Optimization of the radiotransparent constructions in a mode of extreme heat loads

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Abstract. An experimental method has been developed for optimizing the composition of multilayer radiotransparent structures operating under extreme thermal loads. To optimize the composition of the layers of the radiotransparent radome researchers for the following materials with structures of the glass filler are carried out: glass-fiber laminate (GFR-CM), reinforced quartz material of SiO\textsubscript{2}–SiO\textsubscript{2} class (HTRC-CM), organosilicon rubber with a ground mica filler (TCT). The parameters of the heat loads that cause physicochemical transformations in radiotransparent materials and significantly affect the transmission and reflection coefficients of materials, as well as their complex permittivity, are determined. It is shown that the decrease in the transmission coefficient for the construction made of HTRC-CM material is up to 3–4 dB in the frequency range from 2 to 40 GHz, and for constructions made of GFR-CM+TCT is up to 25 dB, respectively. As a result, the radome made of ceramic matrix composite HTRC-CM has the best radiotransparency characteristics.

1. Introduction

Radiotransparent components in the form of windows, inserts, nose fairings, fairings are widely used in the design of modern high-speed aircraft (HSA) with a view to provide a protection of receiving and transmitting radio-technical devices from the effects of aggressive plasma air flows, extremely heat and mechanical loads [1, 2].

Radiotransparent constructions can be made both single-layered and multi-layered, in the latter case the outer layer is usually made of supporting material providing thermal protection of the base material in the product. In this paper, we consider approaches for selecting and justifying the composition of the multilayer radiotransparent body of the HSA radome, taking into account the effects of highly intensive trajectory heating on the electromagnetic properties of the product.

2. Radiotransparent multilayered structures

Structures made of radiotransparent heat-insulating materials should ensure the preservation of radiotransparency throughout the flight, the tightness of the hull and the necessary thermal conditions in the compartment where the antenna-feeder equipment is located.
Table 1. Comparative characteristics of the radiotransparent thermal protection materials.

| Name of characteristics | TCT     | GFR-CM  | HTRC-CM |
|-------------------------|---------|---------|---------|
| $\rho$, g/cm$^3$        | 1.20    | 1.60    | 1.75    |
| $\sigma$, MPa           | 2.5–3.6 | 215–60  | 18.0–17.3 |
| $\lambda$, W/(mK)      | 0.22–0.16 | 0.54–0.58 | 0.42–1.01 |
| $C$, kJ/(kg K)        | 1.23 at 50 °C | 0.76–0.82 | 0.73–1.36 |
| $\varepsilon$          | 2.81    | 3.2–3.4 | 2.9–3.1  |
| $\tan \delta$         | 0.02    | 0.005–0.008 | 0.003–0.005 |
| $\Delta \varepsilon$, no more, % | —      | 15      | 5        |

In order for products from radiotransparent heat-shielding materials to withstand trajectory loads, these materials must have high and stable dielectric characteristics in a wide range of operating temperatures, combined with high thermochemical resistance and resistance to high-intensity heat fluxes and pressures [3]. To meet these requirements the supporting materials are often used to provide a thermal protection of the main bearing material of the radiotransparent item.

The main comparative characteristics of one carrier material and two typical basic radiolucent materials are presented in table 1. The following notation has been used: density is indicated by the symbol $\rho$, tensile strength at temperatures 20–1000 °C is indicated by the symbol $\sigma$, coefficient of thermal conductivity at temperatures 20–1000 °C is indicated by the symbol $\lambda$, specific heat at temperatures 20–1000 °C is indicated by the symbol $C$, relative permittivity at the frequency of $10^6$ Hz is indicated by the symbol $\varepsilon$, dielectric loss tangent at the frequency of $10^6$ Hz is indicated by the symbol $\tan \delta$, change of relative permittivity up temperature 1200 °C is indicated by the symbol $\Delta \varepsilon$.

The supporting material TCT (thin-film thermal-protection coating) is used as a sublimation material for external heat protection of radiotransparent load bearing body of the radome. TCT coating is a composition based on a liquid low-molecular organosilicon rubber and dispersed filler in the form of ground mica. GFR-CM (glass-fiber radiotransparent ceramic composite material) and HTRC-CM (high-temperature radiotransparent ceramic composite material) materials are reinforced composite materials of SiO$_2$–SiO$_2$ class. A distinctive feature of the material HTRC-CM from the material GFR-CM is the absence of an organic component in its composition and, accordingly, a higher operating temperature (up to 2200 °C short-term). The research results presented in [4] demonstrated that the high-temperature treatment simulating aerodynamic heating leads to increased dielectric losses in the GFR-CM material caused by the appearance of fine carbon (soot) in the inner layers of the material as a result of high-temperature physicochemical transformations. It is known [5] that the mechanical characteristics of organosilicon fiberglass are stable only until the beginning of thermal degradation (decomposition) of the binder ($t > 400$ °C), as a result of which the tensile strength drops sharply with further increase in temperature to 1000 °C. Therefore, the heat of the radiotransparent body made of GFR-CM to a temperature above 1000 °C, on the one hand, leads to an increase in dielectric losses, and, on the other hand, significantly reduces the mechanical strength. As a result, the use of the radiotransparent radome body made of single-layer material GFR-CM at extremely high heat loads is impossible without additional external thermal protection, for example, with the use of TCT material.
3. Modeling of high-temperature processes over the surface of radome body

The two options of the radiotransparent radome bodies are considered:

- two-layer material TCT+GFR-CM;
- one-layer material HTRC-CM.

Figure 1 shows the results of the high-temperature processes in a two-layer radome body made of TCT+GFR-CM. Figure 1(a) shows a general view of the sample under test with a square size of 200 mm. Figures 1(b) to 1(f) show enlarged fragments of the samples.

The required level of heat effect was formed by the flow of combustion products from the special designed gas burner of stoichiometric combustion, in which a pre-prepared mixture of fuel and oxidizer is burned with a controllable excess coefficient of oxidizer (oxygen)—\( \alpha \). This
method allows one to research a nature of thermochemical processes over the extended surfaces for the required time [4].

Let us consider in more detail how the structure of thermal protection coating TCT changes. The process of heating TCT samples to a temperature above 350–400 °C is accompanied by the formation of bubbles on the outer surface of material, shown in figure 1(a), as a result of a decomposition of organosilicon rubber with a release of significant masses of gaseous products (mainly steam from mica and hydrogen from rubber). This leads to the formation a porous, strongly erupted structure of the subsurface layer of the TCT with a predominance of lenticular, horizontally positioned pores. Heating the sample to a temperature of 1000 °C, shown in figure 1(b), leads to the formation on the outer surface of a continuous layer of sintered mica in the form of a white film with swelling and bubbles.

Figure 1(c) shows the sample after heating the surface up to the temperature of 1250 °C for 60 s with the coefficient \( \alpha = 0.95 \). The formation of black crust of fused mica with cracks, swellings, and bubbles is visible. An estimated 2 mm of TCT material has burned out. In this case, due to the absence of free oxygen in the gas flow with a coefficient \( \alpha < 1 \) a soot layer appears on the surface.

Figure 1(d) shows the result of heating the sample surface to the temperature of 1470 °C for 60 s with \( \alpha = 1.1 \). Local surface swellings with the formation of numerous pores are observed. During the first 30 s a crater was formed on the surface, which gradually expanded in the future. Mica drops accumulated on its periphery. For control, the composition of these drops was analyzed using the scanning electron microscope (SEM) Nova NanoSEM 50. The results of the SEM analysis show the following molar composition, calculated as oxides (concentrations are indicated in mol %): 67.5% SiO\(_2\); 22.3% MgO; 6.8% Al\(_2\)O\(_3\); 2.1% K\(_2\)O; 0.4% F\(_2\)O\(_4\); 0.5% Na\(_2\)O and 0.3% TiO, that does not contradict to the vision of the decomposition of a rubber and the melting of a mica.

The fact is the presence of oxygen in the flow as a result of burning rubber over the surface leads to the appearance of white formations of sintered or melted mica. Inside the material, due to the absence of oxygen, the rubber does not burn out, but decomposes to produce fine carbon (soot). The walls of the pores and internal channels formed as a result of intensive gassing are covered with a continuous layer of soot—the final product of the thermal decomposition of an organosilicon binder in which more or less sintered mica particles are distributed. It is important that such soot films are electrically conductive (with high electrical resistivity), that significantly affects on the radiotransparency of the material.

Figure 1(e) shows the result of heating the sample surface to the temperature of 1850 °C. The heating process took place in the following sequence: at the 20th s there was a crater breakthrough with the formation of a new layer of melted mica, which after a while breaks through again and so on. Probably, at temperatures above 1200 °C, the nature of the processes over the surface of the samples does not change, but only accelerates.

The cross-section of the sample shown in figure 1(e) is presented in figure 1(f). The image shows that TCT layer in the center of the crater was burned to a residual thickness of about 1.5 mm, and the entire remaining layer of TCT is saturated with black pores similar to lenses, oriented along the surface.

Figure 2 shows the results of simulation of high-temperature processes in the sample of the radiotransparent radome body made of HTRC-CM.

After heating and holding for 180 s at the temperature of 1850 °C, the surface layer of HTRC-CM sample received a slight melting, where the pores are visible. In this case, the mesh structure of the material became invisible.
Figure 2. HTRC-CM sample (a) in its original condition and (b) after heating the surface up to 1850 °C with α = 1.1 for 180 s.

4. Radiophysical properties of multilayer radiotransparent radome bodies

The influence of high-temperature effects on the radiophysical properties of samples of radomes made from radiant materials was estimated from the results of measurements of transmittance and reflection at normal incidence of a plane electromagnetic wave in the microwave range from 2 to 40 GHz in accordance with the method [4].

Figure 3 shows the measurement results of reflection and transmission coefficients of samples of a two-layer radiotransparent radome body made of TCT+GFR-CM materials.

The measurement results for two-layer samples of TCT+GFR-CM before and after thermal ablation (see figure 3) showed that the TCT coating, after high-temperature processing, almost completely loses its radiolucent properties, especially in the short-wave region of the spectrum: Transmission coefficient is not more than minus 25 dB in frequency range from 20 to 40 GHz. As noted above, this is due to the formation of highly heated conductive layers of fine carbon (soot) in the inner layers of the material as a result of carbonation of carbon–hydrogen binders in the absence of oxygen.

The results of measuring the reflection and transmission coefficients of a sample of a single-layer radiotransparent body of a fairing made of HTRC-CM are presented in figure 4.

It can be seen from the graphs above that the high-temperature influence HTRC-CM material had practically no affect on its radiophysical properties (the difference in the values of reflection and transmission coefficients before and after thermoablation is insignificant). So the change in the transmission coefficient is about 1–4 dB in the microwave range from 2 to 40 GHz, i.e., the level of radiotransparency of HTRC-CM samples.
Figure 3. Comparative measurement results of reflection (a) and transmission (b) coefficients of TCT+GFR-CM samples in their original condition and after thermoablation.

Figure 4. Comparative measurement results of reflection (a) and transmission (b) coefficients of HTRC-CM samples in their original condition and after thermoablation.
5. Conclusions

Our deductions are as follows:

- A comparative research of the two options of the radiotransparent radome bodies made of TCT+GFR-CM and HTRC-CM materials showed that only the second option allows the radome radiotransparency to be maintained under conditions of highly intense heat impact.

- The radiotransparency of samples of radome body made of HTRC-CM remain essentially unchanged after long-term heating of its surface to the temperature of 1850 °C. The changes in the magnitudes of transmission coefficients before and after high-temperature treatment reach 1–4 dB in the frequency range from 2 to 40 GHz for HTRC-CM material, whereas for two-layer material TCT+GFR-CM these values reach 12–35 dB.

- It is shown that the cause of the increasing dielectric losses in TCT+GFR-CM under intense heat impact is the appearance of pores on the surface inside TCT material, where oxygen does not have time to enter, of semiconducting soot layers as a result of carbonation of carbon–hydrogen binder of this material.

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