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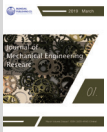

ARTICLE

Predicting Performance of a Thermal Shield of a Spacecraft in a High-temperature Gas Flow

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ABSTRACT

A fundamental understanding of the mechanism of material interaction with a medium is based on correspondence between experimental studies and actual operating conditions of a given model or a structure. The study of performance of thermal shield structures was based on computations brought about considering physical properties of materials obtained under conditions simulating re-entry of a spacecraft into the atmosphere. A thermal shield consisted of a layered type shell, made of fiber glass with phenol-phormaldehide matrix. The mechanical and the thermo-physical properties were studied as a function of temperature. A thermal-stressed state of a cylindrical shield subjected to action of a high-temperature gas flow, is defined based on solving a 3D problem simultaneously using equations of theory of elasticity, thermal conductivity, and numerical analysis. The results showed that the largest compression stresses in a thermal shield shell made of fiberglass are concentrated at the vicinity of the surface being heated, and are not larger than the strength limit of the material under a given temperature.

1. Introduction

Thermal shield materials (TSMs) for aerospace technologies are classical examples of objects operating in a supersonic high-temperature gaseous medium.

Problems of thermal shield (TS) of a spacecraft while in motion in the dense layers of the atmosphere, both on a passive and on an active trajectories, are of special importance for spacecraft technologies. It is known that due to action of a high-temperature gas flow on the surface of a spacecraft, some cracks can be developed in its thermal shield, which brings to the loss of a shield's operation ability [1].

For solving this problem, an experimental study was realized and a theoretical approach was used to evaluate thermal stresses and deformation in TS, depending on conditions simulating real ones in re-entry of the descent apparatus (DA) in dense atmospheric layers.

2. Principles of Thermal Shield Action. Extreme Maintenance Conditions

Most of thermal shield's functionality is based on using a

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principle of destruction of a surface layer for the sake of creating a working thermal regime of either inner layers or a structure as a whole. The choice of materials should be used under conditions for extreme external exposures, a major criterion is durability that defines the maximum possible time value during which the material performs its function. In every specific case, this time value depends on material properties, a damage type, and on a maintenance regime.

Extreme conditions are determined by temperature levels, by acting mechanical stresses, a heating time, by a degree of chemical aggression of an external medium and by its pressure, by powerful radiation, abrasive-erosion action, etc. Under real conditions, thermal, force, and chemical actions on materials of thermal shields occur simultaneously. This is a special threat in terms of durability of a TSM.

Currently, in thermal shield science there is search of "self-healing" methods of defects in the volume of the material, i.e., creation of self-repairing materials.

Intense heat flows directed towards inside of a structure, owing to non-uniformity of temperature distribution in its elements, which causes development of temperature gradients that bring to thermal stresses. Thermal deformations that appear in shields, as a result of physical and chemical transformations in a material under conditions of a high-temperature heating, are a source of additional stresses that superimpose themselves on a field of thermal stresses, might overcome the strength limit of the material and can cause instability and destruction of TS.

There are two types of space flights that require return of a spaceship to Earth: (i) orbital flights around the Earth, (ii) flights to the Moon and to other planets.

After an orbital flight, the spaceship returns to the Earth atmosphere with velocity 7.9 km/s. After the flight to other planets the velocity is 11.1 km/s. Orbital spacecrafts, both manned and unmanned, are exposed to instantaneous thermal loads (q_w= 6000 kW/m^2) during a substantially greater duration of thermal action [2].

Under conditions of a high-temperature heating, irreversible changes of thermal and physical properties of a material occur, such as its density reduction, an increase in gas permeability, development of a secondary porosity, changes in thermal conductivity. Shrinkage is developing under certain temperature values, and thermal expansion is of a non-monotonous type, and, as a consequence, local extremes of expanding (shrinking) tangential stresses occur. These all bring to cracking of a composite.

An estimate of a level of thermal stresses in a thermal shield, made of polymer composite materials, that appear due to thermal deformations and due to temperature gradient under conditions simulating real ones on descent trajectory of DA in dense atmospheric layers enables an effective development of the thermal shield for DA and allows us to choose a material with required physical and chemical parameters.

Thermal shield laminates for multi-flight, reusable spacecrafts (Shuttles, "Buran") should withstand thermo-mechanical loads in an oxidizing medium in heating up to 1700 degrees Celsius without decrease in strength, both in multiple flights in space and in returns to Earth. Carbon-carbon composites are such materials [3-5], and metallic composite materials as well, the latter ones received a development impetus lately [6].

Currently, in the thermal shield material science there is some search for methods of "self-healing" of defects in the volume of the material, i.e. creation of 'self-recovering' materials.

3. Study of Thermal Expansion of Destructing TSMs Using a Non-contact Optical Method under Conditions Simulating Real Ones

Specific weight of a structure is of the most importance for spacecrafts. The less its weight, the more useful space load it can deliver. Thermal shield is a ballast weight for a missile, therefore it is natural to desire to reduce the weight of TSMs without reliability loss of its thermal shield function.

The design of TSMs is based on some criteria such as parameters of heating and destruction of materials under minimal weight of the shield. Physical modeling of natural conditions of thermal shield use (temperature, heating/cooling rate, composition, and pressure of gas medium) is based on the dependence of temperature T of a side surface of thermal shield on the time of descent in dense atmospheric layers.

Thermal shield material is a fiberglass (FG) made by a method of hot pressing of silica cloth saturated with phenol-phormaldehide resin with a standard ratio of volumes of filler and matrix: 67% and 33%.

To calculate a thermal stressed state of the shield, both physical and mechanical characteristics of TS are defined experimentally under conditions that are very close to actual ones. Solving problems of strength and of deformation of TS structures at temperatures up to 1000 ^{0}C and above made it necessary to define coefficients of thermal deformation for such materials under conditions simulating real ones: while varying heating conditions, heating rate, chemical composition, gas pressure, etc. In the Institute for Problems of Strength (Kiev), dilatometer setups were designed that allow one to measure expansion

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(shrinkage) of samples made of either polymer or carbon composite materials using non-contact optical method in heating, under conditions simulating real ones in one-, two- or three mutually orthogonal axes simultaneously [7, 8].

The values of thermal deformation of the fiberglass were implemented on a linear dilatometer setup DTM that provides a capability to study deformation properties of samples made of thermal shield materials under either homogeneous or one-sided heating, at various pressure values, and under any heating rate (1…900 degrees Celsius/min) [9]. A working medium is argon, nitrogen, air.

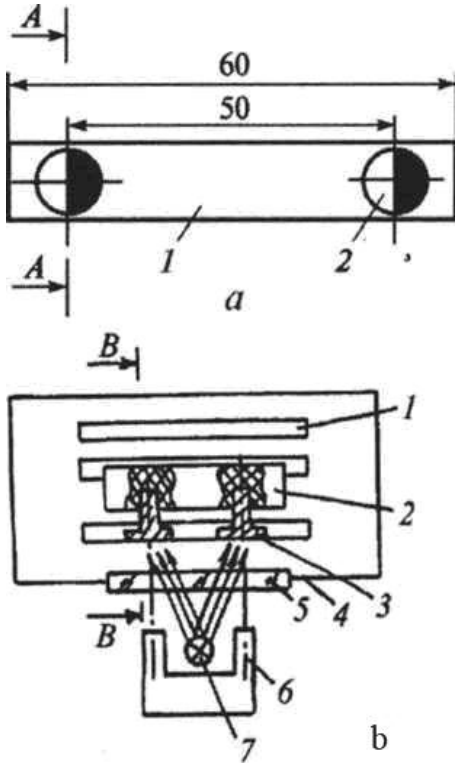

Figure 1. A sample and its placement in a testing chamber of the DTM setup (a) side view: 1 – sample, 2 – fiducials (b) top view.

The setup DTM (Figure 1, b) consists of a high-temperature oven (4), heating system (1) of the sample (2), regulation and change of its temperature, non-contact photo-recording module (5, 6, 7), system of maintaining and measuring gas pressure inside the oven, and a cooling system of the oven as well. The basis of deformation measurement is the distance between two fiducials of a special shape (3) (Figure 1, b).

Sample deformations in heating are measured automatically using a specially designed two-channel optical system OSS-50-1300 [10, 11] that is utilizing a method of continuous photo-tracking of fiducials imbedded into a sample. DC voltages that correspond to fiducials' displacements for both measuring channels are sent to an integrator where they are algebraically summed up. Secondary detecting devices (an electronic potentiometer, a computer) record a continuous curve of change of thermal expansion (shrinkage) of the sample in coordinates ΔL (displacement) – T (temperature) [12].

Thermal deformation of the TSM was studied in the temperature range 20…1100 ^{0}C at a varying heating rate, and under uniform thermal action. Deformation measurements were brought about by an automatic tracking system using an opto-electronic method (Figure 1) that excluded errors due to indentors' pressure on a softening sample in heating. Dilatometering was implemented in air with heating rates V_h equal to 5, 10, 20, 25, 50, 75, and 100 ^{0}C/min.

Reinforced polymer composite materials based on a thermo-reactive binder are used for thermal shielding of a descent apparatus. Their widespread use in new technologies is due to their ability to protect structures of a spacecraft from over-heating. They are able to absorb large heat quantities in destruction of plastics that in heating followed by cooling are going to a solid, non-melting, and an indissoluble state. Glass, silica, boron, and carbon threads are used as reinforcing elements [13]. Melted glass and silica (quartz) threads exhibit a high melting temperature, low density, and a rather high strength [14]. Boron and carbon threads belong to a class of the most promising reinforcing elements due to their low density (1.4 - 1.8 g/cm^3) and due to very high strength: E = 2500 MPa for low-modulus threads and E = 4000 MPa for high-modulus ones [6].

Use of reinforced plastics for thermal shield of single-use spacecrafts is due to not only a low value of their thermal conductivity but also due to their large heat absorption while destructing.

The maximum rate of disintegration for phenol resins is in the range 300...600 ^{0}C. As a result of resin disintegration, a part of the binder is transformed into gaseous products, while the other one (up to one half) remains in the cloth matrix as a condensed carbon [15, 16]. Physical and chemical transformations in a material in high-temperature heating cause a change in geometry of a thermal shield layer, both expansion and shrinkage.

A fiberglass based on a thermo-reactive matrix is a traditional material for the thermal shield of a side surface of a descending spacecraft in the dense atmospheric layers. A thermal shield material is a fiberglass laminate (FL) made using a method of hot pressing of the silica cloth fed with phenol-phormaldehide resin with a standard ratio of the volumes of the filler and the matrix: 67% and 33%.

Figure 2 shows curves of thermal deformation of sam-

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ples of the size 3x10x60 mm, being heated with various heating rates (seven-eight samples are tested under a given heating rate value) [17]. In general, a curve of expansion-shrinkage of a reinforced plastic is characterized by the following processes:

Expansion of the material up to the temperature values of solidification of the binder;

Sample shrinkage caused by decomposition of a polymer binder with extensive discharge of volatile components in this temperature range, and by formation of coke;

Fiberglass laminate shrinkage that occur simultaneously during pyrolysis, and an increase of the material volume due to formation of pores and cracks from one side, and thermal expansion of the formed coke from the other side;

Completion of pyrolysis, mainly.

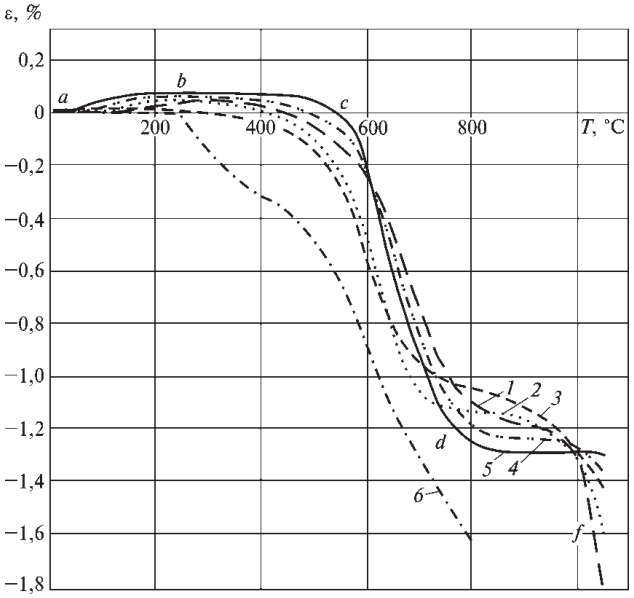

Figure 2. Thermal deformation of fiberglass FG versus temperature at heating rates, ^{0}C/min: 1 – 10, 2 -20, 3 - 25, 4 – 50, 5 -75, 6 -5.

Figure 2 shows that in increasing a heating rate the expansion zone is growing: the beginning of shrinkage and the point of intersection of thermal deformation curves with the temperature axis are shifted towards higher temperatures, with the greatest shrinkage to occur in samples heated with the slowest rate.

Thermal deformation curves of composite polymer materials destructing in heating show an involved character, both poly-extreme and sign-changing. A possibility of analytical formulation of dependencies for thermal deformation as a function of temperature for such materials is getting complicated by their dependence on a number of factors – first of all on a heating rate – this is related to the time of occurrence of both phase and structural transformations in a polymer matrix.

Despite a very complicated character of thermal deformation curves of composites based on destructing matrices, it is feasible to establish their analytical representation using statistical and regression analysis.

4. Thermal Deformation of TSL Made of Fiberglass under Conditions Simulating Real Ones

The dependence of temperature T of the side surface of thermal shield laminate upon the time of descent of DA in dense layers of the atmosphere is a basis of physical modeling of natural environment for a thermal shield (temperature, heating and cooling rates, composition and pressure of a gaseous medium). Figure 3 shows temperature change in a layer of a thermal shield laminate of a descending space vehicle in heating and cooling during descent from the orbit.

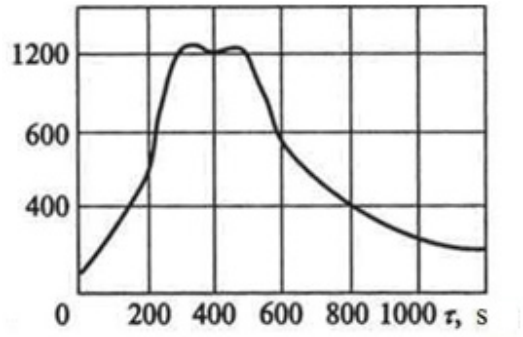

Figure 3. Dependence of temperature in a layer of thermal shield material made of fiberglass on the time of descent from the orbit.

To establish heating rates of the material that occur on a flight trajectory, the dependence T-τ (temperature – time) was cut into some parts with equal tangents of the curve's tilt towards the time axis. As shown on Figure 3, the maximum temperature of 1200 ^{0}C is achieved on the 300th second, with the first 200 seconds of heating up to the temperature 520 ^{0}C, the heating rate being 2.6 ^{0}C/s (156 ^{0}C/min), and in the temporal range 200...300 s it was equal to 10 ^{0}C/s (600 ^{0}C/min). On non-significant decreasing of temperature followed by keeping at a maximal heating rate of 1200 ^{0}C in the time interval (310…470 s), the temperature of the material starts to decrease with a rate of 3.6 ^{0}C/s (216 ^{0}C/min) down to 700 ^{0}C, then the cooling rate drops down to 1.1 ^{0}C/s (66…50 ^{0}C/min) (Table 1).

A trajectory of the spacecraft descent, divided into time sections, was a basis to study thermal deformation of composite polymer thermal shield material with heating/cooling rates corresponding to real ones.

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Table 1. Values of temperature and a heating rate of TSM in various time intervals of the descent trajectory (values in ^{0}C/min are shown in parentheses)

Time, *t* (s)	*T* ^{0}C	*Heating rate*, ^{0}C/s
20…200	520	2.6 (156)
200…300	1200	10 (600)
310…470	1200	3.6 (216)
470…510	700	1.1 (66)
610…1000	260	-

To get some insight into thermal deformation of a layer of thermal shield with a maximal likelihood, we tested samples from the FG material with heating rates of 150 and 600 ^{0}C/min (values in the parentheses in the Table 1 above). To compare data we used a rate of 50 ^{0}C/min. Testing was brought about in a neutral gaseous medium (argon) up to temperatures of 1000 ^{0}C with uniform heating through the samples. Samples of the size of 60 x 10 x 4 mm were cut in the plane of reinforcement in three directions: along the base, at right angles to the base, and at an angle of 45^0 to the silica cloth.

Results for thermal deformation of polymer composite FG in three directions under various heating rates are shown on Figure 4 [8, 18]. Dashed lines show deformation of the composite in cooling. Testing was brought about with sample heating rates: 1 - V_h = 50 ^{0}/min; 2 - V_h = 150 ^{0}/min; 3 - V_h = 600 ^{0}/min (Figure 4).

Curves of thermal deformation of composite polymer materials destructing in heating are of an involved, poly-extreme and sigh-changing character. Dependencies of thermal deformation are typical for fiber glasses based on phenol resins: there is expansion up to temperatures 100 …200 ^{0}C followed by shrinkage connected to evaporation of adsorbed water and completion of matrix polymerization. Beginning with 300 ^{0}C and above, there is some disintegration of organic binder accompanied by an extensive discharge of gas [15, 19].

A further increase in temperature is characterized by two competing processes: a developing destruction of the polymer and a started structuring of coke remainder. An interplay of these processes affects the character of the dependencies of thermal deformation of composites on the polymer base. An increase in heating rate effects thermal expansion (shrinkage). Change in deformation properties occurs in heating rate increase up to 600 ^{0}C/min.

Thus, with an increase in a heating rate V_h in the range of 50…150 ^{0}C/min (Figure 4) the temperature of appearance of the first extremum on curves is shifted just on 25…30 ^{0}C, while under V_h = 600 ^{0}C the value of this temperature (300 ^{0}C) is doubled in comparison with that of under V_h= 50 ^{0}/min. Material shrinkage in the temperature range 200…500 ^{0}C (the first peak on dilatometric curves) under V_h= 50 ^{0}C/min is 0.2%, under V_h= 150 ^{0}C/min – 0.4%, and under V_h = 600 ^{0}C/min – 0.9%.

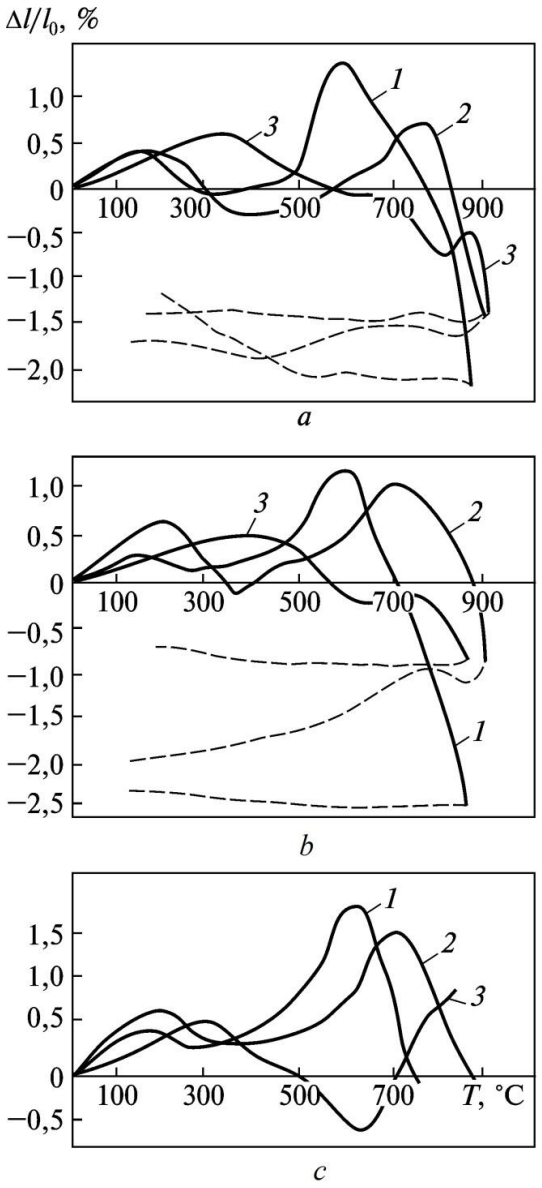

Figure 4. Temperature dependencies of relative thermal deformation of the material FG for samples cut on the cloth base (a), on weft (b), (c) at 45^0 to the base.

We found out analogous dependencies for the second extremum on the curves: with an increase of the heating rate, the peak of relative quantities of thermal expansion is shifted towards the region of higher temperatures, with maximum deformation values being decreased.

An increase in the heating rate in the experiments affects the values of the shrinkage of FG in the studied temperature range. Regardless of the direction of the sample cut (base, weft, 45^0 towards the base), heating acceleration brings to diminishing of the shrinkage in heating, and, cor-

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respondingly, to the decrease of residual deformation in cooling. A more significant thermal expansion and much smaller shrinkages under high heating rates are owing to the decrease in time of occurrence of physical and chemical processes. Dilatometric curves are shifted towards the region of higher temperature and deformation values.

Figure 5 shows dilatometric curves obtained in heating of FG in a neutral gas medium in three directions in the plane of reinforcement of the composite: along the base, weft, and at an angle of 45^0 to the cloth base. Testing was brought about with the sample heating rates: (a) $V_h = 50\ ^0$/min; (b) $V_h = 150\ ^0$/min; (c) - $V_h = 600\ ^0$/min (Figure 5). One can see from these Figures that under the same temperatures in the material along the direction of the cloth base expansion can occur, shrinkage can occur along the weft, and vice versa. This means that for coefficients of thermal deformation in mutually orthogonal directions and at an angle 45^0 there are not only different values but also different signs.

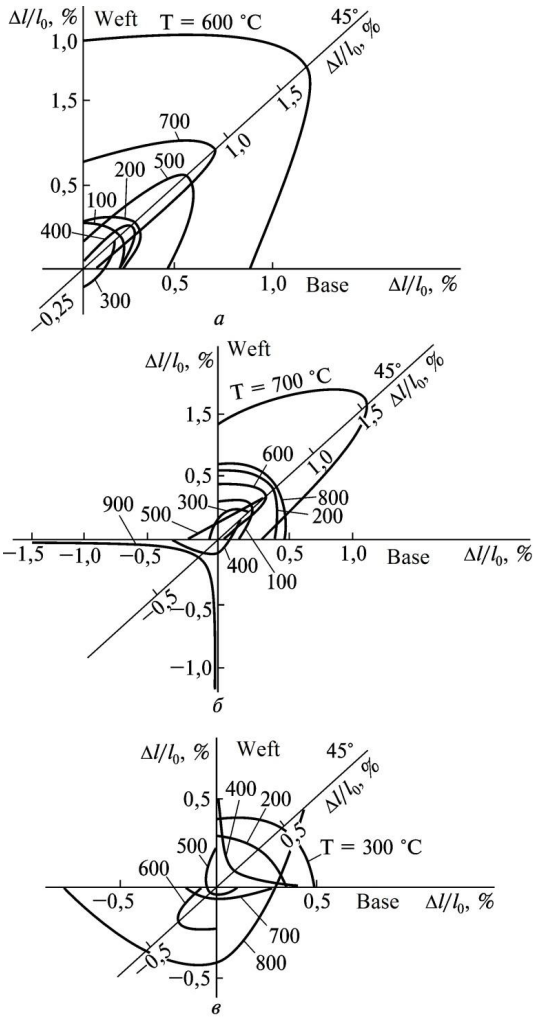

Figure 5. Relative thermal deformation of FG along the anisotropy axes of the material under a varying heating rate.

An increase of the heating rate (Figure 5, b, c) promotes expansion and shrinkage decrease. This affects a coking material in the direction of growth of the overall amplitude of change of its thermal deformation.

To evaluate performance and reliability of the thermal shield, it is necessary to take into account conditions that develop themselves during its operation, particularly, changes in character and heating intensity on the descent path.

Thus we attempted to model heating conditions in a layer of material FG in descent from the orbit (Figure. 2) while determining dependencies of thermal deformation of the polymer composite in three directions of material reinforcement. For that, in correspondence with the data on both time and temperature intervals shown on Fig. 3 and in Table 1, all of the research process was brought about according to a following program: heating with the rate $V_h = 150\ ^0$C/min, 200 s → $600\ ^0$C/min, 120 s → curing under an achieved temperature value → 150 s → cooling down with the rate of $V_c = 200\ ^0$C/min, 140 s → $V_c = 60\ ^0$C/min, 600 s.

The results of the experiment provide rather complete information on the character of the change of thermal deformation of the material FG, where 1 – thermal deformation on the base, 2 – along the weft, 3 – at the angle 45^0 to the base (Figure 6). As shown on the Fig. 6, the overall amplitude of the change of characteristics of deformation is large (4%), with input of the thermal expansion being no more than 0.3 – 0.8%, the remainder 3% being shrinkage. For the maximal in our case temperature (T = 900 ^{0}C), shrinkage along the base is equal to 0.7% in heating, and in the case of exposure during 150 s under this temperature, its values is increased up to 1.8%, i.e., as large as twice. For the direction of sample cut at an angle of 45^0 towards the base, the increase of shrinkage under an analogous exposure is 1%.

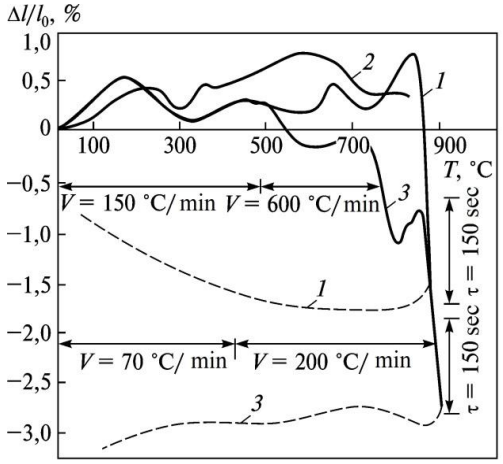

Figure 6. Temperature dependence of the relative thermal deformation of the material FG, heated (solid lines) and cooled (dotted lines) according to the program of orbit descent.

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Shrinkage either does not change under cooling conditions with a rate derived from the program, or change insignificantly (Figure 6, curve 3). In cooling of samples that were cut along the base, the residual deformation was more than 3%.

As a result of studying the thermal shield polymer composite material FG in a neutral gas medium (argon), we established that dependencies of thermal deformation of the composite reveal a complex poly-extremum and sign-changing character. In a given temperature range there are:

Simultaneous (under the same temperature) expansion and shrinkage of the material cut in three directions – parallel, at right angles, and at an angle 45^0 towards the base of the filler, with the difference of relative values of thermal deformation being no more than 2%;

Maximal shrinkage (more than 2.5%) for the material FG, cut in the weft direction, with the transition temperature of the composite from shrinkage to expansion in this case being increased.

Increasing of the heating rate in dilatometer measurements of samples from the material FG:

(1) brings to an increase of thermal expansion of the composite. Thus, for the base, the maximum expansion under a heating rate $V_h = 150\ ^0$C/min as large as two times, and under $V_h = 600\ ^0$C/min more than seven times as large as that of under $V_h = 50\ ^0$C/min. For the weft, the difference in values of thermal expansion under $V_h = 50$ and $600\ ^0$C/min is increased by the order of magnitude. This is 1% for relative thermal deformations;

(2) is displacing the peak of thermal expansion values towards temperature increase; for the direction of the base the temperature increase ($V_h = 50$ and $600\ ^0$C/min) is 70-80, and for the direction of the weft it is more than $150\ ^0$C;

(3) is decreasing the value of shrinkage in directions of the base and weft of the composite (as much as five times), and in the direction 45^0 to the base, in the temperature range 400-500 ^{0}C is increasing it by the order of magnitude;

(4) is shrinking the temperature interval of physical and chemical transformations of the material, as if "compressing" curves of thermal deformation along the temperature axis, which is especially observed under a heating rate $V_h = 600\ ^0$C/min (Figure 6). Thus, if under heating rates $100\ ^0$C/min and less thermal expansion of a coked material starts at temperatures above $1000\ ^0$C, under $V_h = 600\ ^0$C/min the start of intensive thermal expansion is observed already at $400\ ^0$C for the directions of the weft and at 45^0 towards the base, and at $550\ ^0$C for the base direction as well.

In studying thermal deformation of FG according to a program that corresponds to temperature-temporal intervals on a descent trajectory, it is found out that the overall amplitude of change of relative thermal deformation of the material is almost 4%, with thermal deformation being no more than 1%; cooling of FG under a rate given according to the program is stabilizing shrinkage process and is bringing to (in most cases) to the decrease of the residual deformation.

Thus, as a result of studying thermal deformation of thermal shield laminate made of a polymer composite material based on a phenol-phormaldehide matrix, under conditions simulating temperature-temporal interval of the descent of a space vehicle from the orbit, it is shown that maximal thermal deformations in the plane of reinforcement of the composite arise in the direction of 45^0 towards the base of the filler cloth. The amplitude of dilatometric values is essentially decreased with an increase in heating rate. A residual relative thermal deformation of a thermal shield material tested according to the program of the descent form the orbit could reach up to 2% and more [18, 20].

5. Computation Methodology for a Thermal Stressed State of a Thermal Shield Laminate of DA

The goal of this study is to determine the thermal stressed state in a thermal shield laminate made of polymer composite materials arising due to thermal deformation and temperature gradient under conditions simulating real ones on the descent trajectory of DA in dense atmospheric layers.

Computation of a thermal stressed state is carried out for a structural element of DA in the form of a cylindrical shell made of real thermal shield material FG corresponding to an actual temperature distribution in a layer of thermal shield laminate in the process of apparatus descent from the orbit through dense layers of the atmosphere (Figure 3).

A theoretical basis of a proposed approach to estimate a thermal stressed state of the thermal shield laminate of the DA is a study of its stressed-deformed state under temperature action. A thermal stressed state of the thermal shield laminate of a structural element of DA in the form of a cylindrical shell is determined based on solving a system of equations of the 3D theory of elasticity in cylindrical coordinates, with joint use of thermal conductivity equations and numerical analysis [21, 22].

A starting point is relations of the linear theory of elasticity for a non-homogeneous body. Taking into account a hypothesis of Duhamel – Neiman, for the equations of a generalized Hook's law in cylindrical coordinates z, θ, r

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for an i-th layer ($r_{i+1} \le r \le \le r_i$, i = 1, 2, ..., N) of an anisotropic material with a single plane of elastic symmetry r = const we have [23]:

$$\begin{aligned}
e_z^i &= a_{11}^i\sigma_z^i + a_{12}^i\sigma_\theta^i + a_{13}^i\sigma_r^i + a_{16}^i\tau_{z\theta}^i + \alpha_1^i T^i,\\
e_\theta^i &= a_{12}^i\sigma_z^i + a_{22}^i\sigma_\theta^i + a_{23}^i\sigma_r^i + a_{26}^i\tau_{z\theta}^i + \alpha_2^i T^i,\\
e_r^i &= a_{13}^i\sigma_z^i + a_{23}^i\sigma_\theta^i + a_{33}^i\sigma_r^i + a_{36}^i\tau_{z\theta}^i + \alpha_3^i T^i,\\
e_{r\theta}^i &= a_{44}^i\tau_{r\theta}^i + a_{45}^i\tau_{rz}^i + \alpha_{23}^i T^i,\\
e_{rz}^i &= a_{45}^i\tau_{r\theta}^i + a_{55}^i\tau_{rz}^i + \alpha_{13}^i T^i,\\
e_{z\theta}^i &= a_{16}^i\sigma_z^i + a_{26}^i\sigma_\theta^i + a_{36}^i\sigma_r^i + a_{66}^i\tau_{z\theta}^i + \alpha_{12}^i T^i,
\end{aligned} \tag{5.1}$$

where $\sigma_r^i\,\sigma_r^i$, $\sigma_z^i\,\sigma_z^i$, $\sigma_\theta^i,\sigma_\theta^i$, $\tau_{z\theta}^i,\tau_{z\theta}^i$, $\tau_{rz}^i\,\tau_{rz}^i$, $\tau_{r\theta}^i$ $\tau_{r\theta}^i$ - are stress components. Elastic characteristics a_{mn}^i a_{mn}^i, coefficients of thermal expansion $\alpha_1^i\,\alpha_1^i$, $\alpha_2^i\,\alpha_2^i$, $\alpha_3^i\,\alpha_3^i$ in the directions z, θ, r and shear moduli α_{12}^i, α_{12}^i, $\alpha_{13}^i\,\alpha_{13}^i$, $\alpha_{23}^i\,\alpha_{23}^i$ depend on coordinate r. Coefficients of linear expansion can be presented in a following form:

$$\begin{aligned}
\alpha_{11}^i &= \alpha_1^i\cos^2\varphi + \alpha_2^i\sin^2\varphi,\\
\alpha_{22}^i &= \alpha_1^i\sin^2\varphi + \alpha_2^i\cos^2\varphi,\\
\alpha_{12}^i &= 2(\alpha_1^i - \alpha_2^i)\sin\varphi\cos\varphi,\\
\alpha_{33}^i &= \alpha_3^i\ \ \alpha_{13}^i = \alpha_{23}^i = 0,
\end{aligned} \tag{5.2}$$

where φ is the tilt angle towards Z-axis.

It is worth mentioning that the last condition is taking into account an arbitrary change of elastic properties of the material through its thickness. The problem of theory of elasticity must satisfy not only the equation of equilibrium, dependencies deformation – displacement, Hook's law but also some boundary conditions on all the surfaces of the body and conjugation conditions of layers. In most cases, the contact is rigid provided that all the layers are deformed without slipping and stratification. Then, conditions for components of the displacement vector and for components of stress tensor should satisfy:

$$\begin{aligned}
\sigma_r^i &= \sigma_r^{i+1}\ \ \tau_{rz}^i = \tau_{rz}^{i+1}\ \ \tau_{r\theta}^i = \tau_{r\theta}^{i+1},\\
u_r^i &= u_r^{i+1}\ \ u_z^i = u_z^{i+1}\ \ u_\theta^i = u_\theta^{i+1}.
\end{aligned} \tag{5.3}$$

The temperature field for an i-th layer of the cylinder is defined from the thermal conductivity equation, which in cylindrical coordinates is:

$$K_r^i\frac{\partial}{\partial r}\left(\frac{\partial T^i}{\partial r}\right) + rK_z^i\frac{\partial^2 T^i}{\partial z^2} + \frac{K_\theta^i}{r}\frac{\partial^2 T^i}{\partial\theta^2} = 0, \tag{5.4}$$

Where $K_r^i = K_r^i(r)$, $K_z^i = K_z^i(r)$, $K_\theta^i = K_\theta^i(r)$ - coefficients of thermal conductivity acting in the directions r, z, θ. It is assumed that conditions of thermal continuity are satisfied all over the surface of layers' contact:

$$T^i = T^{i+1} \qquad K_r^i\frac{\partial T^i}{\partial r} = K_r^{i+1}\frac{\partial T^{i+1}}{\partial r}. \tag{5.5}$$

In our case, the butt ends of the cylinder z = 0, z = l are not displaced in their planes and are not subjected to action of a normal load.

In constructing the equations we took into account that unknown functions should satisfy conjugation conditions for adjacent layers and conditions on contiguous surfaces $r = r_0$, $r = r_N$ in the most simple way [23].

On transforming equations of elasticity (5.1) and of thermal conductivity (5.4), and on dividing variables for each pair of values K and n for an i-th layer, we obtain a solving system of equations in the form [24]:

$$\begin{aligned}
&\frac{d\bar{\sigma}_{kn}^i}{dr} = C_{kn}^i\bar{\sigma}_{kn}^i + \bar{f}^i,\\
&\bar{\sigma}_{kn}^i = (\sigma_{r,kn}^i, \tau_{rz,kn}^i, \tau_{r\theta,kn}^i, u_{r,kn}^i, u_{z,kn}^i, u_{\theta,kn}^i, T_{kn}^i, T_{kn}'^i),\\
&C_{kn}^i = \left\|c_{mq,k}^i(r)\right\|,\\
&f^i = (f_1^i, f_2^i, \ldots, f_8^i),
\end{aligned} \tag{5.6}$$

m, q = 1, 2,..., 8,

Where σ_r is a radial stress τ_{rz}, $\tau_{r\theta}$ - tangential stresses, u_r, u_z, u_θ - radial, axial, and circumferential displacements in cylindrical coordinates; T – temperature, T' – temperature gradient.

Matrix elements $C_{kn}^i\,C_{kn}^i$ depend on mechanical characteristics of a material layer, components of the vector f depend on the temperature load. Integration of equations (5.6) is carried out using a numerical method that allows one to get a solution with high accuracy. Choices of basic values that are used to formulate contact conditions for layer conjugation allow us to get automatically and continuously solutions for a given number of layers. A stable numerical method of discrete orthogonalisation is used to solve the boundary problem [20, 25].

6. An Estimate for a Thermal Stressed State for the Thermal Shield Laminate of DA

An estimate of a stressed-deformed state of a hollow thermal shield shell made of material FG for conditions simulating real ones in descent of DA from the orbit is carried out according to the above method and in correspondence with a real temperature distribution in a layer of thermal shield in the process of descent of DA in dense atmospheric layers (Figure 3).

Physical and mechanical characteristics for computation of thermal stresses are determined experimentally.

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Coefficients of thermal expansion α corresponded to ones obtained under conditions simulating real ones (Figure 6), elasticity modulus E in stretching and in compression, and in shear $G_{z\theta} = G_{\gamma z} = G_{\gamma\theta}$ are obtained in the temperature range 20…1000 ^{0}C in heating with the rate of 100 ^{0}C/min in a neutral gas medium.

Some results of solving a problem of a thermal stressed state for a thermal shield cylindrical laminate being heated from the surface are shown on Figures 7, 8.

Computation is made for a hollow cylindrical shell made of fiberglass with the base FFS, with the length L = 340 mm, radius of a middle surface R = 90 mm, and the wall thickness δ = 5 mm. Figure 7 shows distribution of radial translations U_r. Figure 8 shows tangential stresses $\tau_{z\theta}$ and $\tau_{r\theta}$ acting along the length and through the thickness of the shell simultaneously [20].

Table data demonstrate that the largest thermal stresses for a thermal shield with δ = 5 mm are obtained in outer layers of a heated surface; $\tau_{z\theta}$ = -115,36 MPa.

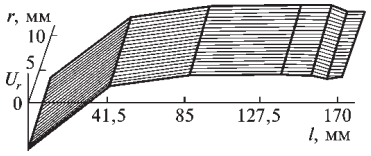

Figure 7. Distribution of radial translations along the length and thickness of a thermal shield shell made of FG.

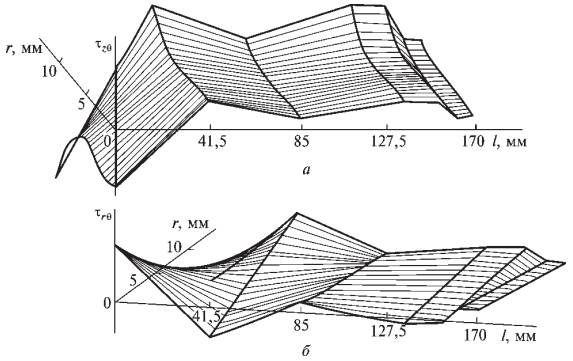

Figure 8. Distribution of the values of tangential stresses $\tau_{r\theta}$ and $\tau_{z\theta}$ along the length and thickness of the thermal shield shell made of FG.

Table 2. Extremum values of tangential stresses along the thickness and the length of a cylindrical thermal shield laminate on the descent trajectory

r, мм	$\tau_{z\theta}$, MPa		τ_{rz}, MPa	
	max	min	max	min
1	—	—	—	—
2	—	—	—	—
3	—	–115,36	—	—
4	—	—	45,66	—
5	55,54	—	—	–37,08

The above curves show that tangential stresses are changing through the thickness of the cylinder according to a nonlinear dependence. Stretching tangential stresses acting at the depth of 2…2.5 mm from the outer surface of the cylinder in the temperature range 300…700 ^{0}C (Table 2) - in the temperature range of binder thermal destruction, are the largest ones.

In a given case, tangential thermal stresses in the cylindrical shell made of fiberglass based on FFS are developing due to anisotropy of temperature expansion of the composite: in the reinforcement plane of a thermal shield material at one point can occur both expansion and shrinkage simultaneously while heating. This inevitably brings to shear deformations, that are getting superimposed on thermal stresses in the material due to temperature gradients, become the cause of crack development without application of any external forces.

7. Conclusion

Both experimental and theoretical studies of an outer layer of the thermal shield shell FG for conditions simulating descent trajectory in the Earth atmosphere are implemented.

In studying thermal deformation according to the program that corresponds to using temperature-temporal intervals on the descent trajectory, it is established that an amplitude of change of relative deformation characteristics of the material is almost 4%, with thermal expansion being no more than 1%. Cooling of fiberglass under a given rate according to the program stabilizes the shrinkage process and causes (in most cases) the decrease of the residual deformation.

Results of computation of thermal stresses showed that thermal stresses that develop themselves in a thermal shield layer are changing through the thickness and along the length of the cylinder according to a nonlinear dependence and are caused by action of shear deformations that, in their turn, are a result of anisotropy of thermal deformation of a destructing in heating polymer composite.

The largest stretching tangential stresses that are developed in a thermal shield layer are not larger than 55.5 MPa and they act at the depth of 2…2.5 mm from the outer heated surface of thermal shield laminate in the temperature range 300…700 ^{0}C, a temperature interval peculiar to the process of thermal destruction of the material.

The largest compression stresses in a thermal shield shell made of fiberglass are 115.4 MPa, they are concentrated at the vicinity of the surface being heated, and are not larger than the strength limit of the material under a given temperature.

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Implemented studies showed that, based on a proposed approach that includes both experimental and theoretical components, one can choose materials with optimal physical and chemical characteristics that provide strength and reliability of functioning for FG while going through dense layers of the atmosphere.

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Nomenclature

q_w	=	instantaneous thermal load
V_h	=	heating rate
E	=	elasticity modulus
ε, %	=	thermal deformation
$\Delta l/l_0$	=	relative thermal deformation
V_c	=	cooling rate
i	=	index for a layer of material
a^i_{mn}	=	elastic characteristic
σ^i_r	=	stress component in the direction r
σ^i_z	=	stress component in the direction z
σ^i_θ	=	stress component in the direction θ
$\tau^i_{z\theta}$	=	stress component zθ
τ^i_{rz}	=	stress component rz
$\tau^i_{r\theta}$	=	stress component rθ
α^i_1	=	coefficient off thermal expansion in the direction z
α^i_2	=	coefficient of thermal expansion in the direction θ
α^i_2	=	coefficient of thermal expansion in the direction r
α^i_{12}	=	shear modulus
α^i_{11}	=	coefficient of linear expansion
ϕ	=	tilt angle towards z-axis
u^i_r	=	component of the displacement vector
K^i_r	=	coefficient of thermal conductivity acting in the direction r
T	=	temperature
T’	=	temperature gradient
$G_{z\theta}$	=	shear modulus
δ	=	wall thickness
$\tau_{z\theta}$	=	tangential stress
U_r	=	radial translation

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