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Development of Ultra-Light Weight Carbon Fibre Space Reflector Antenna's Manufacturing Process

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Abstract
In this paper, the object of the research was the antenna reflector made of polymer composite materials with high geometric stability for telecommunication satellites. The aim of this study was to develop the carbon fibre reinforced plastic space reflector antenna manufacturing process, by using the vacuum assisted resin infusion technology. In this study, the rein impregnation process and curing process of the space reflector had been developed. Two types of carbon woven fabric structures were investigated: standard fibre tow type, which has a cylindrical cross-sectional shape and spread tow type, which has a rectangular cross-sectional shape. Modelling of the kinetics of the impregnation process for the two types of carbon fabric's unit cell structures was performed using software RAM-RTM. This work also investigated the influence of the angle between warp and welt of the unit cell on the impregnation time. The results showed that decreasing the angle between warp and welt of the unit cell the decreasing of the permeability values was occurred. The optimizations of the cure cycle with and without consideration of the exothermic effects during the curing process were presented. The impregnation and curing processes were experimentally investigated. The comparisons of the experimental and modelling results were also presented.

1. Introduction

As a structural material in the manufacture of telecommunication satellite's reflector antenna, carbon fibre reinforced plastic CFRP are widely used, which is associated with a complex of their unique thermal physical characteristics that ensure that the requirements for thermal stability in space conditions are met, low in mass and at the same time high rigidity and strength.
However, the cost of carbon fibre products is higher than using other structural materials, which is largely due to the moulding process time and the high prepregs costs. The curing process of the carbon fibre products in autoclave leads to significant increase in their initial cost, which in many respects limits the areas of their application. The development of new manufacturing technologies of the products from polymer composite materials, which exclude the requirements of autoclave technology and high cost of prepregs, appear to be of significant practical importance.
Reducing the cost of the products can be achieved by using non-impregnated fabrics. With the technology of vacuum assisted resin infusion - VARI (Vacuum Infusion), the manufacturing process of CFRP is combined with the impregnation and curing processes. This allows to significantly reduce the cost of production, but the porosity content in final products is higher, which leads to a decrease in their mechanical characteristics [1,2]. That is why at present there are numerous studies related to the optimization of technological modes and quality improvement.
During the curing of epoxy binders, which are the most common oligomeric systems used in the production of carbon fibre products, heat is released. The amount of heat released depends on the chemical composition of the binder, the heating rate, the thermal physical characteristics of the fabric used, and so on. This additional heat flow can lead to overheating, which will contribute to the appearance of thermal stresses and, as a result, the strength and heat resistance of the moulded products. Considering the heat generation during the development of curing cycle would not only reduce its negative impact, but would also lead to a certain reduction in the duration of the curing process, which will also have a positive impact on cost reduction [3,4].

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Thus, the work focused on the substantiation of production technologies for thin-walled reflectors of telecommunication satellite from polymer composite materials with improved strength properties can be considered relevant as directed at solving a complex scientific and technical problem that has practical significance.

2. Impregnation process

The impregnation process of VARI mainly depends on the unit cell structures of carbon fabrics. These geometrical parameters determine the porosity and permeability of carbon woven fabrics. The structure of unit cell was considered in accordance with the theory of P.L. Chebyshev [5,6,7], according to which two families of fibre tows that intersect on the surface form network. Two types of carbon woven fabric structures were investigated: standard fibre tow type Hexcel brand, which has a cylindrical cross-sectional shape and spread tow type (Aspro A60 and A80 brands), which has a rectangular cross-sectional shape. If the surface of the mould on which fabric is placed has a double curvature shape, the network angles inside each unit cell change. The network angle of any textile fabric is the angle between the warp and welt direction.

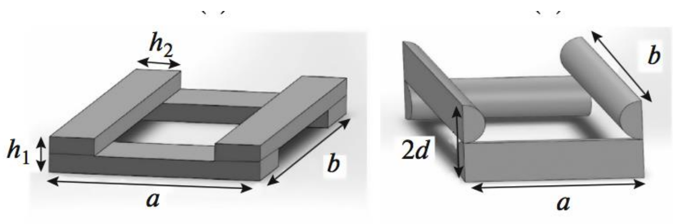

Figure 1: Fabric unit cell structure of spread tow Aspro and standard fabric Hexcel

2.1 Methodology

During lining of fabric on a curved surface, its density in different points would also be different due to the change of the network angle. Volume of an elementary cell in a deformed state V_{def} is

$$V_{def} = abh_1 \sin\alpha \tag{1}$$

Minimum porosity value Π_{min}, which was determined from Eq. (2), is 0.09.

$$\Pi_{min} = 1 - \frac{\pi}{4 sin 60} \tag{2}$$

Because the volume of elementary cell does not change upon deformation, can be written as in Eqs. (3).
The coefficient of permeability varied with the change of the network angle, which occurred upon fabric layup on a curved surface:

$$V_f = V_{f\,(ini)} = \frac{h_2 h_1}{2}(a+b)(1-\Pi_{min}) \tag{3}$$

$$K_{def} = \left[\frac{ab - \dfrac{h_2/2(a+b)(1-\Pi_{\min})}{sin\alpha}}{ab - h_2/2(a+b)(1-\Pi_{\min})}\right]^3 sin^2\alpha K_{ini} \tag{4}$$

$$K_{1,2} = K_{def}\sqrt{\frac{1+cos\alpha}{1-cos\alpha}} \tag{5}$$

$$K_{ini} = \frac{\Pi \mu \, x^2}{2\Delta p \tau}$$

where K_{ini} is the permeability coefficient of fabric in a non-deformed state, K_1 and K_2 are the permeability coefficient by the warp and welt, l and b are the length and width of experimental sample of fabric, τ is the impregnation period, Π is the porosity of fabric, and ρ is the density of carbon plastic, x is the length of studied fabric, μ is viscosity of the resin.

2.2 Results

In this work, the permeability coefficient of fabric is experimentally evaluated; procedure of its evaluation for an elementary cell of standard fabrics was considered in [8,9]. The results are given in the table 1.

Table 1: Experimental results of permeability coefficients and porosity

Type of carbon fabric	***П***	K_1, K_2
Aspro A60	5	3.9×10^{-8}
Aspro A80	3.8	3.6×10^{-8}
Hexcel	13.3	7.24×10^{-8}

The size of studied samples of fabrics was 300 × 90 mm. The studied samples were composed of four layers of fabric with lining angles of 0/±45/90. For considered elementary unit cell, the values a = b and h_1 = 0.3a and, therefore, permeability coefficients for the warp and welt directions are equivalent (table 1). The dependence of permeability coefficient on the network angle change can be calculated by Eq. 4 and 5. In Fig. 2, the permeability coefficient is denoted as $K_{1,2}$.

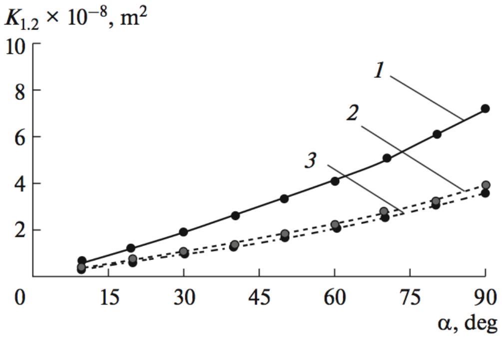

Figure 2. Dependence of permeability coefficients on network angle changes of carbon fabric brands; (1) Hexcel, (2) Aspro A60, (3) Aspro A80

The presented data show that the permeability coefficients of spread tow fabric (Fig. 2, curves 2, 3) are significantly lower than those for carbon fabric with a circular section of fibres (Fig. 2, curve 1).

The obtained permeability coefficients were used in calculations upon modelling of the kinetics of impregnation using a RAM–RTM program. For modelling, the surface of the reflector was split into 2928 triangular finite elements. The results are given in Figs. 3. During calculations, the binder viscosity was set at 0.3 Pa s and working pressure at 1atm and diameter of reflector is 550mm.

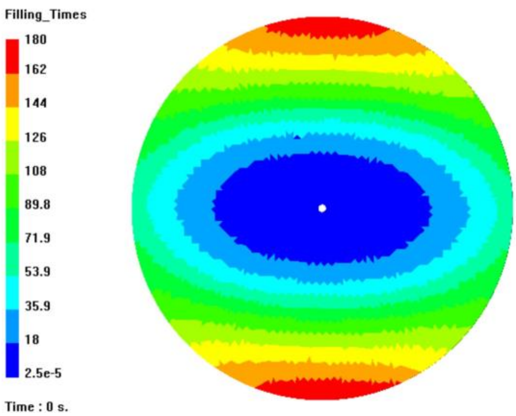

Figure 3. Modelling of the kinetics of impregnation of reflector antenna using a RAM–RTM program

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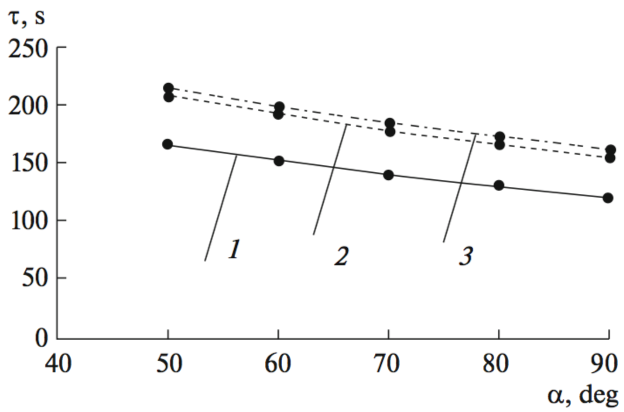

Figure 4. Dependence of impregnation time on network angle changes of carbon fabric brands; (1) Hexcel, (2) Aspro A60, (3) Aspro A80

Based on the obtained results, it was determined that, with a decrease in the network angle, permittivity coefficient also decreases; standard (that is, non-spread) fabrics impregnate faster than spread ones.

3. Curing process

The process of curing products from PCM is the longest technological operation and, therefore, it is necessary to optimize the heating cure cycle, which would reduce the time and, accordingly, reduce the cost of finished products [10]. When modelling the heat transfer occurring in the PCM during the curing of the binder, it is first necessary to determine the temperature distribution arising in the material with and without consideration of the exothermic effects during the curing process.

3.1 Methodology

Femap Nastran program is used to model the curing process. As an object, a reflector of a spacecraft with a diameter of 550 mm and a thickness of 0.6 mm was chosen. The problem of mathematical modelling was solved in two stages: determination of temperature fields in the reflector during the curing process without taking into account the heat generation during the chemical curing reaction; determination of temperature fields in the reflector taking into account the heat generation during the chemical reaction. The geometric model of the reflector is divided into 24125 Quad-Tri elements using Topo-Mesh (Fig. 5).

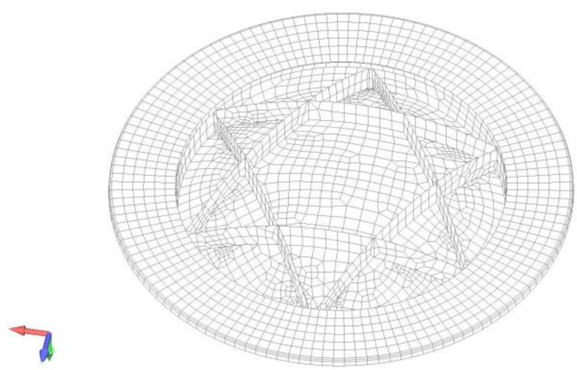

Figure 5. Finite element model of reflector antenna and mould

For the first stage of modelling, the following boundary conditions for heat exchange were adopted during the curing of the reflector: convection through the air according to the curing regime in table 2, the heat transfer coefficient is 15 W / m^2·K; radiation from the surface of the reflector according to the curing cycle.

Table 2: Given cure cycle

Temperature, °C	Time, s
Ascent to 125	3015
Exposure at 125	6615
Ascent to 180	8265
Exposure at 180	26625
Cooling to 20	36225

3.2 Results

The obtained modelling results of the distribution of temperatures (without taking into account the heat release) during the curing process of the binder are shown in Fig. 6-7.

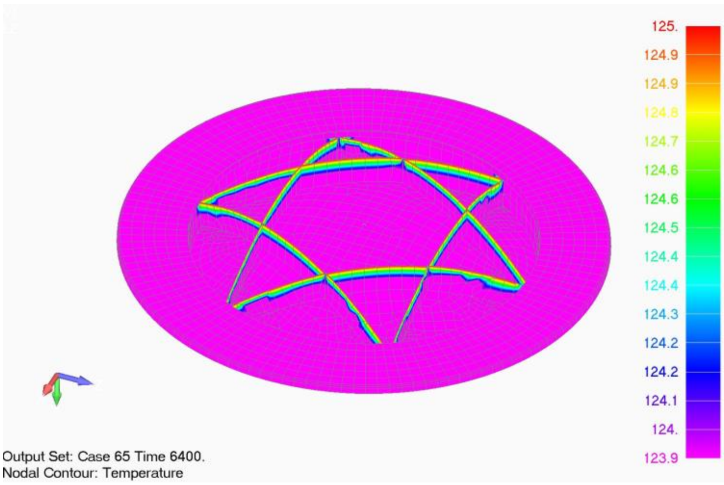

Figure 6. The temperature distribution without considering the heat generation at 6400 s

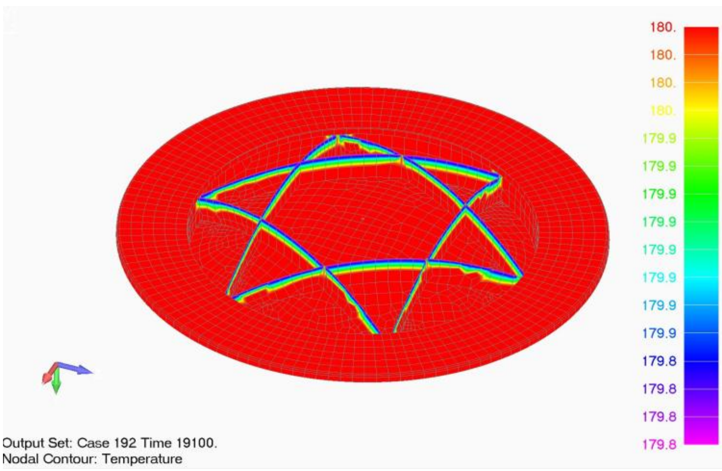

Figure 7. The temperature distribution without considering the heat generation at 19100 s

As a result, it was found that the given temperature 180°C is set at 8265s, if the model is used in calculations without considering the heat release and at 14240s. Thus, the temperature gradient at the initial stages of heating does not exceed 3°C, and in the holding phase it is even smaller and is 0.2°C.

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To determine the amount of heat released during the curing of the binder, a differential scanning calorimeter of the DSC 204 F1 Phoenix model was used. For the same binder sample (Araldite LY8615 + XB 5173), several successive runs were performed, differing in the rate of heating. The amount of heat released was determined from the area of the exothermic peak, the values of which were determined automatically. The results obtained are shown in table 3.

Table 3: DSC results

Heating rate, °C / min	**The maximum value of temperatures, ° C**	**Amount of heat released during curing, J / g**
1	171,3	115,4
2	177,57	194,3
5	187,06	196,3
10	194,26	224,5
15	198,14	225,2
20	202,28	263,6

The boundary conditions for the second stage of the heat transfer simulation during the curing of the reflector are as follows: convection through the air according to the curing regime in table 2 and a heat transfer coefficient of 15 W / m²·K; radiation from the surface of the reflector to the environment; internal heat generation occurs in the volume of the reflector with heating rate 2 °C / min according to the DSC results in table 3.

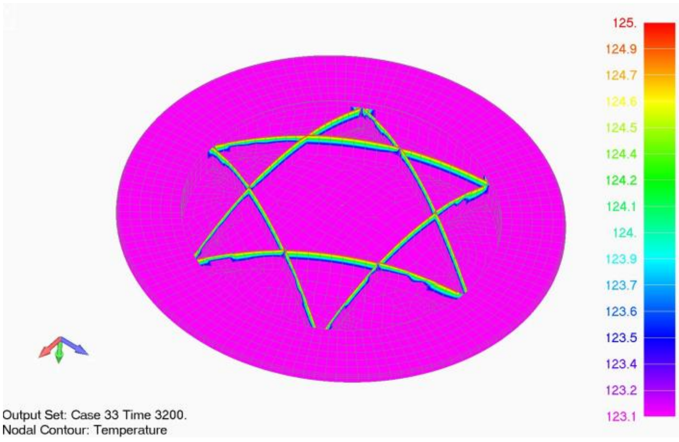

Figure 8. The temperature distribution with considering the heat generation at 3200 s

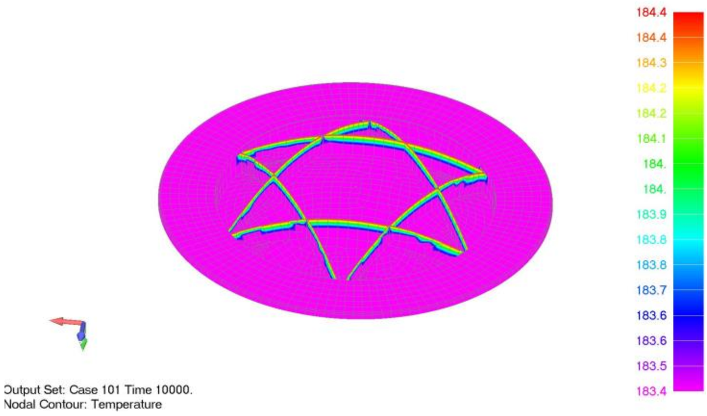

Figure 9. The temperature distribution with considering the heat generation at 11000 s

Table 4: Comparison of modelling results with and without heat generating during curing process

Temperature, °C	**Model without heat generation (2°C / min)**	**Model with heat generation (2°C / min)**
Ascent to 125	6600	6600
Exposure at 125	6615	6615
Ascent to 180	14240	9980
Exposure at 180	26225	19200
Cooling to 20	36225	28800
Ascent to 125	6600	6600

The modelling results and comparison of the models with and without taking account the heat generation during cure cycle are presented in fig.8-9 and table 4. As a result of the studies it was established that the set temperature of 180 ° C is reached in 9980s. At 16236s of heating, a uniform temperature distribution of the sample takes place, which makes it possible to reduce the exposure time at 180° C.

Table 4: Comparison of the experiment and theoretical results

№ п/п	Temperature, °C	Time, min		Error, %
		Experimentally	Theoretically	
I	125	105	110	5
III	180	27	29,75	9

As a result of the conducted studies it was established that a relatively low error exists between the theoretical and experimental results, which allows us to use the developed design model for estimating the kinetics parameters of the curing processes of the reflector designs.

4. Conclusion

Calculations have been performed for permeability coefficients in an elementary cell of fabrics and it was determined that deformation of the network angle occurs upon their lining on the curved surface. With a decrease in network angle, the permeability coefficient also decreases. Comparison of two types of fabrics (spread and non-spread) showed that standard fabrics are impregnated faster than spread ones, which have a rectangular section. In curing process the models with and without taking account of the heat generation during currying cycle were developed. The results show that considering the heat generation during the development of curing cycle would not only reduce its negative impact, but would also lead to a certain reduction in the duration of the curing process, which will also have a positive impact on cost reduction.

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