Scientific Journals
of the Maritime University of Szczecin

Zeszyty Naukowe
Akademii Morskiej w Szczecinie

2017, 52 (124), 23–29
ISSN 1733-8670 (Printed)
ISSN 2392-0378 (Online)
DOI: 10.17402/241

Received: 06.11.2017
Accepted: 10.12.2017
Published: 15.12.2017

The role of innovative composite materials in the safe and efficient operation of floating marine structures

Janusz Grabian[1,✉], Wojciech Ślączka[2], Patrycja Pawłowska[3]
Waldemar Kostrzewa[1]

Maritime University of Szczecin
[1] Faculty of Marine Engineering, The Institute of Fundamental Technical Sciences
ul. Willowa 2-4, 71-650 Szczecin, e-mail: {j.grabian; w.kostrzewa}@am.szczecin.pl
[2] Faculty of Navigation, The Institute of Maritime Navigation
1-2 Wały Chrobrego, 70-500 Szczecin, Poland, e-mail: w.slaczka@am.szczecin.pl
[3] Faculty of Economics and Transport Engineering, The Institute of Transport Engineering
11 H. Pobożnego St., 70-507 Szczecin, Poland, e-mail: p.pawlowska@am.szczecin.pl
✉ corresponding author

Key words: metal composite materials, application, transport, safety, structures, properties

Abstract

This work indicates that new and innovative materials used in the construction of floating and stationary marine structures can contribute to increased operational safety in addition to reduced service costs and frequency and other reduced operating costs, including the costs of staff and running maintenance. Such materials include metal-ceramic composites whose properties, such as high resistance to abrasive wear, favourable coefficient of friction, good thermal conductivity and low thermal expansion, allow them to be used in tribological pairs in mechanisms, control elements and actuators of various devices operating in marine power plants, thereby increasing their operational reliability. Properties of metal-ceramic composite foams, i.e. vibration and noise damping, good thermal insulation performance, dissipation of electromagnetic waves and absorption of explosive energy, make them ideal for use in shipbuilding and construction of drilling towers, at the same time increasing the levels of comfort during operation. Composite metal-ceramic foams can significantly reduce the effects of fires as they are durable, water-resistant and creep resistant thermal insulators which can limit the destruction (deformation) of steel structures. This paper presents proposals for the application of these materials to selected technical solutions in offshore structures.

Introduction

Metals and their alloys, plastics, wood, glass and ceramic materials are used in the machine-building industry and in maritime transport. Any possible combination of these mentioned materials constitutes a composite. Composite materials are being increasingly used in various industries. Virtually all base materials can be used in the manufacture of composites (Figure 1); therefore, composites can have properties tailored to their applications. Taking their matrices into account, they fall into the categories of metal, polymer and ceramic composites. Composite properties are not the sum of the properties of the constituent components. Most frequently, one of the components is the matrix that affects the shape, cohesion, hardness and elasticity of the composite; the other component, known as the reinforcement, contributes to the ultimate strength of the product and provides the structure with compressive or tensile strength.

The development of new structural materials known as composites at the end of the 20th century was mainly concerned with glass fibre reinforced polymeric composites. In the field of maritime applications, these materials were used for the production of hulls and superstructures of watercraft, virtually displacing traditional materials. This was particularly true for recreational and sports craft made on a large scale. This is related to the ease of product formation, water resistance, ease of repair and lack of magnetic properties, among other benefits. Currently, the development of composite materials based on reinforced matrices involves combining, theoretically, all material groups: metals, polymers, ceramics and glass, as well as organic materials can be combined to generate any number of material combinations and a multitude of characteristics and functional properties. In the specific, difficult operating conditions that occur offshore, emphasis should be placed on the use of metal matrix composites, for example aluminium matrices with ceramic oxide or carbide reinforcement or hybrid composites with mixed reinforcement, e.g. of ceramics and graphite.

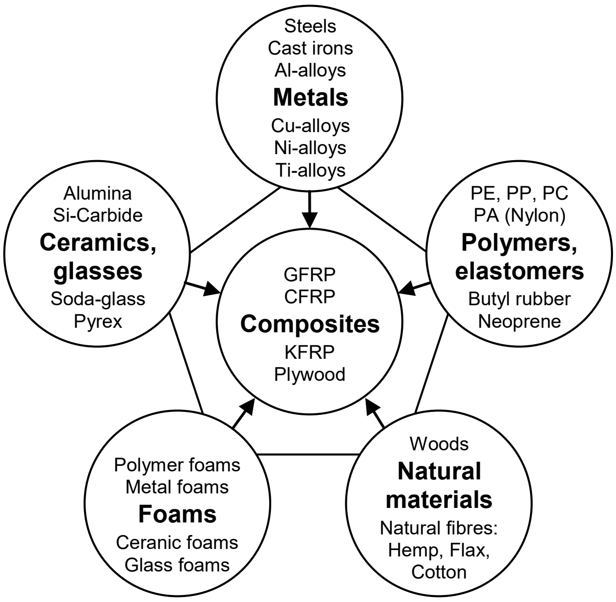


Figure 1. The world of materials (Giudice, 2017)

Some metal-ceramic composites can also appear in foam form, giving rise to a new group of porous materials with specific properties. These materials can be used in the construction of floating and stationary marine structures, e.g. mining facilities, in order to significantly increase the level of operational safety and efficiency. This paper is a brief overview of the described materials and aims to popularize them.

The possible impact of new composite materials on increasing the operational efficiency and safety of marine structures

In order to ensure the prescribed reliability of equipment, on top of proper design, assembly and operation, it is necessary to select materials with suitable functional properties. These include:

- static and dynamic load-bearing,
- resistance to environmental factors,
- contact interaction with materials of cooperating elements,
- abrasion resistance,
- specified coefficient of friction,
- characteristics of thermal expansion.

Traditional structural materials such as carbon and alloy steels, cast steel, cast iron and non-ferrous metal alloys have inherent properties and it is becoming less and less possible to upgrade them. Composite materials create new perspectives in machine building, including floating and stationary marine structures. These include monolithic composite materials and foams.

Monolithic metal-ceramic composites

As examples of metal-ceramic composites, those with a metal matrix made of aluminium–silicon alloy were used in structures operating in the marine environment. This alloy, traditionally used for cast structural elements, bodies and housings, is characterized by low processing costs, low weight and good corrosion resistance (Sobczak, 2001; Grabian 2012; Mavhungu et al., 2017). Due to the high content of hard silicon, it forms a structure similar to that of a composite with very good abrasion resistance; it is used, for example in the tribological pairing of an internal combustion engine piston and cast iron cylinder liner. Mechanical properties of particle-reinforced composites depend on factors such as the particle fraction, particle size and distribution in the composite matrix, the properties of the phase boundary of the matrix and reinforcement materials and the properties of the individual components. Large particles, with a characteristic size of more than several micrometres, distributed randomly in the volume, generally do not reinforce the composite and their presence has a beneficial effect on other special properties (Konopka, Łągiewka & Zyska, 2008). A sample of a composite of AlSi9 alloy matrix with a ceramic reinforcement of 20% fraction of SiC particles (1) is shown in Figure 2. It is characterised by good resistance to abrasive wear as shown in Figure 3, compared to such materials as composite AlSi11 reinforced with short, unstructured aluminosilicate fibres amounting to 14% (SIBRAL) (2), composite AlSi11 reinforced with short, unstructured aluminosilicate fibres amounting to 15% (SAFIL) (3) and composite AlSi11 reinforced with short, unstructured carbon fibres amounting to 12% (4).

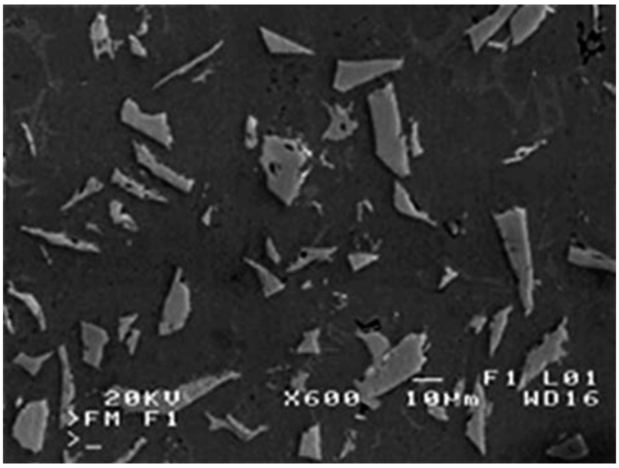


Figure 2. Structure of the composite AlSi9 – 20% SiC (Grabian, 2012)

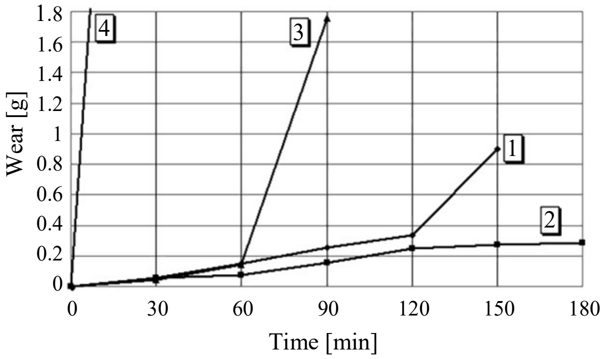


Figure 3. The abrasive wear of materials under dry friction conditions, description of curves in the paper (Grabian, Gawdzińska & Głowacki, 2004)

By modifying how this composite is manufactured, one can additionally introduce graphite particles, thereby obtaining a favourable coefficient of dry friction (Sobczak, 2001; Ravindran et al., 2012; Singh, 2016). This composite has the structure shown in Figure 4.

Slide bearings made of a composite material based on traditional aluminium bearing-type alloys with additional graphite will not only have a significantly increased wear resistance compared to existing solutions, but also a low coefficient of friction and significantly reduced sensitivity to hindered or impossible lubrication. In addition, composite bearings will better absorb vibrations (Figure 5.)

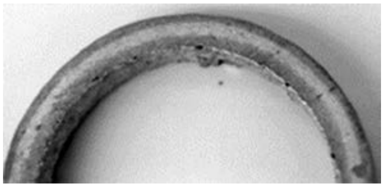


Figure 5. Hybrid bearing with two layers enriched with SiC (outer layer) and graphite (inner layer) AlSi7Mg/15% SiC by volume/5% graphite by volume (Sobczak & Wojciechowski, 2002)

The presented properties of these composites, related to manufacturing techniques, also make them suitable for marine applications. These materials increase, in particular, the reliability of tribological pairs that slide and rotate. This is particularly true for:

- components of devices and mechanisms;
- control and automation components;
- actuating mechanisms;
- internal combustion engines and other thermal machines operating in conditions with high fluctuations in temperature, humidity, and limited operational maintenance or in maintenance-free watercraft (Zboina, 2017).

Foamed metal-ceramic composite materials

By foaming the selected metal–ceramic composite material, for example the composite AlSi9-SiC, a porous material is obtained with a specific weight of 0.3–0.5 g/cm^3 and gas bubble size of 1–5 mm (see: Maritime University of Szczecin).

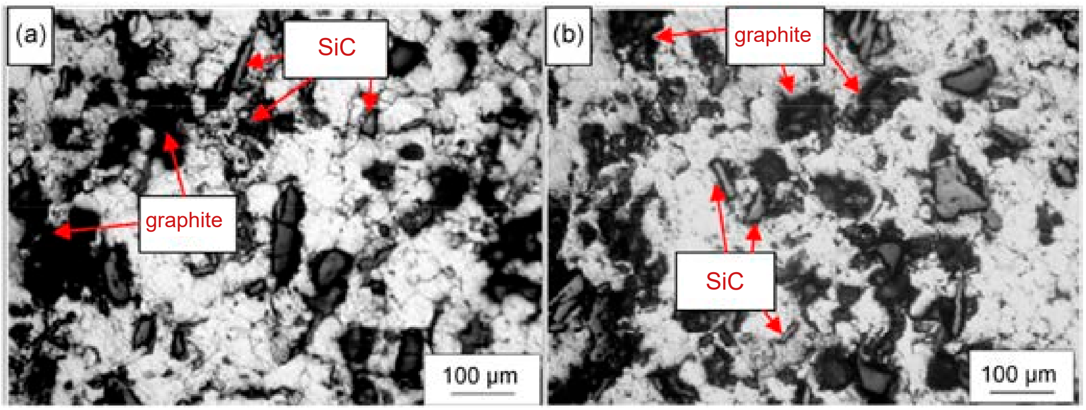


Figure 4. Hybrid composite (a) Al2024/5%SiC/5% graphite, (b) Al2024/5%SiC/10% graphite (Ravindran et al., 2012)

The three-dimensional structure of the foam is shown in Figure 6.

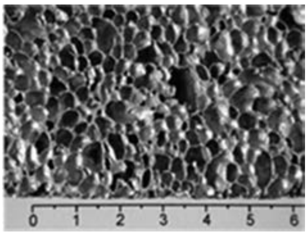


Figure 6. Foamed composite material AlSi9-SiC, made at the Maritime University of Szczecin (measurement unit = 1 cm) (own elaboration)

The basic properties of the obtained metal-ceramic foam are as follows:
- effective vibration and noise damping;
- capability of absorbing explosive energy;
- good thermal insulation performance;
- effective dissipation of electromagnetic waves;
- retention of the above properties at high humidity.

Foamed metals already have a practical application in land and air transport. Similarly, they can be used in the construction of the hulls of watercraft, vessels and ships, especially those designed to be used in areas where hull reinforcements are required in the form of profile filling or stiffener. They can be used, for example, to reduce the effects of collisions at sea and the consequences of striking the quayside when mooring, as well as minimising the effects of overly dynamic contact between watercraft and other facilities in severe weather conditions (turbulent sea or strong wind). The occurrence of very high static and dynamic loads is seen in the areas of the bow, sides of the bow and engine room, collision bulkhead and stern bulkhead. The bow section requires special attention as it is most exposed to impacts from bottom obstacles, floating objects or the quayside. It is estimated that the use of aluminium foams for the construction of the vessel hull would allow a weight reduction of 30%; there are also such elements and zones of the hull and superstructure where the introduction of metal foams would improve the safety of the crew. It is relatively simple to introduce metal foams into the structure of watercraft made of polyester–glass composites. To date, this typically includes those with hulls of less than 100 m in length and numerous small sport, recreation and utility units, e.g.: pilot boats, service boats, on-demand boats, etc. Hulls of watercraft made of polymer-glass composites can incorporate aluminium foam sandwiched between polymer/glass composite layers in panels. Panels made in the Department of Shipbuilding Material Engineering at the Maritime Academy in Szczecin, shown in Figure 7 are characterized by the ease with which they are manufactured and good bonding between the polyester–glass composite and metalfoam layers. The application of metal foams in this way can increase the stiffness and impact resistance of hulls and aid in buoyancy after a collision.

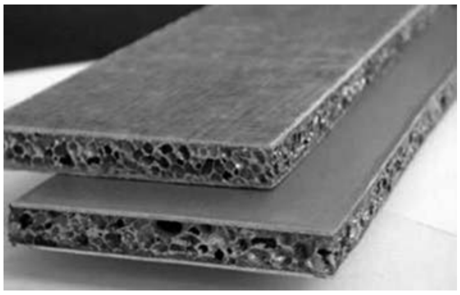


Figure 7. Panel: polyester–glass composite/aluminium–ceramic composite foam/glass polyester–glass composite, made at the Maritime University of Szczecin (own elaboration)

The application of metal foams can make a significant contribution to improving the comfort of working and staying aboard seagoing vessels. Figures 8 and 9, showing the longitudinal and transverse cross-section of a ship's hull, highlight the areas that require special protection against vibrations (Chybowski, Laskowski & Gawdzińska, 2015) and noise (Marczak, 2009). The design of the hull (dividing it

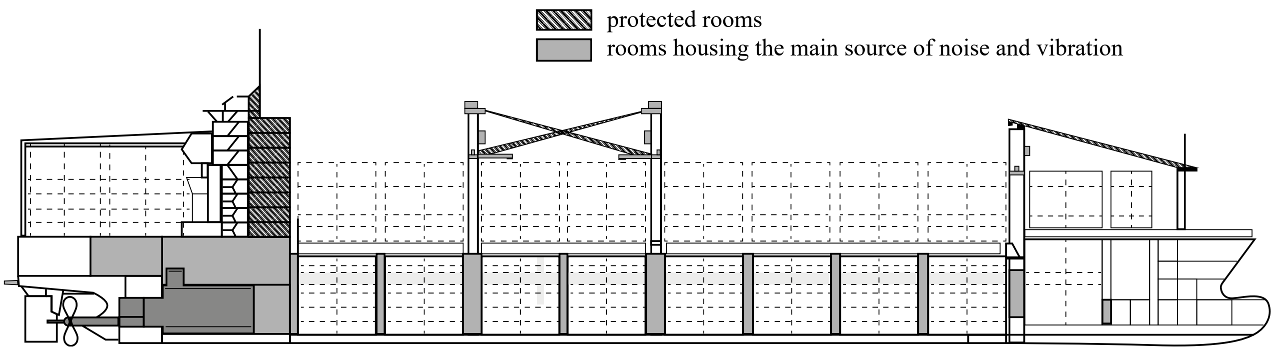


Figure 8. Layout of ship rooms (Marczak, 2009)

with flat steel sheets) allows for the simple use of acoustic insulation panels made of metal–ceramic composite foams (Skowroński, 2001; Kuśmierek--Ochrymiu, 2008).

Figure 9. Layout of walls and decks on the cross–section of the hull (Grabian, 2012)

Fires and explosions on watercraft are the third most frequent contributor to accidents at sea (Figure 10) (Gawdzińska et al., 2015).

Composite foams can play an important role in limiting the effects of fire (as a fireproofing material). Layers of this insulation can play an important role in mitigating the effects of fires and explosions, by limiting the dynamics of fire propagation and increasing the stability of the protected steel structure. In fire conditions, steel used as a construction material, for both floating and stationary marine structures, relatively quickly reaches the so-called "critical temperature" at which the strength (load-carrying ability) of the material, and hence the structure, is lost. This temperature varies in the range of 500–700°C and depends on the so-called 'massiveness' of the steel element (Woźniak, 2008). The fire resistance classes (A, B, C) of partitions – bulkheads, walls and decks – are determined for a maximum fire test period of no longer than 60 minutes as defined in the Classification and Construction of Marine Ships, Part V (PRS, 2013; EN 1993-1-2:2005). Extreme fires, for example on drilling towers, often preceded by an explosion, go beyond this standard (Figure 11). When used for thermal protection of steel structures, composite metal–ceramic foams with a high proportion of ceramic in their structures, which maintain their shape at high temperatures, can significantly increase the operational safety.

Figure 11. Fire on a drilling tower in the Gulf of Mexico (Wikipedia, 2010)

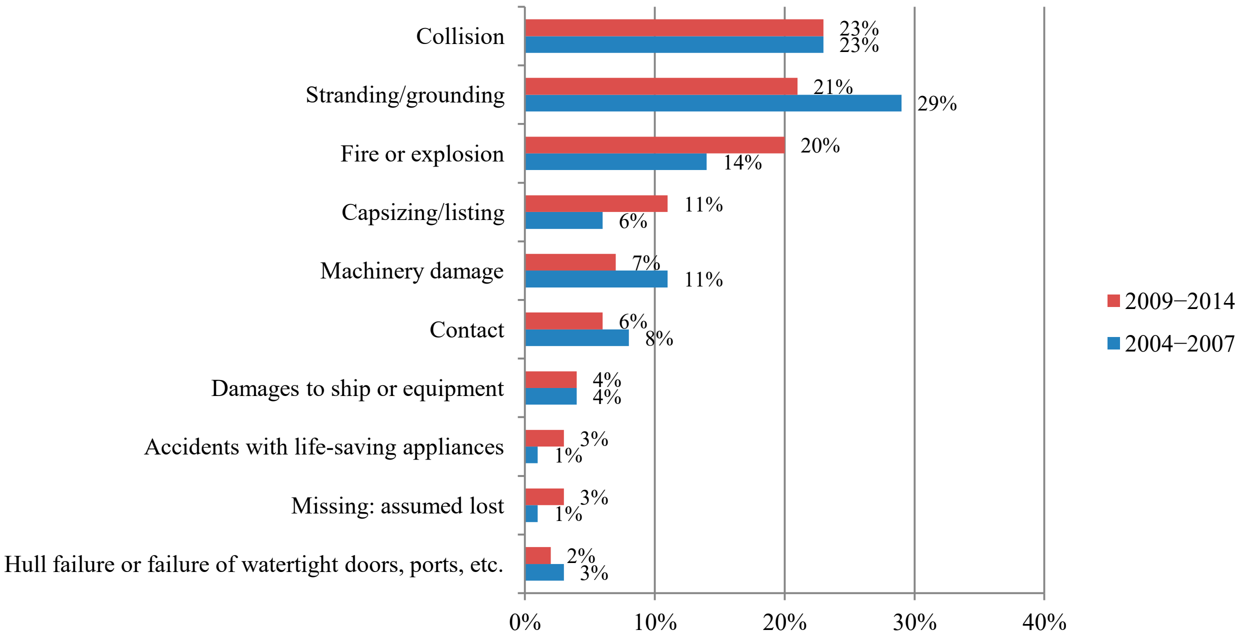
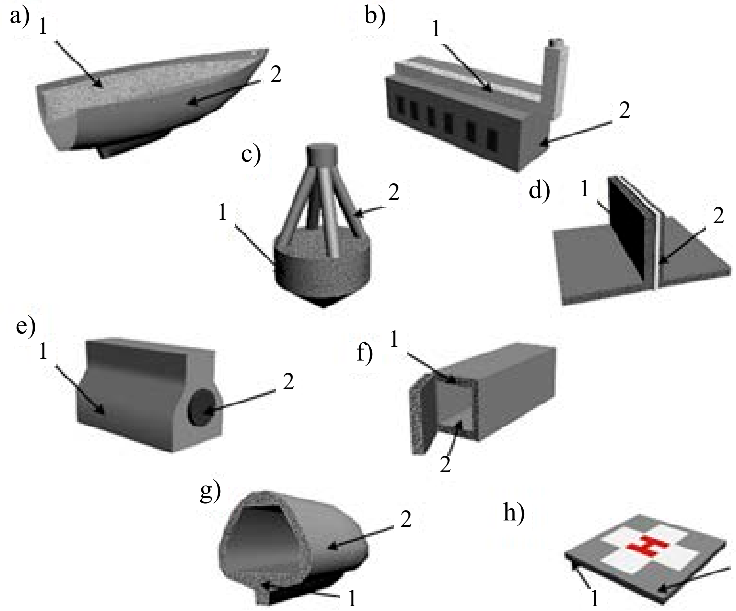


Figure 10. Causes of accidents on marine ships in the years 2004–2007 and 2009–2014 (Gawdzińska et al., 2015)



a) Segments increasing the rigidity and buoyancy of sport and recreational craft:
1 – formed low-density foam elements;
2 – laminate shell;
b) Thermal and acoustic shields for exhaust systems of combustion engines:
1 – formed foam elements (exhaust manifold muffs);
2 – combustion engine;
c) Floating elements of buoyages:
1 – filler material made from low-density foam;
2 – structure of the buoyage sign;
d) Fire-thermal insulation of walls, ceilings and decks of ship hulls:
1 – composite foam insulation layer;
2 – bulkhead wall;
e) Main engine acoustic enclosure:
1 – removable noise-damping foam segments;
2 – combustion engine;
f) Container for the transport of hazardous materials:
1 – composite foam filler that absorbs explosive energy;
2 – outer and inner shell;
g) Free-fall lifeboat with increased stiffness and fire resistance:
1 – integral foam segments;
2 – laminate outer shell;
h) Lightweight flight deck platform:
1 – foam layer increasing the rigidity of the platform;
2 – metal exterior panel.

Figure 12. Applicability of composite metal foams in shipbuilding (Grabian, Gawdzińska & Szweycer, 2008)

Composite metal-ceramic foams with a specific gravity of 0.3–0.45 g/cm^3 and porosity P = 80–90% can therefore be used in:

- acoustic shields for the main engine;
- acoustic and thermal shields for exhaust systems;
- thermal and acoustic insulation in main engine exhaust systems, auxiliary units, boilers, waste incineration plants;
- layers of the outer hull shells and superstructures of high-speed patrol watercraft;
- fire-resistant linings of walls and bulkheads;
- lightweight landing sites for helicopters;
- acoustic partitions within the engine room;
- explosion-proof doors;
- thermal and acoustic shields for power generators;
- containers for transport of dangerous goods;
- elements of hulls of sport and recreational boats;
- elements of hulls of free-fall launches, fast rescue boats, units that support drilling towers to increase thermal resistance and fire resistance, increase stiffness and shock absorption;
- float elements of buoyages;
- as a base material or component of machinery parts, installations and auxiliary equipment existing at floating and stationary marine structures.

Selected proposed applications of metal–ceramic composite foams are presented in Figure 12.

Conclusions

From among the numerous types of composite material, this paper discusses selected characteristics of metal matrix composites (in particular aluminium alloys). Metal composite materials, due to the presence of a reinforcing structure, are characterized by their diverse spatial distribution in the product and the different types, shapes and dimensions of reinforcing structure which influence their quality, properties and applications (Gawdzińska, 2013; Gawdzińska, Bryll & Nagolska, 2016; Gawdzińska et al., 2016; Przestacki, Szymański & Wojciechowski, 2016). As shown in the example of a composite matrix made of AlSi9 alloy and reinforced with ceramic particles, new advanced composite materials based on aluminium and ceramics can replace traditional materials, exhibiting beneficial properties and performance. It can also be noted that the ranges of selected functional parameters are wider, e.g. permissible operating temperature and resistance to abrasive wear. Composite foams can compete with traditional thermal insulation materials such as polymer foams and basalt fibrous insulation materials that no longer fulfill their function or become dangerous under certain conditions; traditional insulating wool does not function well when damp and toxic chemicals can be given off in conditions of a fire.

The rational use of new composite materials, if supported by scientific research and relevant regulatory bodies, may significantly contribute to the functional safety, efficiency and cost-effective operation of marine facilities.

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