Computational Modeling of the Curing of a Frame of an Inflatable Satellite Antenna in Near-Earth Orbit

A. Yu. Eliseeva\textsuperscript{a,}\textsuperscript{*}, L. A. Komar\textsuperscript{b,}\textsuperscript{**,} and A. V. Kondurin\textsuperscript{c,}\textsuperscript{***}

\textsuperscript{a} AO ODK-STAR, Perm, Russia
\textsuperscript{b} Institute of Continuous Media Mechanics, Ural Branch, Russian Academy of Sciences, Perm, Russia
\textsuperscript{c} Ewingar Scientific, Ewingar, New South Wales, Australia

\textsuperscript{*}e-mail: anastasia_elis@mail.ru
\textsuperscript{**}e-mail: komar@icmm.ru
\textsuperscript{***}e-mail: kond@mailcity.com

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Abstract—Temperature analysis of a new technological process, curing of prepregs in near-Earth orbit, is performed via computational modeling. The problem arose with the currently discussed possibility of using inflatable antennas for small space satellites. Inflatable antennas have a number of advantages over classic extendable metal antennas. However, in order to ensure continuous operation of inflatable antennas, it is necessary that they acquire rigidity over time and stop depending on the air pressure in them. This can be achieved by using a solid frame made of an orbital-curable prepreg. Placement of special equipment for heating prepregs in the satellite body is undesirable, because it increases weight and dimensions of a satellite. The authors propose heating structural elements in space by radiation emitted from the Sun and the Earth. This novel idea requires justification and verification by means of field experiments and computational modeling. In this work only one of the aspects (the temperature effect) of the in-orbit curing technological process is analyzed using the results of numerical experiments. The peculiarity of the thermal boundary value problem is in boundary conditions where the heating of the frame of inflatable antenna by the Sun’s radiation flux and its cooling as a result of heat radiation of the structure itself in space are taken into account. It is established that, to achieve the required temperatures, instead of a simple prepreg frame, the prepreg with a thin layer of copper coating is to be applied. The features of the temperature distributions in the structure in the course of its rotation are revealed. The time intervals are determined at which the antenna orientation with respect to the solar flux should be changed to obtain the temperatures to cure all elements of the frame in the course of a small number of revolutions around the Earth, that is, as long as a high gas pressure preserves in the inflatable antenna.

Keywords: inflatable antenna, satellite, near-Earth orbit, prepreg, hot curing, solar radiation, temperature, numerical simulation

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1. INTRODUCTION

The antenna is a key element of each space satellite. It is used to link with ground-based stations for satellite communication. Using small spacecraft (nanosatellites and minisatellites), recently increasingly often launched to the near-Earth orbit, puts new demands for design engineers. For instance, equipment of these satellites with small-sized antennas provides only a small communication range. A weak signal is sent to the Earth, and it is impossible to transmit a large amount of information with a high bandwidth without losses. Frequently, such devices are lost because of communication failures. It is impossible to mount a large-sized antenna because of the small dimensions of the satellite itself. Therefore, it seems to be promising to use inflatable antennas that occupy less volume in the satellite body at its launch to orbit, but acquire the specified dimensions after developing to the working state [1–7].

If it is planned to use a spacecraft for a sufficiently long time, then one more problem inherent to inflatable structural elements arises: the interior air pressure falls. This occurs, because the air slowly diffuses through the shell and gradually exits via gaps at the places where the inflatable element is mounted to the spacecraft body, via the microdefects of the shell, etc. In addition, an inflatable antenna may be damaged by micrometeorites and space junk. Therefore, it is required to either constantly maintain the pressure by
an inflow of additional air into the inflatable antenna (which is problematic on orbit) or transform the antenna to a rigid structure independent of the air pressure. The latter is possible if we make the carrying frame of the antenna of prepreg and cure it on orbit after development. The current study is aimed at analyzing one of the aspects related to development of such technology, the temperature mode of curing while the antenna elements are situated in space.

The prepreg consists of reinforcing fabric and uncured polymer bond, which usually is the epoxy resin. On one side, the curing conditions of the prepreg with epoxy bonding agent on the near-Earth orbit distant from the Earth surface by hundreds of kilometers are substantially different from those at the Earth’s surface. It is difficult to create them in laboratory. It requires using costly experimental stands and reproducing the temperature mode of the near-Earth orbit and the damaging action of all radiations and active high-speed atoms of the rare, but existing, atmosphere. On the other side, forced provision of the temperature level necessary for the hot curing during flight of the artificial satellite leads to equipping it with special apparatus, which makes the satellite heavier, reduces the useful capacity, and increases its cost. The output is the heating of prepreg under the action of the Sun’s radiation and radiation from the Earth.

In view of this, numerical investigation of the in-orbit curing process is of great interest. The computational modeling allows answering the following questions: how is the frame of the inflatable antenna heated and does the temperature achieve the level necessary for hot curing? Here, we must take into account properties of the conditions in space. For the hot curing of prepreg, the reaction must begin under the action of high temperature directly on orbit, not in storage at the launch site or at orbital injection of the satellite.

As an example, we consider features of the flight of the space station. Its orbit is located at a height of approximately 385 km. The station moves with a speed of 27 700 km/h, performs a complete revolution around the Earth in approximately 90 min. In the course of half this time, the station is on the sunward side of the Earth, and, in the course of the other half, in the Earth’s shadow. The temperature at the surface of the metallic parts of the spacecraft may vary from –65 to +155°C in the course of a single revolution around the Earth. Does the temperature vary in the same range in the frame elements of the inflatable antenna if we take into account its complicated geometry and the radiation reflection of the material used? In addition, some parts of the frame may appear in shadow and the radiation is incident on some other parts at an oblique angle. How should we rotate the structure? At which time should we perform the revolution of the antenna? The answers to these questions may be given by the results of the computational experiment.

Now, the reaction is carried out under the open space conditions. The curing agent of the reaction compound must satisfy the hot process conditions and have low volatility; otherwise, removal of components from the curing agent during reaction would vary the stoichiometric ratio in the bond and the prepreg would not be cured. The evaporated substances may sediment on sensitive elements of the spacecraft (windows, optical devices, antennas, and solar panels) and thus reduce their operability. Hence, using materials which may emit some substances in space is prohibited. Due to this, not each prepreg is suitable for spacecraft. Moreover, additives to the reaction mixture, for instance, carbon black particles, may adjust the duration of curing [8]. It is no less important in which orbit the antenna is situated and how it is oriented with respect to the Sun and the Earth. Spatial rotation of the antenna may help regulating the heating of the prepreg and promote uniform curing of all elements.

Many publications are devoted to selection of the curing agent appropriate to hot curing. For instance, such curing agents of epoxy resins as iso-MTHPA (isomethyl tetrahydrophthalic anhydride), TETA (triethylene tetramine), TETA-1 (triethanolamine titanate), and SF-340A (aniline formaldehyde resin) are suitable for this purpose. They show good results in hot curing of epoxy resins and compounds on their basis [9–16]. The volatility factor is estimated in a substantially lower number of works. The authors of [17] investigated the curing of epoxy resins using TETA (triethylene tetramine) and varied the temperature from 25 to 154°C. The study results confirm that the evaporation processes in space may be so considerable that they violate the stoichiometric ratio of active components and stop the polymerization reaction.

We may analyze the features of the hot curing of epoxy resin and prepreg using both experiments and mathematical models [4, 14, 16–33]. For instance, in [14] the kinetics of the hot curing of the reaction mixture consisting of epoxy resin ED-20 and curing agent iso-MTHPA is described in detail and the chemical reaction time is computed. The authors of [16] follow the principle of hot curing of the reaction mixture under space conditions and show that the hot curing may be performed in the case when there is a thin aluminum film on the prepreg surface at the outside of the inflatable element of the antenna. A similar conclusion is made in [29]. However, the provided computed temperature values in prepreg (above 300°C) seem to be too high. In particular, it is meaningless to apply a polyethylene terephthalate (PET) film with a metal coating at such temperatures in space: the material will be destroyed [34, 35]. Exempli-
fied by prepreg CE 8201-200-45S widely used in various industry fields, including the aerospace industry, the authors of [33] obtained the temperature dependences of the curing ratio and demonstrated that prepreg is cured over nine hours at a temperature of 80°C, whereas at 160°C the process lasts just 20 min.

In the present work we carried out a more accurate analysis of the structure whose general design ideas are given in work [29]. In contrast to [29], we varied the frame geometry: it consists of a larger number of elements, which makes it stronger. The frame heating process may be controlled by varying its reflection properties. We show that we can accelerate the prepreg curing process without admitting out-of-range temperatures if we deposit a thin layer of copper on its surface. We study the effect of antenna revolutions with respect to the radiation source (the Sun) on the curing process of its elements.

The advantage of prepreg with a copper layer is demonstrated in comparison with prepreg without a layer and with prepreg with an aluminum coating. It appears that the temperature in prepreg with a copper coating reaches more quickly the values at which, according to experimental and calculation data [33], the antenna frame may be considered a rigid structure. The time interval after which the subsequent operation of the antenna with a copper layer is independent of the gas presence in its inflatable parts is shortest compared to the considered structures. From this point of view, this problem was not investigated previously.

2. PROBLEM FORMULATION

2.1. Antenna Design

The antenna design considered in this work consists of two parts (Fig. 1): the cupola (the upper part intended to reflect the radio signal) and the cone (the lower part transparent to radio waves). To provide the structure rigidity, thin prepreg plates are glued to the cupola and cone; after curing they play the role of stiffening ribs in the antenna frame.

The cupola shell is made of polyethylene terephthalate (PET) film. To improve the reflection of the radio signal, the inner part of the cupola is coated with a metallic layer, for instance, aluminum [34–36]. The cone-like part of antenna is made of the same film as the cupola, but the film is transparent. In such a design it allows transmitting the Sun’s rays. The antenna diameter at the junction of its parts is 1 m; the cupola and the cone have heights of 21.5 and 31.2 cm, respectively. The prepreg plates are glued to the PET film from the outer sides of the cupola and cone and around the perimeter of their connection.

Note that the PET film, including that with a metallic coating, has been used in space starting from the 1960s of the last century in inflatable structures of Echo-1 type, which were filled with gas after orbit injection. Thus, the temperature range is completely acceptable for its operation in space. However, when the film is subject to temperatures above 250°C, it is destroyed [35] with the release of carbon monoxide, terephthalic acid, and acetaldehyde. Hence, we should point out that the limit temperature range of the antenna operation must not exceed 250°C.

The stability of the antenna shape is provided by nine stiffening ribs (nine prepreg plates) with a width of 30 mm and a thickness of 5 mm. Eight of them connect the apices of the spherical cupola and the cone, and the ninth stiffening rib is situated on the perimeter of their contact. A very thin metallic coating is preliminarily deposited on outer sides of prepreg. We have mentioned its necessity in the Introduction, and we will show below which metal is more efficient. In calculations we consider two coating variants for comparison’s sake: the aluminum coating and the copper one. The prepreg plate, taken as the reference, is labeled in Fig. 1 by the letter A.
To the material constants we assign the values corresponding to prepreg which is used for preparing composite materials applied in space structures operating on orbit. This prepreg is characteristic due to a long lifetime and rapid curing process both at low temperatures on the Earth and in tests under outer space conditions [19, 33]. The warranty period of such prepreg is equal to approximately one month if we store it at room temperature. This must be taken into account in manufacturing and storing antennas before launching to orbit. The composite material based on this prepreg can be exploited up to $250^\circ C$.

2.2. Mathematical Model for Determining Temperature in the Antenna

Suppose the temperature is somehow redistributed over the antenna elements. In addition, the elements are heated by the radiation from the Sun and the Earth, but this radiation cannot lead to the appearance of an arbitrarily high temperature. Concurrently to heating, another process occurs, heat emission by the antenna to the space environment. At some time, equilibrium may be achieved when the heating under the action of cosmic radiation is balanced by the cooling due to emission of the antenna itself.

To determine the temperature field in the antenna frame, in the numerical experiments we solve the boundary value problem based on the classical heat equation

$$\frac{\partial}{\partial t} (\rho c_v T) = \nabla (\lambda \nabla T),$$

where $t$ is the real time, $\rho$ is the material density, $c_v$ is its heat capacity at constant volume, $\lambda$ is the thermal conductivity, and $T$ is the absolute temperature (in kelvins). Prepregs used in industry are anisotropic materials. In this work, in order to simplify the problem, the material is assumed to be isotropic. In the authors’ opinion, it should not substantially affect the results which follow from the computational experiments. We deal with the principal answer to the question: is it possible to perform hot curing without special heating of the prepreg in space. Therefore, specific features of the prepreg structure may be omitted at this stage of study.

The boundary conditions at the antenna surface take into account two processes: a part of energy is spent on its heating and a part is reflected by the surface. It is important at which angle the radiation flux is incident to the frame surface of inflatable antenna. The flux absorption is determined by

$$q = (1 - R) q_0 \cos \alpha,$$

where $q$ is the variation in the flux density dependent on the angle $\alpha$ between the radiation direction and the normal to the surface at the incidence point, $R$ is the reflection coefficient, and $q_0$ is the density of the incoming flux equal to the incoming heat flux of the Sun’s radiation at the near-Earth orbit: $q_0 = 1367 \text{ W/m}^2$. The radiation of the antenna surface is computed by the Stefan–Boltzmann law

$$S = \varepsilon \sigma T^4,$$

where $\varepsilon$ is the emissivity and $\sigma$ is the Stefan–Boltzmann coefficient.

The temperature distributions obtained with Eq. (1) in the prepreg without a coating and with an aluminum or copper coating are analyzed in terms of the ability of the prepreg to approach the solidified state. The difference in the solutions is due to different values of the emissivity and reflection factors. For prepreg without a deposited layer, the coefficients $\varepsilon$ and $R$ are specified to 0.795 and 0.2, for prepreg with an aluminum coating the coefficients are 0.09 and 0.98, and for prepreg with a copper coating they are 0.1 and 0.5. For the remaining parts of the antenna, their values are presented in Table 1. The material constants of the structural elements of the antenna are given in Table 2.

Table 1. Optical properties of materials

| Constants                     | Inner side of dome, PET covered by aluminum | Outer side of dome, PET | Inner and outer sides of body, PET |
|-------------------------------|---------------------------------------------|-------------------------|-----------------------------------|
| Emissivity ε                  | 0.09**                                      | 0.64*                   | 0.82 [37]                         |
| Reflection coefficient R      | 0.98***                                     | 0.68**                  | 0.1 [32]                          |

* Data correspond to PET with a thickness of 20 $\mu$m and aluminum layer from 0.02 to 0.04 $\mu$m [35].
** Data correspond to a wavelength of 10 $\mu$m at a temperature of 20°C [35].
*** Data correspond to a wavelength 10 $\mu$m [36, 37].
It is important to note that in solving Eq. (1) we have ignored the following:

– The effect of radiation from the Earth, because its contribution is several times less than the contribution of the Sun’s radiation.

– The exothermal heat release in the curing reaction, which just promotes the acceleration of the curing process and finally allows stopping the inflow of new air into the inflatable antenna even earlier.

– The retardation factor of the polymerization reaction of prepreg in the vacuum of space because of the loss of volatile curing agent components, because we assume that the chosen curing agent has weak volatility.

It is clear that, to improve the accuracy of the results, we need to take into account all the above-mentioned factors, but ignoring them does not prevent finding a way to study the technological process of hot curing in space in order to find such prepreg optical properties and such positions of the antenna relative to the Sun, at which a temperature arises in the antenna that, firstly, is sufficient for prepreg curing and, secondly, does not lead to destruction of the material of all the antenna components. Introduction of the above-mentioned factors into the model only leads to its complication.

Equation (1) is solved by means of the finite element method implemented in ANSYS. The problem has a three-dimensional formulation. To construct its discrete analog, we use quadrilateral elements in the form of a second-order tetrahedron. Transient thermal analysis is carried out in Ansys/Mechanical. The minimum time step is 0.1 s. The geometric three-dimensional model of the calculation domain is created by means of the SpaceClaim module. The mesh consists of 1 332 417 tetrahedral elements Tet10.

3. DISCUSSION OF CALCULATION RESULTS

Calculation of the temperature variation in the antenna begins from the instant when the outer side of the spherical cupola of the antenna is in the constant vector field of solar rays whose direction is prescribed by the coordinates of the vector \( \mathbf{r} \) in the spherical coordinate system \( \{ r, \theta, \phi \} \). The origin of coordinates is located in the apex of the cone. At time \( t = 0 \), the angles \( \phi \) and \( \theta \) determining the solar ray position are \(-19.8^\circ\) and \(15^\circ\), respectively, and the temperature in the antenna is \(22^\circ\)C, which corresponds to the temperature of the satellite just launched to the orbit. The temperature distributions are computed under the assumption that the satellite carrying the antenna is situated on the equatorial orbit, and the antenna performs rotational motion about its central axis.

The results of solving Eq. (1) are plotted in Fig. 2. We show the variation in the temperature of the prepreg without a deposited layer (Fig. 2a), the prepreg with an aluminum coating (Fig. 2b), and the prepreg with a copper coating (Fig. 2c). The temperature values found in the prepreg point closest to the cupula apex and initially occurring under the action of zenith solar rays (see Fig. 1) are depicted by the solid line, the temperature values found at the point closest to the contact are depicted by the dashed line, and the values found at the cone apex are depicted by the dot-dashed line.

During the first three hours, the antenna rotates with respect to the Earth so that the apex of its cupula always remains directed toward the Sun. Over the next three hours, the antenna cone apex is directed toward the Sun. Such a revolution of the antenna about the central axis is carried out in order to cure the prepreg uniformly in both parts. Each 45 min the antenna undergoes a change in the temperature mode, namely, exactly for 45 min it, being at the sunny side of the Earth, is heated under the action of solar rays, and then cooled to negative temperatures for 45 min after entering the Earth’s shadow.

Analysis of temperature fields in the antenna during the first 90 min (at the first complete revolution around the Earth) shows that, in the prepreg without coating and in the prepreg with aluminum coating, positive values of temperature are lower than that in the prepreg with a copper layer. Therefore, in this

| Constants                  | Prepreg | PET | Aluminum | Copper |
|----------------------------|---------|-----|----------|--------|
| Density of material \( \rho \), kg/m³ | 1200    | 1390| 2700     | 8900   |
| Heat capacity \( c_v \), J/(kg K) | 1000    | 1320*| 920**    | 400    |
| Heat transfer coefficient \( \lambda \), J/(s m K) | 0.18    | 0.19 [34] | 225     | 390    |

* Data correspond to the temperature 25°C [34].
** Data correspond to the temperature 20°C [36].
work we do not perform the subsequent study of temperature fields in these two prepregs as it is not interesting from the point of view of further determination of the optimal curing time.

In studying the temperature in the presence of the copper coating, we reveal that during first three hours the sum of time intervals at which a temperature of 150°C is observed in the part of prepreg close to the cupola apex is equal to 34 min: at the first revolution it is observed from 32nd to the 47th minute, and at the second revolution it is observed from 120th to 137th minute (Fig. 2c, solid line). According to calculation and experimental data presented in work [33], at such a temperature 22 min are enough for curing. Hence, in the part of prepreg near the cupola apex, curing is almost finalized.

We similarly analyze the temperature variation in the part of prepreg close to the contact between the cupola and cone (Fig. 2c, dashed line). Here, during the first three hours, the sum of time intervals at which the temperature is 120°C is 51 min: at the first revolution it is observed from 26th to 50th minute, and at the second revolution it is observed from 115th to 140th minute. According to the data of work [33], at this temperature 48 min are enough for curing. Thus, in this part of prepreg, curing is also finalized.

In Fig. 2c, we also see (the dot-dashed line) that, during the first three hours, the temperature in the cone part of prepreg gradually decreases to −60°C. To initiate curing in this part of prepreg, the antenna should be rotated by 180° so that the flux of solar rays becomes directed to the cone apex. In the subsequent three hours, the antenna and satellite perform third and fourth revolutions around the Earth. However, the variation in the antenna orientation leads to the fact that the incidence angle of the solar rays increases substantially, and the temperature appears to be insufficient to cure the prepreg on the cone during these revolutions.

Suppose that the temperature is 100°C. It is known from [33] that at 100°C prepreg is cured in 120 min. In the studied case, the sum of time intervals at which the temperature in the cone part of prepreg does
not fall below 100°C is 60 min: at the third revolution, it is observed from 202nd to 226th minute, and at the third and fourth revolution, it is observed from 284th to 318th minute (see Fig. 2c). The sum of time intervals is just half of the required reaction time. Therefore, in this position the antenna must be on orbit for the next two revolutions.

As a result, to cure a single plate of prepreg connecting the apices of cupola and cone, we need nine hours. This means that during this time the curing process is completely finalized only in a single stiffening rib of the antenna frame and the satellite must perform six revolutions around the Earth. Preparation of all stiffening ribs takes 72 h. Only after this do the functional properties of the antenna cease to depend on the air pressure inside it.

It is clear that this is a simplified way for determining the optimal curing time. The real curing time may be substantially smaller, because all prepreg plates are close to each other, and simultaneously with the heating of the plate that is situated under the zenith solar rays, there is also partial heating of the adjacent plates. This leads to the fact that solidification of each plate requires less than nine hours, because each plate will be sequentially located under the zenith solar rays by analogy to the first due to the rotation of the antenna about its central axis.

Considering the temperature distribution in the antenna as a whole (see Fig. 3), we may be sure that in all elements, including the PET film without a coating on the cone part and the PET film with a copper layer on the cupola, the maximum temperature values do not exceed the permissible bounds. In Fig. 3a, we present the temperature distribution 45 min after the start of the hot curing process. For clarity, the antenna is rotated so that we see the placement of the maximum heating points in the neighborhood of the cupola apex and the contact perimeter. At this time, the zenith solar ray is incident on the point where the temperature is 169.39°C. Figure 3b shows the temperature distribution after 225 min. At this time, the maximum heating is observed at the point near the cone apex. The numbers given in the figures show that the maximum temperatures occur in the prepreg plates, not in the film. The temperatures in the film are significantly below the permissible 250°C. This means that there is no film destruction with release of carbon monoxide, terephthalate acid, and acetaldehyde.

4. CONCLUSIONS

We numerically modeled and analyzed the temperature modes in the frame of the inflatable satellite antenna at which hot curing of the prepreg in near-Earth orbit is possible/impossible. Heating of the frame elements is carried out by means of solar radiation. It was established when this energy is enough to reach the temperatures necessary to cure the frame elements. We have shown that the curing time is reduced if we use a frame with a copper coating. Such a coating allows varying both the reflection coefficient and the emissivity and promotes acceleration of chemical processes without exceeding the required temperature range. We tested the times at which the antenna should be reoriented with respect to the solar radiation flux in order to achieve the best heating of the frame and the optimal curing time.
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