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AN OVERVIEW ON INNOVATIVE COMPOSITE MATERIALS EMPLOYED IN THE CONSTRUCTION OF MICROSATELLITES

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Rezumat. *Industria spaţială cunoaşte un interes sporit pentru misiunile cu microsateliţi, aceştia fiind utilizaţi frecvent în apărare, agricultură, business intelligence, în caz de dezastre, în comunicaţii. În lucrare sunt prezentate date recente din literatura de specialitate despre structura şi proprietăţile materialelor compozite în vederea stabilirii posibilităţilor de utilizare a acestora în construcţia microsateliţilor, în contextul unei dezvoltări durabile. Materialele compozite inovative trebuie să prezinte stabilitate dimensională în timpul expunerii la ciclurile termice din spaţiu, grad de degazare redus, rezistenţă ridicată la microfisurare, radiaţii UV, oxigen atomic, iradiere cu protoni şi la resturi orbitale.*

Abstract. *The space industry has a growing interest in microsatellite missions, which are frequently employed in the defense, agriculture, business intelligence, in case of disasters, in communications. The paper presents recent findings from the literature regarding the structure and properties of composite materials, in order to establish the possibilities of their use in the development of microsatellites, in the context of a sustainable development. Innovative composites must have dimensional stability during exposure to thermal cycling in space, low degree of outgassing, high resistance to microcracking, UV radiation, atomic oxygen, proton irradiation and orbital debris.*

Keywords: microsatellites, composite materials, structure, properties polymer matrices, properties reinforcing fillers

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1. Introduction

Aviation and airspace represent growing strategic areas that are based on the cooperation between public and private industries, with governments funding various civilian space programs with the help of national space agencies (eg NASA in the US, ESA for various European countries).

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Functional safety is essential in the aerospace industry. Supervisory institutions, such as the ECSS, strictly regulate this market with certification standards [1].

The space research activities focus on both the scientific and commercial fields. Microsatellites are employed for various imaging and space inspection applications, to provide everyday imagery that allows for new uses in defense, agriculture, disaster recovery, etc. Over the past decades, advances in the miniaturization and market availability of electronic parts, such as computers and portable devices, have provided a valuable impetus to the construction of microsatellites and their missions [2].

A microsatellite is characterized by a primary structure that supports the on board payloads and a secondary one that facilitates the data acquisition process (Fig. 1.).

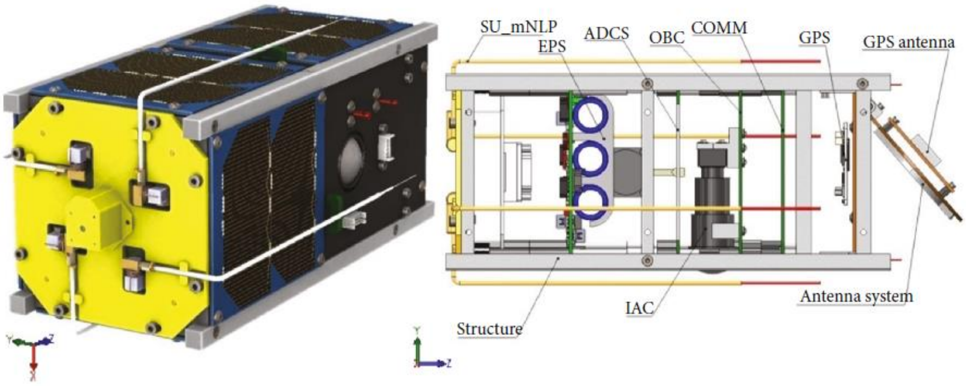

Fig. 1. Structure of a CubeSat satellite: EPS - electrical power supply system, ADCS - attitude determination and control system, OBC - on-board computer, COMM - communication system, TT&C - telecommunications, tracking and command system, ODCS - orbital determination and control system, mechanical structure, payload, propulsion system, thermal control system, electronic components [3]

About 25 % of the malfunctions that occur in satellites are actually due to the space environment that impacts their instruments, their control and management systems. Low-Earth orbiting space environment negatively influences the performance and functionality of microsatellite construction materials through phenomena such as atomic oxygen, ultraviolet radiation, plasma, micrometeoroids, and orbital debris, as well as extreme thermal conditions caused by orbital temperature cycles [4].

As a consequence, the materials employed in the space industry must exhibit high performances, such as: high strength / weight ratio, dimensional stability (low coefficient of thermal expansion) during exposure to thermal cycles in space, low degree of outgassing, high resistance to microcracking, resistance to UV/VUV radiation and ionizing radiation (γ, α, β, X-rays), to the attack with oxygen atoms, irradiation with protons, electrons [5]. At the same time, they must be able to withstand heavy loads, have high wear resistance and ensure good tribological characteristics [6]. In this regard, each material has its relative advantages and disadvantages.

The most common materials that are employed in the aerospace field are:

- conventional materials: aluminum alloys (structural alloys 2xxx, 5xxx, 6xxx or 7xxx of Al [7, 8]); stainless steel [9]; Ti alloys [10]; Ni alloys [10]; metallic materials with metallic coatings (Zn, Al, Cu), intermetallic compounds (Ni-Al: 95-5) or functionally graded material type (Zn/Ni-Al: 95-5, Zn/Ni-Al: 95-5/Cu) [5];
- non-metallic materials (plastics, ceramics, composites).

Innovative composites are widely used in aerospace due to their performance over conventional materials. One such characteristic of composite materials is the density to strength ratio, given the fact that the mass parameter is essential for the launch costs, respectively for the payload of the microsatellite. For example, in civilian aircrafts such as Airbus A350 and Boeing B787, the composite materials employed in the development of structural elements exceeds 50 % of the aircraft's weight [11], which has led to a 25 % reduction in operating costs, along with a significant improvement in fuel efficiency and lower CO_2 emissions [12]. The composite materials are employed in the design of fuselage components, the coverings/radome of the trailing and leading edges of the wings etc. [13].

Deciding the optimal materials for the construction of microsatellites and their manufacturing technologies are considered the key factors in achieving an optimized structure. Additive manufacturing is a technology based on the principle of layer-by-layer deposition, which facilitates the manufacturing of complex geometric structures from lighter materials (i.e. polymers or ceramics) with low processing costs. The use of this method improves the manufacturing cycle time while lowering the product development costs [14, 15]. It is estimated that the use of additive manufacturing facilitates the weight reduction of structural elements of up to 40 - 70 % [2].

2. The structure of composite materials

Composite materials comprise a combination of two different materials, namely: matrix (or resin) and reinforcement (or filler). The materials in the resin matrix consist mainly of polymers, which form the primary structural basis for multifunctional composites [15]. Reinforcement materials are added to the matrix to improve the properties of the pure polymer.

The selection of polymers for space structures made by extrusion / fused material deposition (FDM) is severely limited by the space environment and ECSS standards, as their operation in vacuum can generate outgassing of the material.

This can cause severe changes in material properties (aerospace structure fatigue) and contamination of nearby components. It can also cause the overshoot of temperature controllers, alter the performance of optical instruments and solar panels aboard the spacecraft [2].

In order to optimize the structures of spacecraft, the following must be studied: the anisotropy of the materials, the resistance at the interface between the adjacent layers and the nonlinear constitutive behavior of the polymer [16]. According to ESA-ECSS-Q-70 standards [1] only a limited range of polymers are suitable for space environment.

Fig. 2 [6] shows the most used materials for the resin matrix. Reinforcement materials are also mentioned and classified. These are added to the matrix composition in the form of fibers, particles and nanoparticles or are used as a foil / coating. Depending on the aspect ratio (L / d) of the materials for reinforcement, it is considered that they are of the type: 0D - spherical (particle), 1D - rod (needle), 2D - lamellar (plate) (Fig. 3).

The authors [6] divided the reinforcing fillers into six types: “carbon-based materials, transition metal sulphides, polymers, ceramic nanoparticles, soft metals, silicon mineral salts, and microcapsules”.

Maximizing the properties of composite materials can be achieved by considering the morphology of reinforcing materials, characterized by spatial orientation, content, size, dispersibility, and interfacial strength of the chemical components.

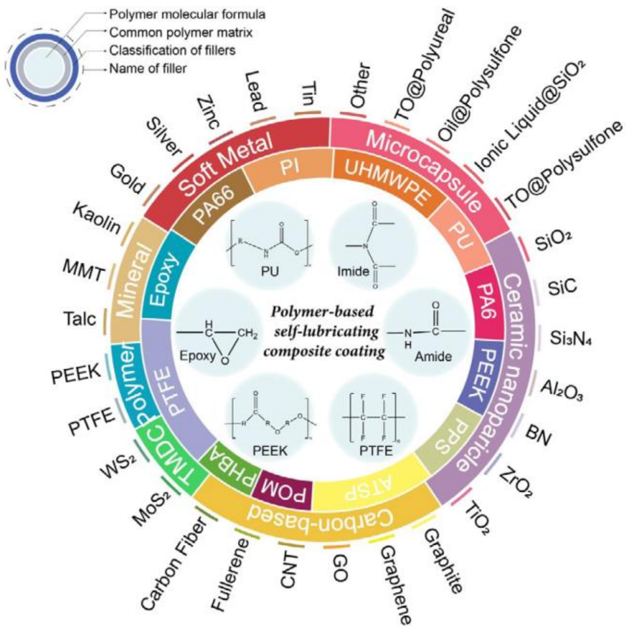

Fig. 2. Composite materials: common matrices and reinforcing fillers [6]

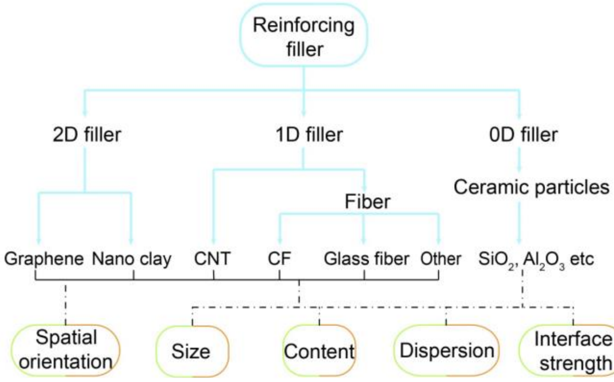

Fig. 3. Reinforcing fillers: classification and influencing factors of these [6]

Gradual variation in volume, chemical composition and structure of reinforcing materials leads to a gradient of mechanical properties which facilitate the development of composite materials or multifunctional surface coating systems [5, 6].

The most popular composite materials that are employed in the development of microsatellites are:

- CFRP – carbon fiber reinforced epoxy polymer [3, 4]; M40 J, M55 J, M60 J – CFRP with high unidirectional modulus [3, 8]; CFRP reinforced with Ta foil, with Babbitt, Zn or Zn / Monel coating - in order to protect against radiation [17]; EP 127-C20-45 T2 – epoxy mixture (cyanate ester) reinforced with 60 % carbon fibers [5]; rCFRP – epoxy polymer reinforced with recycled carbon fiber [18];
- GFRP – epoxy polymer reinforced with fiberglass E [19]; FR-4 – fiberglass-reinforced epoxy polymer [8];
- Kevlar – epoxy polymer reinforced with aramid fabric [19];
- PEEK – polyether-ether-ketone [2, 15];
- CF/PEEK – polyether-ether-ketone with carbon fiber [20, 21];
- sandwich materials [22];
- nano-composite [14].

3. Properties of composite materials

The use of high-performance polymeric matrix composites in microsatellite structures is crucial to limit changes in dimensional stability. It is mainly affected by the characteristics of moisture, thermal expansion, mechanical loading and micro-malleability (caused by microcracking) of the materials.

The mechanical strength of polymer composites is directly related to the strength of the interfacial bond between the polymer matrix and the reinforcing materials: “0D materials improve mechanical properties; 1D materials can especially improve tensile strength, and 2D materials in particular improve bending characteristics” [6].

In addition to the mechanical requirements, the thermal conductivity of the polymer and the ability of the structure to dissipate the heat that is generated by the internal equipment are important factors. An acceptable value of thermal conductivity is λ = 5 W/m·K [2]. If the thermal conductivity of the polymer is reduced, it reaches high temperatures, which locally reduce the stiffness of the material and thus, significant thermal shifts and non-negligible displacements occur.

The materials employed for microsatellites should have as a minimum: RML (recovered mass loss) < 1.0 % and CVCM (collected volatile condensable material) < 0.10 % as per [1].

Composite manufacturing techniques negatively influence some properties and the life cycle of parts manufactured from these materials [13].

3.1. Properties polymers matrices

Resin matrix materials can be thermoset materials (eg epoxy (EP) and polyurethane (PU)) or thermoplastics (eg polypropylene (PP), polyamide / nylon (PA), acrylonitrile-butadiene-styrene (ABS), polylactic acid (PLA), polyether-imide (PEI), polyether-ether-ketone (PEEK)) [13, 15]. Table 1 presents properties of some of the most commonly used materials [2, 6, 14, 23, 24, 27].

Table 1. Some properties of a few polymer matrices used very often

Polymer matrices	*Tensile strength [MPa]*	*Young's modulus [GPa]*	*Glass transition temperature / Melting temperature / Heat distortion temperature [℃]*	*Coeffi-cient de friction*	*Density [g/cm³]*	*Recy-clabi-lity*	*Biode-grada-bility*	*Chemical resistance*
EP	52.98	3.15	50-80 / * / 120	0.6-0.7	1.15 - 2.25	-	-	Good
PU	24.8	57.8	-42 / 168 / 85	0.34	0.21-1.50	-	-	Fair
PP	17-21	0.79-0.88	-/ 150-160 /-	-	0.872-1.68	-	No	-
PA	35-168	0.45-3.5	59 / 224 / 120	0.41	1.4 - 1.58	-	No	Only alkali
PEEK	90-100	3-4	143 / 343 / 260	0.3-0.4	1.3	Yes	No	Good
ABS	11-65	1-2.65	95-105 / 220-280 / 100	-	1.04	Yes	No	-
PLA	26.4-65	2.3-2.9	55-60 / 160-230 / 55	-	1.25	Yes	Yes	-

The current trend in the choice of matrix polymers is towards “green” polymers due to the fact that they facilitate sustainable development while improving the conservation of used materials, thus reducing pollution and the amount of environmentally harmful waste [24].

Thermoplastics are used because they can be heated to their softening point, cooled and reheated without rapid degradation [25]. Of these, “PEEK and polyetherimide (PEI) exhibit optimal mechanical properties, while meeting the outgassing requirements and harsh environmental conditions that characterize the outer space” [2].

PEEK is a high performance semi-crystalline thermoplastic polymer with outstanding mechanical properties (high Young’s modulus, high tensile strength with low density, good hardness, rigid rupture), high thermal stability and superior chemical resistance. Its behavior is considered “linear-elastic, isotropic and homogeneous if it is manufactured by injection molding. PEEK provides a thermal conductivity λ = 0.25-0.32 W/m·K, which is 3 orders of magnitude smaller than that of metals used in aerospace applications (eg λ_{Al} = 170 W/m·K)” [2]. All of these properties make it an ideal material for replacing Al or steel in aerospace constructions [15]. The major disadvantage is the non-biodegradability [14]. In the solid state, PEEK can be machined, for example, by milling on CNC machines, but with emphasize on the proper handling of stresses in the material. Its high price limits its use, usually for high quality parts, which are thermostable and electrically and thermally insulating.

In [15], the authors present characteristics of the PEEK material according to its manufacturing processes. For example, the value of the experimental tensile and bending modulus as well as the final strength of 3D printed PEEK are lower compared to the PEEK values obtained by the traditional manufacturing process (injection molding) due to anisotropy. In contrast, the compressive strength values of 3D printed PEEK exceed those of injection molding parts: a compressive strength of 126.4 - 125 MPa was obtained, so an improvement of 11 – 12 %. Also, the hardness is inferior compared to PEEK obtained by injection molding, and in the breaking section the surface is smooth due to brittle fracture.

3D printing has a significant impact on the outgassing properties because the materials are not completely dense, and the porosity can influence the RML and CVCM. In the case of 3D printed PEEK polymer, the outgassing requirements are fully met, “the RML being well below the maximum acceptable value (average value of 0.11 %) and CVCM ten times below the maximum acceptable value, according to ECSS” [2]. “Bending strength and tear deformation are significantly affected by 3D printing speed and fill percentage, respectively. Young’s modulus and final tensile strength are mainly influenced by the percentage of filling” [14]. In conclusion, “the 3D printing process slightly affects the mechanical properties of the PEEK material, while the thermal properties remain unaffected. It is necessary that the temperature does not exceed the glass transition temperature of the polymer in order to avoid the decrease of the mechanical properties (especially in terms of rigidity)" [2].

For 3D printing the most commonly used polymers are ABS and PLA. In aerospace industry, they have a limited use due to the outgassing properties, radiation resistance, etc. [16]. However, these polymers are used, their mechanical properties and thermal conductivity being improved by various reinforcement materials [13, 23 - 25].

ABS is a thermoplastic, amorphous, non-biodegradable polymer and has a medium toxicity. The properties of parts manufactured from ABS by FFF (fused filament manufacturing) technology are influenced by the filling percentage [14].

PLA is a biodegradable and biocompatible polymer, sensitive to high temperature (about 200 °C). The fill percentage is the printing parameter that positively influences the mechanical properties, and the raster angle influences the Young modulus of the PLA parts obtained by FFF [14].

3.2. Properties of reinforcing fillers

Composite materials with fiber-reinforced fillers are employed for the microsatellite components that are subjected to heavy loads. The binding mechanisms at the fiber-matrix interface are made in the form of a molecular network interwoven after inter-diffusion, by electrostatic adhesion, by chemical bonding or mechanical interlocking. The loads applied to the resin matrix (characterized by low density and good shear properties) are transferred from fiber to fiber (characterized by low density, strength and high rigidity) to develop composite materials that combine the properties of both components. Such materials also exhibit "an optimum strength-to-weight ratio, good anti-wear properties and improved anti-aging capabilities compared to conventional materials" [13].

There are many types of reinforcing fibers: long (10 - 25 mm), short (0.2 - 0.4 mm) or very short / nanofibers (50 - 200 μm / diameter 3 - 100 nm).

The authors [6] mentioned that "conventional reinforcing fibers have a higher strength and modulus of elasticity than matrices materials, which can improve the mechanical properties of composite materials". For example, carbon fibers are lightweight fibers with a high mechanical strength and good stability to aggressive chemical factors. Table 2 compares the properties of composite materials reinforced with different types of fibers.

Some examples of composite materials for the construction of microsatellites are presented below.

Table 2. Properties of fiber reinforced composite materials [13, 27]

Filler - Fibers	*Density [g/cm^3]*	*Young's modulus [GPa]*	*Shear Modulus [GPa]*
Carbon	1.41	2.62-323	1.93-5.60
Glass - E	2.54-2.60	85.5-86.9	35
Al_2O_3	3.96	370	160
Kevlar	1.47	179	2.3
Boron (BN)	3.49	41.0-103	7.8
Silicon Carbide	3.10-3.21	410	180

Cyanate ester resins are used to manufacture the structural components of satellites. An example is EP 127-C20-45 T2, an epoxy mixture reinforced with 60% carbon fiber. It was chosen due to its high resistance to both negative and positive temperatures (-55 ... +185 ^oC). The structural design of the material was intended to increase the protection of the structure against cosmic rays consisting mainly of protons, electrons, heavy ions and particles α [5].

The sandwich materials consist of: composite layers (cyanate ester resin and carbon fibers; they are made by preimpregnation), perforated aluminum honeycomb core and joints in the form of threaded inserts made of aluminum (for Helicoil type assemblies) or headless rivets. The core and composite layers are also bonded with epoxy adhesive in the form of a film. Some composite layers also contain a copper mesh in the epoxy adhesive film on the outer surface. The materials are ECSS certified [22].

In a satellite project of the Kyushu Institute of Technology, CF/PEEK (carbon fiber/polyether-ether-ketone) was used as the main material for the external structure of the Shinen-2 spacecraft launched into space. CF/PEEK is a high-performance thermoplastic composite due to its inherent dimensional stability properties. The hardness of PEEK resin offers excellent resistance to microcracking induced by the thermal cycle. In CF/PEEK, the internal stretch is dissipated internally inside the structure, not by microcracking. Heat is generated due to internal dissipation. As a result, both microcracking and changes of the coefficient of thermal expansion (ppm/°C) can be kept to a minimum. For this purpose, in order to observe the influence of different space factors, coatings with POSS (silsesquioxan - $RSiO_{3/2}$) type protection layers for atomic oxygen and Yttrium oxide (Y_2O_3) type protection layers for UV radiation were tested. The tests were carried out both in situ and in space in the low Earth orbit, aboard the Ten-Koh satellite in 2018. Analysis of the orbit data indicated that the values of the coefficient of thermal expansion show a non-linear temperature dependence and there was no change of parameters after four months [20].

In the papers [13, 23], the authors compare the tensile strength of composite materials reinforced with different types of fibers, of different lengths (Fig. 4) or with different reinforcement percentages (Fig. 5), in the case of FDM processing. Short fibers have a lower reinforcing effect than longer or continuous fibers [6].

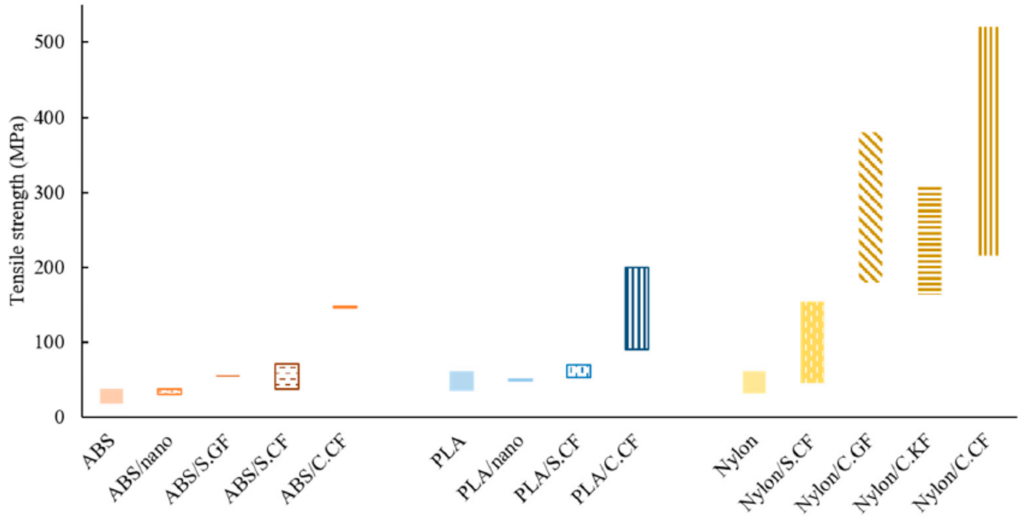

Fig. 4. Tensile strength of composite materials obtain of several types of polymers (ABS, PLA, and nylon) and reinforcing fillers (carbon fiber (CF), glass fiber (GF), and para-aramid fiber (Kevlar fiber, KF)) with nano, short (S) and continuous (C) lengths [23]

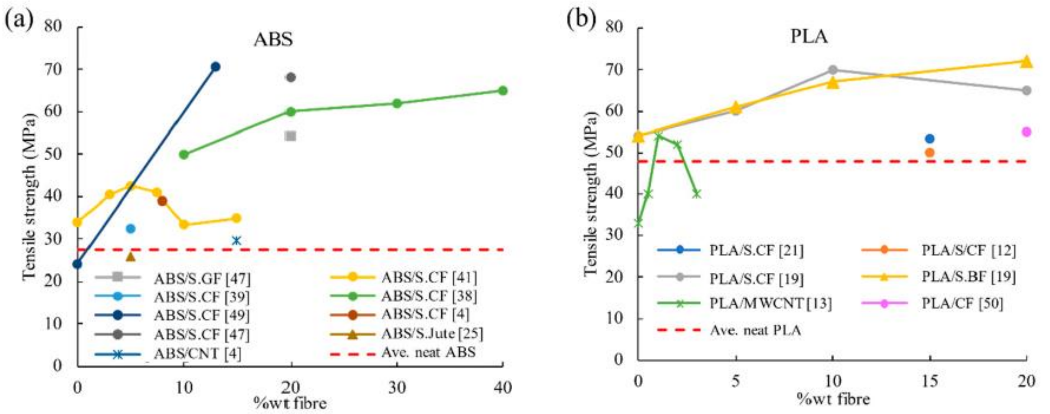

Fig. 5. Tensile strength of composite materials processed by FDM containing different percentages of reinforcing fillers in (a) ABS and (b) PLA; the red line shown the average strength of the neat thermoplastics polymers; wt % – weight procent, S – short fiber [23]

When analyzing the tensile strength of 3D printed composites, they always exhibit a higher stiffness than pure polymer filaments. This may be due to the layer-by-layer manufacturing process leading to porosity, poor inter-raster bonding and rough surface finishing in the 3D printed structure [23].

Recent studies [13] also indicate that the development of carbon fiber-reinforced thermosetting composites through the UV-assisted 3D printing process “has led to a significant increase in the toughness and modulus of elasticity of composites”.

FFF technology is used in the aerospace industry for the development of structural prototypes, microframes, repair parts for drones, elements for the integration of electronic parts [14]. FFF is considered one of the most promising additive manufacturing methods for its versatility, reliability and affordability. With this technology, microsatellites and other structures could easily be manufactured in space [2].

The paper [13] emphasizes the materials that are commonly used in FFF technology as matrix and reinforcing fibers. The need for high-performance materials has also led to the production of microparticle and nanoparticle-reinforced composites for FFF technology. Table 3 shows the comparative properties of some of these materials, and Table 4 shows the thermal conductivity values.

Table 3. Comparative properties of some composite materials [14]

Dimension of filler	*Polymer matrices*	*Filler*	*Content of filler [%]*	*Tensile strength [MPa]*	*Young's modulus [GPa]*
fibers	PP	glass	30	28-45	1.4-2.2
	PA	glass	-	156-212	3.28-4.91
	PA	carbon	-	198	8.46
	PA	Kevlar	-	110-161	4.23-4.76
	PEEK	CNT	-	65-100	-
micro and nanoparticles	PP	Glass	30	8.1-20.6	1.05-1.65
	PLA	graphene, Cu, Al	1.6-4	15-40	-
	ABS	TiO_2	5	18.4-3.22	1.35-1.71
	ABS	$BaTiO_3$	10-35	13.7-25.5	2.6-3.3
	ABS	graphene	20	30	2.4
	ABS	Cu	10-50	26.5-42	0.9

Table 4. Thermal conductivity (λ) of different fillers [26]

Group fillers	*Filler*	*Thermal conductivity [W/m·K]*
Carbon-based	carbon nanotubes (CNT)	2000-6000
	graphene	3000
Metallic	Cu	483
	Ag	450
	Au	345
	Al	204
Ceramic	BN (boron nitride)	250-300
	Al_2O_3	30

Nanoparticles widely used in thermal and electrical conductive applications are: graphene oxide, graphene nanoplatelets, graphite nanomodels, BN, CNT, metals.

CNTs are used due to their one-dimensional, fiber-like structure and high strength. Another reinforcement solution is the uniform matrix distribution of multi-walled carbon nanotubes (MWCNT). For example, there is an increase in modulus and breaking strength (up to 140 %) of PEEK with MWCNT compared to pure PEEK, but without any significant increase in crystallinity. Breaking strain after annealing has values comparable to those of pure PEEK [2].

ABS and PLA filaments were analyzed in the paper [24], various polymeric additives (CNT, graphite) were added. These materials can be used for laser-assisted fused filament 3D printing, to increase the strength of the interlayer binding of the printed part.

In the paper [25], the authors highlighted the mechanical and breaking behavior of pure PLA samples compared to PLA samples with particle inserts (Cu, Al and graphene), as well as the influence of the filament deposition angle in the FFF process on these mechanical properties. A hierarchy of fiber elongation, respectively fiber height, was performed after the tensile test, finding that the highest elongation values were achieved for pure PLA (approximately 4.1 %), followed by the insertion of PLA + Al (3.2 % - 4 %), the insertion of PLA + graphene (2.6 % - 4 %) and the lowest values were for the insertion of PLA + Cu (1.8 % - 2.7 %). Regarding the fiber heights measured after sectioning / breaking the materials (fiber ductility potential), the highest values were for pure PLA, then PLA + Al, PLA + graphene and PLA + Cu. It was also found that regardless of the chemical composition of the samples, the same type of evolution of the values of mechanical strength can be noticed: they increase slightly with increasing filament angle (from 45° to 60°) and decrease with increasing degree filling (from 60 % to 80 % and 100 %). The authors also established a correlation between the appearance of the sectioning surfaces and the mechanical properties, the breaking mechanism being formulated according to the filament deposition angle.

Metal powders and ceramic materials, used as nanoparticles, improve the mechanical, thermal and transport properties of polymer composites. For example, silica nanoparticles provide higher thermoelasticity of thermoplastic polymers, and silsesquioxan oligomeric polyhedral nanoparticles (POSS) have increased bending strength by 22 %, modulus of bending by 9 % and hardness by 117 % compared to pure PLA. Thermal properties also increase depending on the size (diameter) of the powder particles [14].

Some reinforcing materials such as polytetrafluoroethylene (PTFE), graphite, graphene, MoS2, black phosphorus, Au and Cu improve the friction properties of polymers in the same time with their mechanical properties [6].

Conclusions

Polymer matrix composites are increasingly used in the construction of sports equipment, vehicles, military vehicles, ships, spacecraft and microsatellites due to the high strength-weight ratio, high rigidity and low coefficient of thermal expansion.

Reinforcing fillers are used to improve the performance of polymer matrices, such as improved mechanical properties for higher stresses, high conductivity and thermal stability, stable and low coefficient of friction. For example, the final properties of parts made by 3D printing, depend on the properties of both materials.

The literature is extremely diverse. The variations of the physical and mechanical characteristics of composite materials are presented with emphasize on the properties and quantities used in the materials of the matrix and those for reinforcement, their manufacturing and processing technologies, their fields of application, advantages and disadvantages, etc. Combining different materials is a method for improving and optimizing the properties of the resulting structure.

There is a tendency to expand the use of “green” polymers that contribute to the conservation of used materials, reducing pollution and the amount of waste that is harmful to the environment. Future research needs to focus more on recycled materials for reinforcement.

The development of new materials and their integration is a challenge in the construction of microsatellites.

Abbreviations

NASA – National Aeronautics and Space Administration, USA

ESA – European Space Agency

ECSS – European Cooperation for Space Standardization

FDM – Fused Deposition Modeling

FFF – Fused Filament Fabrication

UV/VUV – ultraviolet / vacuum ultraviolet radiation

RML – recovered mass loss

CVCM – collected volatile condensable material

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