Developing Tooling for Making Experimental Antenna Reflector Prototypes of PCM

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Abstract

Background/Objectives: The relevance of this research is determined by rapid development of composite materials and their increased application in space engineering. Therefore, this research aims at determining the optimum lay-up sequence for maximum dimension stability of tooling under the action of static temperatures. Methods: Simulation of a transfer molding process, using computer-aided engineering systems and finite element analysis is the basic approach to investigating this challenge. Findings: Assumptions that are used for simulating the tooling were described. Heat calculations of the tooling for 9 alternative reinforcements have been performed. Tooling geometry has been developed. The best lay-up type of the reinforcing material has been selected, based on the calculation data. Optimization of lay-up angles of reflector tooling was done as a part of development. Novelty: The calculation of the stress-strain state of the reflector tooling models suggests a conclusion that the tooling is least deformed when subjected to static thermal load with symmetrical lay-up sequence \{90^0/0^0/45^0/-45^0\}. This model has a maximum volumetric strain at a rate of 0.041 mm.

Keywords: Antenna Reflector, Composite Materials, Molding Tooling, Layup Optimization

INTRODUCTION

Space antenna reflectors for perspective communications satellite must have low mass per unit length and maintain high accuracy of shape and dimensions in a broad range of operational temperatures. For satisfying the above requirements, polymer composite materials that are known for their low specific weight and high rigidity are broadly used in the structure of solid rigid reflectors. Challenges in development and manufacture of such antenna reflectors is dictated by a significant negative effect of the mean square deviation of the paraboloid reflector shape on the target reflector specification, i.e. gain factor, with the increasing operational frequency range and reflector dimensions, which is due to the defect of form that is derived from manufacture and deformations due to temperature differences in operation of the reflector.

Development of light reflectors of mirror antennas of PCM that are at the same time stable in their shape and dimensions is of key importance for intersatellite communications systems. Low linear density (a measure of mass per unit of length) and high dimensional stability are crucial operating characteristics of reflectors. At the same time, requirements to reflector profile precision rise with the increasing antenna frequency. Tolerable deviations of reflector shape must not exceed \(\Delta = \frac{\Lambda}{15}\), however, even more strict deviation requirements of \(\Delta = \frac{\Lambda}{50}\), where \(\Lambda\) is operating wavelength of the antenna, are imposed. Due to high relative strength, low TCLE and relatively high thermal conduction, carbon fiber-reinforced plastic is broadly used for manufacture of reflectors.

Mechanical loads that act on the reflector in flight are rather low and temporary; as long as they occur in final orbit insertion, when change in orientation and maneuvering of the spacecraft take place. Temperature deformations contribute most to reflector shape alterations. Certain sections of the antenna reflector may heat in the daylight portion of the orbit up to 150°C and cool down to 150 °C below zero and more, when the spacecraft enters the shaded portion of the Earth. For the stable reflector shape, the threat lies with temperature fluctuations on the surface up to tens and even hundreds degrees.

Detailed investigation of possible temperature values, temperature fluctuations and temperature deformations is quite complicated. However, one may not develop a light structure, which is stable in its shape and dimensions in long-term space operation, unless such tasks are solved. The major requirement that is imposed on materials used to make reflectors is high thermal dimensional stability, i.e. capability of minimum alterations of structure's dimensions.
under the action of thermal strain. A whole new class of
design tasks of dimensionally stable structures has been
established for the last years and they are much in demand by
the modern industry. Preservation of the given dimensions
under varying environmental factors, such as humidity,
radiation and other outer space factors, but first of all,
temperature is the basic requirement that determines
functionality of such structures.

Therefore, structures with their thermal coefficient of linear
expansion equaling to or close to zero in the given directions
and in the set temperature range are often called proper
dimensionally stable structures.

Challenges of developing dimensionally stable structures are
versatile. They include, along with direct design tasks, a maze
associated with technological implementation of the project,
experimental development etc. Considering the subject matter
of this research, tasks of optimum selection of composite
structures to satisfy dimensional stability requirements only
are considered here.

Dimensional stability conditions are common for all structures
of such type. At the same time, requirements to durability,
rigidity, thermal conduction and requirements associated with
other properties of composite structures may be imposed in
each specific case. Pre-design becomes especially important
under the circumstances to discover the possibility of
compromised combination of these requirements.

Determination of structural composite parameters to ensure
certain components of the deformations vector equaling to
zero under the action of temperatures is the key design
condition for dimensionally stable structures. This problem is
reduced to the task of managing thermal expansion properties
of the material, i.e. coefficient of linear thermal expansion. If
the operating temperature range of the structure is narrow,
average TCLE values of the material are enough. For broad
temperature ranges, temperature dependence of the TCLE, as
well as rigid characteristics of the composite must be
accounted for. Step-by-step procedures may be applied in
such cases, including piecewise-linear approximation of
temperature deformations at each step by temperature. The
problem of search of optimum properties combinations of the
composite structure is not essentially complicated; all one has
to do is using corresponding integral characteristics for the
given temperature range, instead of current TCLE values.\textsuperscript{9–10}

TLCE management is a necessary but not so often sufficient
condition of design of dimensionally stable structures. For the
purpose of dimensional stability, humidity deformations and
other environmental effects (gas composition, radiation etc.)
must also be accounted for in most cases.

Moreover, in order to implement optimum projects,
investigation of immunity of the resulting solutions to
unavoidable deviations of structural and technological
parameters and spread in performance of base materials is also
important.

Structures differ in their requirements to stability of
dimensions and shape; a practically unique concept of
dimensional stability is required for design of each structure.
At the same time, overall classification of design tasks of
dimensionally stable structures is available, which comprises
three major types:

\begin{itemize}
  \item one-axle tasks of dimensional stability;
  \item two-axle tasks of dimensional stability; and
  \item special concepts of dimensional stability.
\end{itemize}

Elimination of thermal deformations in a single given
direction is required in the first case to ensure necessary
operating characteristics. Examples of such structures include
dimensionally stable rods, lens tubes of optical modules etc.
Complete elimination of thermal deformations in the plane of
multi-layer material is the aim in the second case.

These are satellite platforms for devices and appliances.
Finally, special concepts find application in design of
structures, where not material properties management in the
whole volume of the structure, but coordinated deformation of
two or more given points is important.

While requirements not to a single TLCE, but two TCLEs are
imposed for the antenna reflector, a task of compromised
optimization is reasonable in this case, where the efficiency
vector comprises requirements to both characteristics under
consideration coming closest to zero.

It is apparent that the achievement of the least absolute
magnitude of one TCLE value ($\alpha_x$ or $\alpha_y$) is always
accompanied by the growth of absolute value of the other
coefficient.

In case when both measures under investigation are equally
important for this structure, e.g. for the reflector, optimum
values of such parameters correspond to the so called
quasiisotropic composite structures. These structures are made
up by repeated layout of elementary packings, each of which
comprises several layers of the materials that are oriented in a
certain way.

For the purpose of minimization of any errors that occur as a
result of tooling heated in manufacture and further operation,
layup of tooling layers must be optimized for selecting
optimum mutual arrangement.

A great number of methods are used to optimize layers of
composite structure layup. The following optimization
methods are known:

\begin{itemize}
  \item optimization of laminated composite plates with the help
        of level set method;
  \item table permutation method for optimization of composite
        laminate layup;
\end{itemize}
- layup optimization for maximum loss of stability of composite plates, using Harmony search algorithm; and
- optimization of composite plate layup for ensuring maximum strength, using a genetic algorithm and isogeometric analysis.\(^{11-14}\)

**CONCEPT HEADINGS.**

A geometric model of relative positioning of structural elements of an experimental prototype of an antenna reflector made of PMC (Figure 1) was used for input data.

The molding surface of the tooling has a shape of paraboloid according to the geometric model of the reflection surface of the reflector (mirror).

Nominal tooling thickness is 7.66 mm. Design thickness is 8 mm.

A layup scheme is presented in Table 1. Twill 2/2 3K-1500-240 is used to lay layers 1 and 2 (facing layers), and Twill 2/2 12K-1200-450 is used for layers 3 to 18.

**Table 1. Lay-up sequence**

<table>
<thead>
<tr>
<th>Layer number</th>
<th>Material</th>
<th>Lay-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Twill 2/2 3K-1500-240</td>
<td>0°/90°</td>
</tr>
<tr>
<td>2.</td>
<td>Twill 2/2 3K-1500-240</td>
<td>+45°/-45°</td>
</tr>
<tr>
<td>3.</td>
<td>Twill 2/2 12K-1200-450</td>
<td>0°/90°</td>
</tr>
<tr>
<td>4.</td>
<td>Twill 2/2 12K-1200-450</td>
<td>+45°/-45°</td>
</tr>
<tr>
<td>5.</td>
<td>Twill 2/2 12K-1200-450</td>
<td>0°/90°</td>
</tr>
<tr>
<td>6.</td>
<td>Twill 2/2 12K-1200-450</td>
<td>+45°/-45°</td>
</tr>
<tr>
<td>7.</td>
<td>Twill 2/2 12K-1200-450</td>
<td>0°/90°</td>
</tr>
<tr>
<td>8.</td>
<td>Twill 2/2 12K-1200-450</td>
<td>+45°/-45°</td>
</tr>
<tr>
<td>9.</td>
<td>Twill 2/2 12K-1200-450</td>
<td>0°/90°</td>
</tr>
<tr>
<td>10.</td>
<td>Twill 2/2 12K-1200-450</td>
<td>0°/90°</td>
</tr>
<tr>
<td>11.</td>
<td>Twill 2/2 12K-1200-450</td>
<td>+45°/-45°</td>
</tr>
<tr>
<td>12.</td>
<td>Twill 2/2 12K-1200-450</td>
<td>0°/90°</td>
</tr>
<tr>
<td>13.</td>
<td>Twill 2/2 12K-1200-450</td>
<td>+45°/-45°</td>
</tr>
<tr>
<td>14.</td>
<td>Twill 2/2 12K-1200-450</td>
<td>0°/90°</td>
</tr>
<tr>
<td>15.</td>
<td>Twill 2/2 12K-1200-450</td>
<td>+45°/-45°</td>
</tr>
<tr>
<td>16.</td>
<td>Twill 2/2 12K-1200-450</td>
<td>0°/90°</td>
</tr>
<tr>
<td>17.</td>
<td>Twill 2/2 12K-1200-450</td>
<td>+45°/-45°</td>
</tr>
<tr>
<td>18.</td>
<td>Twill 2/2 12K-1200-450</td>
<td>0°/90°</td>
</tr>
</tbody>
</table>

Twill 2/2 3K-1500-240 (T240) and Twill 2/2 12K-1200-450 (T450) carbon fibers with their density of 240 and 450 g/m\(^2\), respectively, were assumed to be reinforcing fillers for the tooling. A high-temperature epoxy system by Huntsman (H), comprised of Araldite LY 8615 (epoxy resin) and Hardener XB 5173 (amine hardener) was used for binding. Properties of materials that are used for making reflector tooling are given in Tables 2 and 3.

**Table 2. Properties of reinforcing fabrics**

<table>
<thead>
<tr>
<th>Material</th>
<th>Density [g/cc]</th>
<th>TCLE [(c^{1-10^{-5}} C^{-1})]</th>
<th>Poisson's constant</th>
<th>Elasticity modulus [MPa 10(^4)]</th>
<th>Shearing modulus [MPa 10(^3)]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>X      Y      Z</td>
<td>X      Y      Z</td>
<td>X      Y      Z</td>
<td>X      Y      Z</td>
</tr>
<tr>
<td>Twill 2/2 3K-1500-240</td>
<td>1.5</td>
<td>-4.70·10(^{-2}) 3.00 3.00</td>
<td>0.27 0.40 0.27</td>
<td>13.90 0.91 0.91</td>
<td>4.70 3.10 4.70</td>
</tr>
<tr>
<td>Twill 2/2 3K-1500-450</td>
<td>1.57</td>
<td>-4.00·10(^{-2}) 3.00 3.00</td>
<td>0.27 0.40 0.27</td>
<td>20.90 0.94 0.94</td>
<td>5.50 3.90 5.50</td>
</tr>
</tbody>
</table>
Based on the requirements to ensure production process of molding a binding epoxy system, this item will be impregnated and cured at the temperature of 60°C for 24 hours, until the item is removed from the master model.

To ensure necessary physical and chemical and performance properties of the item, post-curing, i.e. exposure to certain temperature conditions must be done.

Post-curing of the structure will be done in accordance with the temperature conditions that are provided in the epoxy system specification. Post-curing temperature conditions are presented in Figure 2.

![Figure 2. Post-curing temperature conditions](image)

**Figure 2.** Post-curing temperature conditions

Strain-stress state analysis of the tooling for various interlayer spacing patterns is required to solve our task for the purpose of selecting the layup scheme that ensures minimum thermal deformations.

A computational model of the tooling is given in Figure 3. A computational loading pattern was developed to calculate the strain-stress state and such pattern is given in Figure 4, where \( q \) is heat flow.

![Figure 3. Geometric model of tooling](image)

![Figure 4. Design model](image)

Physical and mechanical properties of carbon fiber-reinforced plastic that are presented in table 4 were used for the calculations.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density [g/cc]</th>
<th>TCLE ([\text{c}^{-1}, 10^{-5}, \text{C}^{-1}])</th>
<th>Poisson's constant</th>
<th>Elasticity modulus ([\text{MPa} 10^3])</th>
<th>Shearing modulus ([\text{MPa} 10^3])</th>
</tr>
</thead>
<tbody>
<tr>
<td>T240+H</td>
<td>1.5</td>
<td>([-4.70 \cdot 10^{-2}, 3.00, 3.00])</td>
<td>([0.27, 0.40, 0.27])</td>
<td>([13.90, 0.91, 0.91])</td>
<td>([4.70, 3.10, 4.70])</td>
</tr>
<tr>
<td>T450+H</td>
<td>1.57</td>
<td>([-4.00 \cdot 10^{-2}, 3.00, 3.00])</td>
<td>([0.27, 0.40, 0.27])</td>
<td>([20.90, 0.94, 0.94])</td>
<td>([5.50, 3.90, 5.50])</td>
</tr>
</tbody>
</table>

Nine calculation models were considered for the optimization, and an 18-layer packing was set for each of the models as follows: two layers of material of the T240+H type and sixteen layers of material of the T450+H type.

One of nine different symmetrical lay-up sequences was set for each model:

1) \( [90°/0°/85°/5°] \)
2) \( [90°/0°/80°/10°] \)
3) \( [90°/0°/75°/15°] \)
4) \( [90°/0°/70°/20°] \)
5) \( [90°/0°/65°/25°] \)
6) \( [90°/0°/60°/30°] \)
7) \( [90°/0°/55°/35°] \)
8) \( [90°/0°/50°/40°] \)
9) \( [90°/0°/+45°/-45°] \)
Lay-up sequence of layer packing \{90^0/0^0/+45^0/-45^0\} is given as an example in Figure 5.

![Figure 5. Layup sequence \{90^0/0^0/+45^0/-45^0\}](image)

A finite element mesh was built up as a part of this problem solving process, using an integrated mesh control technique (Body Sizing – molds the mesh by calibrating the body. Typical element size was 5 mm, and number of resulting finite elements was 31,442. A graphic representation of the finite element mesh is given in Figure 6.

![Figure 6. Mesh.](image)

Calculation of strain-stress state at temperature expansion was required to optimize laying up of layers. As long as these tooling will be exposed to thermal stress in a convection oven, temperature that acts on the whole volume of tooling models under consideration was taken as our stress. Thermal stress value was selected, based on the production process of molding a dimensionally stable reflector and was equal to 60°C. Loading process was statistic; therefore, calculation data are static deformations.

The following assumptions were made for simulating the strain-stress state:

- materials used were assumed to be solid and homogeneous, and and non-destructible;
- chemical composition and appearance of materials was assumed to be constant for the calculation.

Physical specifications, such as density, linear coefficient of thermal expansion, elasticity modulus, Poisson’s constant, heat capacity and thermal conduction, did not account for anisotropy of given materials.

A finite element mesh (Figure 6) was generated by the adjusted technique in the volume of the developed model (Figure 3). Various layer packings were simulated and properties of the materials that are presented in table 4 were assigned to each layer, and thermal load in the form of temperature of 60°C that was distributed across the whole model volume was applied.

### RESULTS

Calculations produce maximum and minimum deformations in the tooling model body and maximum and minimum stresses in layers of packing models. Maximum and minimum deformations in the tooling and maximum and minimum stresses in layers of packing models, accordingly, are provided in comparative table 5.

<table>
<thead>
<tr>
<th>Packing layup</th>
<th>Deformations [mm]</th>
<th>Stresses [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum</td>
<td>Minimum</td>
</tr>
<tr>
<td>{90^0/0^0/85^0/5^0}</td>
<td>0.168</td>
<td>0.005</td>
</tr>
<tr>
<td>{90^0/0^0/80^0/10^0}</td>
<td>0.277</td>
<td>0.017</td>
</tr>
<tr>
<td>{90^0/0^0/75^0/15^0}</td>
<td>0.352</td>
<td>0.022</td>
</tr>
<tr>
<td>{90^0/0^0/70^0/20^0}</td>
<td>0.379</td>
<td>0.022</td>
</tr>
<tr>
<td>{90^0/0^0/65^0/25^0}</td>
<td>0.384</td>
<td>0.026</td>
</tr>
<tr>
<td>{90^0/0^0/60^0/30^0}</td>
<td>0.375</td>
<td>0.021</td>
</tr>
<tr>
<td>{90^0/0^0/55^0/35^0}</td>
<td>0.367</td>
<td>0.021</td>
</tr>
<tr>
<td>{90^0/0^0/50^0/40^0}</td>
<td>0.365</td>
<td>0.018</td>
</tr>
<tr>
<td>{90^0/0^0/45^0/-45^0}</td>
<td>0.041</td>
<td>0.009</td>
</tr>
</tbody>
</table>

Graphic representation of volumetric deformations of the tooling is given in Figures 7 to 15 and stresses in packing layers are shown in Figures 16 to 23. A diagram of maximum deformations and material layup angle in the tooling model is given in Figure 24.
Figure 7. Volumetric strains of tooling model, including layup \{90^\circ/0^\circ/85^\circ/5^\circ\}

Figure 8. Volumetric strains of tooling model, including layup \{90^\circ/0^\circ/80^\circ/10^\circ\}

Figure 9. Volumetric strains of tooling model, including layup \{90^\circ/0^\circ/75^\circ/15^\circ\}

Figure 10. Volumetric strains of tooling model, including layup \{90^\circ/0^\circ/70^\circ/20^\circ\}

Figure 11. Volumetric strains of tooling model, including layup \{90^\circ/0^\circ/65^\circ/25^\circ\}

Figure 12. Volumetric strains of tooling model, including layup \{90^\circ/0^\circ/60^\circ/30^\circ\}
Stresses in Layers of Tooling Packing Model to Form a Dimensionally Stable PMC Reflector

Figure 13. Volumetric strains of tooling model, including layup \(\{90^\circ/0^\circ/55^\circ/35^\circ\}\)

Figure 14. Volumetric strains of tooling model, including layup \(\{90^\circ/0^\circ/50^\circ/40^\circ\}\)

Figure 15. Volumetric strains of tooling model, including layup \(\{90^\circ/0^\circ/45^\circ/-45^\circ\}\)

Figure 16. Stresses in tooling package model, including layup \(\{90^\circ/0^\circ/85^\circ/5^\circ\}\)

Figure 17. Stresses in tooling package model, including layup \(\{90^\circ/0^\circ/80^\circ/10^\circ\}\)

Figure 18. Stresses in tooling package model, including layup \(\{90^\circ/0^\circ/75^\circ/15^\circ\}\)
Figure 19. Stresses in tooling package model, including layup \{90^\circ/0^\circ/70^\circ/20^\circ\}

Figure 20. Stresses in tooling package model, including layup \{90^\circ/0^\circ/65^\circ/25^\circ\}

Figure 21. Stresses in tooling package model, including layup \{90^\circ/0^\circ/60^\circ/30^\circ\}

Figure 22. Stresses in tooling package model, including layup \{90^\circ/0^\circ/55^\circ/35^\circ\}

Figure 23. Stresses in tooling package model, including layup \{90^\circ/0^\circ/50^\circ/40^\circ\}

Figure 24. Stresses in tooling package model, including layup \{90^\circ/0^\circ/45^\circ/-45^\circ\}
DISCUSSION

This research describes development of tooling for making experimental antenna reflector prototypes of PCM. Optimization of lay-up angles of reflector tooling was done as a part of development. Nine calculation models were considered for the optimization, and an 18-layer packing was set for each of the models as follows: two layers of material of the T240+H type and sixteen layers of material of the T450+H type. One of nine different alternative symmetrical lay-up sequences of the packing was set for each model. Simulation of a transfer molding process, using Computer-aided engineering systems and finite element analysis is the basic approach to investigating this challenge. Optimization of laying-up of reflector tooling packing is required to minimize deformations in making of the reflector itself, while it depends directly on the deformation of the tooling in molding. Therefore, this subject matter is unique and relevant.

CONCLUSION

Geometry of tooling designed for making an experimental antenna reflector prototype of PCM has been developed as a result of this research. Calculations for nine calculation models have been done, and a 18-layer packing of the material has been set for each model as follows: two layers of material of the T240+H type and sixteen layers of material of the T450+H type. Selection of layer packing has been done, based on the calculations to ensure minimization of technological defects of manufacture.

One may assume from the calculation of strain-stress state of the reflector tooling model that the tooling items are least deformed under the action of static temperature load with symmetrical laying of layers [90°/0°/45°_-45°]. This model has maximum volumetric deformation of 0.041 mm.

ACKNOWLEDGEMENT

Certain outcomes presented have been obtained within the Grant Agreement No 14.577.21.0114 dated September 23, 2014 with the Ministry of Education and Science of the Russian Federation. Unique identifier of applied research (project) RFMEFI57714X0114.

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