Journal
of Achievements in Materials
and Manufacturing Engineering

International Scientific Journal
published monthly by the
World Academy of Materials
and Manufacturing Engineering

Optimizing glue joint of aluminium metallic foams

J. Nowacki *, A. Sajek
West Pomeranian University of Technology, Al. Piastow 19, 70-310 Szczecin, Poland
* Corresponding e-mail address: jerzy.nowacki@zut.edu.pl

ABSTRACT

Purpose: Characteristics of aluminium foams as construction material were given, along with some exemplary applications. The purposefulness of lowering the mass of constructions comprising aluminium foams was discussed, and bonding techniques as well as prospects of reducing the mass of a joint were analysed. A computer simulation was performed for a representative fragment of a glue joint in aluminium foam with the purpose of analyzing existing stresses for three variants of thickness of a layer of epoxy glue.

Design/methodology/approach: Preliminary tests on the complete test specimen were conducted, and then a new model of a joint was made, based on a small part of the geometry of the joint. The methodology employed allowed for a precise investigation of the working conditions of a glue joint in a static shear test depending on the thickness of a layer of glue.

Findings: A high interdependence between stresses in a metallic foam and the thickness of a glue joint was observed – the thicker the layer of glue, the stiffer the joint. The thickness of the glue layer inspected in the simulation does not influence the strength of the joint.

Research limitations/implications: The tests were conducted with the use of an improved yet simplified model of a joint that allowed to determine stresses present both in metallic foam and in the weld. Further course of action in the modelling of glue joints was set with the aim of establishing a more detailed definition of weld work conditions.

Practical implications: Basic factors affecting the efficiency of joining aluminium foams by means of gluing were defined, and guidelines concerning the technology for producing a proper joint were given.

Originality/value: A problem concerning gluing aluminium foams with regard to mass optimization was highlighted. A mechanism for minimizing stresses in the structure of a weld through the regulation of weld thickness was presented.

Keywords: Aluminium foam; Numerical simulation; Glue; Joint design; FEM; Mass optimization

Reference to this paper should be given in the following way:

J. Nowacki, A. Sajek, Optimizing glue joint of aluminium metallic foams, Journal of Achievements in Materials and Manufacturing Engineering 75/1 (2016) 14-23.

ANALYSIS AND MODELLING

1. Introduction

Metallic foams can be produced with different methods, from casting through powder metallurgy to metallic deposition [1,2]. The aim of metal foaming is to produce a material characterised by as low a density as possible. Spatially developed structure with high porosity leads to a considerable mass reduction with simultaneous decline in strength properties. The production of metallic foams is orientated towards obtaining a material of the highest degree of surface development, along with homogenous pore dispersion and wall thickness. The resultant highly porous foams are characterized by optimum mechanical stress [3].

Possible applications of metallic foams are related to their unique properties, i.e. high porosity, low density, low thermal conductivity and crush energy absorption. Therefore, foams are used wherever considerable mass reduction and favourable properties in the conditions of great dynamic deformations are crucial [4,5]. Automotive, rail and aviation industries constitute the most prominent consumers of these materials (Fig. 1).

Fig. 1. An exemplary application of composite materials based on aluminium metallic foams in the construction of a locomotive prototype for high-speed rail [6]

Joining metallic foams should take into consideration the nature of their properties and the optimization of the weight of a joint. The use of screws, bolts or rivets; welding and soldering as well as solid-state diffusion bonding introduce additional elements into the joints, which significantly increases its mass [7-12]. Due to a low density of binders and advantageous features of the technological process, gluing techniques provide a more efficient weight optimization. Due to multitude of glue binders, one can obtain joints of relatively diversified performance. An important yet unresolved issue in optimization of gluing of metallic foams is how to determine the amount of glue needed to produce a joint whose strength would be higher than that of the metallic foam [13,14].

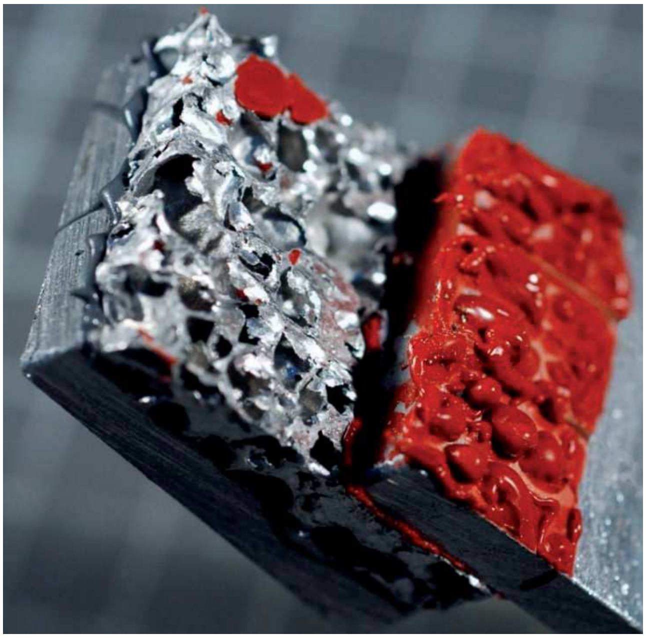

Fig. 2. An example of a damaged glue joint in aluminium foam whose adhesion has been modified with the use of silicone glue

The most widespread construction adhesives used for foam joining belong to the category of epoxy binders. They allow to produce a joint displaying a good adhesion to joined surfaces and high strength [15]. An appropriate preparation of the edge of a joint constitutes a certain problem in the process of joining metallic foams due to structure deformation that occurs during cutting [16,17]. Thermo-expanding glues that would fill the gaps can offer a solution [18]. Regulation of the properties of glued joints is also possible through appropriate activation of joined surfaces and preliminary hardening of the glue before bringing the joined elements into contact (Fig. 2).

Despite being the weakest link of a joint, the foam can be modified depending on its application. It is possible to enhance its strength parameters by filling the surface pores with polymer materials or metal particles. In consequence, energy absorption coefficient is enhanced, and the obtained strength parameters are a few times higher [19,20].

Numerical modelling of spatially developed structure of aluminium foams poses a great challenge for contemporary methods of computer-aided calculations in the FEM convention [21]. In this article, an attempt of carrying out a numerical simulation of the behaviour of a glue joint between the foam and a flat surface of a non-porous material was made. Very small contact area of the joined surfaces puts significant constraints on the process of gluing foams. One solution in this case is to produce bearing surface on the edge of the joint in metallic foam. Being in equilibrium with mass optimization, the bearing surface makes it possible to produce a joint successfully [22].

2. Object and scope of the research

Preliminary FEM simulations were carried out on a complete model of test specimen. Simulations of a butt joint under conditions of tension, and a lap joint under shear conditions were conducted.

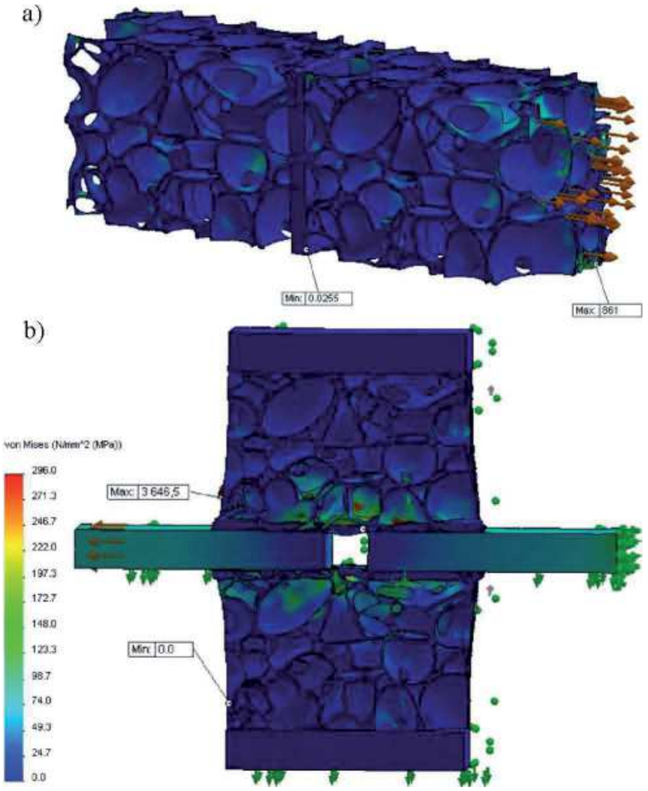

Fig. 3. Model of a glue joint in a static tensile test (a) and a static shear test (b)

While making the foam model, the following assumptions were taken into consideration: the pores are irregular in shape; the diameter of a pore is 1-8 mm; the structure contains both open and closed pores; the thickness of the walls between pores varies.

The glue joint was 2 mm thick with the space being 0.2 mm. The technique of foam modelling used (cutting pores out of a block) allowed to achieve a 72% porosity. The result of the calculations is shown in Figure 3.

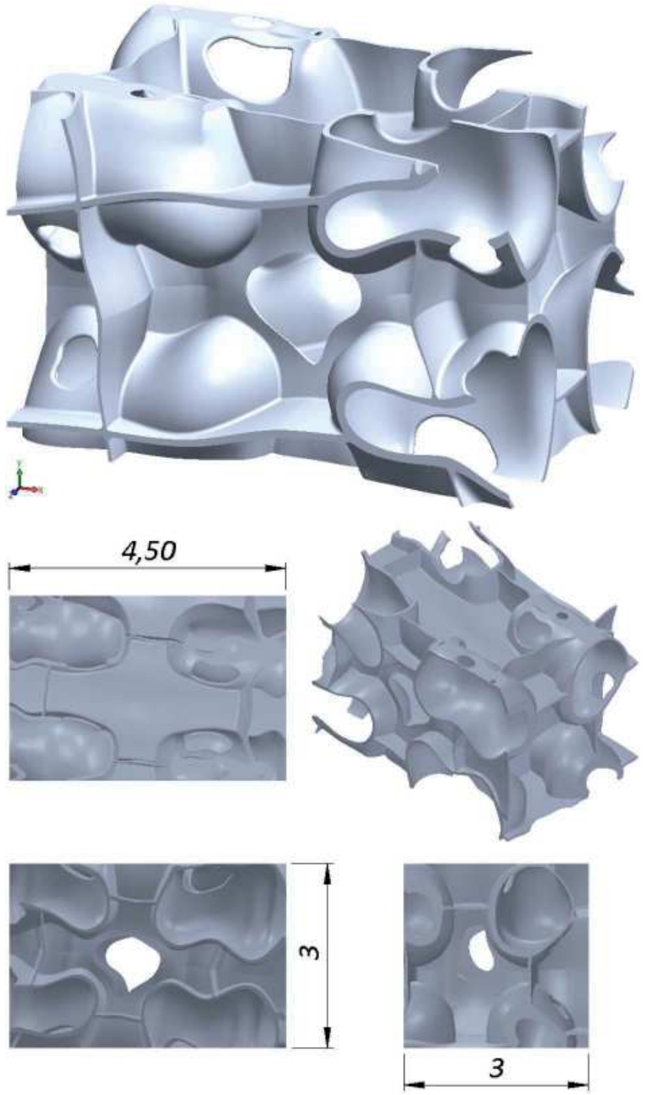

Fig. 4. Dimensions of spatial model aluminium foam with a porosity 92%

In the course of testing, modelling the spatially complex foam structure and optimizing the model with regard to time and precision of the calculations proved highly problematic. The simulation showed that despite the presence of considerable stresses in metallic foam, the stresses in the glue joint were very low. Is 2 mm too big a weld thickness, then? As far as the optimization of the mass of a joint is concerned, each millimetre of weld thickness matters. Further tests were supposed to determine minimal thickness of the glue layer that would allow to transmit the stresses during the shear test.

On the basis of microscopic examination, an improved spatial model of foam was made whose overall dimensions were 3.0 x 3.0 x 4.5 mm. The volume of metal in the block was 3.3 mm^3, and the total volume was 40.5 mm^3, making the resultant porosity reach 92% (Fig. 4). Irregular structure of open pores and varying wall thicknesses were recreated in the model.

Due to a complex shape of developed foam geometry, a fragment of 1.1 x 1.2 x 2.3 mm was used for strength calculations (Fig. 5). The aim of this procedure was to enable the creation of a proper and compatible finite elements mesh between the geometrical elements of the joint.

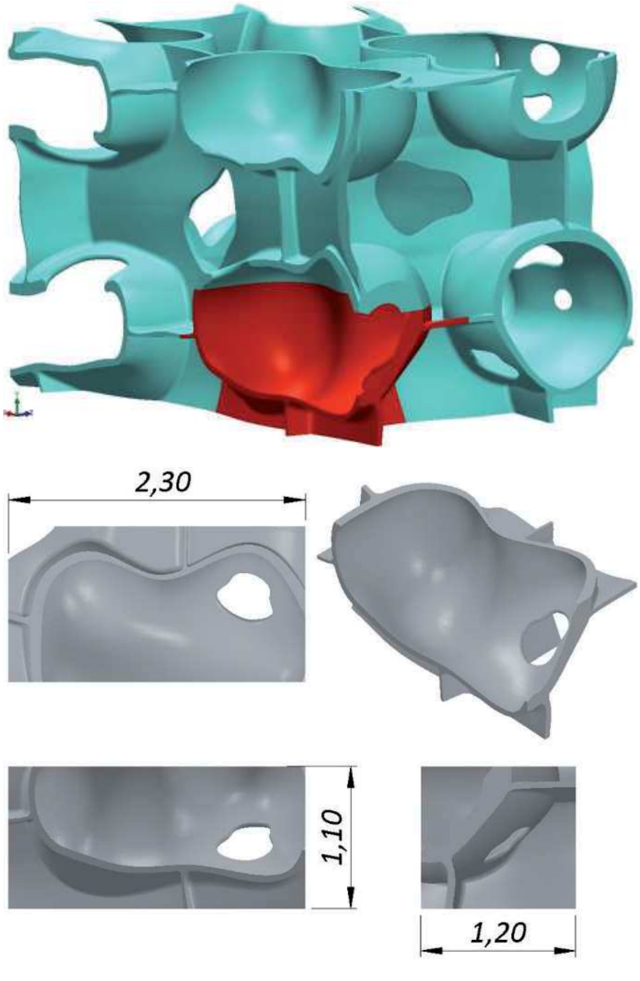

Fig. 5. Foam fragment used to numerical calculations

The model of the joint is based on a bonding technology in which the base to which the foam is glued is covered with an even layer of glue. Typical thicknesses of glue layers were employed, i.e. 50 and 500 µm (recommended by binder manufacturers). In addition, calculations were made for a joint of 200 µm thickness (Fig. 6).

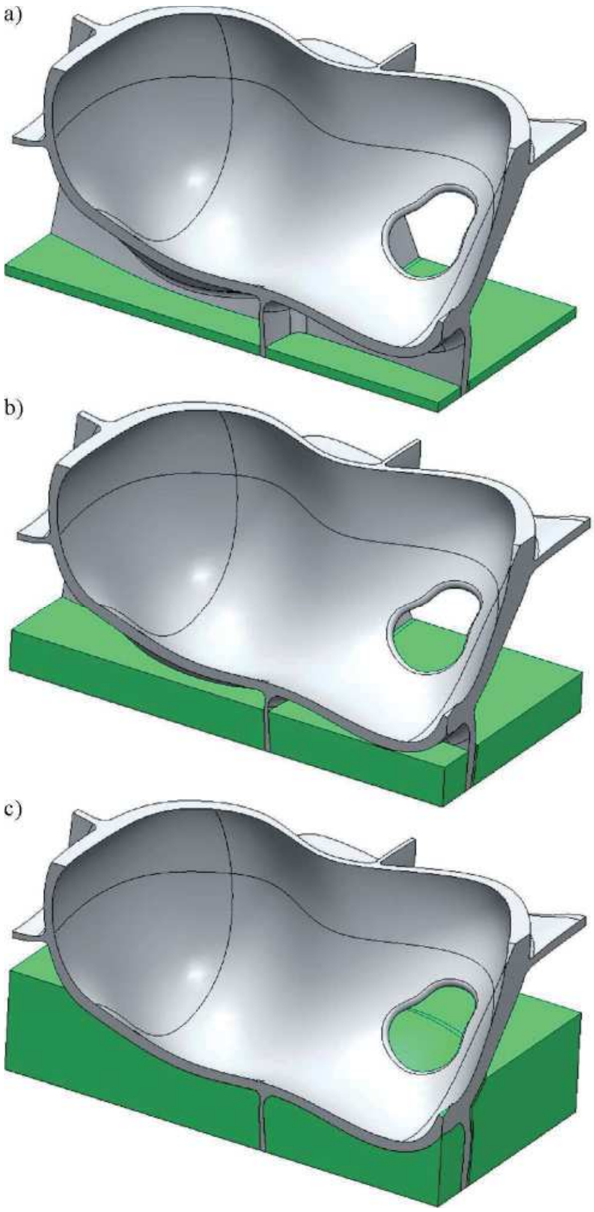

Fig. 6. The analysed variants of the glue joint 50 (a), 200 (b) and 500 (c) µm

Casting silumin AK7 (Al-Si7Mg; 356.0 T6) was used as foam material, its chemical constitution being the following: Si: 6.0-7.5%; Cu max.: 0.25%; Mg: 0.20.0.45%;

Mn max: 0.35%; Ti max: 0.25%, Zn max: 0.2%. Two-component epoxy glue Loctite Hysol 3423 was used as weld deposit. The properties of materials used in the simulation are shown in Table 1.

Table 1.
The mechanical properties of materials used in simulation

Feature	Unit	Hysol 3423	Al-Si7Mg T6
Modulus of elasticity	N/mm^2	1498	72000
Poisson ratio	-	0.36	0.33
Density	kg/m^3	1100	2680
Tensile strength	N/mm^2	24	240
Yield strength	N/mm^2	12	225

Tests in the convention of FEM were conducted. Test procedure described on the basis of 500 µm joint was used.

The model was immobilized at 4 lower planes of glue joint; in order to evoke the state of stress, the model's upper surface was moved into the x direction (to the right) by 0.002 mm (Fig. 7).

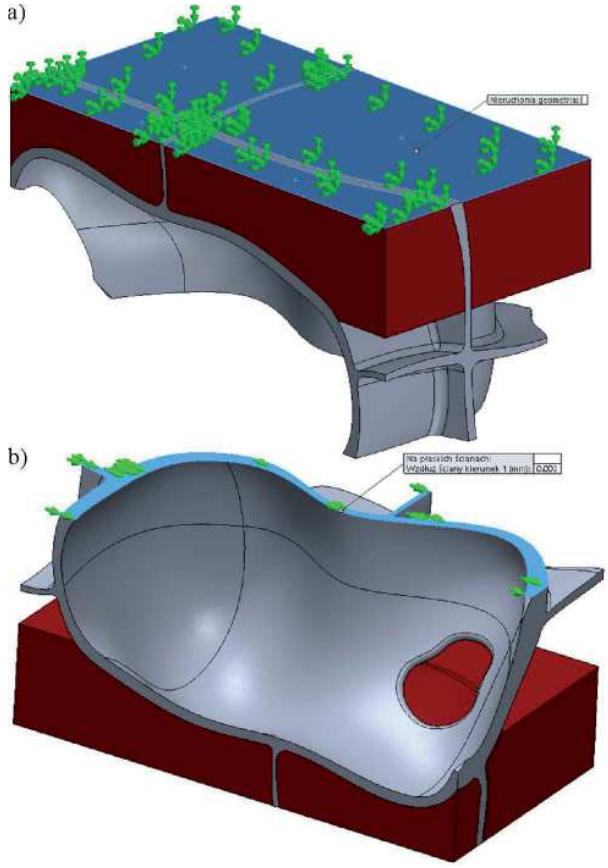

Fig. 7. Model fixing on lower planes of glue joint (a) and foam upper plane translation into the x direction (b)

Bearing in mind that the model constitutes a small fragment of a larger geometry, the back, front and upper planes were secured against displacement in the normal direction.

Materials were assigned to the 5 solid objects (4 glue objects and 1 foam object) present in the simulation. Global contact that defines the bonding between common planes was used. The geometry was divided into a finite elements mesh of 0.04 mm global size and 0.002 mm tolerance. In this way, a solid mesh was obtained which can be seen in Figure 8.

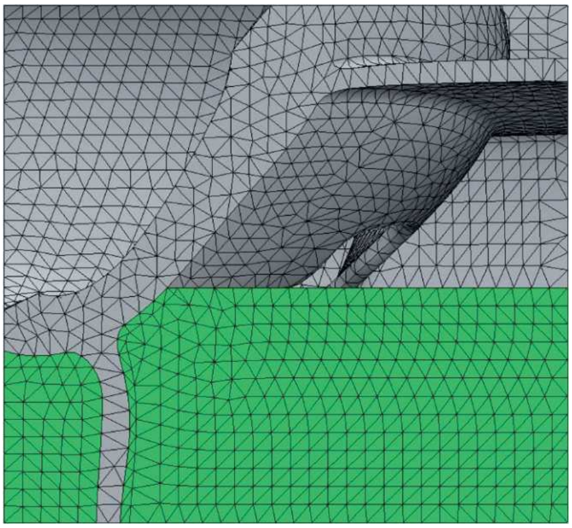

Fig. 8. Foam glue joint divided into a solid finite elements mesh (to the left). On the right side of the model, a transition and common nodes between the foam and glue weld, concentrating near the measurement line, are visible

3. Test results

The results of FEM tests on glue joints of 3 different variants of glue layer thickness are shown below. The main focus was on the analysis of stresses in the whole joint (Figs. 9-11) in order to find out which portion of the stresses is carried by the glue joint (Figs. 12-13).

Locally, the stresses on the foam-glue adhesion boundary reach values exceeding the strength of the glue. There is a risk of occurrence of cohesive fractures in the weld. Still, the values are restricted only to a few spots and they can be a result of the mesh density being too low or local notches that do not actually exist.

In order to verify the calculations, strength tests were conducted on specimens of glued joints with glues layer thickness of 0.5 mm. In technological terms, it is difficult to obtain an even layer having such thickness. When the surface of the sheet is evenly covered, some glue may nevertheless flow out of the narrow gaps, filling bigger spaces of the pores.

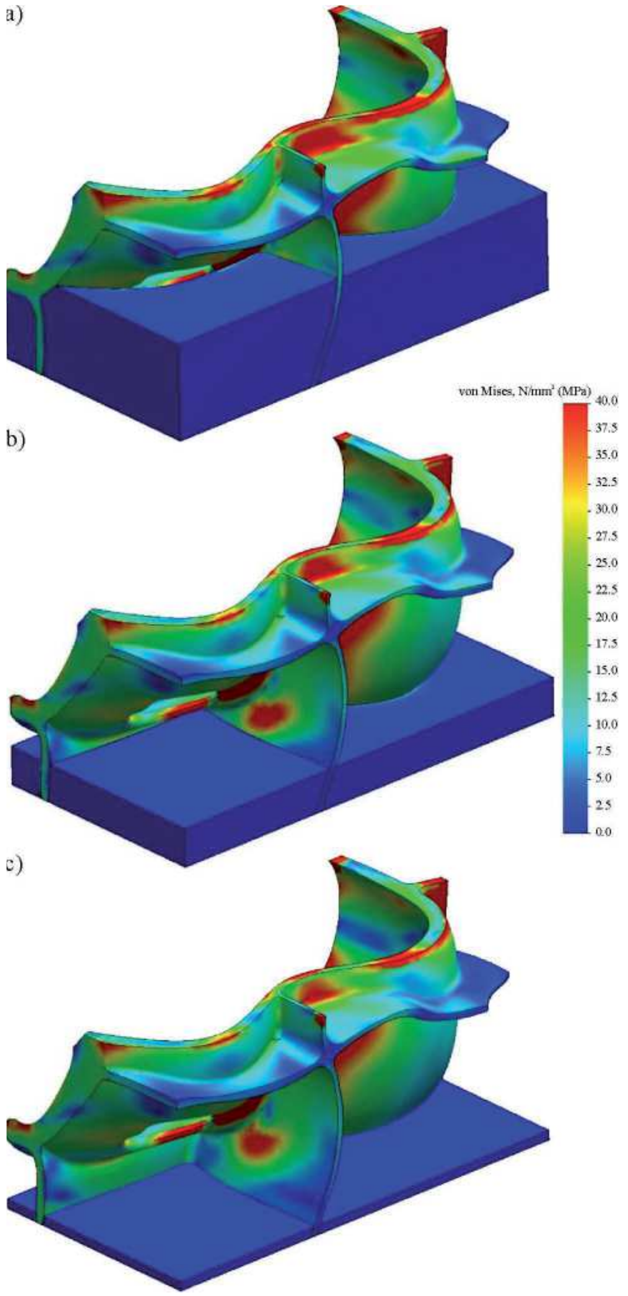

Fig. 9. The reduced stress distribution in the analysed joint in three variants 500, 200 and 50 μm (front view of the model)

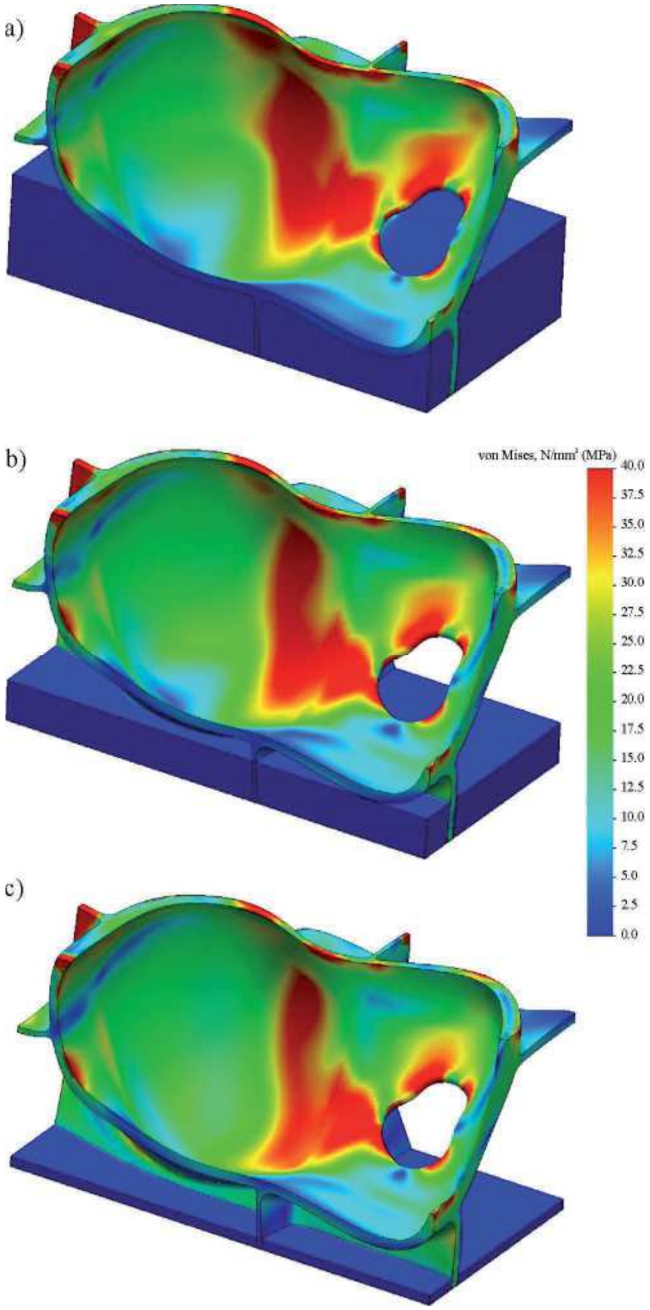

Fig. 10. The reduced stress distribution in the analysed joint in three variants 500, 200 and 50 μm (rear view of the model)

In all the specimens tested, a fracture in the metallic foam was observed in the section containing individual pores having a big diameter and the thinnest walls. In the photographs of test specimen fractures (Fig. 14), an intact layer of epoxy glue filling the external pores can be seen. The stresses registered in the strength test reach the values of 20-25 MPa.

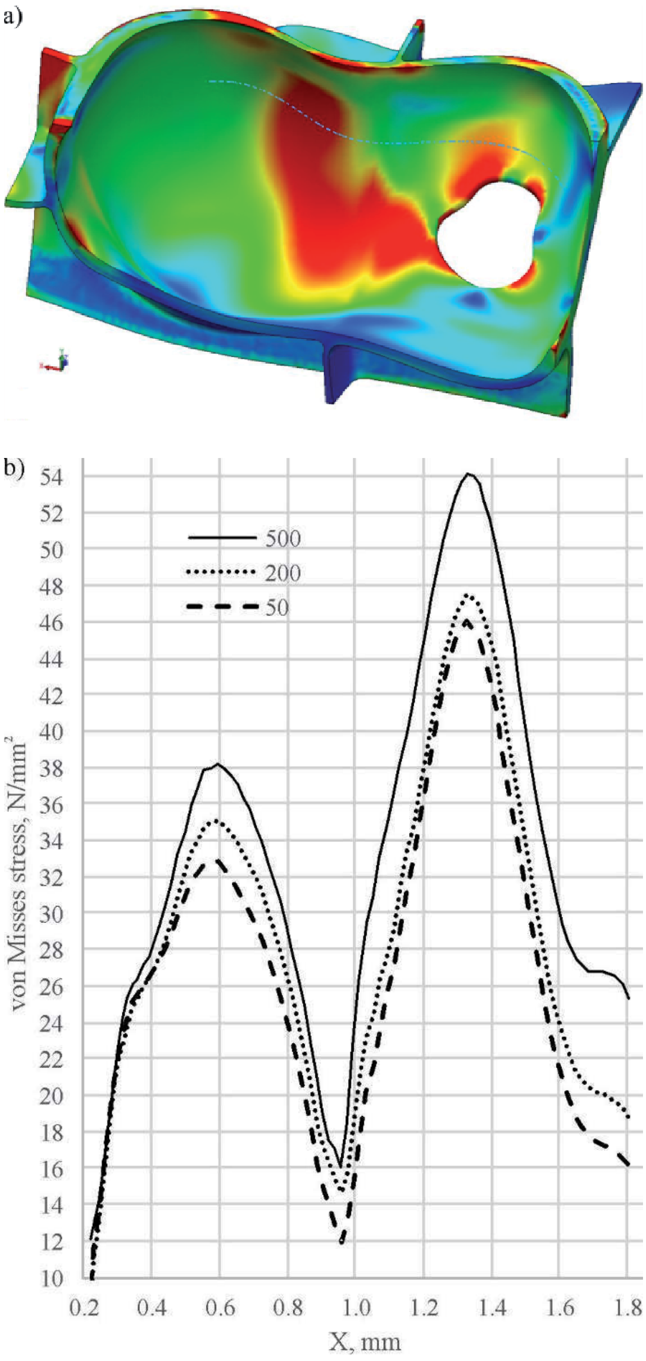

Fig. 11. Stress distribution in aluminium foam along the blue line (a) for 500, 200 and 50 variants (b)

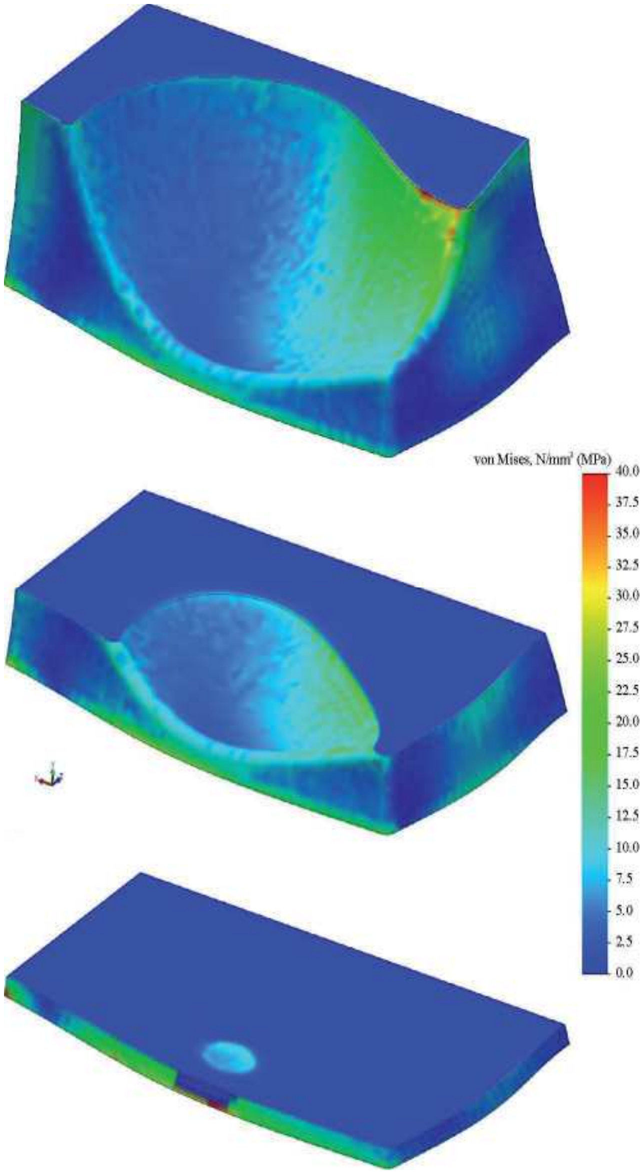

Fig. 12. Stresses in the glue joint for 500, 200 and 50 variants. Lack of even distribution due to mesh density being too low (especially in case of the thinnest layer) can be observed

4. Conclusions

On the basis of conducted numerical simulations of 3 variants of model glue joint of varying thickness in aluminium foam, the following conclusions can be drawn.

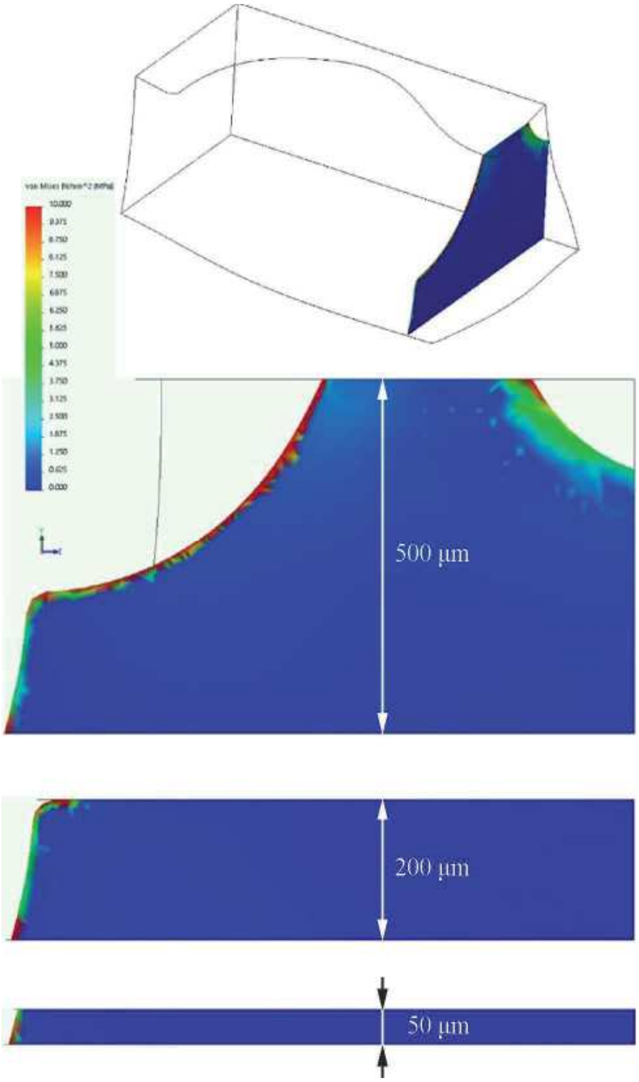

Fig. 13. Analysis of the section in which it is clear that stress values are distributed in a very uneven way

The highest state of stress in the joint, regardless of the thickness of glue layer, can be observed in the metallic foam, and the thicker the glue layer, the higher the stress.

The durability of the joint depends on the stiffness of the connection and one should strive to minimize it by applying the thinnest layer of glue in the weld possible.

A major portion of the binder applied to the flat surface of the sheet does not play any role in stress transmission, thus being redundant from the point of view of the optimization of the mass of the joint.

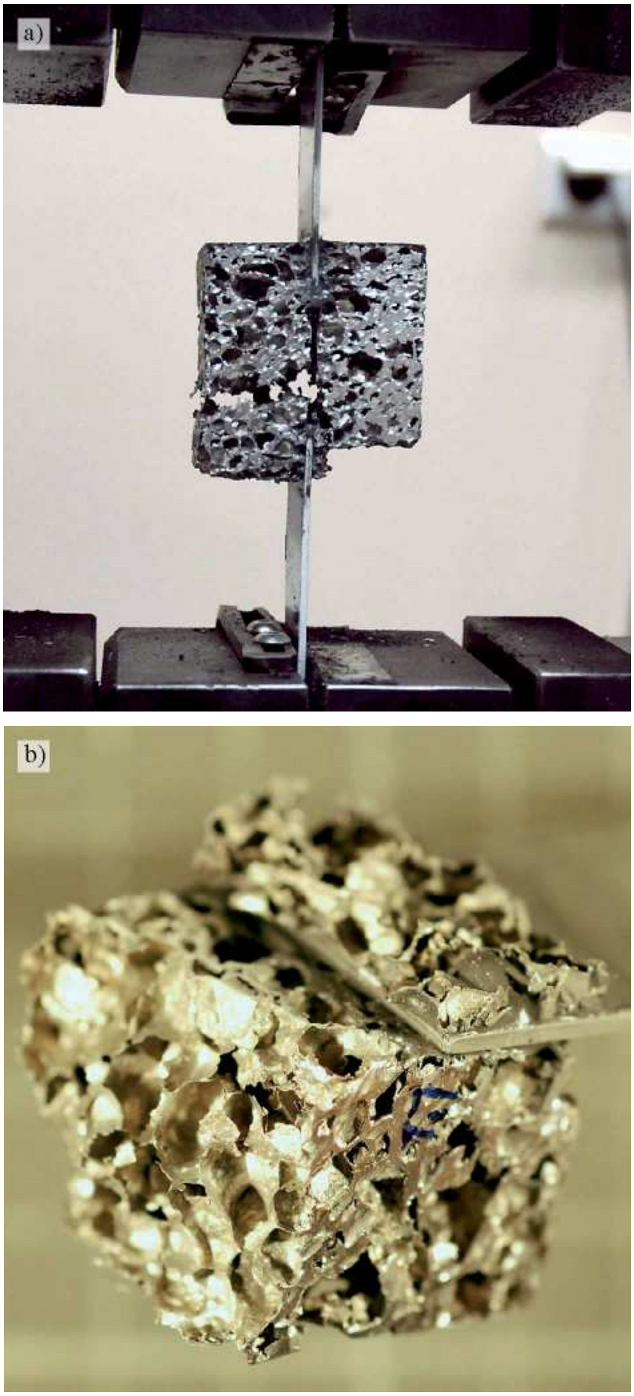

Fig. 14. Fracture that appeared in the course of verification of the calculations of glue joints strength: during tensile testing (a), macrosection of fracture (b)

Changes in gluing technology are necessary: instead of applying glue to the surface of the elements interacting with the foam, one should rather moisten the edges of the foam pores with glue. The process also involves a very careful preparation of the joint before gluing by optimizing cutting technology.

Local stress concentrations noticed in the simulations do not actually exist. The tests verifying the simulation that employed a similar range of stresses did not show any damage in the weld or loss of adhesion in the joint. The maxima observed result from the imperfection of the spatial model and compatibility of meshes of the analysed objects. It is necessary to further develop modelling technique by refining the mesh in the joint area or to do a 2D simulation based on the data obtained from tests carried out on spatial models.

References

[1] J. Lázaro, E. Solórzano, M.A. Rodríguez-Pérez, A.R. Kennedy, Effect of solidification rate on pore connectivity of aluminium foams and its consequences on mechanical properties, Materials Science and Engineering A 672 (2016) 236-246.

[2] M. Liqun, S. Zhenlun, Cellular structure control of aluminium foams during foaming process of aluminium melt, Scripta Materialia 39/11 (1998) 1523-1528.

[3] O.B. Olurin, M. Arnold, C. Körner, R.F. Singer, The investigation of morphometric parameters of aluminium foams using micro-computed tomography, Materials Science and Engineering A 328/1-2 (2002) 334-343.

[4] R. Panowicz, D. Kołodziejczyk, K. Sybilski, W. Barnat, T. Niezgoda, Numerical analysis of dynamic interaction of the pressure wave of the complex structure panel energy-intensive, Mechanical Overview 11 (2012) 40-45.

[5] M. Klasztorny, J. Małachowski, P. Dziewulski, D. Nycz, P. Gotowicki, Experimental and modeling foam aluminum alporas, Design Engineering 12/43 (2012) 97-112.

[6] F. García-Moreno, Commercial Applications of Metal Foams: Their Properties and Production, Materials 9/2 (2016) 85-89.

[7] M.F. Ashby, A. Evans, N.A. Fleck, L.J. Gibson, J.W. Hutchinson, H.N.G. Wadley, Metal foams: a design guide, Butterworth-Heinemann, Oxford, UK, ISBN 0-7506-7219-6, 2000, Hardback.

[8] S. Krajewski, J. Nowacki, Preparation of Aluminium Foam Edges For Welding, Advances in Materials Science 13/3 (2013) 64-75.

[9] M. Kawiak, J. Nowacki, Solderability of AlSi foams and AlSi+SiC composite foams and the joints properties, Advances in Materials Science 14/2 (2014) 24-36.

[10] J. Nowacki, K. Moraniec, Welding of metallic AlSi foams and AlSi-SiC composite foams, Archives of Civil and Mechanical Engineering In Press, Corrected Proof, Available online, 2015.

[11] J. Nowacki, K. Moraniec, Evaluation of Methods of Soldering AlSi and AlSi-SiC Particle Composite Al Foams, Journal of Materials Engineering and Performance 24/1 (2015) 426-443.

[12] K. Kitazono, A. Kitajima, E. Sato, J. Matsushita, K. Kuribayashi, Solid-state diffusion bonding of closed-cell aluminum foams, Materials Science and Engineering A 327/2 (2002) 128-132.

[13] A. Sajek, Aluminium foams gluing, Metallurgy and Foundry Engineering 39/2 (2013) 17-24.

[14] A. Sajek, Adhesive technology and the properties of the connector composite adhesive foam aluminium, Welding Overview 3 (2014) 55-62.

[15] S. Bartolucci, Commercial application of aluminium honeycomb and foam in load bearing tubular structures, Massachusetts Institute of Technology, 2004, thesis.

[16] S. Krajewski, J. Nowacki, Optimization of the process of cutting the composite foam AlSi-SiC, Modern Welding Technology Applications Symposium Departments and Institutes of Welding in Silesian University of Technology, Gliwice, 2014.

[17] S. Krajewski, J. Nowacki, Structure of AlSi-SiC composite foams surface formed by mechanical and thermal cutting, Applied Surface Science 327 (2015) 523-531.

[18] H. P. Degischer, B. Kriszt, Handbook of Cellular Metals, Production, Processing, Applications, CCH Verglag GmbH, 2002.

[19] G. Nianfei, F. Yanan, Y. Hanfeng W. Guilin, W. Duohua, H. Xinyi, Quasi-static axial crushing experiment study of foam-filled CFRP and aluminum alloy thin-walled structures, Composite Structures 157 (2016) 303-319.

[20] R. Matsumoto, S. Kanatani, H. Utsunomiya, Filling of surface pores of aluminum foam with polyamide by selective laser melting for improvement in mechanical properties, Journal of Materials Processing Technology 237 (2016) 402-408.

[21] L. Chengjun, Y.X. Zhang, Y. Chunhui, Numerical modelling of mechanical behaviour of aluminium

foam using a representative volume element method, International Journal of Mechanical Sciences 118 (2016) 155-165.

[22] J. Nowacki, A. Sajek, Polish Patent No. 407878, 407880, 407881 The method of bonding metal foams of aluminium, BUP no. 22, 2015.