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PRODUCTION OF LAYERED COMPOSITES FOR MARINE REFRIGERATED CONTAINERS

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Existing material and structural solutions used in the construction of marine refrigerated containers are insufficient due to increasing operational requirements. The need to reduce fires, environmental impact, and high energy consumption, as well as to minimize operational costs and potentially enable the use of refrigerated containers on autonomous vessels, compels researchers to develop lightweight and durable materials with improved mechanical strength, thermal insulation, and fire resistance. The characterization of such a layered material based on aluminum foam (according to the authors' patent PL 249151 B1), intended among others for refrigerated containers, constitutes the subject of this study.

Keywords: layered composites; aluminum foam; refrigerated containers; thermal insulation; maritime transport

INTRODUCTION

Sandwich structures based on polyurethane and metal foams have been known and applied for a long time. Despite their advantages, such solutions have limitations related to their application potential. Selected industrial sectors are subject to restrictive safety standards, including the flammability of applied materials. Currently, efforts are focused on the use of lightweight sandwich structures functioning as the structural components of machines. These components are intended to transfer stresses resulting from loading conditions, as well as to serve as absorbers of mechanical energy during impact loading. A sandwich structure with polyurethane foam from the Polish utility model description No. PL47410 Y1 is known and employed, in which the partition is convex in the direction of the polyurethane foam injection, while the horizontal walls of the partition are positioned between the outer cladding and the profiled sheet connected to the outer cladding by welding. This type of solution is used in refrigerated containers in maritime transport.

Marine refrigerated containers are specialized transport containers intended for the transportation of perishable goods over long distances. They are equipped with refrigeration units that maintain constant temperature and humidity inside the container, ensuring that the cargo remains fresh and in optimal condition during transport. They play a key role in the global supply chain by ensuring the year-round delivery of fresh products. The conventional design of marine refrigerated containers

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is based on a steel–polymer foam–steel sandwich structure. This configuration provides effective thermal insulation for the cargo and has been widely utilized in refrigerated transport for many years. However, with the development of new transportation technologies, particularly autonomous vessels, conventional solutions may not fully satisfy future operational requirements. A detailed comparison of the energy performance of the insulation materials currently used in refrigerated containers with the novel materials developed by the authors is beyond the scope of the present study and will be the subject of future research.

The operation of refrigerated containers is associated with energy consumption, leading to high operational costs; they are also susceptible to failures of power systems and may even cause fires, which together negatively affect the environment [1]. Therefore, all mechanisms, including the selection of new structural materials, that improve the energy efficiency of refrigerated containers may contribute to reducing operational costs, carbon dioxide emissions, and environmental pollution.

Numerous research studies focus, among others, on the selection of refrigerants [2, 3], as well as on assessing the impact of refrigerated container placement on container ships on the energy consumption of these cargo units [4]. Research has also been conducted on modeling new technologies for storing refrigerated containers in port terminals or on ships [5], which contributes to reducing costs associated with connecting containers to electrical power sources in port storage yards [5, 6, 7, 8, 9]. Available studies [10, 11] focus on the structural analysis of reefers, their dimensions, and weight. Although these studies remain relevant, in the near future they may fail to meet transport requirements demanding enhanced thermal resistance. Consequently, new materials with advantageous performance properties for refrigerated containers are still being sought.

Among noteworthy studies are those by Feng et al. [12], describing new composite materials for vacuum insulation panels used in marine refrigerated containers. The study characterized the composition of pyrolytic gases released from insulation panels utilized as fillers over a range of operating temperatures. A volumetric method was employed to determine the adsorption of gases (hydrogen and ethylene) on activated carbon before and after surface modification of the panels through catalytic loading with metal ions. In turn, Guo et al. [13] determined the effect of vacuum insulation panels on the uniformity of temperature distribution inside refrigerated containers. They developed physical and mathematical models of airflow and heat exchange inside a 20-foot refrigerated container made with vacuum panels and compared it to polyurethane-insulated refrigerated containers. The simulation results indicated that the use of vacuum insulation panels improves the quality of refrigerated transport.

Interesting studies on the selection of construction materials for refrigerated containers were also carried out by Zheng et al. [14]. They identified the adsorption mechanism as effective for developing carbon-based adsorbents for vacuum insulation panels with fiberglass cores employed in marine refrigerated containers. Nevertheless, there is still no description of new structural materials based on aluminum or aluminum-ceramic foams, which could significantly improve the energy efficiency of refrigerated containers. Such improvement may be achieved through the use of innovative materials in the form of aluminum or magnesium sandwich structures with foamed cores exhibiting favorable mechanical properties, good thermal insulation, and fire resistance [15, 16]. This may, in the future, enable the application of such refrigerated containers on autonomous vessels and support safer maritime transportation of electric vehicles.

The innovative solution developed in this study is the proposal of a new lightweight, durable composite material with fire resistance and improved thermal insulation properties that may be utilized in the construction of refrigerated containers.

PRODUCTION OF INNOVATIVE LAYERED MATERIALS

This study presents a patented (PL 249151 B1) composite sandwich structure composed of metal–ceramic foam, metallic foam, a carbon–epoxy composite, self-healing layers, in addition to sheets made of magnesium and aluminum alloys (Fig.1). The central part of the sandwich structure consists of a magnesium alloy sheet with a thickness ranging from 1.0 mm to 1.5 mm. Adhering to the upper surface of the magnesium alloy sheet is a self-healing layer with a thickness of 1.5–2.0 mm, composed of glass fibers filled with 80 wt% methylene polyaspartate and 20 wt% (3-isocyanatopropyl) triethoxysilane, with fiber diameters ranging from 0.3 mm to 0.8 mm, bonded by an epoxy resin. An aluminum–ceramic foam layer with a thickness of 5–6 mm adheres to the upper surface of the self-healing layer. Another self-healing layer, of the above-described composition is adhesively attached to the aluminum–ceramic foam layer. An aluminum alloy sheet with a thickness of 1.0–1.5 mm is then adhesively bonded to this self-healing layer.

On the lower surface of the magnesium alloy sheet is a further, a self-healing layer as described above. An aluminum foam layer with a thickness of 5–6 mm adheres to the lower surface of this self-healing layer. Another self-healing layer, is adhesively attached to the aluminum foam layer. Finally, a carbon–epoxy composite layer with a thickness of 1.0–1.5 mm adheres to the self-healing layer, consisting of carbon fibers with diameters ranging from 7 μm to 10 μm and lengths of 4–5 mm, bonded with epoxy resin.

A key advantage of this solution is the development of an asymmetric sandwich structure characterized by high energy absorption efficiency (studies are ongoing). The incorporation of self-healing layers enables continued load transfer despite initial debonding of the face sheet, which is characteristic of similar classes of materials [16–18]. Furthermore, the structure based on composite foam and aluminum foam exhibits damping properties [15, 17, 18], is non-flammable, and can be applied in industries with stringent safety requirements, such as refrigerated marine containers and battery insulation systems in electric vehicles. The asymmetric arrangement of layers also enables the sandwich structure to function as an absorber of thermal energy [16]. It has been well established that aluminum or aluminum–ceramic foams may be used as thermal insulation materials or to facilitate heat exchange. A key parameter affecting the application-related performance of these materials is the thermal conductivity coefficient, λ [W/m·K]. For simpler systems based on closed-cell aluminum or composite foams [16], λ typically ranges from 8.5 to 9.6 [W/m·K]. The production of the proposed composite material is a complex, multi-stage technological process. It involves aluminum and aluminum–ceramic foam casting, the fabrication of polymer–glass composite laminates using the resin infusion process, as well as pressing and adhesive bonding of the individual layers. Therefore, a detailed description of the production technology, together with an assessment of process scalability and production costs, is beyond the scope of the present study and will be addressed in future work.

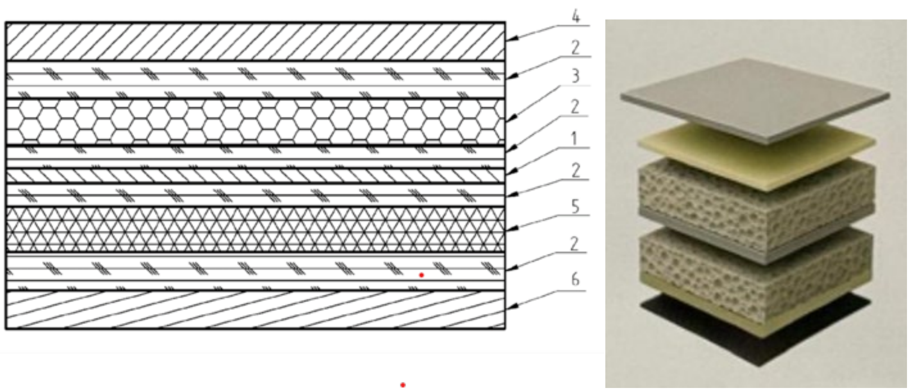

Fig. 1. Composite sandwich structure: 1 – magnesium alloy sheet; 2 – self-healing layer (consisting of glass fibers filled with 80 wt% methylene polyaspartate and 20 wt% (3-isocyanatopropyl) triethoxysilane); 3 – aluminum–ceramic foam layer; 4 – aluminum alloy sheet; 5 – aluminum foam layer; 6 – carbon–epoxy composite layer

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CONCLUSIONS

In the materials developed in this study, the individual layers exhibit different stiffness values, which translate into a specific failure mechanism. This also affects their insulating and mechanical properties. Of particular importance is the fire resistance of the aluminum and aluminum–ceramic foams incorporated into the proposed systems, which significantly contributes to maritime transport safety [19]. These aspects require further experimental validation and are beyond the scope of the present study. This work presents pilot investigations aimed at identifying materials dedicated to refrigerated marine containers, while further research will constitute the subject of a doctoral dissertation by one of the co-authors. A detailed evaluation of the thermal insulation properties of the developed materials, together with an assessment of their potential impact on the energy consumption of marine refrigerated containers, will be the subject of future research and subsequent publications.

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