Polskie Towarzystwo Materiałów Kompozytowych
Polish Society of Composite Materials
12: 2 (2012) 121-125
COMPOSITES THEORY AND PRACTICE

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Received (Otrzymano) 13.03.2012

SKELETON CASTINGS AS A NEW TYPE OF SPATIAL COMPOSITE REINFORCEMENT WITH SPECIFIC MECHANICAL PROPERTIES

The paper presents the research results on the dynamic load resistance of ceramic matrix composites with aluminum spatial skeleton reinforcement, particularly focused on the ability to absorb impact energy. In the considered cases, the composite composition was complemented with a liquid additive. The addition was designed to improve impact energy absorption. The matrix of the composite was simultaneously a foundry core of skeleton casting. Internal channels which reproduce i trusses were created with the use of specially designed templates. The use of ceramic shapes allowed the authors to obtain strong cores with complex geometry, which act at the same time as the composite matrix, influencing its mechanical properties. Strength tests with a dynamic load were performed. The energy absorbed by the composite material was determined. The research was conducted on a specially-designed stand. The concept of the stand was developed based on drop weight tests.

Keywords: **skeleton casting, reinforcement, mechanical properties**

ODLEWY SZKIELETOWE JAKO NOWY TYP PRZESTRZENNEGO WZMOCNIENIA KOMPOZYTÓW O SZCZEGÓLNYCH WŁASNOŚCIACH MECHANICZNYCH

W opracowaniu przedstawiono wyniki badań wytrzymałości na obciążenie dynamiczne kompozytu o ceramicznej osnowie i przestrzennym aluminiowym wzmocnieniu szkieletowym, w szczególności skupiono się na zdolności pochłaniania energii uderzenia. W rozważanych przypadkach skład kompozytu uzupełniony został o ciecz wypełniającą. Dodatek miał na celu poprawę warunków absorpcji energii uderzenia. Osnowa kompozytu pełniła jednocześnie rolę rdzenia odtwarzającego wewnętrzne powierzchnie odlewu szkieletowego. Kanały odwzorowujące łączniki tworzono przy zastosowaniu specjalnych matryc. Użycie kształtek ceramicznych pozwala na uzyskanie wytrzymałych rdzeni o skomplikowanej geometrii, które pełnią jednocześnie rolę osnowy kompozytu, kształtując jego własności wytrzymałościowe. Przeprowadzano badania wytrzymałości przy obciążeniu dynamicznym. Na ich podstawie wyznaczono energię pochłoniętą przez materiał kompozytowy. Badania przeprowadzono na specjalnie do tego celu zbudowanym stanowisku. Koncepcja stanowiska została opracowana w oparciu o próby kafarowe typu Drop Weight Test.

Słowa kluczowe: **odlewy szkieletowe, wzmocnienie, właściwości mechaniczne**

INTRODUCTION

Periodic cellular metals are defined as highly porous when metal occupies about 20% of their volume. [1, 2]. They are multipurpose materials with multifunctional use. Structures like honeycomb are widely used as lightweight structural materials allowing for unidirectional fluid flow, as impact energy absorbers or heat and vibrations absorbers [3]. Materials with prismatic cores among others are also considered as periodic cellular materials. By analogy to gasars, thanks to their elongated elementary cells, the unidirectional flow of fluid is possible e.g. temperature-leveling liquid. These materials are widely used in ship constructions and buildings.

Cellular metals with lattice structures (such as skeleton castings) are also very popular. These three-dimensional structures are created from slender trusses (beams). Almost any shape can be obtained, depending on the targeted applications and additional functionality. Lattice structures are shown in Figure 1 [3, 5-7, 10, 11].

Figure 1f shows the topology of a spatial skeleton casting based on octahedron elementary cells, designed in the Foundry Department of the Silesian University of Technology. The cell is built from two pyramids with a shared foundation. The nodes are placed between the wall and inside them as well. This design creates a continuous web of trusses. The three-dimensional symmetry of this solution should be mentioned. Each of the elementary cells are connected together and create a compact, rigid construction. Skeleton castings as shown can be manufactured with typical foundry techniques, low costs, and take advantage of the very good rheological properties of liquid alloys [8, 10, 11].

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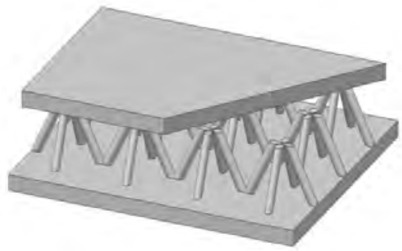

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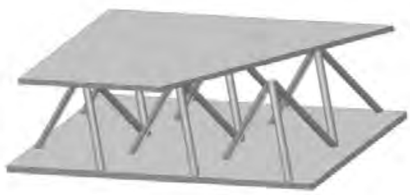

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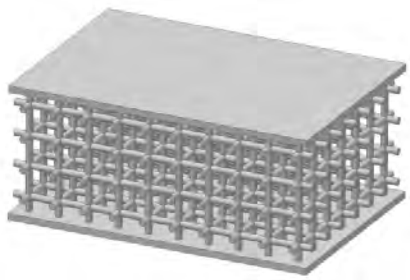

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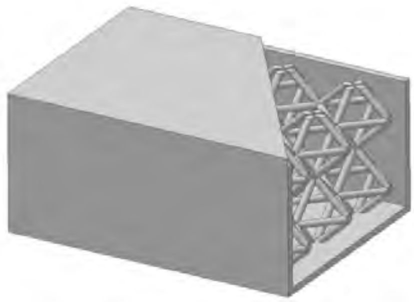
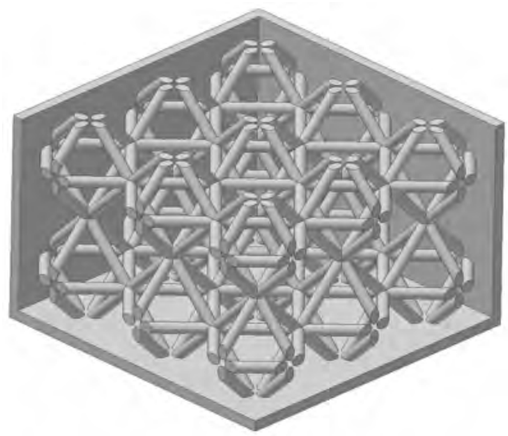


Fig. 1. Topologies of sandwich panels and lattice structures/skeleton castings; a-e) Topologies presented in papers [1-3, 7, 12-17]; f) topology designed in Foundry Department of Silesian University of Technology [8, 10, 11, 21]

Rys. 1. Przykładowe topologie paneli typu sandwich i struktur kratownicowych/odlewów szkieletowych; a-e) Topologie przedstawione w opracowaniach [1-3, 7, 12-17]; f) topologia opracowana w Katedrze Odlewnictwa Politechniki Śląskiej [8, 10, 11, 21]

The development of effective manufacturing techniques especially foundry ones was the result of the good functional properties of periodic porous metals. Foundry techniques (moulding and core making) impose certain restrictions on the internal topology prediction. Limitations on the number of possible skeleton castings topologies can be overcome by using additive manufacturing methods.

Lattice/skeleton structures can also be manufactured from composite materials e.g. carbon fibers with hot compression molding or with the use of preforms. Panels with a compressive strength of 40 MPa can be obtained by this way. This type of constructions confirmed its suitability as blast energy absorbers with specific slight deformation of the back wall [16, 17].



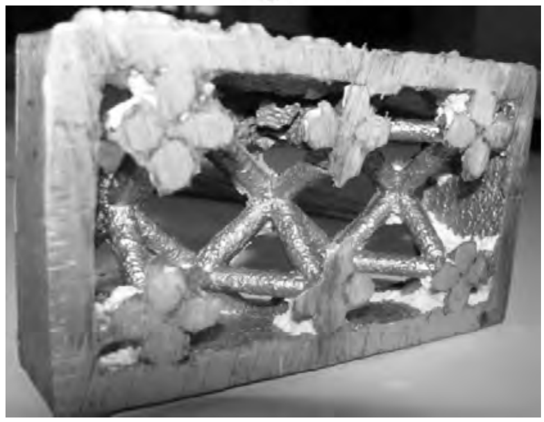


Fig. 2. CAD model of skeleton casting and raw casting cross-section. General dimensions of raw casting - 120x80x120 mm

Rys. 2. Model CAD odlewu szkieletowego oraz przekrój przez rzeczywisty surowy odlew szkieletowy. Wymiary gabarytowe surowego odlewu 120x80x120 mm

The concept of skeleton castings as periodic highly porous materials with opened cells has been developed in the Foundry Department of the Silesian University of Technology [10, 11, 21]. In opposition to sandwich panels, skeleton castings are enclosed structures, limited by walls. Figure 2 shows a CAD model and a full section of raw skeleton casting with octahedron elementary cells. An external wall was removed to present the internal topology. Castings prepared according to this concept can be manufactured i.a. from iron alloys or aluminum alloys and can be filled with a metal e.g. cast iron or steel [20, 21], ceramic [21] or polymer e.g. sulfur polymer [22]. Those types of filling are perceived as the specific matrix of a composite. In this case, skeleton casting is the spatial continuous reinforcement of a composite. Therefore, this type of connection should be characterized by i.a. energy absorption in a few stages. In the first stage, the response of the composite should occur with the deformation of the external walls and the trusses themselves. Next, energy should be dissipated in the filling material, with the use of internal friction forces. Finally, by increasing the stress and deformation, the energy is re-transmitted to the frame using the work of the adhesion components. The intention is to force the reaction and interaction of all the components of the composite skeleton casting and the maximum volume of the filling material.

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 is made, the mechanical properties and the weight of the composite can be changed as well. When selecting the matrix (skeleton casting filler) the manufacturing technique, desirable properties, and end application of the skeleton composite casting should be considered.

METHODOLOGY

The paper presents the results of research on the dynamic load resistance of ceramic matrix composites with aluminum spatial skeleton casting reinforcement, particularly focused on the ability to absorb impact energy. For the purposes of research, three series of composite skeleton castings were manufactured. Their compositions are shown in Table 1.

TABLE 1. **Composition of manufactured composite skeleton castings**
TABELA 1. **Skład wytworzonych kompozytowych odlewów szkieletowych**

		1	2	3
Component volume fraction [%]	AlSi11 alloy	41.4	41.4	41.4
	Ceramics	58.6	16.4	16.4
	Liquid	0	42.2	42.2

The skeleton castings were made from the AlSi11 alloy. As the filling material, porous ceramic shapes were used. In series number 1, a porous ceramic with open cells was only used. In series number 2 and 3, the composition of the filling material was complemented with a liquid addition. The composite filling of skeleton casting was simultaneously the foundry core, reproducing the trusses and internal surfaces of the castings. The channels which reproduce the trusses were made with the use of specifically designed templates. The use of ceramic shapes allows for the obtaining of strong cores with complex geometry, which are at the same time the matrix of the composite, influencing its mechanical properties. Selected properties of ceramic shapes are shown in Table 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.

The internal topology of the skeleton casting was chosen based on previous studies. [9] On the basis of dynamic load strength tests, the energy absorbed by the composite was determined. The research was conducted on a specially-designed stand. The concept of the stand was developed based on drop weight tests.

TABLE 2. **Main properties of JM30 refractory shapes**
TABELA 2. **Główne właściwości ogniotrwałych cegieł JM30**

JM 30			
Classification according to ISO 2245	160 1.0L	Specific heat at 1000°C [kJ/kg·K]	1.10
IFB classification temperature [°C]	1650	Chemical composition	
Density [kg/m^3]	1020	Al_2O_3	73.4
Compressive strength [MPa]	2,1	SiO_2	25.1
Compressive strength of cold [MPa]	2,2	Fe_2O_3	0.5
Thermal conductivity [W/m·K]		TiO_2	0.1
400°C	0.38	CaO	-
600°C	0.39	MgO	-
800°C	0.40	$Na_2O + K_2O$	0.9
1000°C	0.41		

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 matrix was used. The number 1 series (samples 1.1-1.3) consisted of a dry ceramic matrix and skeleton spatial reinforcement. In series 2 (samples 2.1-2.3), a ceramic matrix was complemented with mineral oil. The matrix of series number 3 (samples 3.1-3.3) was complemented with the addition of a polymeric liquid. The research consisted of controlled releases of a working element from the maximum height. After analyzing 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. Figure 3 shows a full section of a selected skeleton casting after the test.

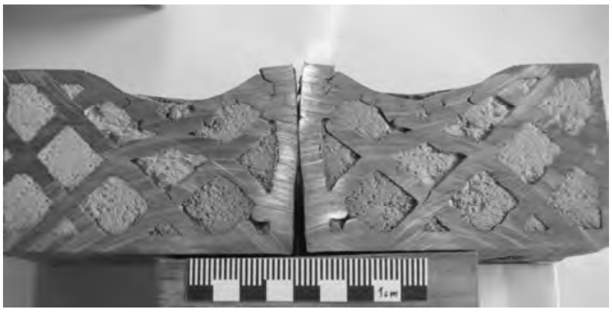


Fig. 3. Full section of selected skeleton casting after test

Rys. 3. Przekrój wybranego odlewu szkieletowego po badaniu

RESULTS OF RESEARCH

The results of these experiments are presented by comparing the maximum values of the obtained deceleration (Fig. 4), comparison of the amount of energy absorbed by the castings during deformation (Fig. 5), and the graphs of deceleration changes during deformation (Fig. 6).

The energy absorbed by the composite skeleton casting (Fig. 4) was calculated as the definite integral of the function approximating the changes of the deformation forces. The potential energy of the system was 1402 J.

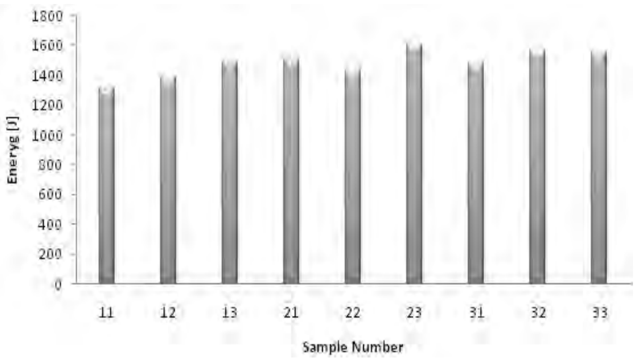


Fig. 4. Graph of energy absorbed by various skeleton castings

Rys. 4. Wykres energii pochłoniętej przez poszczególne odlewy szkieletowe

Some of the energy was dissipated by air resistance and friction of the guide. The calculations show that a large part of the energy is absorbed by the samples. It was also noted that some of the energy is dissipated by elastic deformation of the ground. Because of the invariant conditions of the experiments, the energy consumed by deformation of the ground was treated as a constant. Due to the fact that the amount of energy absorbed by the casting is near the maximum energy of the system, no effect of the liquid additives on the amount of absorbed energy was noted. In some cases, the calculated energy is slightly greater than the maximum potential energy. This suggests that the measurement methods were not accurate enough and the simplification used in the calculations was too large. Unfortunately, the impact of the working element was not reproducible in a satisfactory manner. The castings moved slightly during the impact, which can be observed in the high speed videos.

Figure 5 shows a graph of the maximum registered instantaneous deceleration in each trial. 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 center 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, 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.

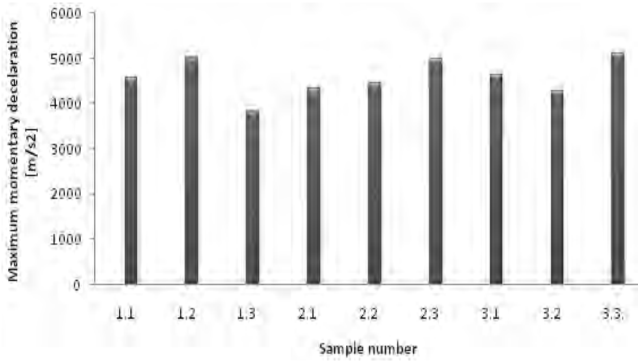


Fig. 5. Graph of maximum recorded instantaneous deceleration

Rys. 5. Wykres maksymalnego zarejestrowanego, chwilowego, ujemnego przyspieszenia

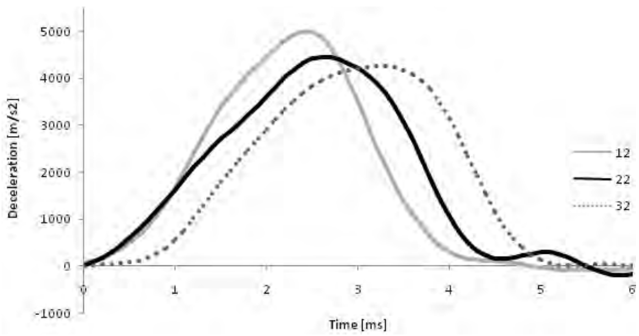


Fig. 6. Selected charts of deceleration growth related to time. Where: 1.2. - Skeleton casting with pure ceramic core, 2.2 - Skeleton casting with ceramic core infiltrated with mineral oil, 3.2 - Skeleton casting with core infiltrated with mixture of polyglycol

Rys. 6. Wyselekcjonowane wykresy przyrostu ujemnego przyspieszenia względem czasu. Gdzie: 1.2 - Odlew szkieletowy z suchym ceramicznym rdzeniem, 2.2 - Odlew szkieletowy z rdzeniem nasączonym olejem mineralnym 3.2 - Odlew szkieletowy z rdzeniem nasączonym mieszaniną poliglikoli

Figure 6 shows the deceleration growth related to time since the working element has contact with the sample until it achieves 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 Fig. 6). 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 armors, where it counts to minimize the deformation and maximize the quick dissipation of energy. Another extreme case is the slow deceleration time and lower maximum value (curve 3.2 in Fig. 6). This suggests a larger deformation progress over time, with lower G - values. This behavior is desirable in the cases of using composite skeleton casting as energy absorbing elements in transportation.

In Figure 6, 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, which 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.

CONCLUSIONS

1. Beneficial effect on the way impact energy dissipation of solid-liquid filler was observed. Fluid filling affects the way the energy is absorbed and deformation mechanisms.
2. It was confirmed that the deformation mechanism can be controlled through the selection of skeleton castings filler parameters.

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