SELECTION OF ENGINEERING MATERIALS AND ADVANCED TECHNOLOGIES FOR SPECIFIC INDUSTRIAL APPLICATIONS

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Abstract

The recent approaches of designers focused on decisions concerning the proper choice of engineering material and manufacturing process appropriate for a specific industrial application considerably inhibit innovations. Designers do not systematically explore all possibilities that could deliver better results and their choices are often based only on an engineer's experience and on the recommendation of product supplier. The results are therefore extremely dependent on the individual knowledge, they are many times mostly identical with the same material or process which has been used obviously before and the producer can only hardly show to customer the quantitative reasoning behind them.

The novel approach presented in this contribution has been outlined recently. This method is based on both the understanding of material properties and the skills in selecting material or process to meet design specifications. The engineers obviously make things and they make them of engineering materials. The extensive computer-based methods and tools are therefore unavoidable in order to help designers to understand much better the preferences of various material families. Information on materials properties are therefore essential to a wide range of people in engineering enterprises – not only designers needing the right property data for engineering simulations, but also managers concerned with regulatory compliance and customers aiming for optimal purchasing decisions. Moreover, this information is also of fundamental interest to the materials engineers, quality assurance, testing personnel and others who generate, control and supply products made of engineering materials.

Key words

engineering materials, advanced technologies, technology transfer

Introduction

R&D and the transfer of the knowledge in the field of engineering materials into the industrial praxis is today strongly affected by its more recent history in which the scientific approach played a great role. During designing of the mechanical structure the engineers are driven by physicist's point of the view leading to the concepts of atomic bonding, geometry of molecular and crystal structures, crystal defects, alloy theory and phase stability, kinetics of phase transformations, mechanisms of plasticity and fracture and so on. This approach gradually moves up through the length-scales from the atomistic through the micro- to the macroscopic and that is why the most important information which the engineer really needs – to perform the proper design of the – product comes only at the end or not at all. The subject of materials is very broad, drawing together understanding from physics, chemistry, mathematics, computer science, etc. At present the applying of various materials in industry bridges these "pure" scientific disciplines and the material science is therefore becoming more or less an applied science. However, the real decisions on proper choice of engineering material and appropriate manufacturing process have much broader objectives, e.g. to minimize not only cost, but also energy consumption or CO_2 footprint per unit of function, etc. The next generation of engineers will need the ability to use conventional as well as advanced materials in ways that meet more demanding technical, environmental, economic and aesthetic requirements than ever before. In particular, the requirements for "eco-design" are today increasingly significant area in which only an integrated materials strategy provides benefits.

That is why an alternative approach is developed over the last 20 years by Prof. Ashby and his colleagues from University of Cambridge [1]. It is based on a specific satellite view of "Planet Materials" – its occupied continents and its empty oceans – giving, from the start, some ability to navigate in this new virtual world of engineering materials (**Fig. 1**). It is then possible to focus in progressively, exposing a gradually increasing level of detail. The main aim of this approach is by no means to reject the fundamentals underpinning of physics and chemistry, but these can be developed as the details requiring them to come into focus. The essential motivation for this helpful concept is to give the engineers the tools that they can immediately start to use in practice and support the project work that can be self-generated by the engineer or set by the customer.

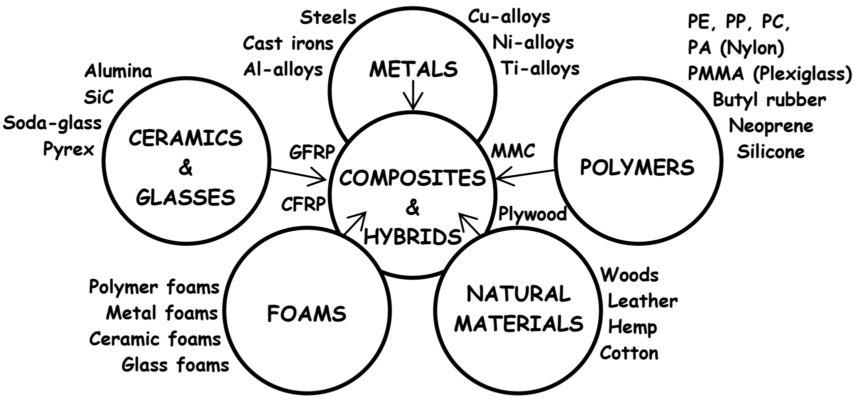

Fig. 1. *The virtual world of engineering materials [2]*

Novel approach to materials selection

The engineering materials (**Fig. 1**) are sorted to the "families", like: polymers, metals, ceramics, glasses, natural materials, and composites and hybrids that can be synthesised by combining of them. Each family embraces classes, sub-classes and members. Every member is characterised by a set of attributes – its "property profile". This structure has the merit that it allows a helpful concept: "material property chart" (see an example at **Fig. 2**) is a map of one slice through the material-property space. This chart plots stiffness, measured by Young's modulus, against weight, measured by density. It is one of a set, mapping the territory occupied by each family and the spaces in between. The bold balloons enclose the members of the families and within each of them there are the classes.

The most efficient materials selection involves four steps: *translation*, *screening*, *ranking* and *supporting information* (**Fig. 3**). In the *translation* step the design requirements are reformulated as constraints on material properties and process attributes and as one or more objectives: minimization of cost, or of weight or of environmental impact, for instance. In *screening*, these constraints are used to eliminate materials that cannot meet the requirements. It is effectively performed using a computerized database containing various material attributes, e.g. values of various physical and mechanical properties or attributes relating to the environmental impact of the production of the material itself: its energy content, the greenhouse and acidification gases created by its production, its toxicity, etc. [3].

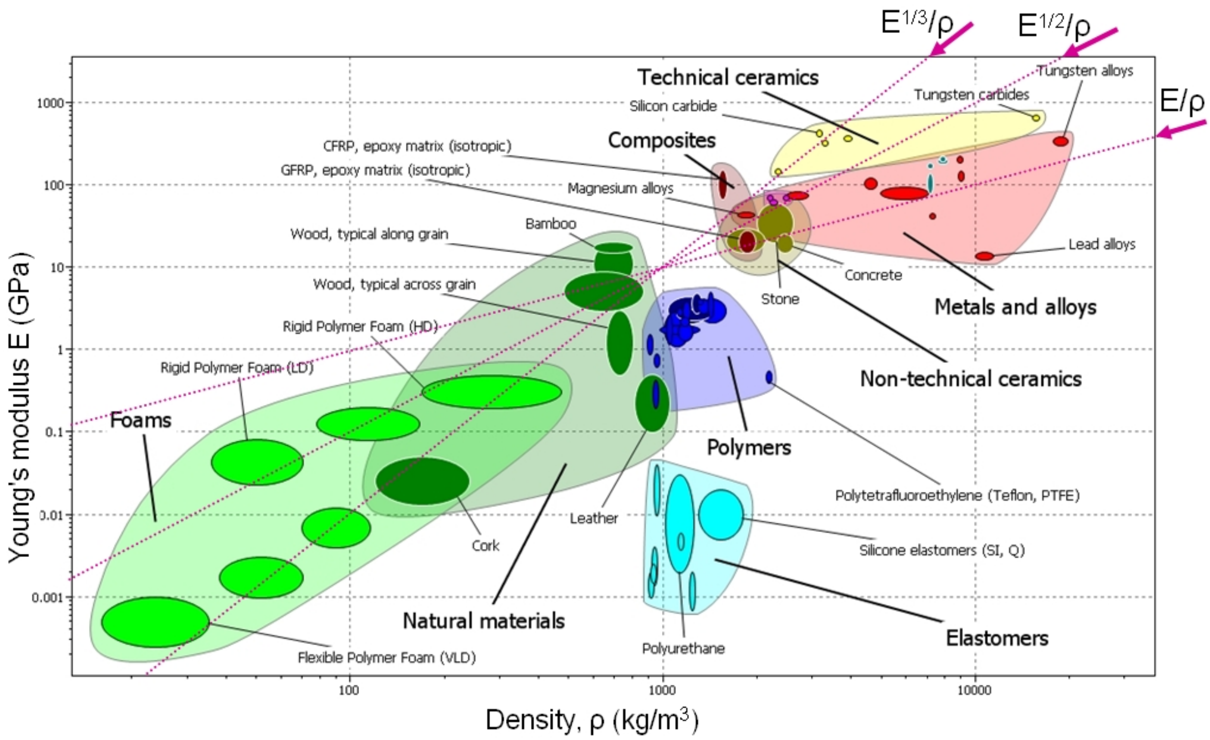

Fig. 2. *E – ρ chart showing guidelines for selecting materials for light, stiff structures according to CES EduPack 2009 [3].*

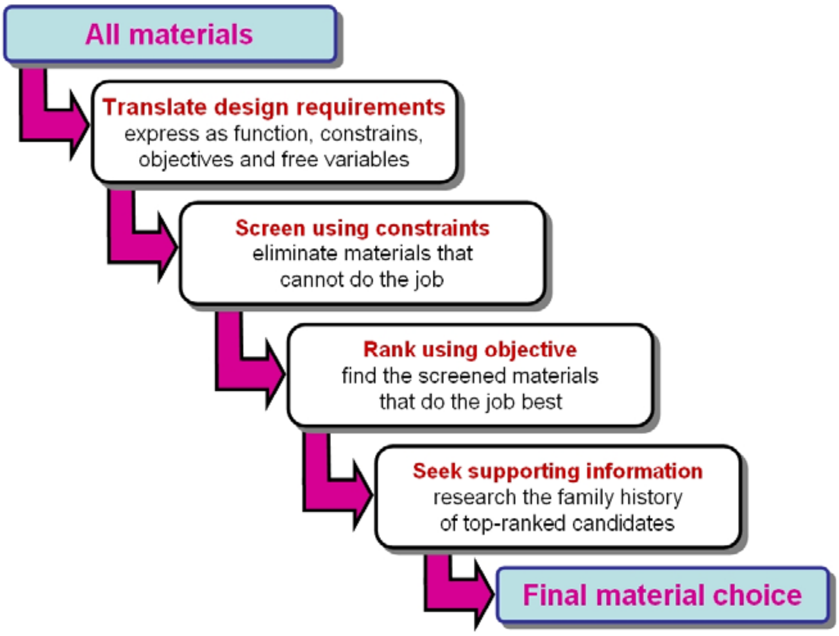

Fig. 3. *The four main steps of the strategy for materials selection*

Ranking is achieved by the use of material indices derived from the objective mentioned above. These are grouping of material properties that characterize performance: the materials with the largest values of an index maximize some aspect of performance. The specific stiffness, E/ρ (where E is Young's modulus and ρ the density), is an example of such index. Material indices can be plotted on a material selection chart, identifying materials that have attractive values of the index. The procedure allows ranking of materials according to the cost per unit of function, mass per unit of function or environmental impact per unit of function.

The output of the screening and ranking is short-list of materials that satisfy the quantifiable requirements of the design. To proceed further the seeking for detailed profile of the top-ranked candidates is required. The supporting non-quantifiable information, e.g. examples of its use, design guidelines, failure analyses, processing information or details of availability and pricing, etc. helps to narrow the short list to a final choice, allowing a definitive match to be made between design requirements and material attributes.

The chart Young's modulus vs. density (**Fig. 2**) guides selection of materials for light, stiff, components. The guide lines show the loci of points for which:

- $E/\rho = C$ (minimum weight design of stiff ties, e.g. in centrifugal loading),
- $E^{1/2}/\rho = C$ (minimum weight design of stiff beams, shafts and columns),
- $E^{1/3}/\rho = C$ (minimum weight design of stiff plates).

The value of the constant C increases as the guidelines are displaced upwards; materials offering the greatest stiffness-to-weight ratio lie towards the upper left hand corner.

Design and manufacturing processes for sustainable products

Designing and manufacturing sustainable products is a most important challenge to the industry of the future. It involves therefore highly complex, interdisciplinary approaches and solutions. **Fig. 4** shows the exponential increase in shareholder value when the innovation-based sustainability concepts are implemented against the traditional cost-cutting, substitution-based growth [5]. Engineers must keep on thinking beyond their traditional considerations of functionality, cost, performance and time-to-market also in terms of minimizing energy, consumption, waste-free manufacturing processes, reduced material utilization and resource recovery following the end of product use. For this purpose, of course, are both the involvement of stakeholders and the development of innovative technologies, tools and methods unavoidable.

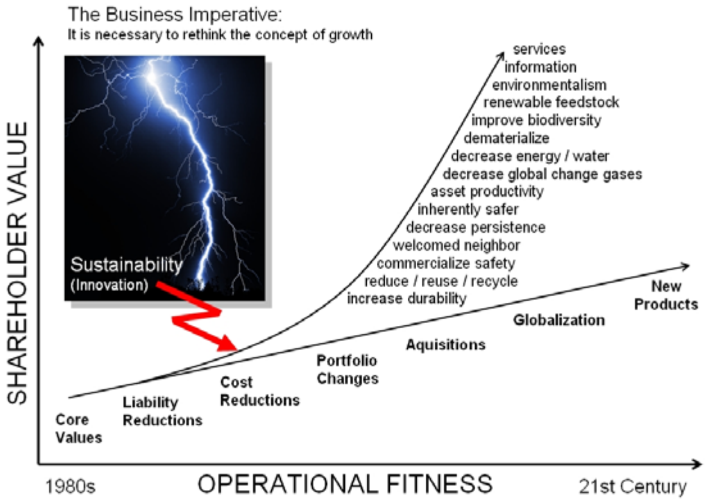

Fig. 4. *The exponential shareholding growth of innovation-based sustainability (adapted from [5]).*

Because of various societal and ethical aspects there is no universally acceptable measurement method for quantifying and assessing of product sustainability as yet. The most appropriate multidisciplinary approach for formulating the product sustainability level was developed at the University of Kentucky in Lexington within the Collaborative Research Institute for Sustainable Products (CRISP) [5]. This includes science based so-called "**P**roduct **S**ustainability **I**ndex" (PSI) which represents the level of sustainability built in a product by taking into account of the following six major contributing factors:

- product`s environmental impact (life-cycle factor – including useful life span; environmental effect – toxicity, emissions, etc.; ecological balance and efficiency; regional and global impact – CO_2 emissions, ozone depletion, etc.)
- product`s societal impact (operational safety; health and wellness effects; ethical responsibility; social impact – quality of life, peace of mind, etc.)
- product`s functionality (service life – durability; modularity; easy of use; maintainability and serviceability – including unitized manufacture and assembly effects; upgradability, ergonomics, reliability, functional effectiveness, etc.)
- product`s resource utilization and economy (energy efficiency and power consumption; use of renewable source of energy; material utilization; market value; instalation and training cost; operation cost – labour cost, capital cost, etc.)
- product`s manufacturability (manufacturing methods, assembly, packaging, transportation, storage, etc.)
- product`s recyclability and remanufacturability (dismountability, disposability, reusability, etc.)

For each major factor a single rating can be used on a percentage basis on a 0-10 scale, with 10 being the best. Each product will be required to comply with appropriate ratings for all groups. The standards are used for establishing of "acceptable" level of rating for each group. The composite rating represents the overall product sustainability (PSI).

Manufacturing processes differ very widely depending on the product being manufactured, the method of manufacture and their key characteristics. The processing cost largely depends on the method used to produce the component and selected material. In order to minimize the manufacturing cost, the industrial organizations are struggling to maintain the product quality, operator and machine safety and power consumption. The following six main influencing factors can be regarded as significant to make a manufacturing process sustainable:

- energy consumption,
- manufacturing costs,
- environmental impact,
- operational safety,
- personnel health,
- waste management.

However, it is clear that due to technological and cost implications all these factors cannot simultaneously achieve their best levels (e.g. energy consumption and environmental impact – minimum; others – maximum). The strong interactions among these factors often require trade-off and only an optimized solution would be practical.

Energy consumption

Savings of energy during manufacturing process is one of the most needed sustainability factor. The power consumption level can be observed and evaluated against the theoretical values to calculate the efficiency of the power usage during manufacturing process. Though the focus on energy efficiency has increased significantly in recent years, the industrial manufacturers have been making major strides for decades. The potential for savings of energy consumption is huge and that is why companies around the globe are highlighting their efforts to improve energy efficiency. The significant reduction in energy intensity, measured by the quantity of energy required per unit of product cost (so that using less energy to produce a product reduces the intensity), has been achieved during last years. If the renewable energy sources are available in abundance and are used in industry widely, the source of energy can significantly help to achieve extremely good sustainability of the manufacturing process.

Manufacturing costs

Manufacturing costs are the cumulative total of resources that are directly used in the process of making goods and products, including the expenses associated with the purchase of raw materials as well as human labour, equipment operation and the general overhead for maintaining the production facility, etc. These costs involve a range of expenditures starting from the process planning activities until the product is dispatched to the next workstation, including the both the idling and queuing time. The criterion for selecting appropriate processing would generally facilitate the cost-effective technological operation. The choice of processing parameters and the cost of tooling are, of course, further important factors affecting final manufacturing cost.

Environmental impact

The International Association for Impact Assessment (IAIA) defines an environmental impact assessment as the process of identifying, predicting, evaluating and mitigating the biophysical, social, and other relevant effects of development proposals prior to major decisions being taken and commitments made [7]. This is a formal process to predict the environmental consequences of human development activities and to plan appropriate measures to eliminate or reduce adverse effects and to augment positive effects.

The ISO 14000 series of standards can be used to help enterprises meet and improve their environmental management system needs. The motivation may come from the need to better manage compliance with environmental regulations, from the search for process efficiencies, from requirements of customers, from environmental campaign group pressures, or simply from the desire to be good corporate citizens.

Operational safety

Operational safety is the collection of safety services that supports operational managers achieve and maintain the high levels of safety and mechanical integrity required by regulation and by their own safety and risk processes. Several recent major industrial accidents demonstrate that industry successes in improving occupational safety have not been mirrored in major accident performance. Most of these accidents did not result primarily from deficient design, rather it was inadequate operational safety not sufficiently addressing specific threats inherent in the operation. Both the ergonomic design of the human interface with the work environment and the proper implementation of regulatory safety requirements are considered in assessing the personnel safety factor.

Personnel health

Assessment of the personnel health element contributing to the technological process sustainability is based on the compliance with the regulatory requirements, imposed on industries by governmental and regulatory enforcement units (such as The National Institute for Occupational Safety and Health – NIOSH [8]) on emissions and waste from technological operations and their impact on directly exposed labour.

Many workplace fatalities and injuries are caused by poor design of equipment and processes, yet design standards for occupational safety and health are few. It is extremely important to eliminate hazards from the workplace that result from design flaws. The prevention against health hazards through desirable design helps engineers, architects, employers and owners to recognize design issues that affect worker safety and to incorporate safe design, equipment and work practices early in the design process.

Waste management

Recycling and the disposal of all types of manufacturing wastes are accounted for in this factor influencing sustainability of manufacturing process. The efforts to find means reduce or eliminate wastes are continuing and increasingly urgent. Zero waste generation with no emissions into the environment is the ideal condition to be expected for industrial products and processes, although it is technologically in many cases very difficult achievable as yet.

Successful case studies of industrial applications of material innovations

Recent trends in development of sustainable products and processes indicate the need for using new science-based approaches for achievement of appropriate values of main factors influencing this sustainability. Institute of Materials & Machine Mechanics of Slovak Academy of Sciences (IMMM SAS) has been long time successfully applied new engineering materials and advanced technologies developed by its scientific and research activities in industrial practice due to the fact that the development of innovative products is systematically focused preferably on those with great potential to achieve particularly high added value thanks to effectively utilized know-how. These innovative products and their manufacturers are therefore predicted to obtain a good competitiveness which will in the nearest future ensure sustainable development of their entrepreneurial activities in specific industrial field.

The following applications of materials developed at the IMMM SAS can be regarded as the significant examples of highly sustainable products and manufacturing processes:

Aluminium foam crash absorber for railway carriages

Aluminium foam is a part of crash absorbing box used for enhancement of passive safety in railway carriages (see **Fig. 5**). The crash box is placed behind conventional spring-based damping element and chassis of carriage, whereas there are 4 such boxes for one carriage, two for each front side. The main objective to use aluminum foam part is to reduce high crash forces in case the absorbing capability of conventional damping elements is exhausted. In such excessive crash between adjacent carriages aluminium foam crushes as the last part of all energy absorbing components in the assembly. It is expected from the crash box to protect chassis of 22 ton heavy carriage in a case of frontal crash at the velocity of 8 km/h. The kinetic energy must be dissipated within about 30 mm deformation length.

These expectations set quite challenging requirements for aluminium foam part, i.e. very high yield stress in compression (above 17 MPa) at rather higher porosity (above 75 %). To meet these requirements special 3D shape aluminium foam component was designed comprising natural “foam skin” and cell walls made from heat treatable aluminium alloy and preferred orientation of pores in the compression direction. Compared to conventional deformation elements as i.e. hollow profiles or honeycomb structures, it was possible to reduce the deformation length needed for required energy absorption by almost 50%.

The supplier of assembled crash absorber is the German company Gleich GmbH, Kaltenkirchen. Aluminium foam component with the weight 1250 g are manufactured and supplied under subcontract by IMMM SAS (current volume 500 pieces per year). There are two world wide leading manufacturers of railway carriages as end users of this innovative crash absorber.

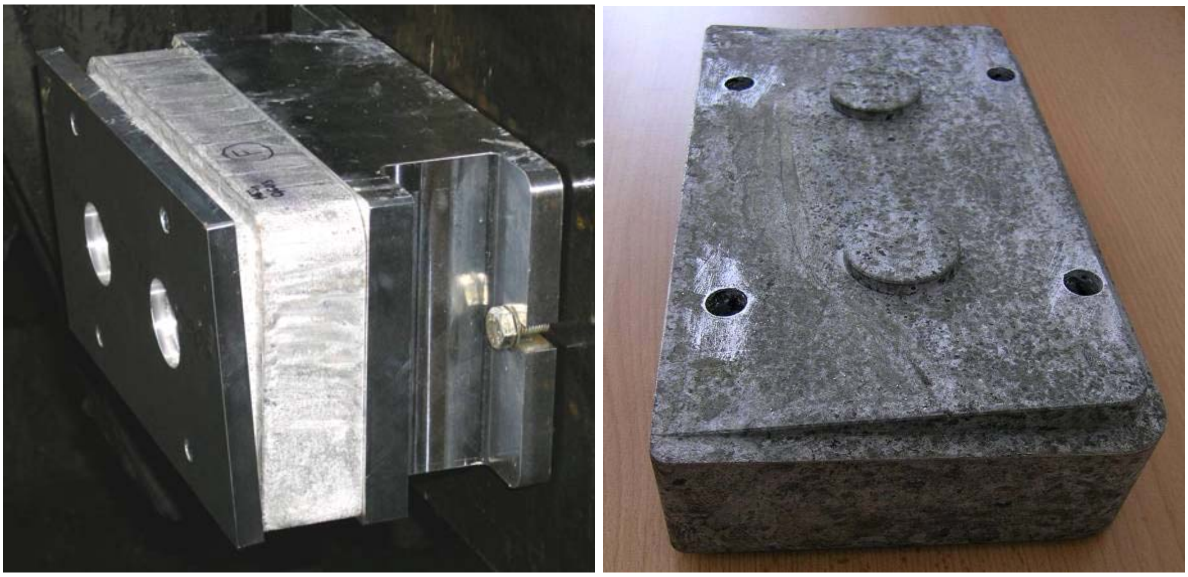

Fig. 5. *Assembled crash box containing Al foam (left) and Al foam component (right)*
Al-foam component for automotive application produced in high volume series

Crash absorbers in automotive sector protect passengers from the effect of sudden impact. This is achieved by converting the impact energy into plastic deformation of absorber, keeping the peak force acting on the protected object below the level which could cause damage. The material of impact energy absorber must also provide a long deformation path to sufficiently reduce rest of the kinetic energy affecting the protected object.

Fig. 6. *Aluminum foam crash energy absorber mounted into the dividing net of Audi Q7 developed by IMMM SAS*

IMMM SAS has developed in cooperation with Austrian company Alulight International GmbH, Ranshofen crash energy absorber (see **Fig. 6**) which is produced fully automated in high volume series (200.000 pieces per year) since August 2005 and mounted into the cars Audi Q7. This crash energy absorbing component is part of the upper segment safety net build in to separate the trunk from the passenger area. In case of sudden rear impact net has to protect the passengers against serious injuries caused by catapulted luggage items. One part of the impact energy gets absorbed by the net itself, the other part has to be transformed in the anchorages of the net to avoid them from breaking. Large energy is absorbed by the net in the case that a plateau stress stays constant for a long deformation path. This characteristic gets fully achieved by abovementioned aluminium foam crash energy absorber (see **Fig. 7**). The German company Reum GmbH & Co. Betriebs KG, Harheim decided in favour of this absorber for the new design of their dividing net protected by utility model [10]. The tube-shaped absorber made of aluminium foam mounted in the upper profile channel of the net gets strained by pressure via a pin during impact and the kinetic energy of approximately 100 kJ is transformed by deformation of absorber. The commercialisation of this crash absorbing system is carried out by the German company BOS GmbH & Co. KG, Ostfildern [11].

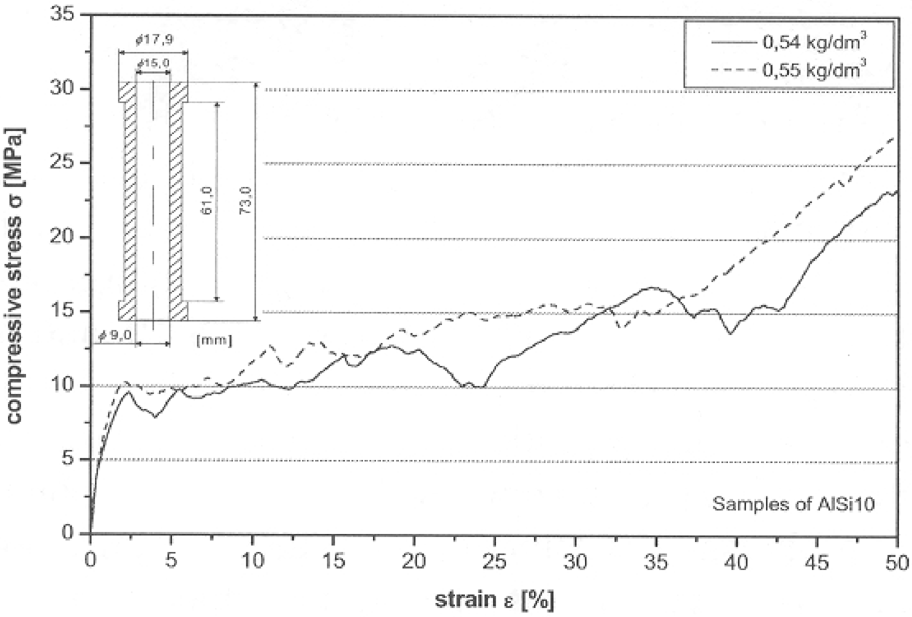

Fig. 7. *Stress-strain characteristics of aluminium foam crash absorbers [11]*

Cooling and heating panels using aluminium foams

Heating/cooling floor or ceiling panel (developed recently by IMMM SAS) which utilize aluminium foam as heat spreader has also the great potential for industrial applications. The Institute received the European patent for invention of their production in 2007 [12]. The basis of innovative approach to the new design of heating/cooling panels is aluminium foam panel with integrated copper tubes for distribution of heating/cooling medium. Aluminium foam in floor and ceiling panels in the combination with thick layer of plaster is the unique technical solution utilized firstly in industrial praxis. Uniformity of the temperature distribution in the panel, enhancement of its radiating emissivity and considerable reduction of reaction time after the temperature changes are the main advantages that can not be achieved by any other technical solution as yet.

This kind of innovative cooling possesses very low operating costs. Energy consumption is very low as well as it is almost maintenance-free and the natural water sources can also be utilized as source of cooling medium. Using these systems the air inlet volume can be reduced to a minimum, just up to a necessary fresh air volume and for sufficient thermal comfort (because of radiant heat exchange) is already 26°C enough. Beside the all benefits, a drawback of cooled ceilings is only their limited cooling power, because they operate with low temperature difference. This difference can not be wider because of danger of dewing (dew point is about 14°C; the cooling water circulating in panels must be above the dew point). On this account, rooms with cooled ceilings may be equipped with additional fan air-conditioning in order to ensure cooling ability also during the temporary extreme conditions. Panels for cooled ceiling with prevailing radiant heat exchange posses cooling performance max 100 W/m^2 for 10 K temperature difference. Cooling ceiling panels with combined radiant and convective heat exchange are able to reach about 150 W/m^2 for 10 K temperature difference.

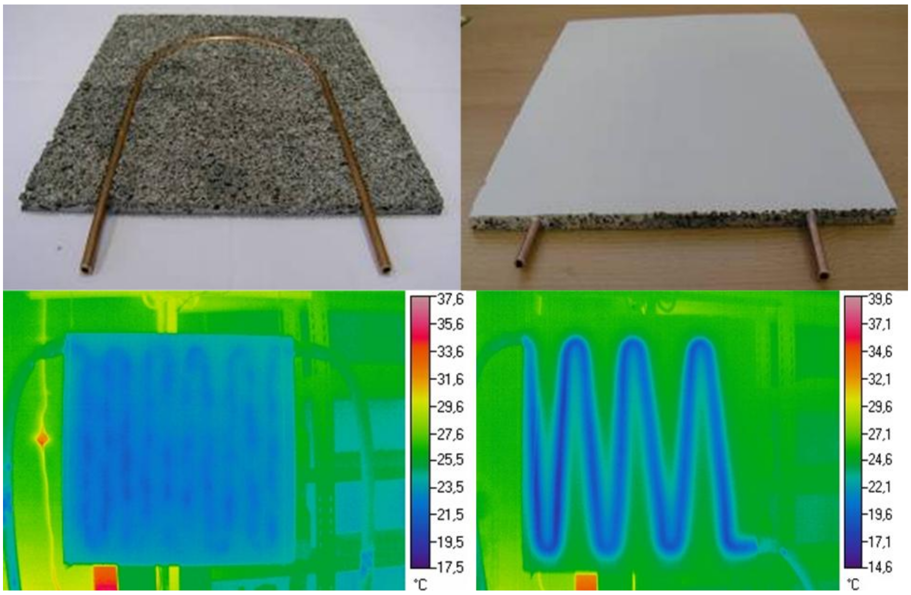

Fig. 8. *Heating/cooling floor and ceiling panels developed by IMMM SAS utilizing aluminium foam as very effective heat spreader. The lower figures shows the comparison of the temperature distribution in innovative cooling panels made of aluminium foam (left) and standard plasterboard panel with integrated tube for distributing cooling medium (right)*

Conclusion

The new innovative engineering materials and advanced technologies developed by scientist working on IMMM SAS have been long time successfully applied in various industrial fields. Besides case studies described in this contribution there are many further examples of successful cooperation with developers of cooperating industrial partners. Extremely profitable industrial innovations are e.g. aluminium foam stiffener of a hollow aluminium profile mounted in the frame of luxury cabriolets Ferrari (produced in the series of 40.000 pieces per year), stator ring for adjusting the position of camshaft in automobile engines produced for BMW by company Sapa Profiles Inc. Žiar nad Hronom using novel powder-metallurgically prepared aluminium alloy, sliding electrical contacts for trolleybuses and railway locomotives made of graphite infiltrated with copper developed in collaboration with Slovak company Elektrokarbon Inc. Topoľčany, ceramic/lead composite plates prepared by the melt infiltration process for the new type of bipolar batteries based on lead-infiltrated-ceramic – LIC™ plates developed for Swedish company EFF – Power, Hisings Backa etc. Development of innovative products is systematically focused preferably on those with great potential to achieve particularly high added value thanks to effectively utilized know-how.

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