USE OF METAL FOAMS AS AN ACTIVE ELEMENT IN THE DEFORMATION ZONES

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Abstract

The metal foams are materials with great potential for use in various fields of industry. The pores created deliberately in the structure give them many exceptional properties; one of the most important features is the ability of energy absorption. In the experimental part the castings of metal foam with a regular internal structure were manufactured by simple foundry way (infiltration of metal into the cavity of the mold is filled preform). The samples made from porous material were subsequently tested in mechanical testing. For a comparison of experimental data 3D math ideal model (model with perfectly smooth wall) was created. The initial model was calculated by using an explicit dynamics, which is primarily used in areas of extreme deformation with a small increment of time, e.g. car crash tests. The based on these results it is concluded the opinion, whether it is a convenient time to continue in the optimization of metal walls on the way of simulation or it will be necessary to continue with creating of physical models and experiments.

Keywords: Metal foam, mechanical testing, energy absorption, 3D modeling, deformation zone.

1. INTRODUCTION

Metal foams are metallic materials containing pores in their structure that are intentionally created. These materials may be formed for example of molten metal, metal powders, metal vapors or metal ions. Porosity may reach 30 % to 93 %. Depending on the manufacturing method and the material used can obtain a porous structure with different pore sizes and shapes and with different types of arrangements (regular or stochastic). Compared with polymeric foams is their rigidity higher order. They are also stable at higher temperatures, are non-combustible and fire from them does not emit toxic gases. The important fact is that they are relatively easily recyclable compared to polymers or ceramics [1, 2, 3].

2. CHARACTERISTICS AND APPLICATIONS

Among the important properties of metallic foams are low density and high rigidity along with high energy absorption capability. Thanks to these unique characteristics, the metal foams are used in many different areas of human activity - e.g. construction, automotive, aerospace, medical, etc. Absorption (damping) energy: it uses the ability of this type of material to deform under pressure and to absorb, in a relatively small volume [4, 5, 6]. This property may be used in case of traffic accident (**Fig. 1**) [7].

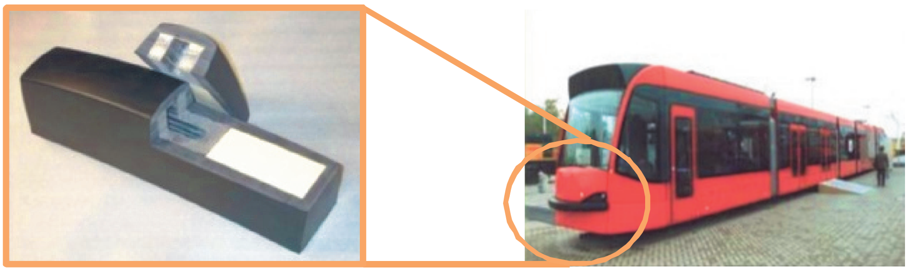

Fig. 1 Example of the use of foam in the bumper [7]

3. FOUNDRY PRODUCTION METHODS

3.1. Infiltration of the metal into the mold cavity filled with the preform

Foundry technology of production of metal foams with regular internal structure (**Fig. 2**), whose principle consists in this case on metal infiltration into the mold cavity filled with preform, has been designed and tested in laboratory, pilot plant conditions on VSB - TU Ostrava and operating conditions in Slévárna a modelárna Nové Ransko s.r.o.

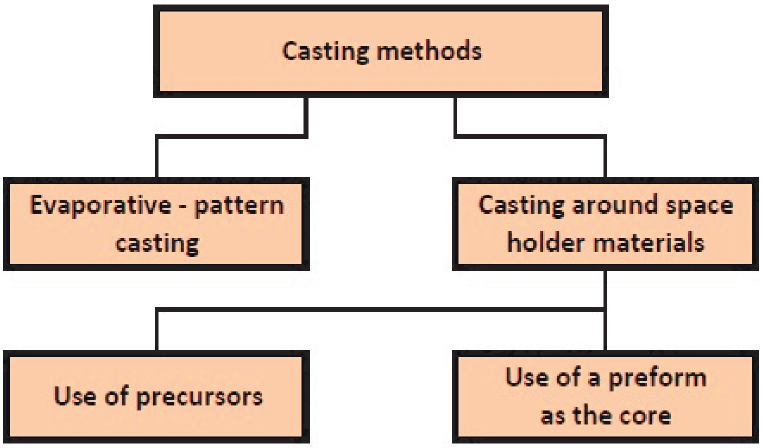

Fig. 2 Scheme of casting methods of production of metal foams

Regular arrangement of the pores may be achieved by using blanks of different shapes, which fill the mold cavity. The blank - preform - with a regular cell structure is placed in the mold cavity and casted by molten metal. In our case, cores were made with polyurethane cold box technology, which is based on a two-component binder system and constitutes a suitable method for the production and thus geometrically complex shape preforms. Gradually produced cores were subsequently assembled into one unit to form the preform (**Fig. 3**), which is the negative of regular internal cavities of the casting (metal foam). The resulting cast (**Fig. 4**) is characterized by a regular arrangement of internal cavities and a rigid surface layer. The cast material was aluminum alloy (AlSi10MgMn, CSN 424331). The porosity of such castings is 50%. From these castings samples for the pressure test were made (**Fig. 5**).

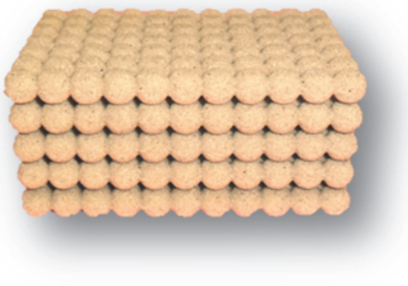

Fig. 3 Core (preform) composed of five layers of cells

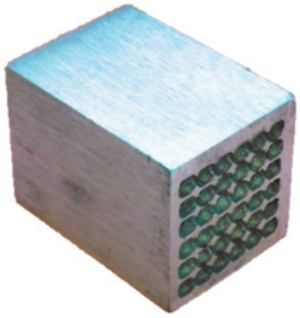

Fig. 4 Metal foam with a regular arrangement of internal cells

Fig. 5 The sample for the pressure test

4. EXPERIMENTAL

4.1. Evaluation of selected mechanical properties of real castings

For the purpose of evaluating of mechanical properties of casting (metal foams) with a regular inner structure experimental works were made. These experimental works were based on pressure tests in real castings. Pressure tests were carried out on a Zwick Z600 device (Vítkovice Testing Center, s.r.o.) at a constant crosshead displacement rate of 10 mm / min. The resulting values are listed in **Table 1**. The course of the pressure curves of the samples of material AlSi10MgMn (ČSN 42 4331) is apparent from **Fig. 6**. In this case the maximum peak value of the deformation work (2197 J) obtained in sample no. 6 (**Fig. 6**).

Table 1 Conditions pressure tests and results

Sample number	Material	Size [mm] (HxWxD)	Max. compressive force F_{max} [kN]	Max. deformation [mm]	Deformation work *W* [J]
1	AlSi10MgMn	31x47x65	69.88	27.70	1255.20
2	AlSi10MgMn	32x47x65	87.48	31.20	1939.90
3	AlSi10MgMn	31x47x65	82.70	33.80	2115.10
4	AlSi10MgMn	30x47x66	59.76	28.50	1116.20
5	AlSi10MgMn	31x48x64	86.56	26.20	1686.70
6	AlSi10MgMn	31x48x65	87.09	36.50	2197.00

4.2. Pressure test and calculation of deformation work

To verify the ability of the metal foam to absorb energy the deformation test (pressure test) was made. The ability of a material to absorb energy can be determined by evaluating the curve of stress - strain. Depiction of such a curve is on (**Fig. 7**) on the left. On the curve we can indicate three sections: the first corresponds to the linear elastic deformation of the sample, at the end of this section; the tip may be occurred. The second section shows the deformation at a constant strain and the third one extends a sharp increase of strain due to hardening of the material by deformation. There are the following requirements for materials intended to absorb impact energy: the first peak on the graph should be as low as possible and the section no. 2 should be long and preferably without fluctuations. The energy absorbed by a unit volume of the material corresponds to the area under the curve of the stress - strain (**Fig. 7**, right) [8, 9]. The calculation procedure was chosen according to the authors of the article [10].

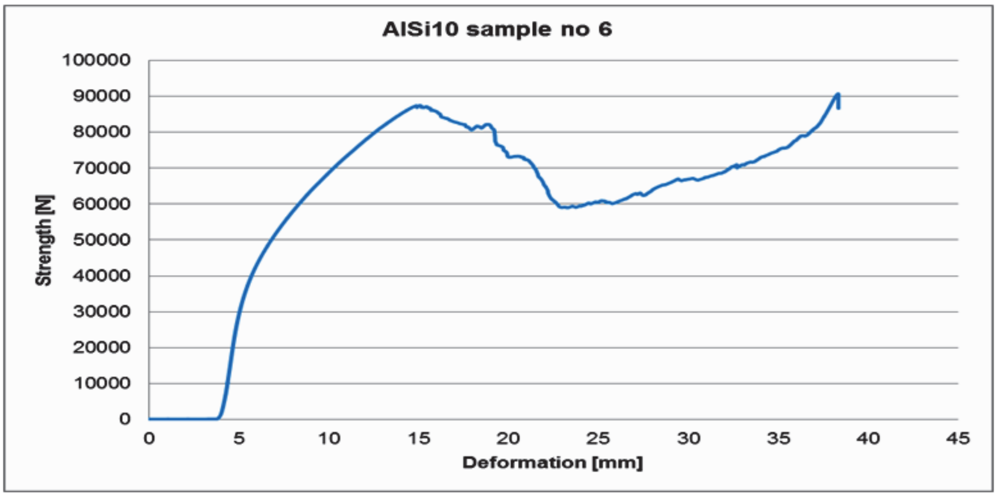

Fig. 6 The course of the pressure curve material AlSi10, deformation work 2197 J

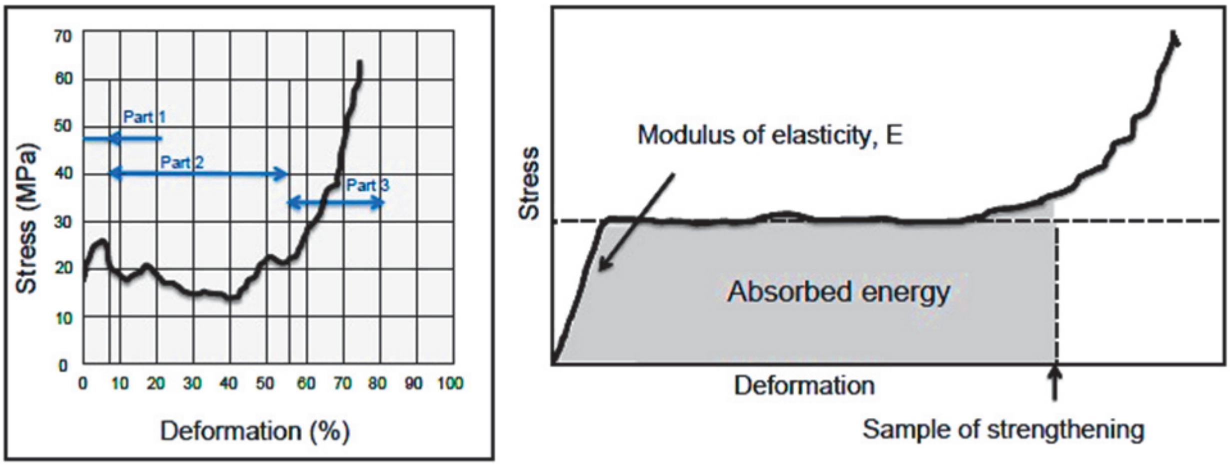

Fig. 7 The curve of stress - strain in the pressure tests [8, 9].

4.3. Evaluation of selected mechanical properties of a mathematical model

4.3.1. Generation of a 3D model

Mathematical model was created by the Design Modeler modulus of the program environment Ansys 14.5. For convenient and quick creation of the 3D model, perfect spheres with a diameter of 10 mm were used.

Explicit dynamics is a powerful tool where the solution fails in the fields of non-linearities. However, these positives are being undermined by long calculation times and demanding on a computer hardware. Therefore, for a start ball with absolutely perfect shape was chosen including an absolutely smooth surface. Three-dimensional mesh of balls was created by array and an inverse volume was drafted for a final researched model, **Fig. 8**.

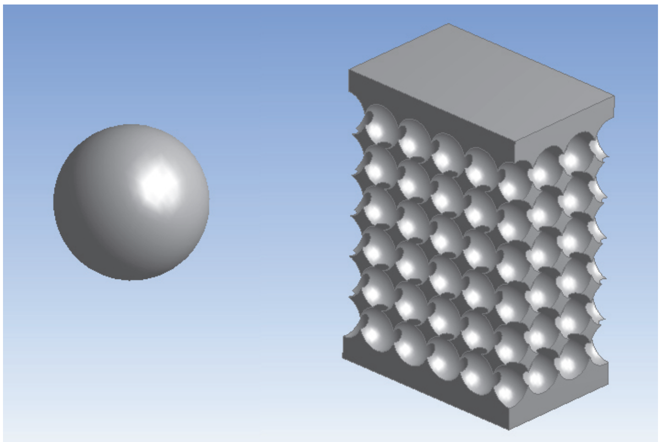

Fig. 8 Model of the steel foam

Material properties for classical aluminum were used from the program database Ansys 14.5. Model is determined by bilinear isotropic description, **Fig. 9**. Other material parameters are given in **Table 2**.

Table 2 Material properties of classical aluminum

Density [kg/m^3]	Young´s modulus [MPa]	Poisson´s constant [-]	Yield stress [MPa]	Tangent modulus [MPa]
2770	71000	0.33	280	500

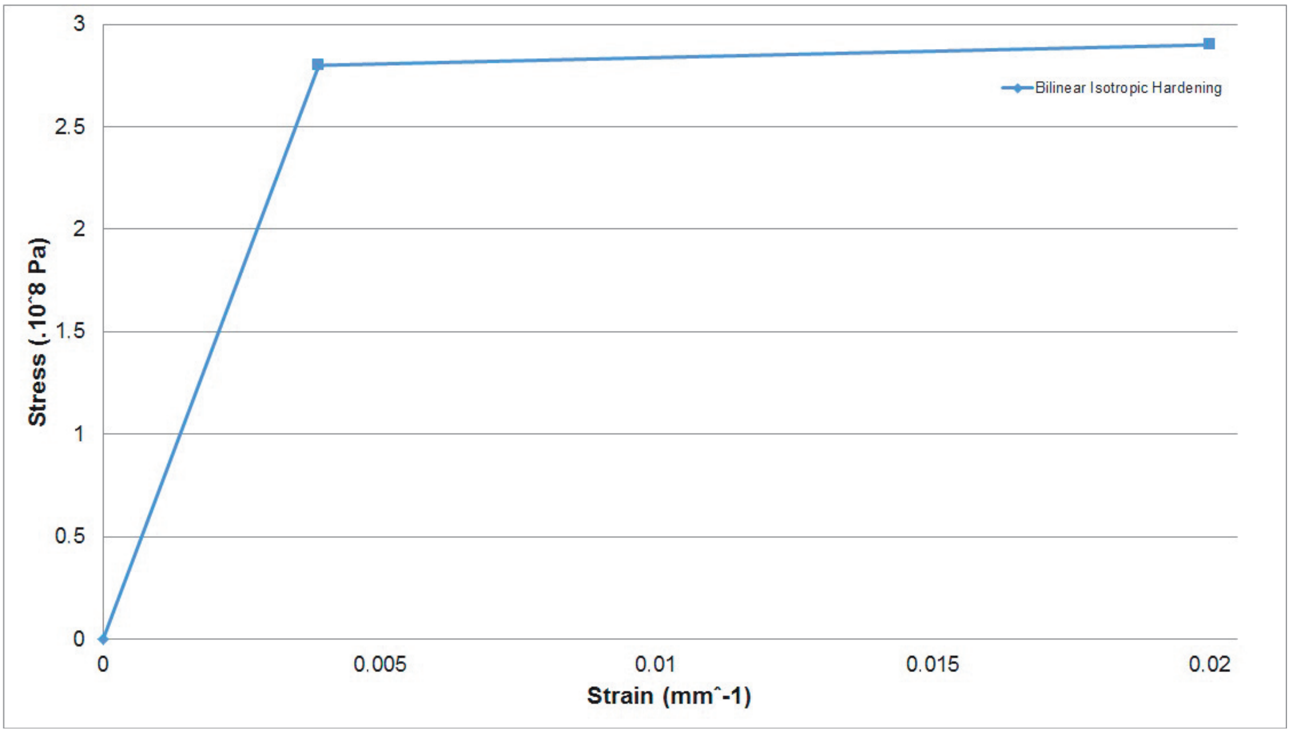

Fig. 9 Bilinear isotropic description of classical aluminum

4.3.2. Boundary Conditions

The model was meshed by using tetrahedr´s elements only. The total number of nodes was approx. 35000 and approx. 147000 elements, **Fig. 10**.

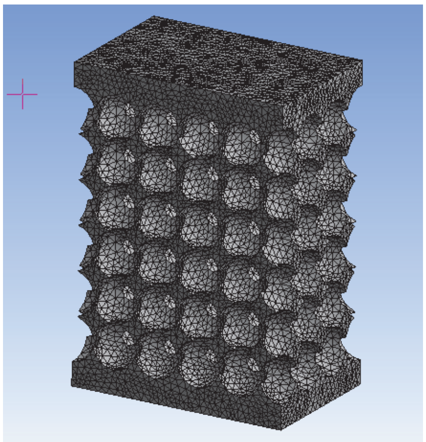

Fig. 10 Mesh

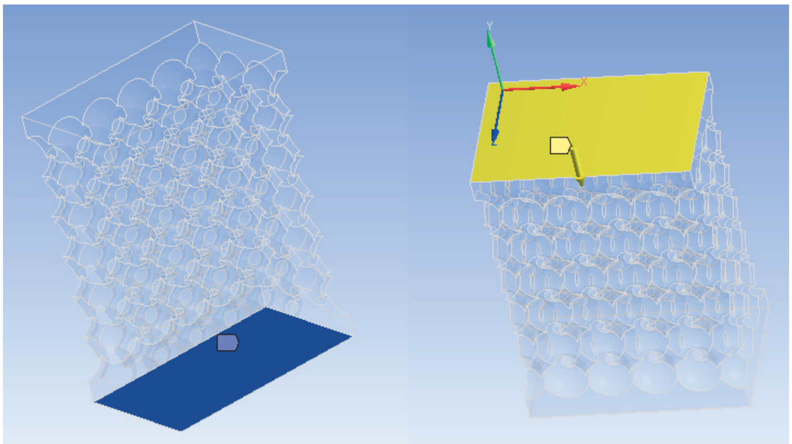

Fig. 11 Boundary conditions

Boundary condition of perfect restraint was chosen on the base model. The experimental model was compressed at a rate 10 mm / min, and therefore boundary condition displacement was chosen instead. However, after the experiences of a previous analyzes was chosen equivalent to 40 mm displacement condition for 4 seconds. Generally displacement boundary conditions have a good influence on a convergence calculation. **Fig. 11** shows on a left side the boundary condition of perfect restrained and on the right side the displacement.

The calculation was set at 4 seconds total time. The initial time step was elected $1 \cdot 10^{-5}$ s. The maximum and minimum time step was chosen automatically by the program. The energy error was originally set to 0.1.

5. RESULTS

Time-step of a calculation was selected by the program $1.7 \cdot 10^{-8}$ s. Thus the results are interpreted in the time at $2 \cdot 10^{-3}$ s, or after 24 hours of counting on an ordinary PC. If the computing time values would be extrapolated, we would get the total calculation takes about 80 days. The calculation was terminated prematurely. **Fig. 12** shows the results HMH equivalent stress and displacement.

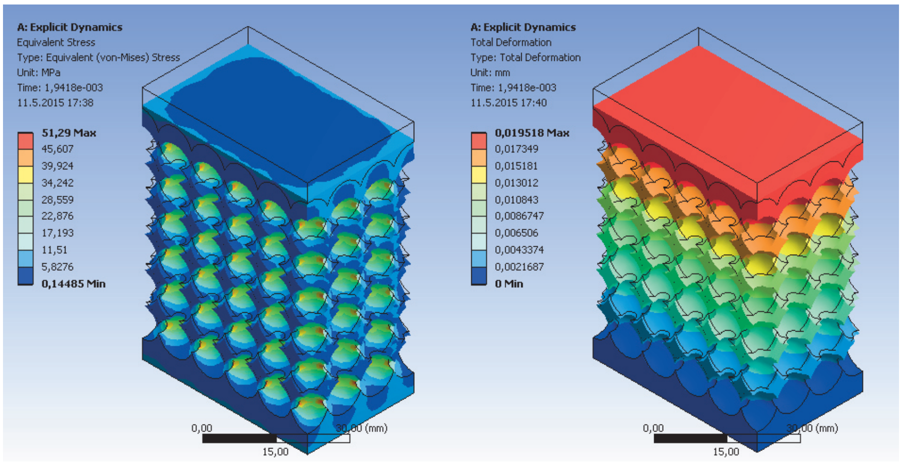

Fig. 12 Results of the HMH equivalent stress (left side) and the total displacement (right side)

Energy conservation is a measure of the quality of an explicit dynamic simulation. Bad energy conservation usually implies a less than optimal model definition. This parameter allows you to automatically stop the solution if the energy conservation becomes poor. Enter a fraction of the total system energy at the reference cycle at which you want the simulation to stop. For example, the default value of 0.1 will cause the simulation to stop if the energy error exceeds 10% of the energy at the reference cycle.

Reference Energy Cycle is the cycle at which you want the solver to calculate the reference energy, against which it will calculate the energy error. Usually this will be the start cycle (cycle = 0)

When performing an explicit dynamics analysis with reduced integration elements, it is always important to determine whether hourglassing effects have significantly degraded the results. As a general guideline, the hourglassing energy should not exceed 10% of the internal energy. Hourglass energy is dependent on the deformation of the mesh during a calculation.

The global energy is accounted as follows:

Reference Energy = [Internal Energy + Kinetic Energy + Hourglass Energy] at the reference cycle

Current Energy = [Internal Energy + Kinetic Energy + Hourglass Energy] at the current cycle

Work Done = Work done by constraints + Work done by loads + Work done by body forces + Energy removed from system by element erosion + Work done by contact penalty forces

Energy error = (|Current Energy - Reference Energy - Work Done|) / (max (|Current Energy|, |Reference Energy|, |Kinetic Energy|)

The Total Energy is ideally must be equal to the Work Done, then Error Energy shall be zero.

Fig. 13 shows the curve of the total energy (violet), the work done (green), energy error (red) and reference energy (blue). The total energy overlaps with the work done. At time $2 \cdot 10^{-3}$ s value of the work done is 83 mJ.

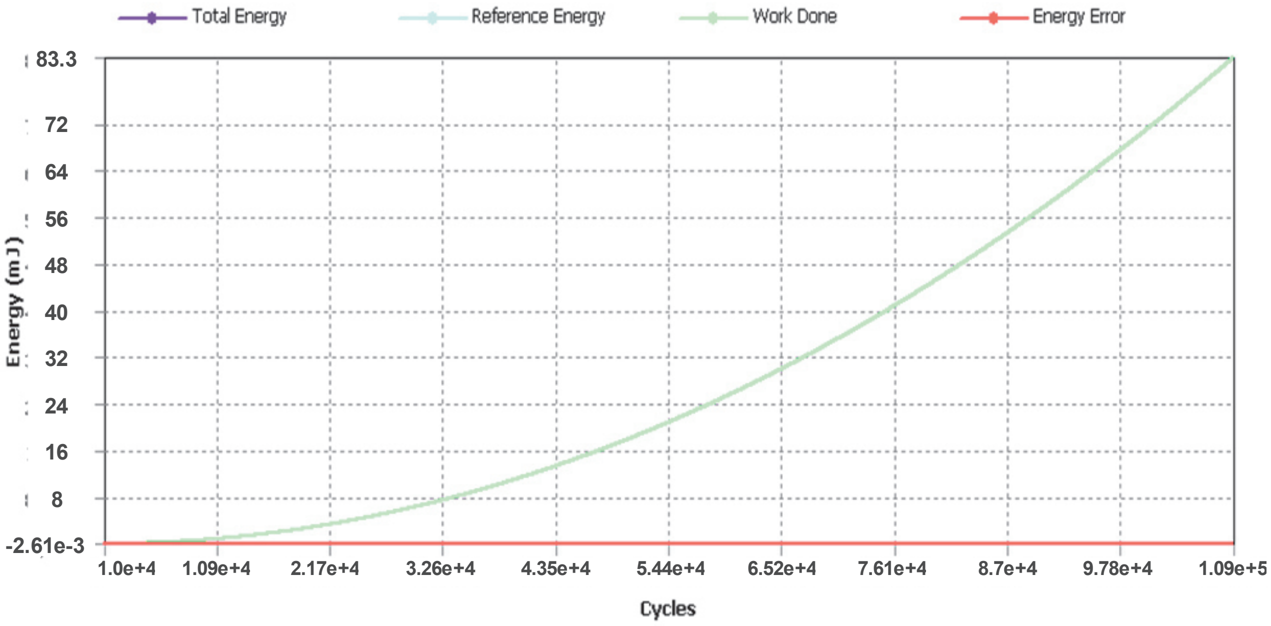

Fig. 13 Energy conservation

6. CONCLUSION

Six castings (metal foams) of aluminum alloy AlSi10MgMn (CSN 42 4331) with a regular arrangement of internal voids spherical shape were made. These castings (resp. Samples from them) were tested on mechanical properties. One of the important properties of this material is the ability to absorb energy, which can be evaluated on the basis of the course of the stress - strain curve. For these reasons, the pressure tests were conducted on the prepared samples. The maximal value of energy absorption was 2197 J, which can be defined as the maximum deformation work.

A mathematical model was calculated using explicit dynamics, which is suitable for extreme deformation with a small increment of time, such as crash tests. The final value has not yet been achieved due to high demands on hardware and associated high time demands.

If we compare the computational time and the time needed to produce an experimental model, we find that it still pays to measure an experiment casts. If we used a super computer to solve these computationally intensive tasks, we would be able to choose the option mathematical and thus monetary less demanding.

ACKNOWLEDGEMENTS

This article has been elaborated in the framework of the IT4 Innovations Centre of Excellence project, reg. no. CZ.1.05/1.1.00/02.0070 supported by Operational Programme 'Research and Development for Innovations' funded by Structural Funds of the European Union and the state budget of the Czech Republic and with the support of specific research projects, VSB - TUO SP2015/78 a SP2015/70.

REFERENCES

[1] GAWRONOVÁ M. Cast cellular metals with regular structure. Diploma Thesis, Ostrava (VSB-TUO, FMME), 2013.

[2] SCHMITT Y., PIERROT J.-L., ARBAOUT J., ROYER F.-X. Mechanical properties of a cellular composite: comparison with other structures. Archives of Metallurgy and Materials, Vol. 50, Issue 1, 2005, pp. 111-117.

[3] KORDZIKOWSKI P., JANUS-MICHALSKA M., PECHERSKI R.B. Specification of energy-based criterion of elastic limit states for cellular materials. Archives of Metallurgy and Materials, Vol. 50, Issue 3, 2005, pp. 621-634.

[4] BEDNÁŘOVÁ V., LICHÝ P., HANUS A., ELBEL T. Characterization of cellular metallic materials manufactured by casting methods. In: 21st International Conference on Metallurgy and Materials Metal 2012, May 23rd - 25th 2012, Brno, Czech Republic. Brno: Tanger Ltd., Ostrava, 2012, pp. 1209-1214. ISBN 978-80-87294-31-4.

[5] NOWAK M., NOWAK Z., PECHIERSKI R.B., POTOCZEK M., ŚLIWA R.E. On the reconstruction method of ceramic foam structures and the methodology of young modulus determination. Archives of Metallurgy and Materials, Vol. 58, Issue 4, 2013, pp. 1219-1222.

[6] LICHÝ P., BEŇO J., CAGALA M. Thermophysical and thermomechanical properties of selected alloys based on magnesium. Metalurgija, Vol. 52, No. 4, 2013, pp. 473-476.

[7] BANHART J. Metallic Foams II: properties and application [online]. [cit. 2013-04-22].
< http://materialsknowledge.org/docs/Banhart-talk2.pdf>

[8] Technical manual for CYMAT: Smart Metal [online]. Cymat Corp., Canada, 2009. [cit. 2010-07-05]. URL: <http://cymat.com>.

[9] GAILLARD Y., et al. CTIF's aluminium foams made by foundry processes. Fonderie - Fondeur d´aujourd´hui, No. 250, 2005, pp. 13-24.

[10] RADKOVSKÝ F., BEDNÁŘOVÁ V., LICHÝ P., ELBEL T., KROUPOVÁ I. Metallurgy for evaluation of metallic foams. In: 23rd International Conference on Metallurgy and Materials Metal 2015, Jun 3rd - 5th 2015.