Journal of Achievements in Materials and Manufacturing Engineering
VOLUME 54
ISSUE 2
October
2012

The skeleton castings as a new type of cast lattice structures

M. Cholewa, T. Szuter*, T. Wróbel, M. Kondracki
The Foundry Department, Silesian University of Technology,
ul. Towarowa 7, 44-100 Gliwice, Poland
* Corresponding e-mail address: tomasz.szuter@polsl.pl

Received 13.08.2012; published in revised form 01.10.2012

Manufacturing and processing

ABSTRACT

Purpose: of this paper is to present selected achievements in field of new type material - skeleton structures. Actual state of knowledge about periodic cellular materials was described. The aim of this work is to show results about mechanically optimised skeleton casting with octahedron topology. Correctness of technological parameters was investigated by microstructural research. Most important parameters of the manufacturing process were identified.

Design/methodology/approach: The influence of technological parameters to the microstructure in different points of casting was described. Simulations of the mould filling processes were also carried out. Real experiments were performed to prove the simulation results. The qualitative and quantitative metallographic analysis was also carried out.

Findings: It was found that the octahedron shape of internal cell causes best stress distribution and that the skeleton castings are a good alternative for cellular materials such as metal foams, lattice structures or sandwich panels.

Research limitations/implications: Casting methods used to manufacture materials such as described skeleton castings confirmed their usefulness. Not well known and used yet rheological properties of liquid metals allow obtaining shape complicated structures near to metallic foams but with periodic structure.

Practical implications: Technological parameters of the skeleton castings manufacturing process were developed. Without use of advanced techniques there is a possibility to manufacture relatively low cost skeleton structures in a typical foundry.

Originality/value: Three dimensional cast skeleton structures with internal topology of octahedron confirmed their usefulness as elements used for energy dissipation. Obtaining the homogenous microstructure in the whole volume of complicated shape castings can be achieved.

Keywords: Skeleton casting; Metallic alloy; Porous materials; Aluminium casting; Simulation purpose

Reference to this paper should be given in the following way:
M. Cholewa, T. Szuter, T. Wróbel, M. Kondracki, The skeleton castings as a new type of cast lattice structures, Journal of Achievements in Materials and Manufacturing Engineering 54/2 (2012) 250-259.

1. Introduction

Novel structural materials are expected to beyond its basic use also multifunctionality. From economics and ecology point of view they should allow to lower the weight of the constructions. This makes possible to save resources and sometimes energy used in manufacturing processes. Lower weight in aerospace and automotive industry also connects with lower energy consumption. Most challenging while designing lightweight material is to achieve good proportion between strength/stiffness and weight. One of the solutions is periodic cellular metals. [1-9] (Terms like macrostructure, internal geometry, and topology have similar meaning and are used alternately.) Classification of the cellular materials with highly ordered structure is based on the end-use application, internal topology or manufacturing techniques. One of the groups of periodic non-monolithic materials is sandwich structures. Elementary cells can be opened or closed. The question it seems to be import is: Where is the line between terms material and semiproduct or product – maybe it should be said cellular construction (CC)?

Classification based on the cell dimensions resulting from crystalline structure of alloys seems to be reasonable. It is proposed that to the cellular structures of cell size comparable to the dimensions of the primary crystals adopt "cellular material" term. However, in the case of the cellular structures with larger dimensions (measured in millimetres) to accept the term "cellular structure" (CS). The examples of mainly used topologies of sandwich structures are shown in Figure 1 [3].

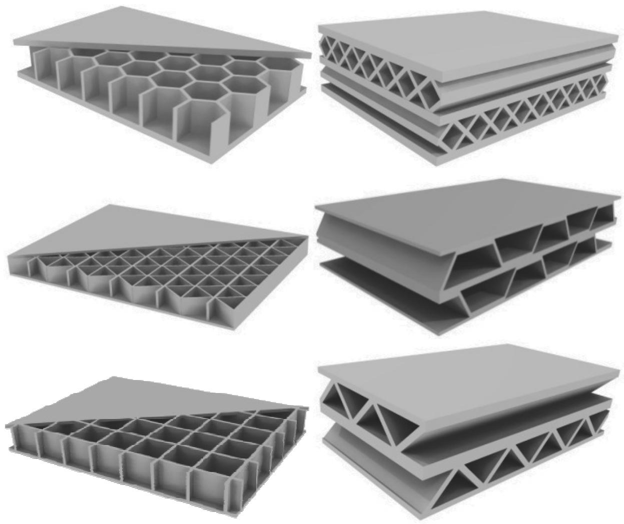

Fig. 1. Periodic cellular metal sandwich structures

The core of such material is build from cells arranged symmetrically in two dimensions between two outside walls. The material is similar to a honeycomb. The shape of the cells can be differentiated (triangular, square, hexagonal, etc.). If the core is rotated by 90° along the horizontal axis it is possible to achieve additional functionality, such as flow of the liquid inside the panel [2, 10-14]. These materials exhibit high stiffness and compact design, low susceptibility to buckling and good kinetic energy absorption [5, 15-17].

Figure 2 shows examples of topology of cellular materials used in the manufacture of sandwich panels from aluminium alloys, steel or carbon composites. These structures are also called micro-truss structures [18-20]. These are considered as the most competitive in comparison to metallic foams.

Technologies of cellular materials are largely based on plastic forming and bonding methods. The panels are made from sheets and rods. This technology is suitable almost exclusively for materials with a high degree of plasticity [21, 23].

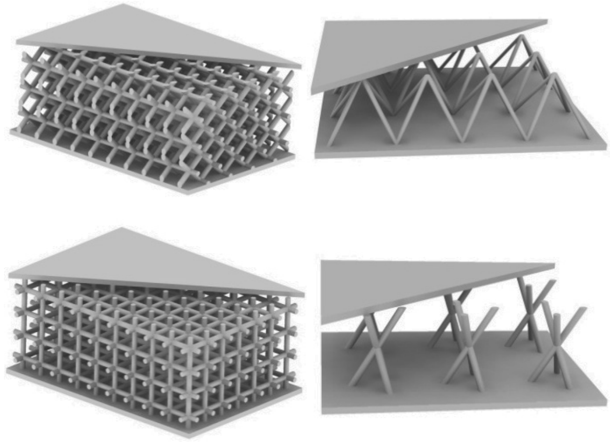

Fig. 2. Sandwich type periodic lattice cellular metals

For panels with a low relative density (a small wall thickness) to avoid destruction of connections or decohesion of the material during processing particularly important is an appropriate bonding of individual sheets. Good results can be achieved by using modern adhesive methods, laser welding or diffusion bonding [5, 22]. Those technologies are complicated and applicable only under certain wall thickness. Too thin walls hinder the appropriate joining of individual sheets. Too thick walls necessitate the use of large forces during joining.

The authors [15, 24] propose the cellular materials manufacturing technique using special gauges. The panels are made layer by layer from rods or hollow tubes. It should be noted that there is a limited number of topologies that can be manufactured. Any change in the geometry of the core needs new equipment. In addition, critical points of such structures are the nodes. The contact areas between individual rods are highly limited. At small diameters of the rods the connection may not provide adequate strength.

Truss-type structures, which "the skeleton castings" are similar to, are characterized by a different approach. Production of components with complex shapes qualifies casting methods as the most suitable for this application. The possibilities of using particularly advantageous rheological properties of liquid alloys allow to produce castings of almost any shape and in a wide range of characteristic dimensions. It is worth mentioning that the rheological properties of liquid alloys allow to get casting wall thickness of 0.5 mm by conventional gravity casting methods. One limitation is the dimensional accuracy resulting from the use of common mould materials and lack of normative regulations in the design of similar technologies. Even in the precise techniques of moulding and casting there is a need for appropriate adaptation.

In summary, "skeleton castings" can be fully open or closed, continuous cellular structures that are created with slender beams of any cross-section of which can be created blocks of any shape, even without the closing walls.

2. Potential applications of cast cellular structure (CCS)

The skeleton casting with rather any dimensions of internal cells (from one millimetre upwards – Figure 3) are still classified as the porous materials, as well as construction materials group or so called "structures". Porous materials with an ordered structure through the development of relatively simple manufacturing methods are becoming more popular. Thanks to the high ratio of strength to weight are more widely used. From the architectural works of Antonio Gaudi – as thermal insulation, the construction materials in the ships building to the micro-scaffold in tissue engineering [17].

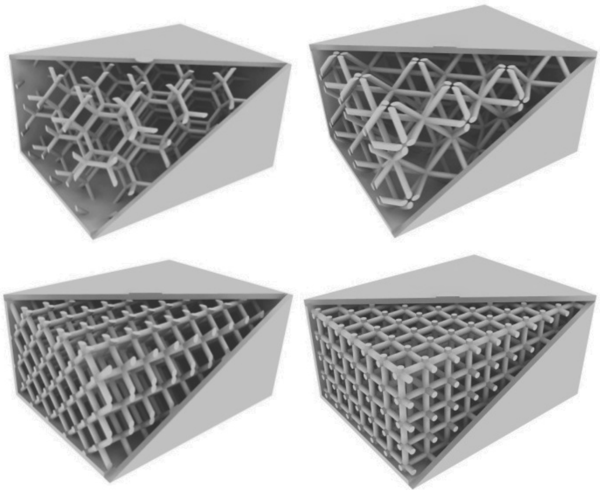

Fig. 3. Example of topologies of skeleton castings designed in Foundry Department of Silesian University of Technology

The usefulness of cellular materials for specific applications depends on many factors. They can be divided into four basic groups [25]:

- *Morphology* – the type of internal structure (open or closed, the elementary cell size, their shape, relative density);
- *Metallurgy* – the type used metal, alloy or composite;
- *Manufacturing* – available methods of manufacturing products with the assumed properties;
- *Economical* – the cost and profitability.

Metallic porous materials are applied in the automotive industry. The increase of the safety level of transportation, in many cases leads to an increase of weight. Most of the automotive companies are increasing emphasis on the environmental friendly of their products. Therefore it is important to reduce the weight, and to lower demand for raw materials and fuel consumption. Compact design in automotive is becoming more and more popular. It creates the heat dissipation problem and make impossible to use of standard vibrations and noise damping materials. Porous materials allow to some extent to eliminate these problems. For example, cellular aluminium can be used as construction material, which also acts as an absorber of the kinetic energy in controlled deformation zones. Used as components of the engine lowers the weight and improve heat dissipation. Daimler Chrysler tested the car floor panel made of aluminium foam with a density of 0.6 g/cm^3. The panel showed a similar stiffness to the panel made by pressure casting from magnesium alloy with similar weight. Independent co-designer of Porsche 911 convertible and Ford Escort RS Cosworth where the combination of rigidity with low weight is crucial tested the spatial cell panels. The use of panels as front and back bulkhead allows reducing weight by 25% and a seven time increase in stiffness of the bodyshell [11, 25].

Kinetic energy absorbing materials are using the phenomenon of plastic or brittle irreversible deformation [27]. Most of the cellular materials are characterized by deformation at almost constant stress [28]. What is characteristic to metallic cellular materials is a small, approximately 3% rebound in the case of dynamic deformation [11]. This is a desirable feature especially while using such materials on the impact energy absorbers. To design the optimal material for various types of collisions material should meet several basic criteria [13]:

- The energy absorption characteristics close to the ideal, with a large deformation at constant stress.
- High absorption capacity per volume, length or weight unit.
- The possibility of changing the nature of energy absorption from the isotropic, through gradient, to the fully anisotropic - due to the inability of prediction the direction of impact, the material has to absorb energy in all directions.

The cellular materials proved their usefulness in impact or explosion energy damping [16, 17, 29]. They show much higher strength compared to similar weight monolithic materials. Internal topology and relative density are key factors influencing on the properties of periodic cellular materials. In the first stage of deformation the mechanism of destruction of the internal structures determines the amount of kinetic energy absorption.

Application examples of periodic cellular metals as part of impact energy absorbing panels are deforming barriers used in automotive crash tests. Their ordered structure allows to create a precise numerical model to proceed the simulations. The flexibility of adaptation of mechanical properties allows using them to tests at different speeds.

Another problem that metallic cellular materials are favourable to is common in the automotive problem of vibration and noise. The most common solution today is the cellular polymeric materials. Due to the fact that these elements often have to be high temperature resistant and high strength it seems reasonable to use for this purpose metallic cellular materials. Such material made for example from aluminium alloy besides damping function is resistant to heat and can act as construction-radiation component. Many features of the cellular aluminium materials allow to reduce noise and vibrations.

Young's modulus of cellular metals is lower than that of monolithic elements made from the same raw material. The resonance frequency is moved in the lower ranges. In addition, the damping factor of cellular materials is generally about 10 times higher. Thanks to use of cellular materials for structural elements of machine and vehicle vibrations are dampened more effectively.

In addition, open pores of cellular materials with a periodic geometry allow to reuse internal free space. For example, in cars with hybrid drive free space can be filled with an energy carrier and thus do not take up passenger's space. In the case application of periodic cast materials, for example, skeleton castings, thanks to their multifunctionality and benefits like easy to implement technology can increase profitability, while maintaining favourable thermal, acoustic and mechanical properties.

Automotive is not the only industry which can use the undoubted benefits of cellular metals. From the structural point of view low weight in aerospace applications is a key factor for use of modern, metal porous materials. Therefore, metal foams are very popular in this sector. A current example of application cellular material is the use of cellular honeycomb panels in a helicopter in order to minimize the consequences free fall from limited height. The tests were carried out involving the throwing machine from 10 m of height. The use of porous material minimized the damage the helicopter. The hull of the machine remained intact [30].

The use of cellular materials in rail vehicles, in principle, subject to the same rules as for the automotive industry. Some trains are equipped with bumpers made of aluminium foam in order to improve safety during impact [5, 7, 11]. It seems reasonable to use materials with a periodic and spatial structure. Skeleton castings can be cast as one element in almost any shape. Their symmetry in three planes allows to modular construction and their use in the more geometrically complicated solutions as a set of several components.

In architecture, cellular metals serve as supporting and decorative structures. Their esthetical qualities are generally very appreciated. Architects often use unusual materials in order to emphasize the aesthetic qualities of their projects. The materials used, for building facades must be resistant to weather conditions, respectively rigid and, above all, comply with the fire fighting regulations. Cellular material could be useful in design of high-speed elevators. Large g-forces created under high acceleration and deceleration enforce the use of cellular materials, which, are construction materials, the kinetic energy absorbers and vibrations dampers as the same time. In addition, skeleton castings with relatively low specific density, also offer the possibility of their fulfilment with for example ceramic material, characterized by low thermal conductivity. While maintaining high strength can act as walls, bearing supports and fireproofing barriers in buildings. Cellular aluminium materials, despite the relatively low melting point are surprisingly resistant in contact with open flame because of strong oxidation in such conditions [19] and the relatively large heat of fusion – for the pure element – 398 kJ/kg. For comparison, heat of fusion for iron is 268 kJ/kg.

3. Description of the research

The aim of work is to present selected results of research on aluminium skeleton castings as a new type of spatial lattice material which are within group of CCS – cast cellular structure.

The key importance of this technology is the core manufacturing techniques. It assumes the use of production possibilities for a typical, small foundry, without the use of laboratory equipment and high precision technology. Important was the high symmetrical accuracy of cores and castings as well. On the one hand due to the isotropy of mechanical properties and, second, the use of modular design and flexibility to match the overall dimensions to the application needs. Another aspect that should be taken into consideration was the degree of complexity. Also important was the relative density defined as the volume occupied by the metal in the volume of the whole element

Table 1.
Selected physical parameters of skeleton casting with octahedron elementary cell

Weight	2.07 [kg]
Volume of block	3000 [cm^3]
Volume occupied by metal	762.6 [cm^3]
Volume without walls	176.6 [cm^3]
Relative density	25.42 [%]
Relative density without walls	6.57 [%]

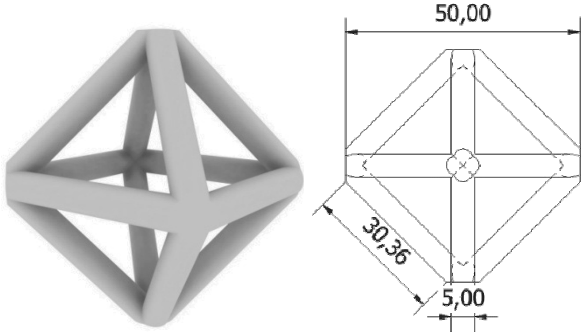

Fig. 4. Example of elementary cell in the form of an octahedron

The maximum allowable relative density was set to 30%. Geometrical parameters of the internal topology of the casting strictly influence on its mechanical properties. While selecting the optimal topology, the aim criterion was mechanical bonding maximum number of skeleton structural elements in order to maximize stresses dissipation in the volume of the casting. This is particularly important requirement in terms of use of the skeleton castings as impact or explosion energy- absorbers elements. Most of assumptions are met by skeleton casting with octahedron elementary cell. In addition, the choice was confirmed by the results of stress distribution simulations presented in the literature [1, 31]. Physical parameters characterizing the model are shown in Table 1. Model of a single cell is shown in Figure 4.

3.1. Mould filling simulation

To develop the optimum technological parameters the simulations of mould cavity filling by aluminium alloy were carried out. Simulations were carried out in the Nova Flow & Solid environment. The model of skeleton casting was completed with the feeding system and then imported into STL file to the Nova Flow & Solid. During the simulation location of the shrinkage in the liquid-solid state was analysed. The share of liquid phase while mould cavity filling was analysed. Figure 5 shows distribution of metal temperature while pouring process respectively for 20, 40 and 80% of metal in mould cavity (axial cross-section). Assumed speed of pouring (0.5 kg/s – time of pouring about 6.6 s) allowed for undisturbed flow of liquid metal and complete filling of mould cavity.

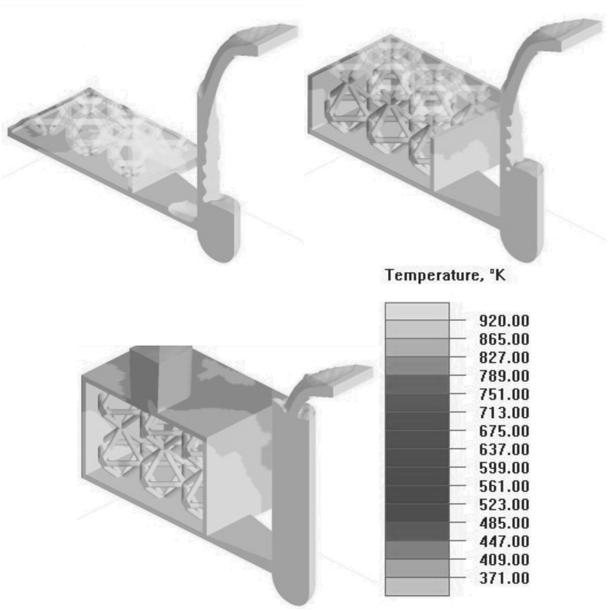

Fig. 5. Liquid metal temperature distribution while pouring (axial cross-section)

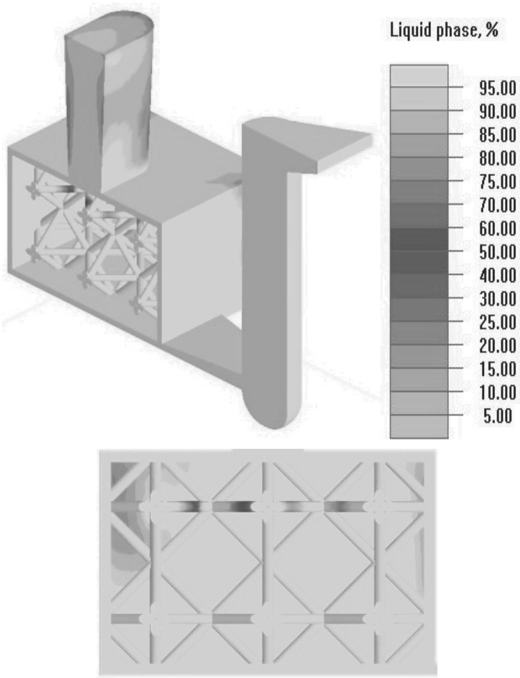

Fig. 6. Liquid phase distribution after filling (cross-axial section)

This allows for good filling of all the ligaments. With increasing the speed of pouring, the turbulent flow of metal appeared and as a consequence the reflection of liquid metal and rapid increase of liquid level in the opposite to the feeding system side of the form appeared. Simulations results showed that with the assumed parameters mould cavity is completely filled.

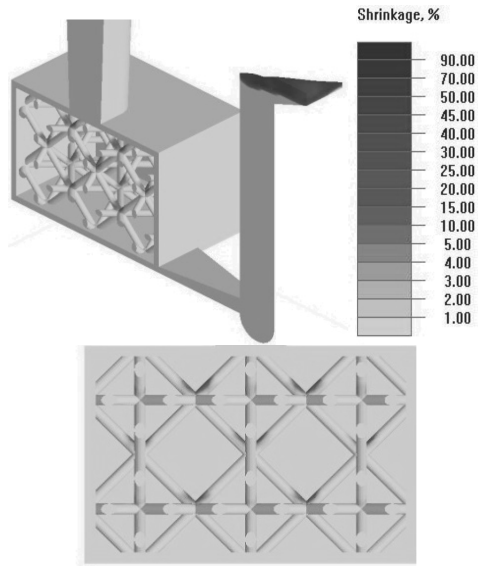

Fig. 7. Areas of possible shrinkage porosities

According to Figure 6 solidification of the casting starts at the corners of closing walls and ligaments arranged in a horizontal plane. It was observed as supposed possible occurrence of shrinkage porosity located near the geometric nodes of skeleton casting, which are also hot spots (Figure 7). In each of the observed areas of possible porosity reaches an average of 8%. This means that in a given volume 92% is occupied by the metal and the remaining 8% is empty. It can not be told if it occurs in the form of shrinkage cavity or dispersed microporosity in the entire volume of the indicated area. The use of a ceramic core with a low thermal conductivity improves the filling conditions and allows to achieve required quality of the casting.

3.2. Microstructure investigation

Skeleton casting macrostructure can be formed in rather everyway way by selecting the proper techniques of the core manufacturing. An important factor that puts the casting technique over other methods of producing cellular materials is the possibility of selection of mechanical properties through the influencing of the microstructure of the alloy [32]. The influence on microstructure of skeleton casting can be achieved through the selection of thermal properties, especially thermal conductivity of mould and core materials [33]. The application of high insulating materials ensure correct fill if the mould cavity and a uniform microstructure in the entire volume of the skeleton casting.

Selection of technological parameters of the casting process is equally important. In addition, metallurgical operations such as refining or modification play an important role in the production of geometrically complex skeleton castings.

The study was conducted to investigate the correctness of the choice of mould material thermal properties, thus different thermal conditions and their effect on crystallization conditions and the microstructure of the casting.

Three skeleton castings with octahedron elementary cell were chosen. Castings were made of near-eutectic AlSi11 alloy. The quartz sand with bentonite moulds were used. At the core porous corundum brick was used.

For the microstructure analysis 5 key areas of skeleton castings were selected. Those areas are schematically presented in Figure 8. Outside closing walls was intentionally removed in purpose to show internal topology of skeleton casting. There were three photos taken of each area in each casting. Quantitative analysis of presented micrographs was carried out with use of computer image analysis system – NIS-Elements by Nikon. The distribution of average number of silicon crystals in each class of size, and averaged stereological parameters of silicon crystals in particular regions of skeleton castings were determined.

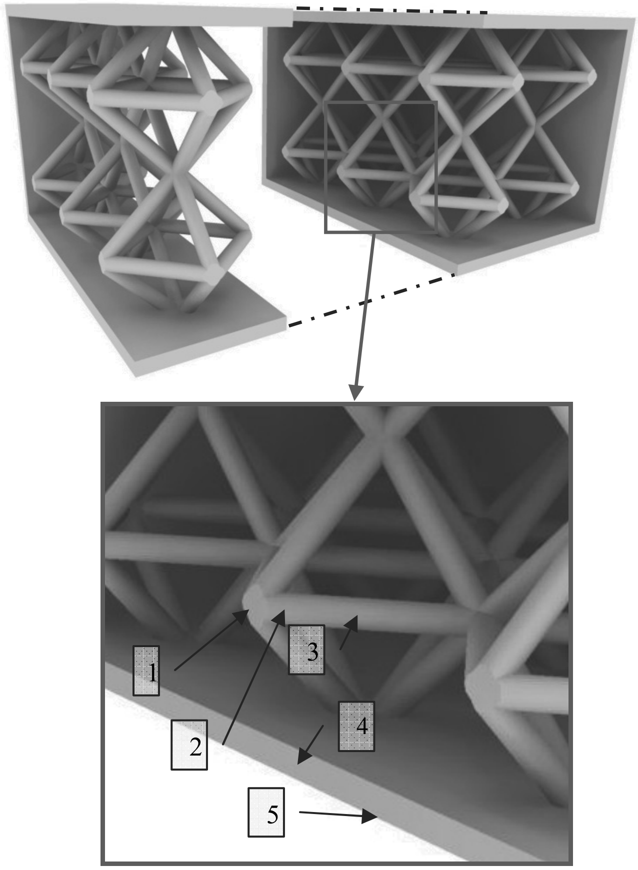

Fig. 8. Specified regions of microstructure investigation; 1 – node; 2 – near node cross-section; 3 – cross-section between the nodes; 4 – cross-section of closing wall; 5 – outside surface of closing wall

Selected micrographs representing particular regions of skeleton casting (according to Figure 8) are show in Figure 9. Additionally it should be noticed that the geometrical nodes of skeleton castings are hot spots, so those areas are especially vulnerable to the shrinkage porosity. The simulation carried out with taking into account thermal parameters of classical moulding materials predicted the presence of porosity near the nodes of skeleton casting. In real castings thanks to application of high thermo-insulating corundum bricks the porosity was not noticed.

Table 2 is presenting average stereological parameters of particular regions of skeleton casting. Marks are corresponding with Figure 8. It can be noticed, that the results of analysis of shape parameters are resemblance for all regions. Only perimeter to area ratio of specimen 3 (cross-section between the nodes) is higher. It suggests slightly more prolonged silicone crystals.

Histograms showed in Figure 10 (a-e) presents average distribution of silicon crystal in each class of size. In combination with shape parameters allows describing the proper moulding material selection in terms of thermal properties. The distribution of sizes of silicone crystals is independent of region from which the specimen was taken.

Table 2.
Average stereological parameters of silicone crystals

Region	Area A [μm^2]	Perimeter P [μm]	Length L [μm]
1	27.35	24.43	9.83
2	36.61	28.23	11.35
3	23.97	22.15	8.97
4	32.25	26.62	10.8
5	27.75	23.17	9.15
Region	**Width B [μm]**	**Shape parameter B/L**	**Shape parameter P/A**
1	2.52	0.34	1.24
2	2.92	0.34	1.06
3	2.27	0.35	1.41
4	2.66	0.33	1.18
5	2.67	0.39	1.17

The sample number 3 which was taken from cross-section between the nodes is exception. Microstructure is considerably finer. There is noticeable increase of number of silicone crystals in lowest class size under 5 μm. The difference may be due to specific kinetic of heat transfer in area of ligaments. Because of good thermo-insulating properties of core and low diameter the ligaments crystallizes in whole volume assuring fine structure.

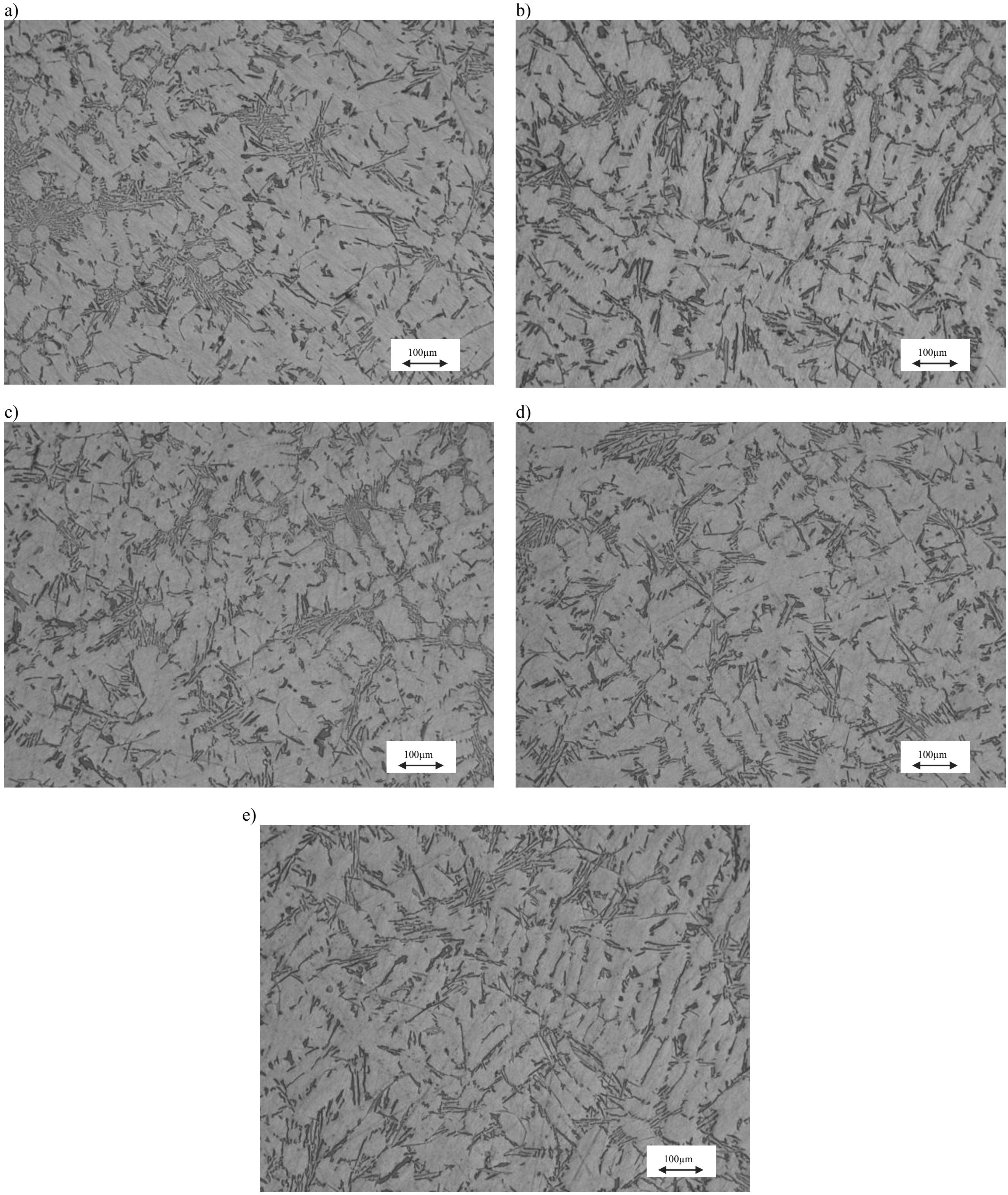

Fig. 9. AlSi11 alloy structure: a – node; b – near node cross-section; c – cross-section between the nodes; 4 – cross-section of closing wall; 5 – outside surface of closing wall

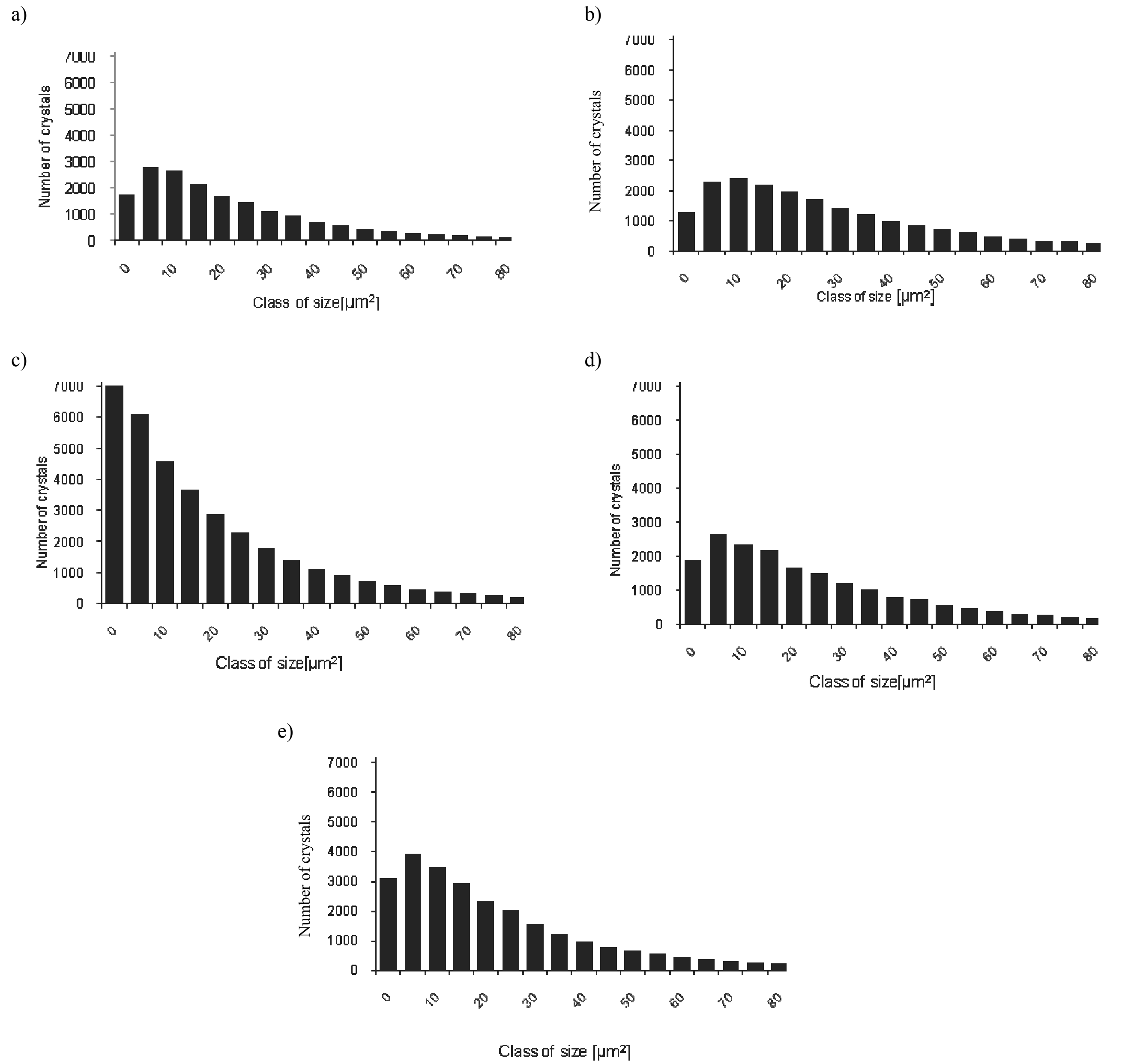

Fig. 10. Distribution of size of grain in each class of size: 1 – node; 2 – near node cross-section; 3 – cross-section between the nodes; 4 – cross-section of closing wall; 5 – outside surface of closing wall

3.3. Dynamic strength tests

The properties of skeleton castings as composite reinforcement can be achieved at the early stage of composite design. By changing the relative density gradient in the direction of the force, the elementary cell shape, its dimensions, the material from which the skeleton casting is made, the mechanical properties and the weight of the casting can be changed as well. When selecting the matrix (the skeleton casting filler) the manufacturing technique, desirable properties, and end application of the skeleton composite casting should be considered.

The section presents the results of research on the dynamic load resistance of ceramic matrix composites with aluminium, spatial, skeleton casting reinforcement, particularly focused on the ability of impact energy absorption. For the purposes of research, three series of composite skeleton castings were manufactured. Their compositions are shown in Table 3.

Table 3.
The composition of manufactured composite skeleton castings

		Sample number		
		1	2	3
Component volume fraction [%]	AlSi11 Alloy	41.4	41.4	41.4
	Ceramics	58.6 with air	16.4	16.4
	Liquid	0	42.2	42.2

In the considered cases, as mentioned above, the composition of the composites was complemented with a liquid filling. In series number 2 it was mineral oil. In series number 3 it was a polymeric liquid. It was assumed that the addition of liquids due to their low compression rate would increase the strength and improve the absorption of kinetic energy of the composite skeleton castings. With the isotropic increase of pressure, the composite should be deformed in the entire volume.

On the basis of a dynamic load strength tests, the energy absorbed by the composite was determined. The research consisted of controlled releases of a working element from the maximum height. After analysing the recorded videos, it was possible to determine the displacement, velocity and acceleration of the destroyed element, from the moment of contact until zero velocity.

The maximum height of free fall of a working element was 5.505 m and its weight – 26 kg. The maximum possible potential energy of the system was 1403 J. For data logging of the experimental procedure, a high-speed Phantom V210 camera was used. Registration proceeded at 10 000 frames per second. The composite skeleton casting was placed on a 0.30 m concrete foundation, limiting the influence of deformation of the ground.

There were three series of experiments. In each of them a different filler of skeleton casting was used. The number 1 series consisted of a dry ceramic core skeleton casting. In series 2, a ceramic matrix was complemented with mineral oil. The matrix of series number 3 was complemented with the addition of a polymeric liquid.

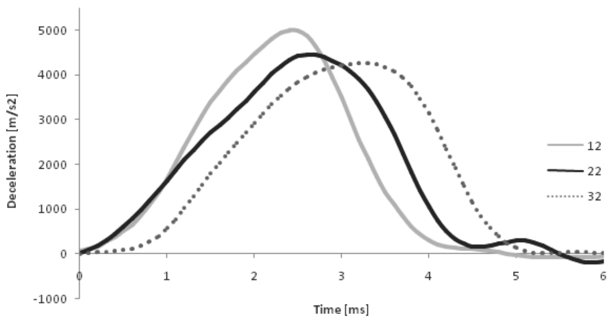

Fig. 11. Selected charts of deceleration growth related to time; where: 1.2. – skeleton casting with pure ceramic core, 2.2. – skeleton casting with ceramic core infiltrated with mineral oil, 3.2. – skeleton casting with core infiltrated with polymeric liquid

Selected results of carried out test are show in form of chart of change of deceleration in function of time – Figure 11. A key factor affecting the value of the maximum recorded deceleration is the point of impact and so indirectly the rigidity of the structure. When the impact point was closer to the geometric centre of the wall, the value of deceleration was reduced. If, however, it was closer to the edge of the sample, the maximum value of deceleration was increased. In this type of dynamic tests repeatability is critical. However, due to their nature, a the large number of variables and the dynamics of the entire system, in order to attain close to 100% repeatability, adequate improvement of the research methods is required. Currently only the level of required accuracy was described.

Figure 11 shows the deceleration growth related to time, since the working element has contact with the sample until it achieves a zero velocity. The changes in deceleration in time are crucial to determine the changes in the way of deformation and dissipation of impact energy. There are two opposite kinds of changes in acceleration during deformation - the rapid growth of deceleration to a maximum value and the equally rapid decline. The changes curves are similar to the Dirac impulse (curve 1.2 in Figure 11). The deformation in this case is fast and slight. There are large G-values. It seems to be the use of such composites for blast energy absorbers such as ballistic armours, where it counts to minimize the deformation and maximize quick dissipation of energy. Another extreme case is the slow deceleration time and lower maximum value (curve 3.2 in Figure 11). This suggests a larger deformation progress over time, with less lower G-values. This behaviour is desirable in the cases of using composite skeleton casting as energy absorbing elements in transportation.

In Figure 11, the impact of the liquid additive to the nature of deformation is shown. In the case of the dry ceramic filler, quick and slight deformation and a rapid growth of deceleration were observed. After completing the matrix with mineral oil, the deceleration growth rate decreased. The addition of polymeric liquid also positively influenced the nature of the deformation caused a less dramatic slowdown of the working element (lower rate of changes of deceleration in time), and a smaller maximum recorded value of deceleration.

4. Conclusions

- Analysis of size distribution of silicone crystals showed that the most of the silicone crystals are less than 20 μm.
- Depending on the area, from which the specimens were taken it can be noticed the similar degree of silicone crystals fragmentation.
- The study confirmed the structural correctness of the skeleton castings manufactured with proposed moulding materials.
- To determine the effect of microstructural properties on the strength of skeleton casting there is need to perform analysis of the distance between the secondary arms of dendrites of α phase (SDAS).
- Materials selected for moulding ensure good fill of mould cavity and contribute to the reduction of shrinkage porosity in nodes of skeleton castings.
- Octahedron cell confirmed beneficial influence on dynamic mechanical properties of skeleton castings.
- Beneficial effect on the way of impact energy dissipation of solid-liquid filler was observed. Fluid filling affects the way the energy is absorbed and deformation mechanisms.
- It was confirmed that the deformation mechanism of skeleton casting can be controlled through the selection of filler parameters.

Acknowledgements

Research financed from POIG.01.01.02-00-015/08-00 project.

References

[1] M. Cholewa, T. Szuter, M. Dziuba, Basic properties of 3D cast skeleton structures, Archives of Materials Science and Engineering 52/2 (2011) 101-111.
[2] A.G. Evans, J.W. Hutchinson, N.A. Fleck, M.F. Ashby, H.N.G. Wadley, The topological design of multifunctional cellular metals, Progress in Materials Science 46/3-4 (2001) 309-327.
[3] H. Wadley, Fabrication and structural performance of periodic cellular metal sandwich structures, Composites Science and Technology 63/16 (2003) 2331-2343.
[4] J.W.H. Kumar, P.D. Haydn, N.G. Wadley, Z. Xue, Mechanical response of metallic honeycomb sandwich panel structures to high-intensity dynamic loading, International Journal of Impact Engineering 35/9 (2008) 1063-1074.
[5] H.N.G. Wadley, Multifunctional periodic cellular metals, Philosophical transactions. Series A, Mathematical, Physical, and Engineering Sciences 364/1838 (2006) 31-68.
[6] M.F. Ashby, The properties of foams and lattices, Philosophical transactions. Series A, Mathematical, Physical, and Engineering Sciences 364/1838 (2006) 15-30.
[7] A.G. Evans, J.W. Hutchinson, M.F. Ashby, Multifunctionality of cellular metal systems, Progress in Materials Science 43 (1999) 171-221.
[8] M. Hostetter, B. Cordner, G.D. Hibbard, Stochastic honeycomb sandwich cores, Composites Part B 43/3 (2012) 1024-1029.
[9] L. Èí, D. Ostroushko, Z. Szulc, R. Molak, M. Praÿmowski, Properties of sandwich metals joined by explosive cladding method, Archives of Materials Science and Engineering 43/1 (2010) 21-29.
[10] J. Tian, The effects of topology upon fluid-flow and heat-transfer within cellular copper structures, International Journal of Heat and Mass Transfer 47/14-16, (2004) 3171-3186.
[11] J. Banhart, Manufacture, characterisation and application of cellular metals and metal foams, Progress in Materials Science 46/6 (2001) 559-632.
[12] T. Lu, L. Valdevit, A. Evans, Active cooling by metallic sandwich structures with periodic cores, Progress in Materials Science 50/7 (2005) 789-815.
[13] K. Boomsma, D. Poulikakos, F. Zwick, Metal foams as compact high performance heat exchangers, Mechanics of Materials 35/12 (2003) 1161-1176.
[14] T.J. Lu, H.A. Stone, M.F. Ashby, Heat transfer in open-cell metal foams, Acta Materialia 46/10 (1998) 3619-3635.
[15] J. Xiong, L. Ma, L. Wu, M. Li, A. Vaziri, Mechanical behaviour of sandwich panels with hollow Al–Si tubes core construction, Materials & Design 32/2 (2011) 592-597.
[16] K.P. Dharmasena, H.N.G. Wadley, K. Williams, Z. Xue, J.W. Hutchinson, Response of metallic pyramidal lattice core sandwich panels to high intensity impulsive loading in air, International Journal of Impact Engineering 38/5 (2011) 275-289.
[17] A. Ajdari, H. Nayeb-Hashemi, A. Vaziri, Dynamic crushing and energy absorption of regular, irregular and functionally graded cellular structures, International Journal of Solids and Structures 48/3-4 (2011) 506-516.
[18] J. Zhou, P. Shrotriya, W.O. Soboyejo, On the deformation of aluminium lattice block structures: from struts to structures, Mechanics of Materials 36 (2004) 723-737.
[19] G.W. Kooistra, D.T. Queheillalt, H.N.G. Wadley, Shear behaviour of aluminium lattice truss sandwich panel structures, Materials Science and Engineering A 472/1-2 (2008) 242-250.
[20] M.G. Hebsur, Processing of IN-718 Lattice Block Castings, NASA/CR-2002-211332, 2002, 1-10.
[21] D. Manas, M. Manas, M. Stanek, M. Danìk, Improvement of plastic properties, Archives of Materials Science and Engineering 32/2 (2008) 69-76.
[22] G.W. Kooistra, H.N.G. Wadley, Lattice truss structures from expanded metal sheet, Materials & Design 28/2 (2007) 507-514.
[23] K. Mroczka, A. Pietras, FSW characterization of 6082 aluminium alloys sheets, Archives of Materials Science and Engineering 40/2 (2009) 104-109.
[24] D.T. Queheillalt, H.N.G. Wadley, Cellular metal lattices with hollow trusses, Acta Materialia 53/2 (2005) 303-313.
[25] J. Banhart, Aluminium foams for lighter vehicles, International Journal of Vehicle Design 37 (2005) 114-125.
[26] M.F. Ashby, A.G. Evans, N.A. Fleck, L.J. Gibson, J.W. Hutchinson, H.N.G. Wadley, Metal Foams, A design Guide. Elsevier Inc., 2000.
[27] M. Cholewa, Spatial, composite foam castings, Archives of Foundry 3/9 (2003) 81-88 (in Polish).
[28] M. Ashby, The Mechanical Properties of Cellular Solids, Metallurgical Transactions 14 (1983) 1755-1769.
[29] Z. Xue, Preliminary assessment of sandwich plates subject to blast loads, International Journal of Mechanical Sciences 45/4 (2003) 687-705.
[30] http://www.nasa.gov/topics/aeronautics/features/helo-drop-test.html
[31] M. Cholewa, T. Szuter, Geometrical and mechanical analysis of 3D casted skeleton structure, Archives of Foundry Engineering 10/2 (2010) 23-26.
[32] M. Cholewa, M. Dziuba-Kałuża, Structural analysis of aluminium skeleton castings, Archives of Foundry Engineering 8/3 (2008) 29-36.
[33] M. Cholewa, T. Szuter, Heat-insulating moulding sand with the glycol addition, Archives of Foundry 11/3 (2011) 61-64.