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Curing of large prepreg shell in solar synchronous Low Earth Orbit: Precession flight regimes

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ABSTRACT

We investigate the curing of large shell construction made of epoxy resin/carbon fibers prepreg under free space conditions in solar synchronous Low Earth Orbit. The curing kinetics is described by first order kinetic equation with auto-acceleration and deceleration parameters based on the experimental data. Heating of the shell is provided by solar radiation. The heat distribution in the shell is modelled based on partial absorbance of the solar radiation, the prepreg thermal conductivity and thermal capacity, radiation heat transfer between inner surfaces of the shell and the gas thermal conductivity. The iterated algorithm of curing was developed. Three flight regimes based on the circular motion of a construction have been considered: 1 – the axis of a shell lies in the tangent plane to the orbit and makes a constant angle with the tangent; 2 – under conditions (1), a shell rotates around its axis with a constant angular velocity; 3 – under conditions (2), the axis of the shell precesses around the tangent to the orbit. It was found, that the parameters of the motion (i.e. angular velocity of the rotation around the axis, precession angular velocity and precession angle) could be optimised in such way, that the whole shell can be completely cured under the solar radiation.

1. Introduction

Large shell inflatable constructions played an important role in space exploration primarily due to their efficient package for a launch and further deployment in orbit under internal pressure loading [1–3]. The recent studies have suggested the usage of such constructions for reflectors of space telescopes and antennas [4–7], solar concentrators with mirrors and lenses [8,9], life-support modules of habitable spacecraft (laboratories, greenhouses, supplies stocks etc.) [10,11]. The proposed technologies of construction of large space objects have considered the use of prepreg materials, packaging, deployment from the packaged state in the orbit and further curing under solar radiation [12,13]. The problem of packaging and deployment of large shell composite constructions resistant to folding have been explored in the works [14,15]. They have investigated the packaging of cylindrical and conic shells, deploying accordion-like or photo-camera-like respectively; they have formulated the criteria of achieving the required deployment pressure, have defined the properties of a thermodynamic state of gas filling the shell while loading. However, low mechanical strength of the inflatable shell constructions limits the applications of such constructions in space flight missions [16]. The inflatable shell should be strengthened after the deployment on the orbit.

The hardening of the inflatable construction based on the chemical curing reaction directly in free space environment has been proposed in Refs. [12,13]. The studies [17–28] have explored the curing of shell constructions and their behaviour over a wide range of temperatures. An important property of the prepreg polymerisation process under free space conditions is the evaporation of the low molecular fractions from the uncured resin [29]. The recent studies have shown that this process can be controlled by means of preliminary partial curing of the composite [24,26] or by taking into account the vaporisation of the active elements in creation of a reaction mixture [26]. The works [27–29] have investigated under laboratory conditions the influence of several settings on the curing process for polymers, namely: high vacuum, significant temperature differences, high-energy ion radiation, occurrence of addition chemical reactions and several other phenomena. The results have proven in the laboratory experiments on curing of the prepregs under simulated free space conditions and in the stratospheric flights [30].

In this paper, we explore a possibility of the complete curing by heating from solar energy in the case of a large cylindrical shell with spherical bottoms made out of prepreg on solar synchronous LEO

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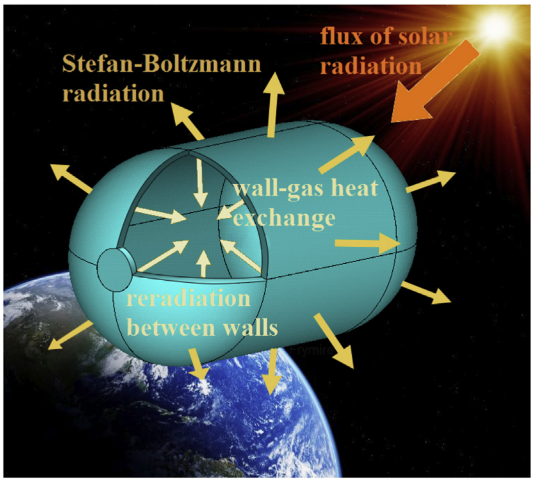

Fig. 1. The large cylindrical shell with spherical bottoms made of prepreg is curing in solar synchronous LEO under solar irradiation.

(Fig. 1). A kinetic master equation is proposed to describe the curing. The calculation of the temperature in the shell is performed based on Fourier's Law for heat conduction, assuming that the shell absorption of solar energy and the energy radiation from its surface occurs according to Stefan–Boltzmann law.

The shell construction is located in a circular solar synchronous LEO and oriented with respect to the sunlight direction. The near-shell space temperature is assumed to be constant with the value being dependent on the orbital radius and taking into account all the effects caused by the planet. A shell is filled in with gas (air) to maintain the required internal pressure and heat transfer within the shell body. The external surface of a shell absorbs solar energy and partially reflects it. The internal surface of the shell re-irradiates the energy between the shell walls and heats up the gas in the shell. The difference in the shell inner volume caused by its deformation resulting from the difference in its internal pressure is neglected. We assume that the shell is made of transversely isotropic prepreg. The thermal properties of the shell material are assumed being independent of the direction.

The problem consists in describing the curing process in the shell prepreg under free space conditions and determining the flight regime parameters required for the complete curing solely under solar energy.

2. Curing kinetics of the prepreg

The curing process of polymer materials is described by the following kinetic equation [31]:

$$\frac{d\eta}{dt} = Q(\eta, T) \tag{1}$$

where η(t) is a monotonically increasing function characterising the degree of curing ($0 \le \eta \le 1$), t is time, T denotes temperature. A function $Q(\eta, T)$ is selected as follows:

$$Q(\eta, T) = B(1-\eta)^{\alpha}\exp\left\{-\frac{A}{T}\right\}, \quad (0 \le \alpha < 1) \tag{2}$$

In equation (2), A, B are constants, α is function of temperature. These parameters are estimated based on the experimental data provided by the producer of the prepreg CE 8201-200-45S (Comfiber, Moscow, Russia) based on E201 epoxy resin and carbon fabric 3 K-200tex with a long shelf life. The prepreg is used in aerospace industry as a construction material. The provided experimental data are a family of curves in the plane (*T, t*) with fixed degrees of curing. When $T = T_i = const \quad (i = 1,2, \ldots, n,\ n$ – number of plane sections), equation (1) takes the following form:

Table 1
Examples of parameter values α_i, b_i for prepreg CE 8201-200-45S.

T_i,° C	α_i	b_i
80	0,66	7,05E-05
100	0,58	3,14E-04
120	0,79	1,14E-03
140	0,84	2,90E-03
160	0,95	4,00E-03

$$\frac{d\eta}{dt} = b_i(1-\eta)^{\alpha_i} \tag{3}$$

where

$$b_i = B\exp\left\{-\frac{A}{T_i}\right\} \tag{4}$$

Equation (3) with initial condition $\eta(0) = 0$ has the following solution:

$$(1-\eta)^{1-\alpha_i} = (\alpha_i - 1)\, b_i\, t + 1. \tag{5}$$

The parameters α_i, b_i are obtained by minimising the standard deviation of the solution (5) from the observed curve $\eta = \eta(T_i, t)$. The values of parameters α_i, b_i for a set of temperatures $T_i (i = 1,2, \ldots, 5)$ in the case of prepreg CE 8201-200-45S are given in Table 1. The theoretical values of the curing degree calculated using (5) and experimental values for different temperature settings T_i are presented on Fig. 2. A good agreement of the theoretical and experimental results is observed and the fitted parameters of the reaction were used for following calculation of the curing reaction in the shell during the orbital flight.

The temperature dependence of α and b is obtained from data approximation. In particular, *b(T)* is approximated as follows:

$$b(T) = B\exp\left\{-\frac{A}{T}\right\} \tag{6}$$

where the parameters A and B are obtained by minimizing the standard deviation of the observed values:

$$I = \left\{\frac{1}{n}\sum_{i=1}^{n}(b_i - b(T_i))^2\right\}^{1/2} \tag{7}$$

3. Algorithm of modelling for the shell curing process in orbit

The degree of curing is calculated numerically at each step Δt of integration over time of the non-stationary heat conduction task based on the spatial model using an engineering simulation software ANSYS. The finite element analysis was used. The gas state within a shell is computed using heat flux equation and Clapeyron-Mendeleev equation.

First, we assume that all parameters of the shell and gas within are known at the step (n-1). They are used to construct a solution at the n-th step as follows:

1) We construct a solution of the problem of heat conduction in a shell, defining the temperature in cells of a finite element mesh on the n-th time step.
2) For each finite element, we define the volume averaged temperature $T_n^{(e)}$. We assume that in the time interval Δt, the average temperature in an element is given by $0.5\cdot(T_{n-1}^{(e)} + T_n^{(e)})$ and is maintained constant on this step.
3) Using formula (5), we define an increment of the degree of curing in time Δt в for each finite element of a shell. We assume that there is a temperature threshold $T*$, below which the curing does not occur or takes very long time that is not acceptable for technological reason.
4) We assume, that the mass and the volume of the gas are kept constant, the heat flux equation takes the following form: