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COMPOSITE MATERIALS IN THE CONSTRUCTION OF TRANSPORT MEANS

ABSTRACT

The saving of energy by reducing the mass of the material represents one of the basic requirements in the development of the transport technology. High potential in this direction has been recognised in the relatively new group of materials known as the composites. Their application is expected to achieve great reduction in the mass of the transport means, especially the road and railway vehicles. This paper attempts to present information about the composites, their status as well as the possibilities of their mass implementation.

KEY WORDS

composites, mass reduction, energy saving

1. INTRODUCTION

The energy crisis and the increase of the environmental awareness over the past several decades have imposed new criteria in the field of engineering materials in general, and in particular in those materials that are intended for the transport means. The focus has been on the density / strength ratio. The modification in one direction means maintaining the weight of the material and at the same time improving its properties, and in the other direction, with low weights achieving equal or better properties compared to those in traditional monolithic materials. The purpose of the latter direction of modification is to replace the heavy materials such as iron, steel, copper, etc.

According to the basic classification in the science of materials, regarding the type of chemical bond, all materials have been classified into three basic groups which are: metals, ceramics and polymers. The joining of substances at a macroscopic level regardless of the group they belong to, is a principle that has opened up unlimited possibilities of moderating properties of the new hybrid materials known as the *composites.*

Although representing a relatively new family of materials, the technologies of their development today have improved so much that more and more highly specialised composite varieties are being produced. These varieties are composed of several dissimilar materials, each of which has been specially developed to perform a certain function within the composite.

This paper attempts to explain the basic notions related to composites, their properties, potentials and role in the advanced traffic means.

2. COMPOSITE MATERIALS – NOTION AND STRUCTURE

In today's technical and technological societies the notion of *composite material*[1] encompasses a great number of structurally dissimilar materials. Very wide-ranged exploitation (from biomedical to recreation purposes), and the galloping development expansion make a systemic approach or their up-to-date classification very difficult. According to the form itself, it would be sensible to make a rough classification into the basic composites, layered products: laminates and panels, popularly known as *sandwich materials*[1] and those of woven structure.

The basic composites are those materials that result from joining two or more substances dissimilar regarding their properties, maintaining the chemical integrity of each substance. If the substances are named phases[2], then these are quasi-homogeneous mixtures composed of two or more separated phases. The phases can be defined as a continuous phase or matrix and a discontinuous or solid phase. The solid phase is in the form of long (virtually infinite) fibres, short fibres and particles: of sphere-, needle- or flake-like form. Technologically processed, the solid phase is incorporated into the matrix resulting in a hybrid i. e. composite material (Fig. 1). In order to compare the properties, the basic composites are usually classified according to the matrix substance into metal, polymer and ceramic composites. The exception are the composites with long fibres, that are usually classified regarding the substance they are made of.

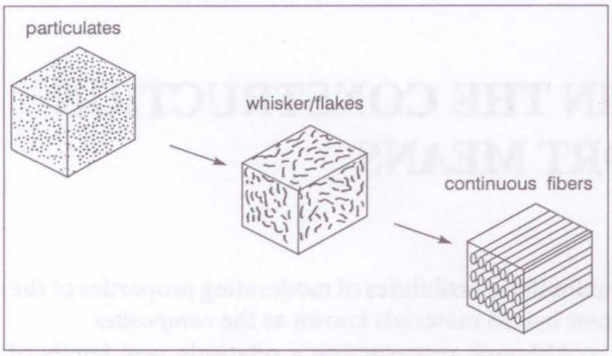

Figure 1 - Structure of the basic composite materials [1]

The joining of composite with composite or with a monolith results in the layered substances of laminar and panel structure (Figures 2, 3, 4) produced of several layers in the form of plates. The main layer or the core is of porous or non-porous structure and is adhesively bonded to the coating thin sheets. The core is the carrier of the crucial properties of materials and is usually made of the basic composite. In laminates, the core is in the form of a compact layer, and in panels it is produced into different geometrical forms (Figure 3). In order to improve a certain property, e. g. strength, the sound or thermal insulation, etc., often the core cells are filled with light materials. Layers with cores made of long fibres are often laid in several directions in order to compensate for the drawbacks of the linear orientation, i. e. in order to increase the isotropy of the properties. A special group of composites consists of the long fibres woven into various three-dimensional forms (Figure 5). Recently, great attention has been paid to the cores made of foam-light metals, polymers or ceramics [1][2][9]

A great advantage of the basic composites over the monoliths is based on the fact that during synthesis the component materials keep their individual mechanical, physical, chemical, electrical, thermal and other properties. A systemic design and carefully controlled processing parameters can produce a low density material with a whole number of improved properties. For instance, by introducing ceramics (Al_2O_3 or SiC) into the non-alloyed mild aluminium using powder metallurgy process (densification by extrusion up to 30vol. % or by infiltration up to 70vol. % ceramics) extremely high hardness is achieved as well as substantial improvement of strength and elasticity. [1]

The shape and the volume share of the solid phase are in direct relation to the mechanical properties and the load transfer mechanism in the composite. Dispersive composites feature volume shares of up to 15% and particles less than 0.1μm in diameter. The primary carrier of load is the matrix and the particles dis-

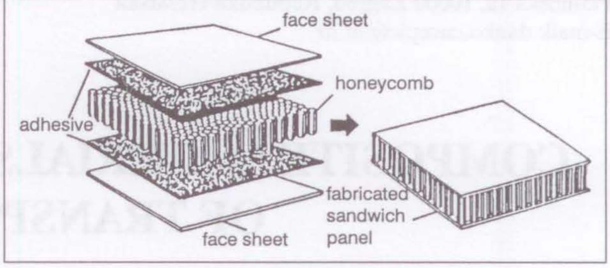

Figure 2 - Structure of a panel design

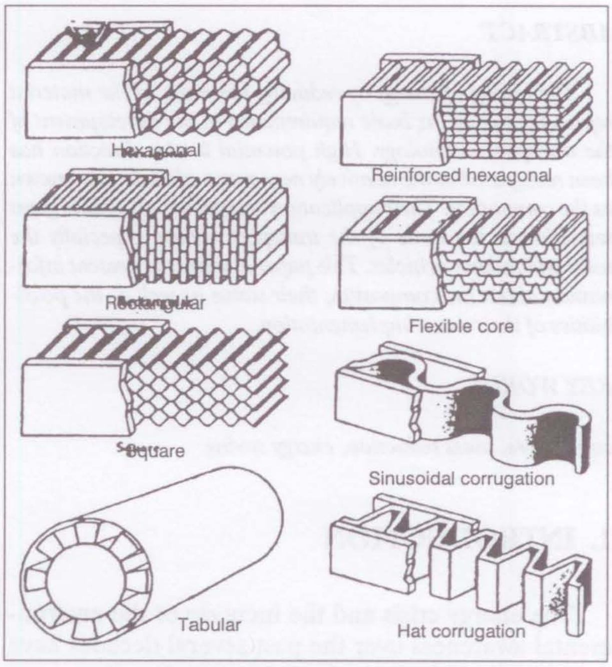

Figure 3 - Panel core geometry [9]

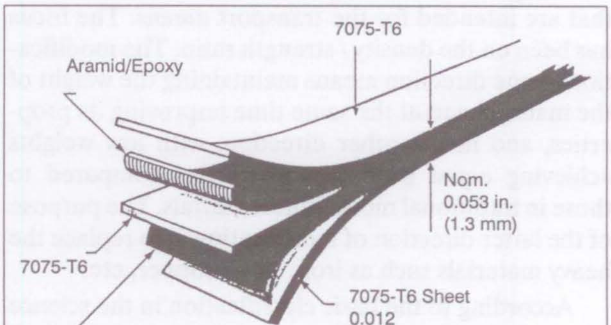

Figure 4 - Structure of laminate design Laminate of the Alcoa Arall company: Aramid-epoxy/7075-T6 Aluminium alloy

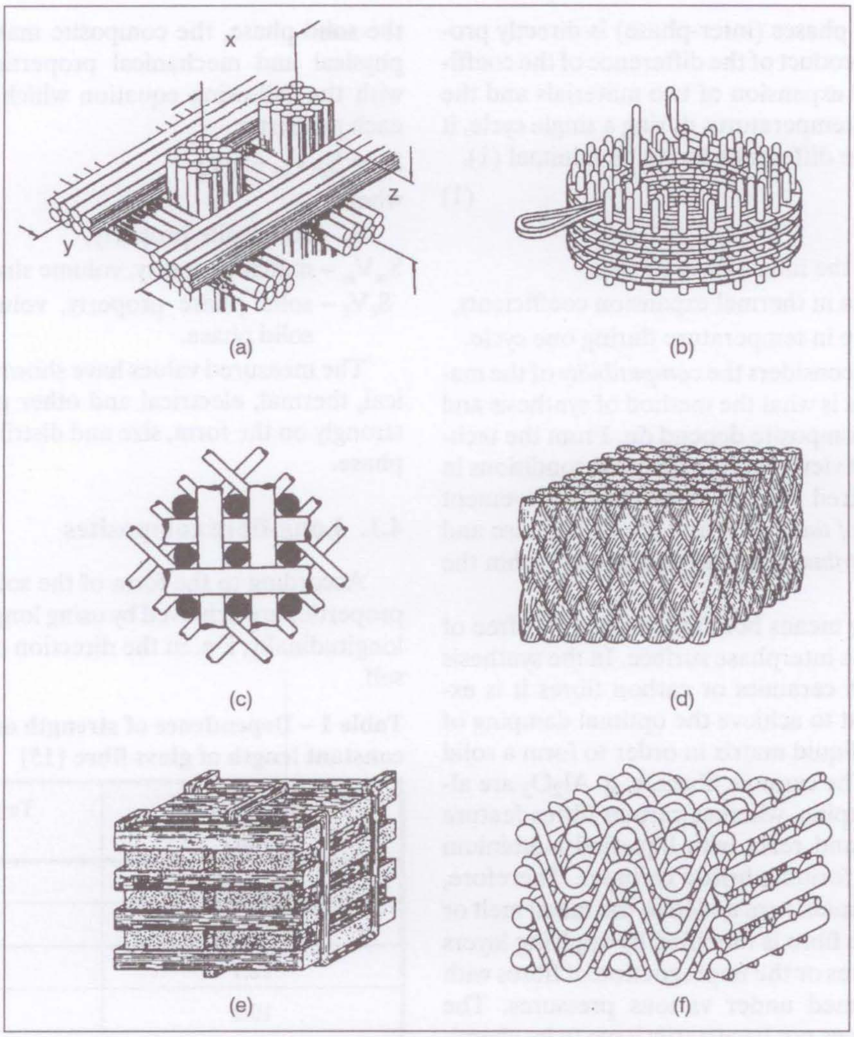

Figure 5 - Geometry of different 3D structures of carbon fibres: (a) rectangular, (b) cylindrical, (c) 5D tangle, (d) braid, (e) rectangular layered, (f) angular tangle [2]

perse in order to avoid the propagation of defects in the matrix. In composites with particle shares greater than 25% and short fibres greater than 0.1μm in diameter, the solid phase shares the load with the matrix. The long-fibre composites feature shares of fibres above 50%. Fibres are primary carriers of load whereas the matrix represents the bonding medium. [1]

3. BASIC PARAMETERS OF THE SYNTHESIS OF THE BASIC COMPOSITES

The initial step in the synthesis of a certain composite is to consider the *exploitation conditions* and these include: temperature (differences, change rate), pressure (differences, change rate), load (types, change rate), chemical condition of the environment, radiation, and the expected life-cycle. After having defined the conditions, the materials are selected whose joining should lend adequate combination of the properties that would meet the required conditions.

To illustrate the complexity and rigorousness of the exploitation conditions, the best example are the spacecraft. Apart from numerous natural phenomena such as vacuum, atomic oxygen, various types of radiation, micro-meteoroids found near the Earth orbit, the space stations, for example, are exposed to very frequent and wide temperature oscillations. During their 30-year service life, entering and exiting the Earth's shadow, the space stations pass through 175,000 thermal cycles ranging from +125°C to –125°C. This shows that the conditions require materials of the lowest possible density with extremely precisely dimensioned stability under high mechanical, dynamic, thermal and radiation loads.

Apart from the good physical and mechanical properties, the component materials have to be combined in such a way as to render the zero-coefficient of thermal expansion of the composites. Since the strain on the margin of phases (inter-phase) is directly proportional to the product of the difference of the coefficients of thermal expansion of two materials and the difference of the temperatures during a single cycle, it is obvious that the difference has to be minimal (1).

$$\varepsilon = \Delta\alpha * \Delta T \qquad (1)$$

where

ε – stress on the inter-phase surface,
$\Delta\alpha$ – difference in thermal expansion coefficients,
ΔT – difference in temperature during one cycle.

The next step considers the *compatibility* of the material because this is what the method of synthesis and the price of the composite depend on. From the technological point of view, the fundamental conditions in realising the desired properties are the achievement of *good bonding of the matrix* and the solid phase and *homogeneous distribution of the solid phase* within the matrix.

Good bonding means bonding of materials free of degradation of the interphase surface. In the synthesis of the metal with ceramics or carbon fibres it is extremely important to achieve the optimal damping of the fibres by the liquid matrix in order to form a solid chemical bond. The ceramic fibres, e. g. Al_2O_3 are almost free of damping, whereas carbon fibres feature strong damping and react with liquefied aluminium and magnesium, forming brittle carbides. Therefore, various active elements are added to the metal melt or the surface of the fibre is modified by applying layers of active substances or the impregnation of fibres with matrix is performed under various pressures. The bond of phases does not necessarily have to be chemical. It may be also purely mechanical as in the case of bonding ceramic phase and the metal matrix in some powder metallurgy techniques.

The best example of difficulties in achieving the *homogeneous distribution* is provided by the composites with spherical particulates in the metal matrix. In case of share of particles greater than 30% and the diameter exceeding 25μm, the aggregation of particles represents a grave problem, regardless whether it is the mixing of particles into the metal melt by using the liquid metallurgy techniques or the powder metallurgy techniques (sintering, extrusion, infiltration). The points of contact between the particles initiate cracking of materials even under minimum load. In the powder metallurgy techniques, the aggregation does not allow full densification and this results in porosity. [1]

4. MECHANICAL PROPERTIES OF THE BASIC COMPOSITES

According to the theoretical model – *the mixing rule,* under ideal processing conditions, i. e. with perfect bond of phases and homogeneous distribution of the solid phase, the composite material should have physical and mechanical properties in compliance with the following equation which yields others for each property:

$$S_k = S_m V_m + S_{\check{c}} V_{\check{c}} \qquad (2)$$

where

S_k – composite property,
$S_m V_m$ – matrix property, volume share of the matrix,
$S_{\check{c}} V_{\check{c}}$ – solid phase property, volume share of the solid phase.

The measured values have shown that the mechanical, thermal, electrical and other properties depend strongly on the form, size and distribution of the solid phase.

4.1. Long-fibre composites

According to the form of the solid phase, the best properties are achieved by using long fibres, measured longitudinally, i. e. in the direction of the fibre axis itself.

Table 1 – Dependence of strength on diameter with constant length of glass fibre [15]

Fibre diameter μm	Tensile strength GPa
19.0	0.7
15.2	0.9
12.7	1.0
10.2	1.3
8.6	1.7
5.1	2.8
2.5	6.0

The mechanical properties of composites are directly related to the diameter and share of fibres. By reducing the fibre diameter and by increasing the share, the longitudinally measured properties mark an extreme increase (Tables 1, 2; Diagram 1). Techno-

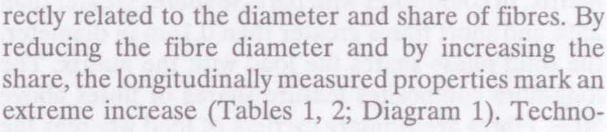

Diagram 1 - Comparison of theoretical and measured strength values: steel fibres in aluminium matrix [9]

Table 2 - Variation of mechanical properties re. angle of measurement of laminar composites: Mg+35 vol.% and Mg+55vol.% + Al_2O_3 of long fibres; [2]

Al_2O_3 fibres vol. %	Angle of measurement, °	Strength MPa	Modulus of elasticity, GPa	Elongation %
35	0.00	383	149	0.26
	22.5	207	116	0.52
	45.0	108	90	0.45
	90.0	104	85	0.42
55	0.00	608	197	0.30
	22.5	196	155	0.81
	45.0	157	124	0.58
	90.0	67	90	0.24

Table 3 - Comparison of measured and theoretical values of mechanical properties in Mg and Al composites with carbon fibres of different qualities, regarding the bonding quality [3]

	Modulus of elasticity, GPa		Strength, MPa	
Carbon fibres	measured	theoretical	measured	theoretical
Mg+63vol.% carbon fibres				
T300	163	161	970	2275
T700S	163	161	936	3120
T1000G	195	202	1079	4046
M30S	197	202	1086	3492
M40	268	263	1099	1760
M55J	337	356	1297	2566
Al+63vol.% carbon fibres				
T300	169	168	358	2241
T700S	157	168	256	3104
T1000G	193	208	285	4030
M30S	192	208	1293	3475
M40	258	270	1084	1743
M55J	359	363	1314	2549

logically, the laminar structures allow maximum share of about 65%, 2D structures 50-60%, and various 3D structures 40-55%. The deviations of the measured values of strength from the theoretical ones are related to the degradation of phases in the margin zones, i. e. impossibility to achieve the optimal bonding of phases. (Table 3)

Since they are the main load carriers and since their share in the composite is high, their basic properties have stronger moderation on the composite properties than the properties of the matrix.

The coefficient of carbon fibre thermal expansion, for instance, is negative, and with light metals of good thermal conductivity such as magnesium this leads to minimal coefficient values of the thermal expansion of composites. Carbon fibres integrated in magnesium represent one of the dimensionally most stable composites intended for the construction of aircraft parts requiring transfer and conduction of heat. Carbon fibres integrated into carbon matrix, on the other hand, yield one of the most resistant materials for exploitation at high temperatures with frequent wide-ranged temperature changes.

The main drawback of the fibres as a solid phase is the non-isotropic properties, which can be seen in Table 2, and the high price of production.

4.2. Short-fibre composites

In comparison with long fibres, short fibres as well as longitudinally directed needle particles yield substantially poorer properties. (Diagram 2)

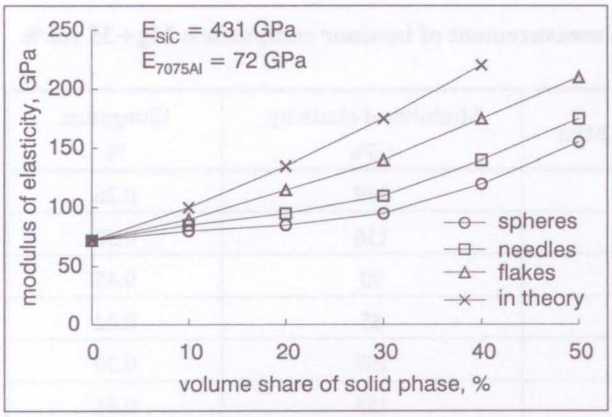

Diagram 2 - Influence of shape and volume share of solid phase (SiC) on the modulus of elasticity of Al/SiC composite [9]

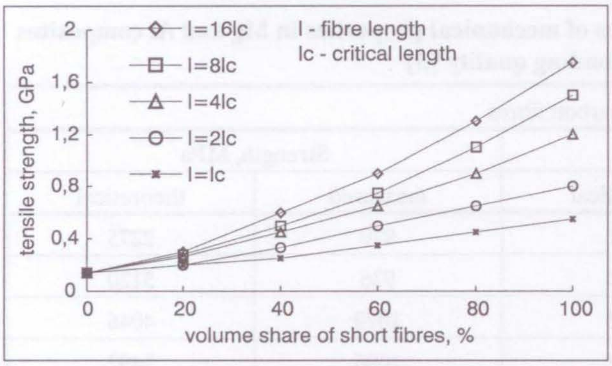

Diagram 3 - Influence of l/lc ratio and volume share of short fibres (SiC) on the strength of Al/SiC composite; at l=16lc the 96% strength of long fibre is reached [9]

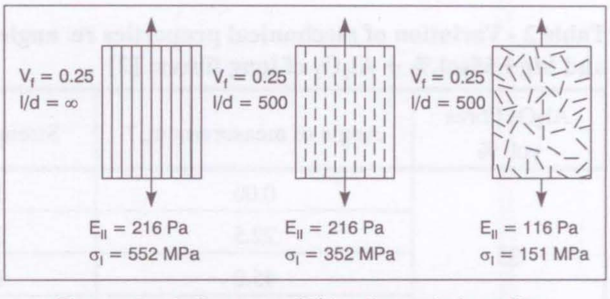

Figure 6 - Influence of l/d ratio and short fibre orientation on longitudinal strength and modulus of elasticity of glass fibre – epoxy matrix composite [2]

The degradation of mechanical properties of short fibres is primarily caused by the difficulties in achieving optimal length and non-longitudinal orientation of the fibres (Diagram 3, Figure 6). The optimal length is the ratio between the length and the critical minimal length necessary for complete load transfer from the matrix to the fibre, expressed by equation (3). In needle solid phases the deviation from the longitudinal orientation is also one of the main causes of the deterioration of mechanical properties.

Isotropic space orientation of short fibres and needle particles in the composite yields much poorer properties than the longitudinal orientation and it is comparable with the properties of composites with spherical particles compared to which it is somewhat better. (Table 4)

$$\sigma_k=\sigma_{\check{c}}\,[V_{\check{c}}(l-l_c/2l + E_m/E_{\check{c}}(l-V_{\check{c}})] \qquad (3)$$

where

σ_k – composite strength,

$\sigma_{\check{c}}$ – solid phase strength,

$V_{\check{c}}$ – volume share of solid phase,

lc – minimal length of the solid phase necessary for complete load transfer from the matrix to the fibre,

Table 4: Comparison of mechanical properties of composites produced by powder metallurgy [2]

Composites	Vol. share %	Limit of proportion. MPa	Tensile strength MPa	Module of elasticity GPa	Elongation %	Fracture toughness MPa/m$^{-1/2}$
needle particles (w), l/t-longitudinal, transversal						
1100 Al-SiCw(l)	18	183	324		5.0	7.1
6061 Al-SiCw(l)	20	443	584	122	1.8	6.3
6061 Al-SiCw(l)	20	409	480	91	3.8	55
2124 Al-SiCw(l)	15	573	718	114	5.3	59
2124 Al-SiCw(t)	15	386	559	95	8.5	
7075 Al-SiCw(l)	18	437	617		2.8	
spherical particles (p),l/t-longitudinal, transversal						
1100 Al-SiCp(l)	19	110	199	95	16	
6061 Al-SiCp(l)	25	345	410	99	4.4	15.8
6061 Al-SiCp(t)	25	350	409	98	4.0	14.5
6061 Al-B4C5p(l)	20	396	464	101	4.7	

$$lc = (dV_{\check{c}}/\sigma_m),$$

d – fibre diameter,

σ_m – matrix strength.

l – solid phase length,

E_m – modulus of elasticity of the matrix,

$E_{\check{c}}$ – modulus of elasticity of the solid phase.

4.3. Spherical particle composites

The spherical particle composites compared to the above-mentioned morphologies of solid phase feature the poorest properties. However, their great advantage lies in the isotropic properties and relatively simple methods of production. They are produced by direct combination of particles and the matrix or nucleation and growth (in-situ composites) of particles in the matrix.

The size of particles has great influence on the properties. The particles of smaller diameter yield better properties (diagrams 4, 5, 6). With the increase in share the bigger particles mark slight improvements. For share greater than 50 vol. % the particle aggregation is characteristic (Figure 7). In case of nucleation(in-situ) techniques it is not as marked as in techniques of direct mixing of the matrix and the solid phase. For the integration of greater shares of big particles the infiltration techniques are used.

The composites with metal matrices and ceramic phase can reach maximal strength values up to double the value of matrix with the modulus of elasticity

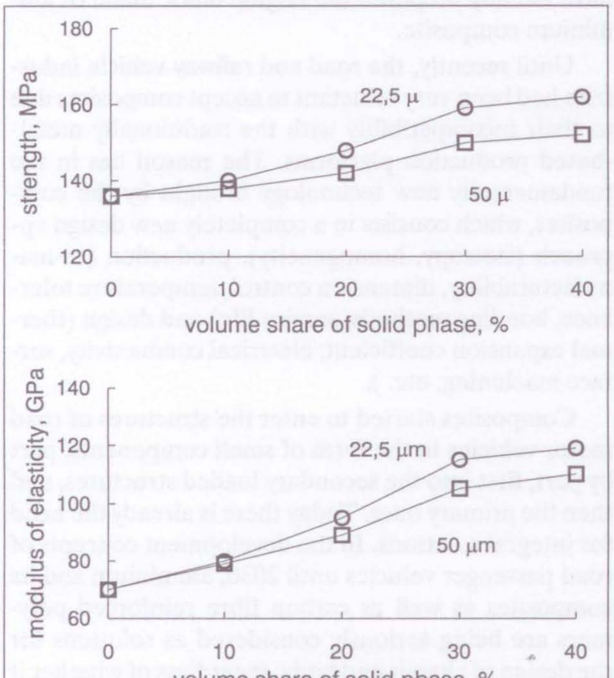

Diagram 4 - Dependence of the strength and modulus of elasticity on the size of the spherical particle: Al/Al$_2$0$_3$ composite [1]

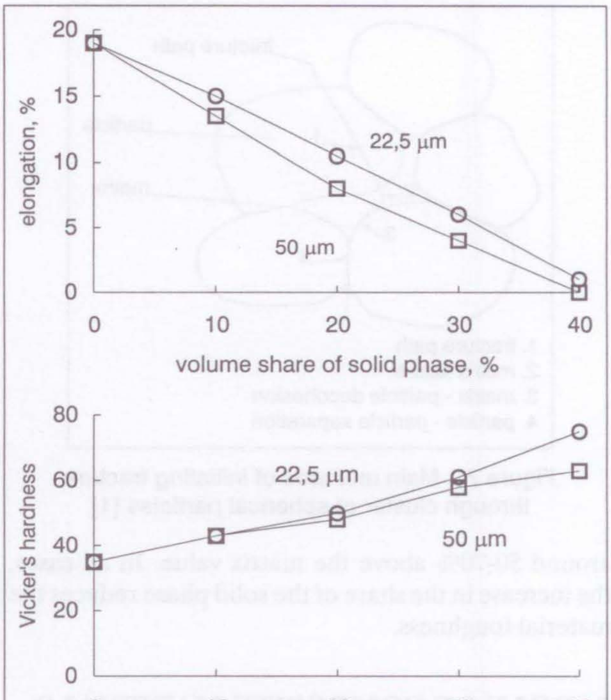

Diagram 5 - Dependence of elongation and hardness of composite on the size of spherical particulate: Al/Al$_2$O$_3$ composite [1]

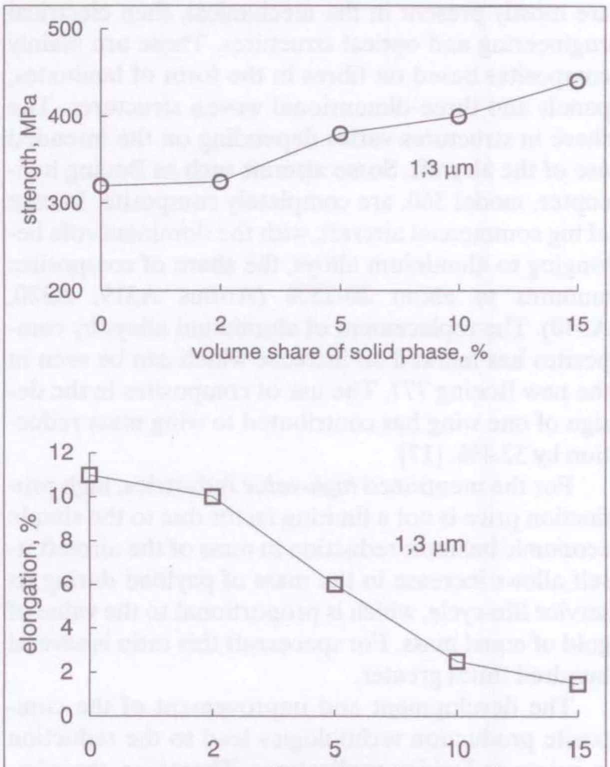

Diagram 6 - Dependence of strength and elongation of Al-4Cu-1.5Mg/TiB$_2$ composite on TiB$_2$ with constant size of particulates [1]

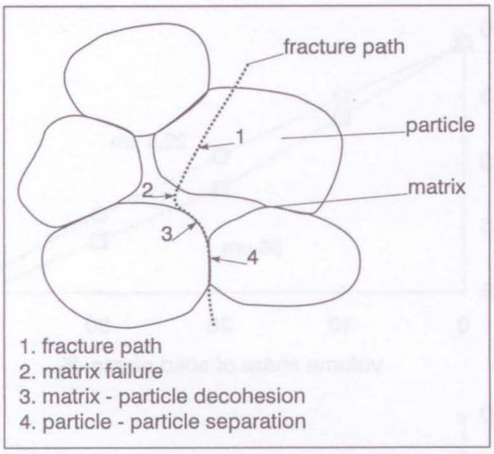

Figure 7 - Main methods of initiating fracture through cluster of spherical particles [1]

around 50-70% above the matrix value. In all cases, the increase in the share of the solid phase reduces the material toughness.

5. ROLE OF COMPOSITE MATERIALS IN TRANSPORT MEANS

The biggest users of composite materials over the last decades and today are the space-, military- and commercial aircraft industries. Regarding mass, they are mostly present in the mechanical, then electrical engineering and optical structures. These are mainly composites based on fibres in the form of laminates, panels and three-dimensional woven structures. The share in structures varies depending on the intended use of the aircraft. Some aircraft such as Boeing helicopter, model 360, are completely composite. In case of big commercial aircraft, with the dominant role belonging to aluminium alloys, the share of composites amounts to about 20-25% (Airbus A319, A320, A340). The replacement of aluminium alloys by composites has marked an increase which can be seen in the new Boeing 777. The use of composites in the design of one wing has contributed to wing mass reduction by 32.4%. [17]

For the mentioned *high-value* industries, high production price is not a limiting factor due to the simple economic balance: reduction in mass of the aircraft itself allows increase in the mass of payload during its service life-cycle, which is proportional to the value of gold of equal mass. For spacecraft this ratio is several hundred times greater.

The development and improvement of the composite production technologies lead to the reduction in prices and wider applications. Therefore, their implementation is expanding fast in the production of advanced water, road and rail transport means.

Due to the lowest production price, the mostly used fibre-based composites are those with glass fibres. From the rest, the most widely used are the aluminium composites with ceramic particles. It is no secret that all the bigger passenger car manufacturers have already prepared the engine block made of aluminium composite.

Table 5 – Materials used in an average passenger vehicle in the U. S. A. in 1994 [14]

Material	Mass/kg	%
Mild steels	631	43.8
High-strength steels	120	8.3
Stainless steels	20	1.4
Other steels	19	1.4
Total amount of steel	790	54.9
Cast iron	185	12.8
Total amount of ferrous materials	975	67.7
Plastic/composites	112	7.7
Aluminium	83	5.8
Rubber	61	4.2
Glass	40	2.7
Copper	19	1.3
Powder metals	12	0.8
Cast zinc	7	0.5
Other materials	45	3.1
Fluids/lubricants	86	5.9
Total	1440	100

Until recently, the road and railway vehicle industries had been very reluctant to accept composites due to their incompatibility with the traditionally metal-based production platforms. The reason lies in the fundamentally new technology brought by the composites, which consists in a completely new design approach (isotropy, homogeneity), production (re-manufacturability, dimension control, temperature tolerance, bonding methods, service life) and design (thermal expansion coefficient, electrical conductivity, surface machining, etc.).

Composites started to enter the structures of road motor vehicles in the form of small components, part by part, first into the secondary loaded structures, and then the primary ones. Today there is already the need for integral solutions. In the development concepts of road passenger vehicles until 2030, aluminium and its composites as well as carbon fibre reinforced polymers are being seriously considered as solutions for the design of chassis and body, regardless of whether it refers to classical engine, electrical battery or hybrid propulsion. The share of ferrous materials in the design of an average passenger car produced in 1994 amounted to 67.7%. (Table 5) If the replacement

Table 6 – Relative mass/price ratio of materials in the design of an average passenger car produced in 1994 [14]

Material	Material to be replaced	Mass reduction, %	Relative ratio of prices
High-strength steels	Mild steel	10-20	1
Aluminium	Steels, Cast iron	40-60	1.3-2
Magnesium	Steels, Cast iron	60-75	1.5-2.5
Magnesium	Aluminium	25-35	1.0-1.5
Composite:Glass fibre / polymer	Mild steel	25-35	1.0-1.5
Composite: Carbon fibres/polymer	Mild steel	50-65	2.0-10+
Composites with aluminium matrix	Steels, Cast iron	50-65	1.5-3.0
Titan	Alloyed steels	40-55	1.5-10+
Stainless steels	Mild steels	25-40	1.2-1.7

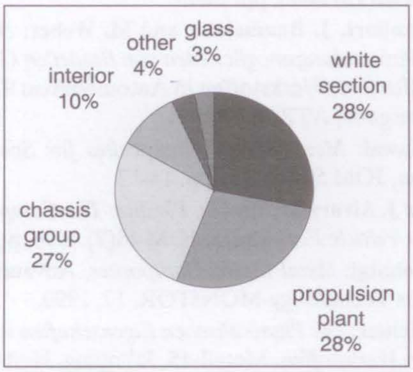

Diagram 7 - Mass distribution per groups in average passenger vehicle manufactured in 1995. White section is the area which theoretically allows complete usage of light materials. [16]

were carried out only with aluminium composites, the vehicle mass would be reduced by somewhat over 50%. The carbon-fibre reinforced polymers are lighter than aluminium by 30% on the average. In both cases the price of the composite is high compared to the ferrous materials. In carbon fibre based composites this ratio can be greater than 10 times (Table 6). The glass fibre reinforced polymers are less expensive but somewhat heavier.

With today's technological possibilities, the mass reduction by about 30% is possible without any major increase in price compared to the baseline material used in the 1994 automotive production (Table 5). The economic balances show that the mass reduction from 30 to 50% would increase the price by about 1.5 times.

6. CONCLUSION

Composite materials are the new generation of materials which has been undoubtedly very successfully replacing the traditional monolithic materials in the design of transport vehicles. Their usage significantly reduces mass and increases reliability, due to the increase in the loading capacity and the service life. In road passenger vehicles, for every 1% of mass reduction the fuel saving amounts to 0.66%. Regarding environmental effects of carbon dioxide emissions, the highest pressure regarding mass reduction is precisely on this group of vehicles. It is responsible for the emission of over 50% of the total amount of carbon dioxide of all the transport means (20% of the total emission of all the activities).

The exclusivity of using composites, due to their high price, belonged until recently to air- and spacecraft. By improving the existing and developing new technologies of production, the price has fallen substantially allowing wider implementation although still selectively (super high-speed trains, higher class passenger vehicles). The composites of aluminium and polymer matrices with discontinuous solid phase have greater chances regarding massive application. Compared to long fibres the discontinuous solid phase shows poorer mechanical properties, but its great advantage lies in the isotropy of properties.

Great challenge to the technical profession today is also presented by the recently discovered nano-composites. Although they have not yet left the laboratory, the preliminary tests promise extraordinary technical properties. The solid phase of nano-metric values is integrated into the matrix in very simple ways. The fibres of nano-metric diameters compared to the above-mentioned micro diameters are dozens of times stronger, and the nano-metric metal crystals, e. g. of copper, are five times harder than the micro ones.

Apart from great challenges there are also big problems related to composites. One of them is the impossibility of classification and standardisation because of the great diversity of properties and designs.

Unlike monolithic materials, composites have introduced a new approach into the materials science based on the technologies of "joining the unjoinable". New technologies have opened the door to unlimited possibilities of creation, making the composites the most prospective materials of the future.

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SAŽETAK

KOMPOZITNI MATERIJALI U KONSTRUKCIJI PROMETNIH SREDSTAVA

Ušteda energije kroz smanjenje mase materijala jedan je od glavnih zahtijeva u razvoju prometne tehnike. Veliki potencijal u ovom smjeru prepoznat je u relativno novoj grupi materijala nazvanih kompoziti. Njihovom uporabom predviđaju se velika smanjenja mase prijevoznih sredstava, osobito cestovnih i željezničkih. Svrha ovog članka je upoznavanje sa kompozitima, njihovom statusu kao i mogućnostima masovnije primjene.

KLJUČNE RIJEČI

kompoziti, smanjenje mase, ušteda energije

REFERENCES

1. In English, the word *composite* is used for both forms, whereas in German the basic composite is known as *Verbundwerkstoff* and the laminates and panels are known as *Werkstoffverbunde*.
2. In engineering thermodynamics, in studying the balance states, the expression *phase* means the aggregate state of the substance in homogeneous systems: in heterogeneous systems such as alloys, the word *phases* denotes separate substances that result from the process of crystallisation, so that e. g. in alloys, the solid aggregate state contains pure metal, solid solutions of one or more metals, or intermetallic compounds. Although the sense of the expression *phase* in alloys is analogue to the expression in the above-mentioned definition of the basic composites, it has not been founded on the thermodynamic criteria.

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