sciendo **Transactions on Aerospace Research** eISSN 2545-2835, VOL. 271, NO. 2/2023, 45-57
DOI: 10.2478/tar-2023-0011

POSSIBILITIES OF USING LOW-DENSITY C–C COMPOSITES FOR THERMAL PROTECTION OF SMALL UNMANNED AERIAL VEHICLES

Taras Yanko[1], **Roman Datsenko**[1] and **Hanna Karpenko**[2]*
[1] SIA UNDERESLAB, Brīvības str. 72 k-2, Centra rajons, Riga, LV-1011, Latvia
[2] Zaporizhzhia National University, Zhukovs'koho str. 66, Zaporizhzhia, Zaporizhia Oblast, Ukraina, 69600

Abstract

The study demonstrates the possibilities of using, as well as the features associated with the use of, unmanned aerial vehicles (UAVs) for military and peaceful purposes. Information is provided on the need to use components that would contribute towards ensuring thermal protection against modern laser weapons. The requirements for such materials are given, according to the field of application of the UAV. An analysis of the available materials that can be used to create thermal protection of UAVs against laser weapons is provided. The thermophysical characteristics of various materials are presented. The work presents technological features of production and properties of low-density carbon–carbon composite materials (CCCM). It is proposed to consider the prospects of using CCCM materials for not only the UAV structural components but also other purposes.

Keywords: carbon–carbon composite material; low-density; fibre; laser weapon; carbonisation
Type of the work: research article

1. INTRODUCTION

The development of small-engine and unmanned aerial vehicle (UAV) aviation technologies has led to the introduction of technical solutions using drones in many areas of human life. Such solutions are implemented for the delivery of goods both in hard-to-reach areas and in densely populated areas; additionally, they are used for high-altitude works, as well as for the surveying of terrain, buildings and technical structures. They are also actively used in agriculture for irrigation, as a means for the delivery or administration of chemicals, and for condition control. Further, they are useful in emergencies, such as fires, floods, avalanches, etc. Technical solutions and aviation techniques for civil and military aviation are also developed with the help of drones [1–4].

The main advantages of using such aircraft are [5]:

- high mobility of air complexes,
- compact size and mobility when transporting the equipment,
- low manufacturing cost, compared to helicopters, airplanes, etc.,
- insignificant consumption of fuel or energy, and
- the possibility of placing payloads of various types, such as cameras, sensors, chemicals, water and weapons.

---

* Corresponding Author: titanlab3@ukr.net

ARTICLE HISTORY **Received** 2022-10-12 **Revised** 2023-01-08 **Accepted** 2023-04-11

The relative disadvantages are a small radius of action, insignificant payload, the possibility of interception of control signals, and dependence on weather conditions [6].

However, the largest distribution and mass production ensures the military use of UAVs. The main applications of military use are reconnaissance operations, delivery of goods, inflicting point strikes in the enemy's area of action, retransmission of signals or jamming in the selected area of influence, adjustment of fire, etc. [7,8]. The effective use of UAVs in local conflicts (Afghanistan, Syria, Nagorno-Karabakh, Ukraine, Palestinian Authority) led to a surge not only in the production of military drones but also in the methods of combating them [9,10]. Methods of combating UAVs through physical destruction by means of air defence, jamming or interception of control signals, and impacting on operators, as well as an elimination of UAVs using specialised weapons characterised by various types of impact—mainly thermal, electric impulse or shock effects—are being actively developed [11].

Against this backdrop, the issues requiring the utmost attention are the ones pertaining to protecting aircraft from possible actions of the enemy. For the same issue, increasing the radius of action and increasing the payload do not lose their relevance. To ensure stable thermal protection of UAV components, it is necessary to use materials considering the specifics of similar products. Since the purpose of UAVs is the effective performance of assigned tasks in the air space, the materials used in the manufacture of such mechanisms must, first of all, be light, reliable and resistant to specified types of load [12].

Recently, the vast majority of anti-drone development has focussed on creating high-energy laser weapons [13–15]. Laser weapons could have several major advantages over traditional weapons:

- Laser beams propagate at the speed of light, and thus there is no need to consider the movement of the target and apply lead when firing at distances of less than 300,000 km. Therefore, it is overwhelmingly impossible to evade a laser 'shot'. In conditions of ground and air combat, it is generally impossible to avoid exposure to a laser beam.
- The laser can change focus configuration on the active area, which can be much smaller or larger compared to the size of the striking element of a kinetic (e.g. firearm) weapon.
- 'Ammunition' of the laser depends only on the source of energy.
- Laser has no perceptible recoil.

The range of use of laser weapons far exceeds the range of traditional (kinetic, ballistic and jet) weapons, but depends on atmospheric conditions and the power of the energy source.

When laser radiation falls on a substance, part of its energy is reflected, and the rest is absorbed in the surface layer. The absorption of laser radiation (LR) in the infrared, visible and near ultraviolet wavelength ranges is described by the Bouguer–Lambert–Beer law [16]:

$$I(x) = I_0(1-R)\exp(-ax) \tag{1}$$

where I_0 is the intensity of the light beam on the surface, R the reflection coefficient, a the absorption rate and x the material-deep coordinate. As can be seen from relation (1), the thickness of the laser radiation absorption layer is proportional to a^{-1}. For metals characterised by a large LR absorption coefficient, the penetration depth of radiation into the volume is a small value not exceeding 10^{-7}–10^{-6} m.

The energy absorbed in the material layer is used to heat it and is transferred by thermal conduction deep into the material. Upon reaching a certain temperature limit of heating on the surface of the irradiated material, thermal destruction of the initial structure of the material and its destruction occurs. For continuous laser radiation, the onset of the destruction of the material is often associated with heating to the melting temperature. The destruction of material that does not decompose at temperatures below boiling is associated with evaporation processes.

To ensure stable thermal protection of UAV components, it is necessary to choose materials considering the specifics of products of this type. Since the purpose of the UAV is to move and effectively perform the assigned tasks in the airspace, the materials used to create such mechanisms should, first of all, be light, reliable and resistant to certain physical loads.

One of the best ways to dissipate heat is to use passive or active cooling with copper-based heatsinks. Copper has high heat-conducting properties; the thermal conductivity is 150–400 W/(m·K), and the heat capacity 400 J/(kg·K). Copper-based alloys are a material that is easy to process and produce parts in many ways. It is also possible to use cooling agents. However, a significant specific gravity (8.6 g/cm^3) does not allow the use of such materials in products intended for flight [17].

Nickel alloys have excellent heat-resistant properties, due to which they are used in the aircraft industry in the hot zones of jet engines at temperatures above 1,000°C [18]. They are fairly easy to process and have high mechanical characteristics. The density is about 8 g/cm^3, the heat capacity 600–700 J/(kg·K) and the thermal conductivity 20–30 (W/m·K).

Titanium alloys are widely used in the aerospace industry as structural materials. Various types of titanium alloys can work reliably in the temperature range from 350°C to 1,000°C. Titanium alloys have high specific strength and corrosion resistance. The density of titanium alloys is 4–5 g/cm^3, the heat capacity 500–700 J/(kg·K) and the thermal conductivity 20 W/(m·K) [19].

As for aluminium alloys, they have a heat capacity of 800–1,000 J/(kg·K), a thermal conductivity of 200 W/m K and a density of 2.5–3.2 g/cm^3. However, aluminium has a relatively low melting point of 660°C, which significantly limits its use.

Carbon–carbon composite materials (CCCM) is the general name for a broad class of materials consisting of a carbon or graphite matrix reinforced with carbon or graphite fibres. CCCMs have a low specific gravity (0.17–1.7 g/cm^3), high mechanical strength at elevated temperatures, high resistance to thermal shock loads, and ablative resistance. Further, they have a thermal conductivity of 0.4–1.0 W/(m·K) [20,21].

It is also possible to use highly porous metals and metal foams to reduce the weight of the UAV and create thermal protection for the device [22]; however, their thermal conductivity, and sometimes density, are mostly higher than those of carbon materials. For example, the thermal conductivity of nickel foam is about 4 W/(m·K) [23], and that of aluminium foam 150–200 W/(m·K) [24].

2. PURPOSE AND OBJECTIVES OF THE RESEARCH

As a binder in the formation of low-density carbon composite materials (CCMs), phenol-formaldehyde resin of the SF-01 (Novohim, Ukraine) brand was chosen, which is characterised by a complex of properties, namely: high mechanical strength, increased heat and thermal resistance, and obtaining of a high coke residue.

As fillers in the formation of low-density CCMs, carbonised carbon fibres (CFCs) based on viscose technical thread were selected. Viscose technical grade B thread and cotton fibres were used as materials for pore formers.

The purpose of the work is to establish the regularities of the formation of the structure and properties of low-density CCMs with increased uniformity and low density for the creation of thermal protection of UAVs. To achieve the goal, it was necessary to solve the following tasks:

- to analyse technologies for obtaining CCCMs with a set of specified properties; and
- to determine the structural composition of the CCCM, encompassing CFC, phenol-formaldehyde resin and pore-forming materials, in relation to obtaining a material with a given density by the method of planting from an aqueous suspension.

3. MATERIALS AND RESEARCH METHODS

Theoretical studies of the processes of forming the structure and properties of composite materials were carried out using the approaches of micromechanics of solid media and mathematical modelling. Experimental studies were performed using modern methods of physical and mechanical tests, including microstructural analysis.

The coefficient of thermal conductivity was determined on the IT-λ-400 (Thermal Conductivity Tester, Ukraine) device according to standard methods, in the temperature range of 293–693 K.

The temperature coefficient of linear expansion (TLE) was determined on a DKT-40 dilatometer (JSC Ukrgrafit, Ukraine) designed for automatic registration of dilatometric curves of solid bodies in the temperature range of 293–693 K.

The structure of the low-density CCCM was studied on an inverted metallographic microscope Zeiss Axiovert MAT (Carl Zeiss, Germany) in reflected light with a magnification of 50–500×.

4. CARBON–CARBON COMPOSITE MATERIAL

Thus, the most promising material for creating protective heat shields for UAVs is low-density CCCMs. CCCMs contain a carbon-forming element in the form of discrete fibres, continuous threads or bundles, felts, tapes, fabrics with flat and three-dimensional weaving, and three-dimensional frame structures. The carbon matrix combines the forming elements in the composite into one whole, which makes it possible to better perceive various external loads.

The creation of carbon–carbon materials was made possible by the development of carbon fibres. The long-term evolution of carbon–carbon composites is inextricably linked with advances in carbon and other heat-resistant fibrous materials.

Fibrous thermal insulation materials are a separate class of heterogeneous systems. All fibrous materials are of artificial origin and therefore can be considered composite materials. Fibrous systems with chaotic structures are widely used as thermal insulation and structural materials. Effective thermal insulation materials for low and moderate temperatures (232–723 K) have been developed based on vegetable, synthetic and glass fibres. At higher temperatures, mineral wool, asbestos and basalt fibre (up to 1,273 K), graphite fibre, and felt and wire mesh made of the heat-resistant metals tungsten and molybdenum (up to 2,773 K) are used.

The dominant influence on the properties of composites is exerted, first of all, by reinforcing fibres. In structural materials, fibres play the role of a power frame, which provides high-strength properties and the possibility of deformations in the desired direction. Structured carbon–carbon composites make it possible to realise the specified properties of the material in different directions of the finished product. Thermal, mechanical and physical properties of the composite can be controlled by appropriate calculation of such reinforcing carcass parameters as fibre orientation; their volume content in the required directions; fibre pitch; frame density; thread type and fibre type. The choice of matrix and the method of manufacturing the composite also exert a strong influence over the properties of the final product.

The diameter of fibres and strips varies widely from fractions of a micrometre to millimetres (Fig. 1). In recent years, new composite materials have been developed based on braided fibres from electrically conductive materials (fabrics with nichrome, fabrics from graphitised viscose), which are used as flexible heat-emitting elements. Flexible heat-emitting elements are used in the development of special heat-protective types of clothing, shoes, thermostatic devices and heaters [25,26].

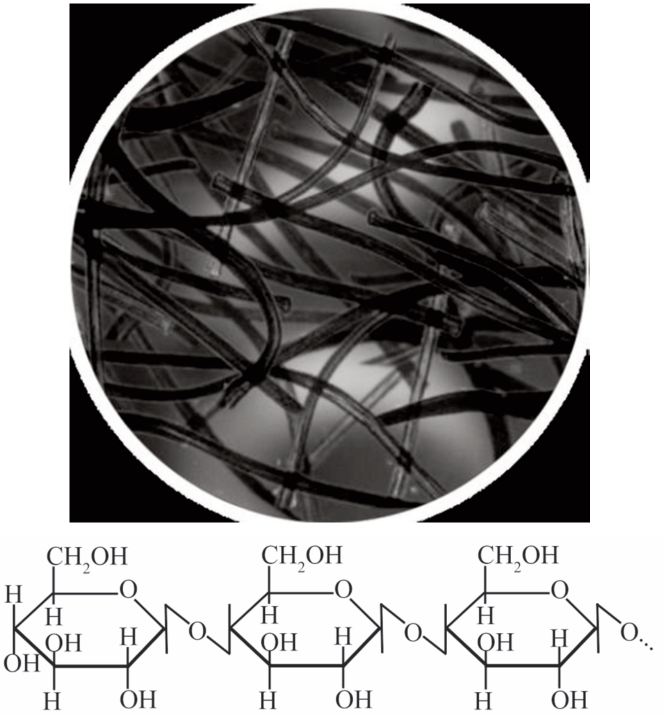

Figure 1. Viscose fibre general appearance and chemical formula.

Fibrous materials, in all their variety, can be divided into three main groups according to the nature of the structure, namely:

- materials with a chaotic distribution of fibres in the volume (wadding, felt, etc.);
- composite materials with an ordered flat distribution of fibres (fabrics, mats, nets, frames); and
- composite materials, representing various combinations of a chaotic and orderly arrangement of layers of fibrous material [27].

The physical properties of carbon fibres depend on the conditions of carbonisation, as well as the nature and quality of the raw material. Many properties of carbon fibres are determined by the final processing temperature. Table 1 shows the most characteristic mechanical properties of carbon fibres. Fibre density, as a rule, increases with an increase in the final processing temperature.

Table 1. Mechanical properties of carbon fibres.

Type of raw material	**Density (g/cm^3)**	**Young's modulus (GPa)**	**Tensile strength (MPa)**	**Strain at breaking (%)**
Viscose cord fibres	1.60	40	500	1.25
PAN fibres	1.80	230	4,500	2.00
Pitch fibres	2.00	520	2,100	0.40

Carbon fibres are characterised by a small coefficient of linear expansion, noticeably smaller than those of metals, graphite and quartz glass. In terms of heat capacity, carbon fibres differ little from other solid bodies. A characteristic feature of viscose-based carbon fibres is their very high thermal conductivity.

Possessing good thermal insulation and satisfactory physical by mechanical properties, carbon fibres obtained on the basis of viscose are the most advantageous for obtaining a whole class of low-density carbon materials.

The main factors influencing the formation of a porous structure in carbon materials include:

- the ratio between the filler and the binder in the press powder;
- the nature of the filler and binder;
- the distribution of binder between particles during mixing and pressing;
- the granulometric composition of the filler;
- the pressing pressure;
- the type and amount of pore-forming additives;
- the firing temperature and duration;
- the presence of additional impregnations followed by firing; and
- the graphitisation temperature.

The size of the pores in graphite can be changed due to the shape and size of the pore-forming additives with the same percentage ratio in the charge. At the same time, it is possible to obtain materials with the same total porosity, but with different pore sizes.

The ideal structure of a structural composite is a material in which a given type and number of reinforcing fibres in the volume of the product are located in such a way that a structural element made of this material can withstand the design loads.

5. TECHNOLOGICAL SCHEME FOR OBTAINING LOW-DENSITY CCCMs

The industry produces a wide variety of composite materials consisting of carbon fibres of various types and a carbon matrix. The properties of such CCCMs vary widely [28,29]. The formation of a low-density CCCM is mostly carried out using two main methods: the formation of the workpiece by the method of draining from an aqueous suspension, and the introduction of a pore former into the workpiece by isostatic technologies.

To obtain a low-density CCCM based on viscose, the following general technological scheme is used [30]:

(a) obtaining and preparation of viscose-based carbon fibres:
  - carbonisation of viscose fibres;
  - grinding of carbon fibres;

(b) preparation of binders and pore formers:
  - preparation of phenol-formaldehyde resin powder;
  - preparation of prepolymer powder;
  - preparation of organic pore formers;

(c) forming the workpiece:

Method of draining aqueous suspension	**Isostatic technology**
• Preparation of aqueous suspension;	• Mixing of components;
• draining the water suspension on the filter; and	• formation of the press mass; and·
• drying of the drained workpiece.	• pressing of workpieces.

(d) carrying out high-temperature processing (carbonisation); and

(e) surface strengthening (if necessary).

CFC based on viscose (Fig. 2), phenol-formaldehyde resin, foamed prepolymer and crushed viscose fibre are the main components in the creation of composite materials by the method of draining the aqueous suspension.

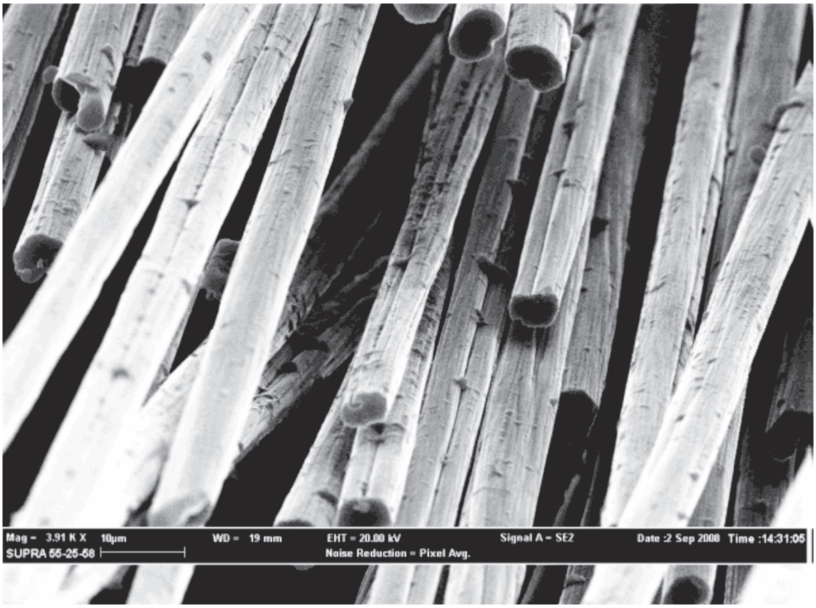

Figure 2. CFC based on viscose. CFC, carbonised carbon fibres.

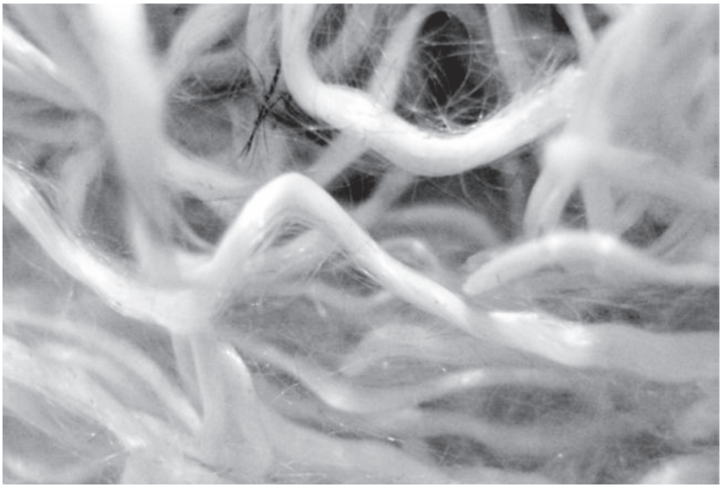

Figure 3. Appearance of viscose fibre before crushing, ×2.

In a low-density CCCM, the phenol-formaldehyde resin forms a matrix and determines its main technological and operational properties. Phenol-formaldehyde resin is used in the form of a powder of a given granulometric composition.

The foamed prepolymer is a material obtained by foaming the binder, with subsequent solidification of the polymer in the foamed state. The composition of the binder for obtaining the prepolymer usually includes: novolac phenol-formaldehyde resin; hardener – hexamethylenetetramine and ethyl alcohol. Hexamethylenetetramine $(CH_2)_6N_4$ is a white crystalline powder, easily soluble in water and ethyl alcohol.

To create additional porosity in the material, which leads to a decrease in the overall density of the sediment, the fourth component of the aqueous suspension is introduced, namely crushed viscose fibre (Fig. 3).

In the process of joint carbonisation of carbon fibres, phenol-formaldehyde matrix and pore formers, the necessary structure of carbonised CCMs is formed [30]. In the process of carbonisation of carbon composites, complex physicochemical transformations occur in the volume of the polymer matrix and pore formers with the formation of coke residue. At the same time, volatile gaseous substances of different chemical composition are released, and the processes of thermochemical shrinkage, thermal expansion and pore formation are realised. Such a variety of processes determines the formations of microcracks, micropores and a structural stress field. To calculate these processes, it is possible to use methods of micromechanics of composites. At the same time, the classical approaches of the micromechanics of composites are supplemented by considering the processes of destruction and changes in the properties of components, both as a result of mechanical loads and temperature effects.

Modelling of the carbonisation process is based on the representation of CCMs as a micro-heterogeneous class B2 environment. For a model environment with variable properties in the heat treatment process, the physical equations can be presented in the following form:

$$\zeta_{ij} = \sum_{k=1}^{N} Q_{ij\alpha\beta}^{k} \cdot \left(1-\omega^{k}\right) \cdot \lambda_{k} \cdot \left[\varepsilon_{\alpha\beta} - \sum_{k=1}^{N} b_{\alpha\beta}^{k} \cdot \left(1-\omega^{k}\right) \cdot \lambda_{k} \cdot \Delta T \right] \tag{2}$$

where ζ_{ij} and ε_{ij} represent microstructural stress and deformation, respectively; Q_{ijmn}^{k} the random modulus of elasticity of the k-th component of the carbon composite material; ω^k the random thermostructural functions that establish the dependence of the elastic properties of the components of the composite material on the degree of structural transformations at temperature T; b_{ij}^{k} the random coefficients of thermal expansion of the k-th component; Ψ^k the random thermoshrink functions that establish the dependence of the thermochemical shrinkage of the k-th component on the carbonisation temperature; the T the temperature of the process; N the number of components in the carbon composite material; and λ^k is a random indicator function.

A mathematical model of the carbonisation process is built to assess the change in properties during the carbonisation process of composite materials. The model is based on the solution of the statistical boundary value problem of the micromechanics of composite materials, which allows determining microstructural stresses and evaluating the level of microstructural transformations, changes in properties and thermochemical shrinkage coefficients in the components of the composite material (carbon fibres, pore former and matrix).

Experimental studies on the determination of physical properties of composites confirm the adequacy of the proposed method (Figs 4–6).

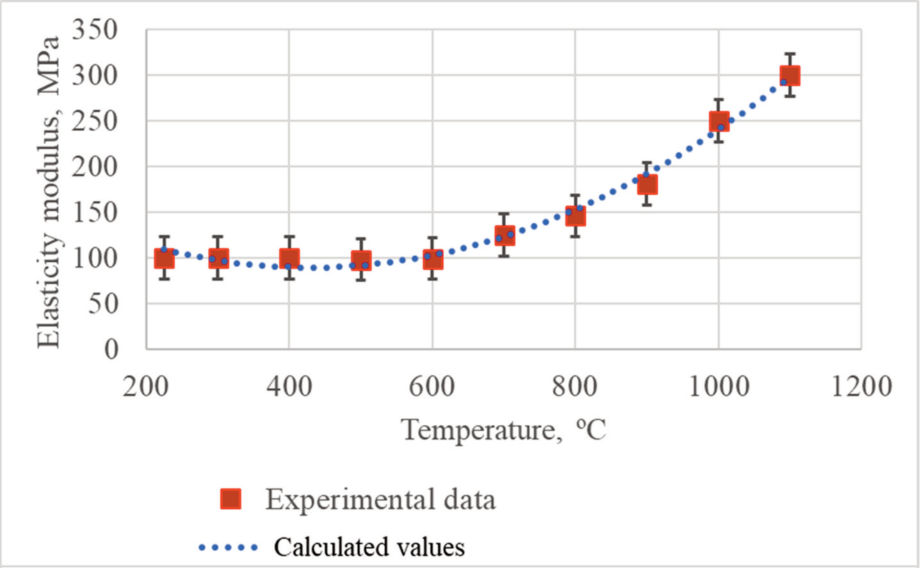

Figure 4. The change in the modulus of elasticity of low-density CCCM depending on the carbonisation temperature. CCCM, carbon–carbon composite materials.

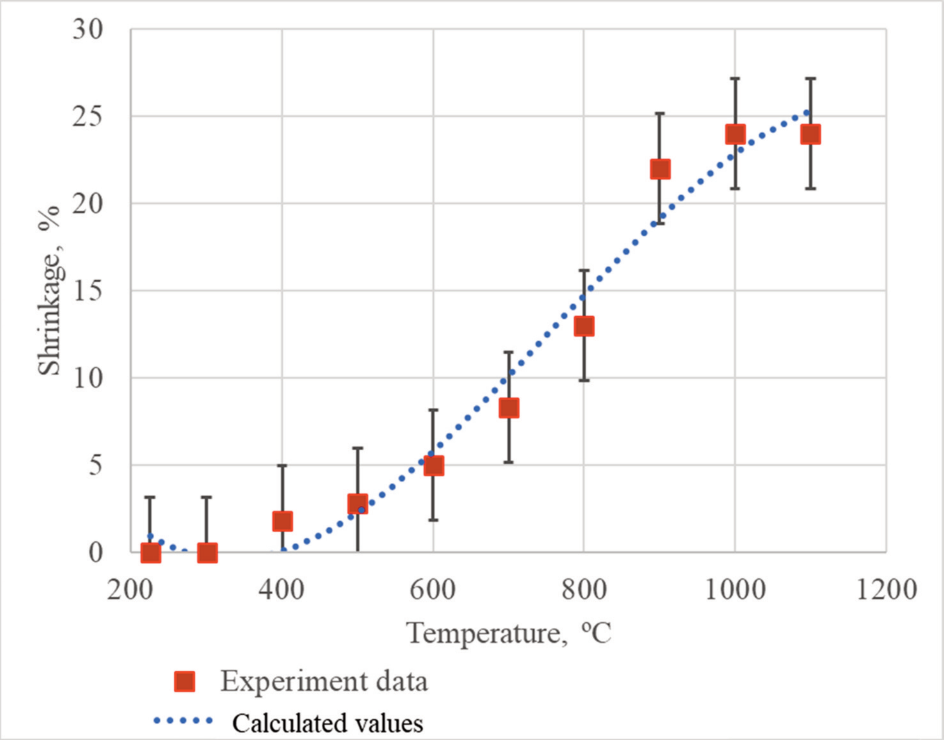

Figure 5. Dependence of shrinkage of low-density CCCM on carbonisation temperature. CCCM, carbon–carbon composite materials.

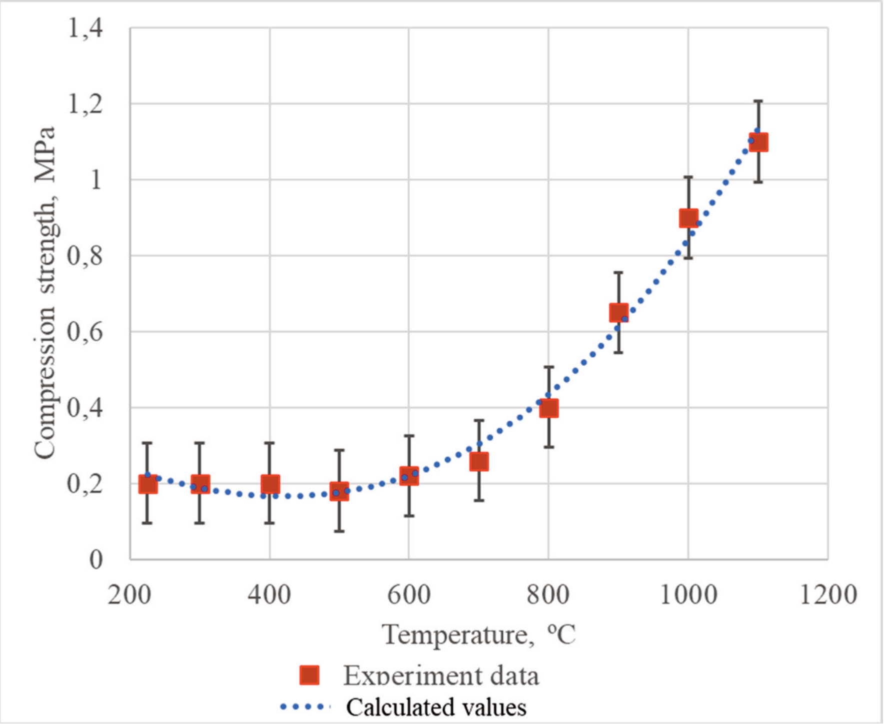

Figure 6. Change in the compressive strength limit of low-density CCCM as a function of the carbonisation temperature. CCCM, carbon–carbon composite materials.

Figure 4 shows that the modulus of elasticity of the composite material increases with increasing temperature. The most dramatic increase in the value of the modulus of elasticity occurs after reaching a temperature of 873 K. Up to this temperature, the modulus of elasticity of the material changes slightly.

The change in shrinkage of low-density CCCM is caused by thermochemical transformations that occur with the components of the composite material during the carbonisation process. Up to a temperature of 473 K, changes occur in the pore-forming materials; as the temperature increases, gaseous substances begin to be released, which is the result of the transformation of the matrix material, phenol-formaldehyde resin, into a polymer with a mesh structure. Upon reaching a temperature of 1,073 K, the material's shrinkage changes slightly (Fig. 5).

As can be seen from Fig. 6, the strength of the composite material in the process of carbonisation changes sharply after 673 K and reaches its maximum value of ~1.2 MPa at a temperature of 1,273 K.

The presented experimental data and the developed mathematical model of the carbonisation process of the composite material, considering the thermochemical transformations of its components, allow us to predict the properties of the resulting material.

The main application of low-density CCCM in protection against laser weapons is the creation of a thermal resistance zone between the external thermal load and the internal equipment of the UAV. Therefore, the most important property of low-density CCCM is its thermal conductivity.

The structure of the pore space of a low-density CCCM has a significant effect on such properties as thermal conductivity, gas permeability, electrical conductivity, sound conductivity and adsorption capacity. The main physical and mechanical characteristics of low-density CCCM obtained by two methods are presented in Table 2.

Table 2. Main physical and mechanical characteristics of low-density CCCM.

Name	**Isostatic technology**	**Method of draining aqueous suspension**
Material density (apparent) (g/m^3)	0.45–0.75	0.17–0.21
Temperature factor of linear expansion (1/K)	$(5.5–6.1)\cdot 10^{-6}$	$(4.3–5.3)\cdot 10^{-6}$
Compression strength limit (MPa)	0.60–0.80 0.85–1.05	0.70–1.10 0.84–1.25
Carbon content (%)	99.6	99.6
Thermal conductivity coefficient (W/(m·K); at 2,000 K)	0.55–0.80	0.45–0.55

CCCM, carbon–carbon composite materials.

In view of the above results, it can be seen that CCCMs have a set of exceptional properties, which allows the use of such materials for the manufacture of heat shields for UAVs. Low density and low coefficient of thermal conductivity allow the creation of thermal protection without significantly reducing the load of the aircraft. The use of fibres makes it possible to create structured composite materials with specified porosity and strong characteristics.

It is also possible to use low-density CCMs as structural elements of UAVs [12]. Low-density carbon composites are widely used in other areas of industry. For example, in metallurgy, chemical apparatus and mechanical engineering for the manufacture of thermal protection of furnaces, filters, bubblers, heat exchange, evaporative and reactor equipment working in aggressive environments [29].

Filter elements in the form of discs, plates, pipes and cartridges can be made from low-density CCCM.

6. CONCLUSION

The analysis of the available materials that can be used to create thermal protection for UAVs against laser weapons showed that CCM is, almost without alternative, the best material. The CCCM combines low specific density and high resistance to thermal effects, which allows the creation of UAVs with the most reliable level of protection and a long flight range or a high payload. The technological process of obtaining CCCM allows variations to be made in the thermophysical properties of the material and strong characteristics within sufficiently wide limits. The developed mathematical model of the carbonisation process of the composite material, considering the thermochemical transformations of its components, allows prediction of the properties of the resulting material.

REFERENCES

[1] Mohsan, S.A.H., Khan, M.A., Noor, F., Ullah, I. and Alsharif, M.H. "Towards the Unmanned Aerial Vehicles (UAVs): A Comprehensive Review." *Drones* Vol. 6 (2022): p. 147. DOI 10.3390/drones6060147.

[2] Nex, F., Armenakis, C., Cramer, M., Cucci, D.A., Gerke, M., Honkavaara, E., Kukko, A., Persello, C. and Skaloud, J. "UAV in the Advent of the Twenties: Where We Stand and What is Next." *ISPRS Journal of Photogrammetry and Remote Sensing* Vol. 184 (2022): pp. 215–242. DOI 10.1016/j.isprsjprs.2021.12.006.

[3] Di, L. "Tian Loong I Fire Fight UAV." 2019. Available at: https://k.sina.com.cn/article_1726918143_66eeadff02000tkw2.html (accessed on 6 September 2021).

[4] Alappatt, T.B., Ajith, S.S., Jose, J., Augustine, J., Sankar, V. and George, J.M. "Design and Analysis of Fire Fighting Drone." In: Sengodan, T., Murugappan, M. and Misra, S. (eds). *Advances in Electrical and Computer Technologies. ICAECT 2020*. Lecture Notes in Electrical Engineering, Vol. 711. Springer, Singapore (2021). DOI 10.1007/978-981-15-9019-1_85.

[5] Alghamdi, Yousef, Munir, Arslan and La, Hung Manh. "Architecture, Classification, and Applications of Contemporary Unmanned Aerial Vehicles." *IEEE Consumer Electronics Magazine* Vol. 10 No. 6 (2021): pp. 9–20. DOI 10.1109/MCE.2021.3063945.

[6] Chiang, W.C., Li, Y., Shang, J. and Urban, T.L. "Impact of Drone Delivery on Sustainability and Cost: Realizing the UAV Potential Through Vehicle Routing Optimization." *Applied Energy* Vol. 242 (2019): pp. 1164–1175.

[7] Cevik, P., Kocaman, I., Akgul, A.S. and Akca, B. "The Small and Silent Force Multiplier: A Swarm UAV – Electronic Attack." *Journal of Intelligent and Robotic Systems* Vol. 70 (2013): pp. 595–608.

[8] Martins, Bruno, Oliveira, Arthur, Holland Michel, and Andrea, Silkoset. "Countering the Drone Threat: Implications of C-Uas Technology for Norway in an EU and NATO Context." PRIO Paper. PRIO, Oslo. 2020.

[9] Antonio, Calcara, Andrea, Gilli, Mauro, Gilli, Raffaele, Marchetti, R. and Ivan Zaccagnini. "Why Drones have not Revolutionized War: The Enduring Hider-Finder Competition in Air Warfare." *International Security* Vol. 46 No. 4 (2022): pp. 130–171. DOI 10.1162/isec_a_00431.

[10] Park, S., Kim, H.T., Lee, S., Joo, H. and Kim, H. "Survey on Anti-Drone Systems: Components, Designs, and Challenges." *IEEE Access* Vol. 9 (2021): pp. 42635–42659. DOI 10.1109/ACCESS.2021.3065926.

[11] Yaacoub, J.-P., Noura, H., Salman, O. and Chehab, A. "Security Analysis of Drones Systems: Attacks, Limitations, and Recommendations." *Internet of Things* Vol. 11 (2020): p. 100218. DOI 10.1016/j.iot.2020.100218..

[12] Palomba, G., Crupi, V. and Epasto, G. "Additively Manufactured Lightweight Monitoring Drones: Design and Experimental Investigation." *Polymer* Vol. 241 (2022): p. 124557. DOI 10.1016/j.polymer.2022.124557.

[13] Sally Cole Johnson. "High-Energy Laser Weaponry Delivers Speed-of-Light 'Hard Kills' to Drones." 2022. Available at: https://www.laserfocusworld.com/lasers-sources/article/14277939/highenergy-laser-weaponry-delivers-speedoflight-hard-kills-to-drones, access date 04.04.2023

[14] Lionis, A., Tsigopoulos, A. and Cohn, K. "An Application of Artificial Neural Networks to Estimate the Performance of High-Energy Laser Weapons in Maritime Environments." *Technologies* Vol. 10 (2022): p. 71. DOI 10.3390/technologies10030071.

[15] Bernatskyi, A. and Sokolovskyi, M. "History of Military Laser Technology Development in Military Applications." *History of Science and Technology* Vol. 12 No. 1 (2022): pp. 88–113. DOI 10.32703/2415-7422-2022-12-1-88-113.

[16] Haim, Abitan, Henrik, Bohr, and Preben, Buchhave, "Correction to the Beer-Lambert-Bouguer Law for Optical Absorption." *Applied Optics* Vol. 47 (2008): pp. 5354–5357. DOI 10.1364/AO.47.005354.

[17] Thangavel, Prabhu, and Ajay, Sekar. "Investigations on Heat Transfer Characteristics of Porous Type Copper Heat Sink with Bifurcations." *Journal of Thermal Engineering* Vol. 7 No. 3 (2021): pp. 584–594.

[18] Pavlenko, D., Dvirnyk, Y. and Przysowa, R. "Advanced Materials and Technologies for Compressor Blades of Small Turbofan Engines." *Aerospace* Vol. 8 (2021): p. 1. DOI 10.3390/aerospace8010001.

[19] Williams, J.C. and Boyer, R.R. "Opportunities and Issues in the Application of Titanium Alloys for Aerospace Components." *Metals* Vol. 10 (2020): p. 705. DOI 10.3390/met10060705.

[20] Bytkin, S.V. "Thermal and Radiation Resistant Materials for Space Electronics." In: Bytkin, S.V., Kritskaya, T.V., Karpenko, H.V. and Yanko, T.B. (eds). *Space Technologists: Present and Future: Abstract. Report of the 4th International Conference*: p. 94. Dnepropetrovsk, April 17–19, 2013.

[21] Park, S.J. (2018). "Carbon Carbon Composites." In: *Carbon Fibers*. Springer Series in Materials Science, Vol. 210. Springer, Singapore, pp. 279-294. DOI 10.1007/978-981-13-0538-2_8.

[22] Zelin, Wang, Bingzhu, Lai, Hui, Wang, Heye, Xiao, and Pingwen, Ming, Effects of Micropore Characteristics in the Metal Skeleton on Heat and Mass Transfer in an Open Foam Structure for Thermal Management in the Hydrogen UAV." *International Journal of Thermal Sciences* Vol. 179 (2022): p. 107628. DOI 10.1016/j.ijthermalsci.2022.107628.

[23] AL-Saleem, Nouf K., Ghrib, Taher, AL-Naghmaish, Aishah, Elshekhipy, Abdelhafeez A., Almalki, Nawal, Gmati, Nabil, and Kamoun Turki, Najoua. Effect of Porosity on Structural, Optical, Thermal, and Electrical Properties of Nickel-Foam Coated Graphene Sheets." *Journal of Materials Research and Technology* Vol. 19 (2022): pp. 300–313. DOI 10.1016/j.jmrt.2022.05.049.

[24] Dyga, R. and Witczak, S. "Investigation of Effective Thermal Conductivity Aluminum Foams." *Procedia Engineering* Vol. 42 (2012): pp. 1088–1099. DOI 10.1016/j.proeng.2012.07.500.

[25] Lu, Pengbo, Cheng, Fan, Ou, Yanghao, Lin, Meiyan, Su, Lingfeng, Chen, Size, Yao, Xilang, and Liu, Detao. "A Flexible and Transparent Thin Film Heater Based on a Carbon Fiber/Heat-Resistant Cellulose Composite." *Composites Science and Technology* Vol. 153 (2017): pp. 1–6. DOI 10.1016/j.compscitech.2017.09.033.

[26] Lee, Sora, Jang, Dawon, Chung, Yong Sik, and Lee, Sungho "Cost-Effective and Highly Efficient Surface Heating Elements using High Thermal Conductive Carbon Fibers." *Composites Part A: Applied Science and Manufacturing* Vol. 137 (2020): p. 105992.

[27] Hu, J.; Jahid, M.A.; Harish Kumar, N.; Harun, V. Fundamentals of the Fibrous Materials. In Handbook of Fibrous Materials; Wiley Online Library: Hoboken, NJ, USA, 2020; pp. 1–36. DOI 10.1002/9783527342587.ch1.

[28] Shcherbakova, E.P., Prokhorova, A.D., Karpenko, A.V. and Yanko, T.B. "Current State of Methods for Low-Dense Constructional Composite Materials Producing (Overview)." *Problems of Atomic Science and Technology (Past)* Vol. 125 No. 1 (2020): pp. 114–120.

[29] Sharma, R., Ravikumar, N.L., Dasgupta, K., Chakravartty, J.K. and Kar, K.K. "Advanced Carbon–Carbon Composites: Processing Properties and Applications." In: Kar, K. (ed). *Composite Materials*. Springer, Berlin, Heidelberg (2017), pp. 315-367. DOI 10.1007/978-3-662-49514-8_10.

[30] Skachkov, V. A. "Obtaining Low-Density Carbon Carbonized Materials." In: Skachkov, V.A., Chervonny, I.F. and Karpenko, A.V. (eds). *Eastern European Journal of Advanced Technologies*, Kharkiv (2013): pp. 48–51.