final graphic post-processing was to remove the lens manufacturing defects (particularly chromatic aberration, barrel distortion) resulting from the optical arrangement of the inner optical members, which may bring substantial error in the results. Another part of post-processing was transfer of an image to black and white color, balance contrast and export Raw format into TIFF format, which is suitable for image analysis in ImageJ software.

Before making of image, metal foam samples were supplemented with accurate measurement tool with an accuracy of 0,25 mm (see Figure 3). This measurement tool served to adequate determination of the scale be-



**Figure 3** Location of measurement tool on edge of sample



**Figure 4** Working environment of ImageJ MeasurementTool application

tween displayed pixels of TIFF format images and the actual size of metal foams in mm.

A substantial part of the method of determining the essential geometric characteristics of the metal foam structure was carried out in a working environment of image analysis software ImageJ. The initial step of the analysis dealt with the definition of ratio between the input pixel value and the desired value in millimeters, which was for all kinds of foams identical 90 pixel/mm.

The second part of the analysis was oriented to identify the appropriate parts of the metal foam structure for performing measurements of individual ligaments, pores and cells (see Figure 4). Their size was recorded using Measuring Tool application that exported resulting values to a text file suitable for all types of spreadsheets.

The uncertainty of the measurement process was performed using Kline–McClintock method [11] at Equation (1). This involved the uncertainty of the ruler, the uncertainty of ImageJ Measurement Tool, uncertainty in determining the edge of the studied objects and finally uncertainty of set scale. As for the precision ruler, the calibration uncertainty was  $\pm 0,25 \text{ mm}$ .

The uncertainty of the ImageJ Measurement Tool was reported by developer as  $\pm 1\%$  of measured value, uncertainty in set scale was determined as 14 pixels/mm (in this case, according to ImageJ, when 90 pixel was 1 mm, this can be edited to uncertainty of 0,15 mm and uncertainty of identification of proper object edges was estimated at 14 pixels/mm, or 0,15 mm.

$$U = \sqrt{\left(\frac{\Delta U_r}{U_r}\right)^2 + \left(\frac{\Delta U_{MT}}{U_{MT}}\right)^2 + \left(\frac{\Delta U_e}{U_e}\right)^2 + \left(\frac{\Delta U_s}{U_s}\right)^2} \quad (1)$$

see: list of symbols

Using these uncertainties the measured geometric characteristics of the metal foam had an average uncertainty  $\pm 0,32 \text{ mm}$ . Within the statistical data processing were calculated standard deviation and standard error with confident level 95 %, what are reported in results and discussion section.

## RESULTS AND DISCUSSION

Described measurement of each geometric characteristics were carried out on randomly selected twenty geometric objects (ligament, pore, cells) that meet the required criteria - visibility, position and orientation relative to the plane of the lens. A summary of the results of measurements contains Table 1.

Table 1 **Geometric properties of metal foam structure**

Geometric properties of metal foam (average)	Pore density / PPI		
	10	20	40
Cell diameter / mm	5,660	2,262	1,165
Mean pore diameter / mm	2,120	0,858	0,368
Ligament length / mm	2,312	1,021	0,528
Ligament thickness / mm	0,505	0,304	0,114

Statistical set with twenty measured data demonstrated the lowest values of the standard deviation (0,022) for measurements on metal foams with pore density of 40 PPI, while the highest value (0,643) attained the standard deviation of metal foam with a density of 10 PPI. The same trend was also recorded for the value of the standard error statistics files, 0,005 for the metal foam with 40 PPI and conversely 0,144 for the metal foam with 10 PPI. The analysis of results was carried out by a graphical comparison of the measured values of the authors Bianchi [12], Kamath [9] and Mancin [10]. Figure 5 depicted the relationship between density and cell diameter (with indicating the error bars for the values presented in this paper).

The result of the comparison is a visible difference in the average value of the cell diameter for all three types of metal foam. Diversion from the values presented in this article can be caused both by measurement error, which the mentioned authors did not describe but also by frequent inability of precision manufacturing, respectively, precision describing metal foams by manufacturers. Also for this reason, it is important to conduct an independent custom analysis of the geometrical

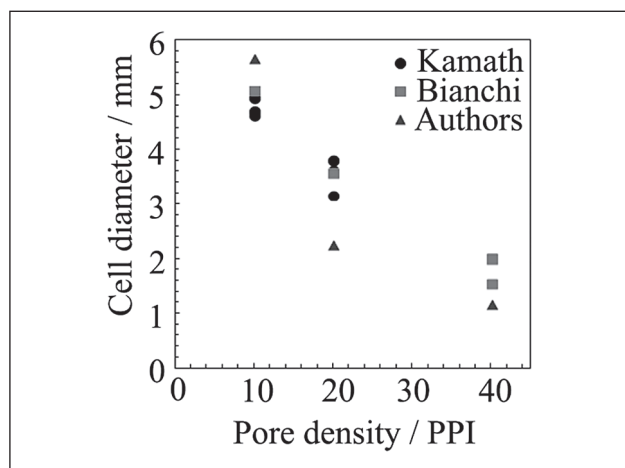


Figure 5 Comparison of the measured values of the cell diameter with previously published values

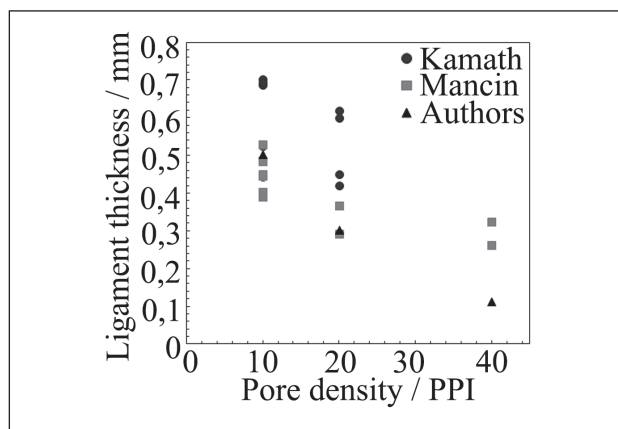


Figure 6 Comparison of the measured values of the ligament thickness with previously published values

properties of the metal foam so that knowledge of examined object could achieve the highest possible degree. Results of measurement that dealt with the ligament thickness (see Figure 6) showed minor deviations within the previously published measurements.

For metal foams with a pore density 10 and 20 PPI, measured values of ligament thickness was in the range of previously published papers, while measured values of metal foam with a pore density 40 PPI had a significant difference within comparison (see Figure 6). The resulting difference can be attributed to the different method used by Mancin [10], what cannot provide sufficient accuracy for such fine structure of pores.

## CONCLUSION

The described method of determining the essential geometric properties of the metal foam structure is using an available simple image analysis tools to identify various geometric shapes (ligament, pore, cell) and quantify them in terms of their dimensions. Accurately described essential geometric characteristics are elementary imputes to the complex calculations leading to the optimal design for various technical applications based on metal foams. The method consists of capturing an image of metal foam with available photography devices, followed by post-processing stage, when images are edited into the desired quality. Next stage consists of actual image analysis in Measurement Tool, what is function application of ImageJ software. Final stage of proposed method is calculation of measurement uncertainty. Within the method were determined geometric characteristic for three kinds of metal foams with a pore density of 10, 20 and 40 PPI, and the results were compared with previously published work dealing with the metal foams and their characteristics. Result of the comparison may be considered in form of clarification of the measured geometric characteristics from previous published work, as a presented method works with higher level of accuracy.

## Acknowledgment

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## LIST OF SYMBOLS, ABBREVIATIONS AND ACRONYMS

$D_c$	cell diameter,
$D_p$	mean pore diameter,
$l_{lig}$	ligament length,
$t_{lig}$	ligament thickness,
$P_{pi}$	pores per inch,
$T_{iff}$	tagged image file format,
$U$	total uncertainty,
$U_e$	uncertainty in identification of edge,
$U_r$	uncertainty of ruler,
$U_s$	uncertainty of scale,
$U_{MT}$	uncertainty of Measurement Tool.

**Note:** The responsible translator for English language is Mgr. František Dankoň, FD-Lingua, Košice, Slovakia