

THE IMPLICATION OF ARAMID FIBRES IN OBTAINING DYNAMIC SOLICITATION-RESISTANT COMPOSITE MATERIALS

Gheorghe Radu Emil MARIES¹, Dan CHIRA²

¹University of Oradea, Romania, maries.radu@rdslink.ro

²University of Oradea, Romania, dchira@uoradea.ro

Abstract—The object of the present study is the analysis of representative properties of aramid fibres and their role in the manufacture of organic composites which are used in the following fields: navy (special equipment for yachts and military vessels, armour plates), the automotive industry (tyre texture, clutches), military technology, sports equipment, etc.

Keywords—aramid fibres, composite materials, automotive industry, military technology

I. INTRODUCTION

CIVILIZATIONS were defined by the construction materials which were used in different historical periods: the Stone Age, the Bronze Age, the Iron Age, the steel age, the aluminium age. The 21st century marks the beginning of the composite materials age.

The current evolution of our society led to the development of new products and services with a higher degree of complexity. Materials used in ever larger quantities, with specialized and diversified properties and improved performance in terms of quality and variety play a significant part in the general development of our society [1,2].

Research studies and attempts to obtain new super-materials led to the development of a class of products known as composite materials.

In its wider sense, the term refers to the combining of two different materials whose qualities complete each other, resulting in a composite, i.e. a heterogeneous material whose global performances are superior to those of its component materials.

Man has been interested in composite materials for a very long time (adobe, for instance, is a composite consisting of clay and straw).

Nowadays, organic composite materials are of great technical interest. These composites consist of an organic matrix and a reinforcing agent, most frequently in the form of powders, fibres or fabrics.

The percentage of reinforcing agent varies according to the technology used and it is the main factor of resistance.

Products based on such materials have a high resistance, comparable or even superior to that of

metals. The assessment of organic composite materials depends on a number of factors:

- the nature of the organic matrix (thermo-reactive or thermoplastic)
- the nature, structure, placement and quantity of the reinforcing agent
- the manufacture technology
- the cost of raw materials
- the production costs
- the mechanization and automation difficulties.

The most important uses of composite materials are in aeronautics and astronautics, as well as in the arms industry. The main reason for this is the materials' low specific weight and their remarkable mechanical resistance. The automotive industry favours molded composites which can be obtained through automation.

In comparison to homogeneous materials, composites have the following advantages:

- superior rigidity and (mass-related) specific resistance when compared to various types of steel and aluminium alloys,
- remarkable fatigue resistance, 2-4 times higher than that of metals,
- excellent resistance to corrosion,
- good tenacity.

Disadvantages:

- ageing under the action of UV-radiation and water,
- low resistance to heat (organic matrix).

II. REINFORCING MATERIALS

The reinforcing material is introduced into the structure of the composite with the direct purpose of increasing and directing the physical and mechanical properties towards the desired goal. To that effect, the introduction of the reinforcing material in the matrix is intended to improve its mechanical resistance, rigidity, hardness and specific resistance [14].

Reinforcing materials also ensure an improvement in terms of thermal behaviour, fire resistance, the coefficient of thermal expansion, resistance to abrasion, electrical properties, etc. [1,3,4,5,6,7,8,9,10].

The influence of the reinforcing material on the composite depends on the nature and type of the

reinforcing agent used, its natural form, the adhesion degree between phases, the technological formation process and the technical conditions during formation.

When choosing the reinforcing material, one must take into account the technological processing of the formed part, the direction of the mechanical efforts and the economic and financial criteria regarding its serial production.

Strictly considering the reinforcing material, it must have the following properties:

- highest possible mechanical resistance (to traction, shock and bending), must be higher than that of the polymer matrix,
- increased resistance to chemical agents,
- a form that can take over the mechanical efforts to which the part is subjected and in accordance with the exterior shape of the object,
- production batches should display constant physical and chemical properties,
- good compatibility and adherence to the polymer matrix,
- should not influence the chemical process and reactions which take place during the polymer-matrix hardening,
- should easily blend with the polymer matrix
- it should not separate from fluid mixtures.

According to their nature, reinforcing materials can be classified as follows:

- vegetable reinforcing materials: wood, cotton, jute, flax, sisal, etc.
- mineral reinforcing materials: alumina, asbestos, mica, etc.
- synthetic reinforcing materials: polyester, polyamide, etc.
- artificial reinforcing materials: boron, carbon, silicon carbide, steel, etc.

According to their form, reinforcing materials can be classified as follows:

- fibre reinforcing materials and
- pulverous or granular reinforcing materials.

The most common fibre reinforcing materials are:

- glass fibres,
- carbon fibres,
- boron fibres,
- high modulus ceramic fibres (alumina and silicon carbide),
- silica fibres,
- asbestos fibres,
- aramid fibres,
- low modulus thermo-stable fibres,
- vegetable fibres (wood, sisal, jute, flax, hemp),
- polyester fibres,
- metallic fibres (copper, aluminium, stainless steel),
- monocrystalline filaments (whiskers).

This category includes materials with a length-to-diameter ratio (l/d) higher than 50, which gives them an elongated exterior shape, since their length is significantly higher than their diameter.

In practice, taking into consideration the l/d ratio, there are:

- short fibres, with $l/d = 50 - 500$,
- long fibres, with $l/d = 1000 - 10000$,
- continuous fibres, with $l/d = \text{infinite}$.

Monocrystalline filaments or whiskers hold a special place among fibre reinforcing materials [1,3,11]. These are single crystals with a diameter of 1 - 25 μm and a length of 100 - 15000 d , which gives the fibre very high mechanical resistance.

Whisker-reinforced polymers ensure better mechanical solicitation resistance and higher elasticity moduli of the composites in comparison to fibres with similar chemical composition. This is explained by the high l/d ratio and by the faultlessness of the crystalline structure, which results in a minimum influence of the defects on the mechanical resistance.

General observations on fibre reinforcing materials:

Short fibres:

- in pressure mixtures they have a statistic arrangement which allows for an even effort take-over in all directions,
- in injected mixtures the fibres are oriented in the flow direction of the polymer melt,
- relatively easy to mix with resin,
- easy dosage and handling,
- they lend better mechanical properties to the composites than pulverous reinforcing materials,
- the efficiency of short-fibre reinforcement depends on the fibre alignment in the direction of the main force, on the even distribution of fibres and on the adhesion between the fibres and the polymer matrix [11,12,13].

Long fibres:

- can be used in pressure mixtures, they have a statistic arrangement, but they have a high degree of local unevenness,
- cannot be used in injected mixtures and create difficulty in extrusion processing,
- dosage and handling difficulties may arise,
- they lend better mechanical properties to composites than short fibres.

Continuous fibres:

- used in the manufacture of axially symmetric products: pipes, bars, tanks (through coiling) and for obtaining woven or spatially structured materials,
- adaptable to semi-continuous and continuous manufacture,
- high values of the reinforcement/resin material ratio can be reached, leading to high mechanical resistance.
- If the fibres are too short, shorter than a critical length, L_{cr} , the fibre resistance cannot be integrally attained. Under this value the material's properties and behaviour tend to come close to the properties and behaviour of granular materials.

In order to obtain a maximum reinforcement efficiency, the fibre length must be higher than the critical length.

Fibre reinforcing materials can also be classified according to the modulus of elasticity, their breakage resistance and their density. (Please see Table I).

Fibres with high resistance and high modulus (mainly carbon fibre, glass fibre, boron fibre and aramid fibres) are used in order to obtain high-performance composites. Boron fibres, silicon carbide fibres and carbon fibres have the highest moduli of elasticity, while carbon fibres, glass fibres and silicon carbide fibres have the highest breakage resistance.

The highest specific resistance (the breakage limit at elongation/density) is attained through the use of aramid fibres, while materials with the highest specific modulus are boron fibre-based composites.

High temperature resistant composites are obtained from thermo-resistant polymer matrices reinforced with quartz, aluminium and silicon carbide fibres. Composite materials employed in the aerospace technology mainly use quartz and carbon fibres incorporated in phenolic, epoxy and polyimide matrices [3,12].

Polymer reinforcement can be achieved by using one type of fibre or by combining two or more different types of fibres in a common matrix. In the second case, a hybrid composite is obtained.

Pulverous or granular reinforcing materials are divided into two categories: organic and inorganic.

Organic pulverous reinforcing materials:

- cellulose powder,
- wood flour,
- starch,
- rubber powder and,
- carbon black.

Inorganic pulverous reinforcing materials:

- silica (diatomite, crystalline silica, amorphous silica, precipitated silica),
- talc,
- mica,
- aluminium silicates,
- asbestos,
- calcium metasilicate,
- natural calcium carbonate (chalk, calcite),
- precipitated calcium carbonate,
- calcium carbonate and magnesium carbonate,
- glass microspheres (solid and hollow),
- natural barium sulphate,
- metal flakes or metallic powders (synthetic oxides and metals).

The granular or pulverous form is specific to a length/diameter ratio (l/d) between 1 and 5 which gives the material certain advantages:

- can be used in any type of polymer matrix,
- reduced hardening shrinkage,
- improved resin flow,
- the composite's tendency to crack during the hardening process is eliminated,
- the formation of smooth- and shiny-surfaced parts is favoured.

III. HIGHLY RESISTANT ARAMID FIBRES

A. General observations

The notion of aramid fibre was used as a generic term for aromatic polyamide fibres, in which over 85% of the amidic groups are connected by two aromatic p-phenylene rings.

These fibres were first produced in 1971 in the USA by Dupont de Nemours, under the name of "Kevlar" [2,3,4]. Shortly thereafter, the (German-Dutch) group Akzo produced aramid fibres commercially known as "Arenka".

The commercialised aramid fibres are divided into two categories, differentiated by their modulus of elasticity:

- Fibres with a modulus of 70 GPa (Arenka D900, Kevlar 29). Kevlar 29 has a medium modulus, high resistance to shock and is used for armour plates (bullet-proof vests),
- Fibres with a modulus of 124 GPa (Arenka D930, Kevlar 49). Kevlar 49 has a high modulus, high resistance and is used for reinforcing organic matrices.

B. Obtaining of aramid fibres

Aramid fibres are obtained through the polycondensation of p-phenylenediamine with terephthaloyl dichloride [2,3].

The polycondensation reaction takes place in a solution, at a temperature of 5-10°C, through intense shaking. The resulting poly-p-phenylene terephthalamide is separated through pulverisation, and then washed and dried. The obtaining of aramid fibres involves: spinning, thermal treating, stretching and resin treating [2].

The polymer spinning takes places in a concentrated sulphuric acid solution, at a temperature of 51-100°C.

The resulting filaments are air-cooled and then submerged in icy water (0-4°C). The obtained fibres are washed, dried and then coiled onto storage rolls.

The aromatic rings in the base chain induce the chains with high rigidity and lead to high thermal and chemical stability.

The linear structure of the macromolecules also contributes to this process, allowing for an advanced wrapping and a high degree of crystallinity.

C. Properties of aramid fibres

Aramid fibres possess unique qualities.

Their resistance and modulus of traction are much higher, while the elongation is much lower compared to other organic fibres.

Aramid fibres can be used up to a temperature of 180°C, they extinguish by themselves and they decompose into ashes at a temperature of 400°C.

They have good resistance to open flame, organic solvents, fuel and lubricants. Table II shows a few physical and mechanical properties of aramid filaments with a diameter of 12 μm . (Please see Table II).

For multifilament roving strings, these values are somewhat lower due to coiling:

- the modulus of elasticity for Kevlar 29 is of 59000 MPa, while for Kevlar 49 it is of 130000 MPa,
- the resistance to traction for Kevlar 29 is of 2700 MPa, while for Kevlar 49 it is of 3000 MPa,
- the elongation for Kevlar 29 is of 3.6%, while for Kevlar 49 it is of 2.1%.

High specific resistance is typical of aramid fibres.

Aramid fibres have the highest specific resistance of all high-performance fibres.

The properties of aramid fibres do not change substantially until 200-300°C, allowing for the use of Kevlar 49 as reinforcing agent in obtaining epoxy-matrix composites which are resistant to prolonged use at 200°C [2].

Fig. 1 shows the modulus of elasticity and traction resistance variation at several temperatures for aramid fibres.

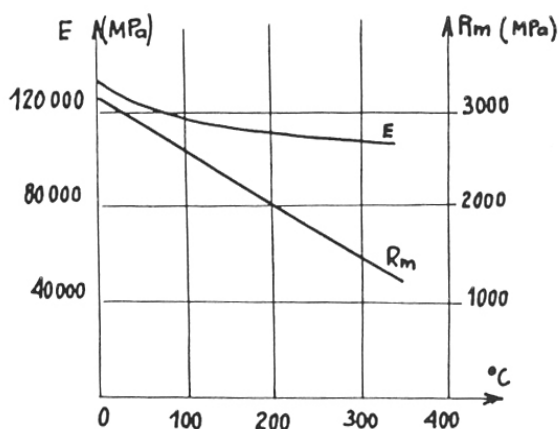


Fig. 1. The modulus of elasticity and traction resistance variation at several temperatures for aramid fibres [2]

D. Aramid fibre-based composites

Aramid fibres are at the basis of obtaining a wide range of composite materials. They can be used in various forms (continuous fibres, short fibres, roving fabrics, etc.), in combination with several types of polymer matrices (thermo-reactive and thermoplastic).

Table III shows the compared properties of composites consisting of reinforcing agents (Kevlar 49, E-glass and carbon) and epoxy matrix (Please see Table III).

The table shows the clear disadvantages of aramid fibre-based composites:

- low compression resistance,
- very low scorching resistance,
- low flexion resistance and
- low interlaminar shear resistance

In order to eliminate these disadvantages, mixed reinforcement is currently used, leading to the

development of hybrid composite materials (Kevlar-E-glass or Kevlar-carbon) with superior properties.

Table IV shows the mechanical properties of composites obtained by combining Kevlar 49 fibres and thermo-reactive polymer matrices (epoxy resin and polyester resin), while Table V shows the properties of composites obtained by combining short aramid fibres and thermoplastic polymer matrices (Please see Table IV and Table V).

Hybrid composites, which use carbon fibres together with aramid fibres, are developed in order to increase the compression resistance of aramid fibre-based composites. Table VI shows the properties of some hybrid composites based on Kevlar fibres-carbon fibres and epoxy resins (Please see Table VI).

Aramid fibres are used for obtaining high-performance composite materials, which are resistant to dynamic solicitations.

Fields of use:

- navy (special equipment for yachts and military vessels, armour plates),
- automotive industry (tyre textures, belts, brake liners, clutches, hoses),
- sports equipment (cords)
- military equipment (helmets, bullet-proof vests),
- aerospace technology.

E. Advantages and disadvantages

Advantages:

- high specific traction resistance,
- they facilitate weight reduction,
- low density,
- excellent fatigue resistance,
- very good shock resistance,
- very good thermal insulators,
- good vibration damping,
- chemical resistance to water, hydrocarbons and solvents,
- do not age in damp environments,
- good wear resistance.

Disadvantages:

- difficult impregnation,
- the fibres must be dried before being used at temperatures of 120°C, because humidity greatly reduces the fibre-resin bond,
- low resistance to strong acids and strong bases,
- high 24h water absorption (4%) in ambient environment (65% relative humidity)
- sensitive to UV-radiation, which rapidly reduces their resistance and leads to yellowing (storing them away from light is recommendable).

TABLE I
MECHANICAL PROPERTIES OF FIBRE REINFORCING AGENTS [2]

Fibres	Density, kg/m ³	Modulus of elasticity at traction, MPa MPa	Breakage resistance at traction,
Polyamide	1170	6300	1300
Polyester	1400	8000	550
Sisal	1450	45000	850
Aramid (K29)	1450	60000	2000
E-glass	2560	75000	2000
R-glass	2500	85000	3000
BM Carbon	1700	180000	1800
Aramid (K49)	1450	140000	3000
Asbestos	2200	180000	2000
Steel	7800	210000	500-2000
Wolfram	19200	350000	2500
Boron	2500	450000	3500
SiC	3200	450000	2000

TABLE II
PHYSICAL AND MECHANICAL PROPERTIES OF ARAMID FILAMENTS [2,3]

Properties	Units of measurement	Kevlar 29	Kevlar 49
Density	Kg/m ³	1440	1450
Filament diameter	µm	12	12
Water absorption at 21°C	%	3.9	4.6
Modulus of elasticity, E	MPa	60000	134000
Traction resistance, R _m	MPa	3000	3600
Elongation, A	%	4	2

TABLE III
UNI- AND MULTILATERAL REINFORCED COMPOSITES (EPOXY RESIN) [2]

Properties	Unilateral composite			Roving fibre composite	
	Kevlar 49	E-glass	Carbon	Kevlar 49	E-glass
Fibre volume, %	60	60	60	50	50
Density, kg/m ³	1380	2080	1520	1330	1900
Traction resistance, R _m , MPa	1380	1100	1240	552	393
Elasticity modulus at traction, E, GPa	75	51	144	32,4	25,5
Elasticity modulus at flexion, E, GPa	76	39	131	32,4	25,5
Flexion resistance, R _m , MPa	620	1170	1990	-	-
Compression resistance, R, MPa	275	490	1100	172	393
Interlaminar shear resistance, Γ, MPa	48-69	83	97	-	-

TABLE IV
MECHANICAL PROPERTIES OF KEVLAR 49-BASED COMPOSITES [3]

Properties	Epoxy resin	Polyester resin
Fibre content, %	50	40
Density, kg/m ³	1330	1300
Elongation resistance, MPa	517	414
Modulus of elasticity at elongation, GPa	31	24
Deformation at break, %	1,7	-
Compression resistance, MPa	83	-
Modulus of elasticity at compression, GPa	31	-
Flexion resistance, MPa	345	207
Modulus of elasticity at flexion, GPa	27,6	20

TABLE V
PROPERTIES OF KEVLAR 49 SHORT FIBRE-BASED COMPOSITES [3]

Polymer matrix	Orientation	Resistance to elongation, MPa	Elongation modulus, GPa	Elongation limit, %
Polyethylene	Randon orientation in a unidirectional plane	73,77 131,7	5,16 10,6	2,3 2,3
Polyamide 12	Randon orientation in a unidirectional plane	106,9 151,7	4,17 8,55	5,9 2,8
Polycarbonate	Randon orientation in a unidirectional plane	115,8 163,4	5,06 9,79	3,0 2,1
Methyl-polymethacrylate	Randon orientation in a unidirectional plane	182,0 207,5	7,79 11,10	3,0 2,0

TABLE VI
PROPERTIES OF UNILATERAL HYBRID COMPOSITES WITH THORNEL 300 – KEVLAR 49 FIBRES IN AN EPOXY MATRIX (THE
FIBRE CONTENT IS 60% VOL.) [3]

Properties	The Thornel 300/Kevlar 49 fibre ratio			
	100/0	75/25	50/50	0/100
Density, kg/m ³	1600	1560	1510	1350
Elongation modulus, GPa	145	120	108	77
Maximum elongation, MPa	1565	1282	1213	1262
Maximum compression, MPa	1007	938	688	286
Maximum flexion, MPa	1606	1358	1103	634
Shear resistance, MPa	91	76	56	49

IV. CONCLUSIONS

Various aspects of organic composite materials, fibre and pulverous reinforcing materials and the role played by aramid fibres in manufacturing dynamic solicitation resistant composites were studied. Furthermore, the main properties of aramid fibres, their advantages and disadvantages, the properties of composites based on these fibres and their fields of use were analysed.

REFERENCES

- [1] B.R..H. Mişca, *Polymer Composite Materials,(Materiale compozite polimere)*. Presa Universitară Clujană, Cluj-Napoca, 2001.
- [2] D. Duedal, *Guide pratique des materiaux composites*. Technique et Documentation Lavoisier, Paris, 1985.
- [3] Gh. Hubca, H. Iovu, M. Tomescu, I. Rosca, O. Novac, Gh. Ivănuş, *Composite materials, (Materiale compozite)*. Editura Tehnică, Bucureşti, 1999.
- [4] J. P. Trotignon, J. Verdu, A. Dobracginsky, M. Pipe-raud, *Matieres Plastiques*. Editions Nathan, Paris, 1996.
- [5] G. Chretien, *Materiaux composites a matrice organique*. Technique et Documentation, Paris, 1986.
- [6] M. Mihalcu, *Reinforced plastics, (Materiale plastice armate)*. Editura Tehnică, Bucureşti, 1973.
- [7] J. F. Pichon, *Injection des matieres plastiques*, Dunod, Paris, 2001.
- [8] C. Ispas, *Composite materials,(Materiale compozite)*. Editura Tehnică, Bucureşti, 1987.
- [9] C. Ştefănescu, G. Neagu, A. Mihai, *Future materials are manufactured today. Composite materials,(Materialele viitorului se fabrică azi. Materiale compozite)*. Editura Didactică şi Pedagogică S.A., Bucureşti, 1992.
- [10] F.L. Mathews, R.D. Rawlings, *Composite materials*. Engineering and Science, Chapman & Hall, London, New York, Tokio, Glasgow, Melbourne, Madrid, 1993.
- [11] *Concise Encyclopedia of Composite Materials*, Ed. Antony Kelly CBE, FRS, Pergamon Press, Oxford, 1989.
- [12] *Engineering Materials Handbook*, vol.1, Composites, Metals Park, Ohio, 1987.
- [13] W.D. Bascom, R.M.J. Jensen, *Adhesion*. 19, pp. 219, 1986,.
- [14] V. Manovicu, Gh. R. E. Mărieş, *Organic matrix composite materials, (Materiale compozite cu matrice organică)*, Editura Universităţii din Oradea, 2005.