Analysis of damaged Alumina Enhanced Thermal Barrier

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Abstract. The paper presents the problem of aerodynamic heating of a damaged Alumina Enhanced Thermal Barrier AETB. At the given minimum dimensions of the cover layers, the impact of damage size on the temperature increase on the skin surface was analyzed. The aim of the study was to determine the temperature curve as a function of the size of damage. In the calculations FreeFem ++ non-commercial environment was used.

1. Introduction

During atmospheric reentry the spacecraft is subjected to aerodynamic heating. This phenomenon is due to the enormous friction surface of the vehicle with the air. Such friction occurs when the vehicle moves at hypersonic speed. Aerodynamic heating is related to high vehicle temperatures. They are so high, that they may cause the melting of the steel. Vehicles skins are made of aluminium alloy, whose operating temperatures are low [1]. Therefore, all the vehicles carrying out orbital and interplanetary missions without adequate heat shield would burn during atmospheric reentry. The paper contains analysis Alumina Enhanced Thermal Barrier AETB-8, which is classified as rigid insulators, Figure 1.

AETB board with TUF1 coating was developed as an extension of the LI900 insulation. AETB tiles have higher strength, which increases safety and have a maximum working temperature of 1371°C. Therefore, in 1996 the AETB tile replaced the HRSI shields made of original material only in areas with high risk of collision with external objects [2]. The AETB is currently used to send an unmanned American X37b shuttle. This material was or is also considered in the design of other space vehicles like the Sierra Nevada Dream Chaser [3]. The system creates a layer of AETB insulation, which is covered with a ceramic TUF1 coating. The insulation is attached to strain isolator pad SIP with RTV glue, which rests on the skin using the same adhesive. The dimensions of the tile are 20 x 20 cm. [4]
2. Formulation of the heat transfer problem

In the analysis for a given heat flux on the outer surface of the tile, the thickness of the insulator was determined so that the operating temperature of the tile did not exceed 150°C (maximum temperature for the skin). Thermal conductivity of the insulator and SIP is dependent on temperature and pressure. The profile of changes in pressure \( p \) and heat flux \( q(t) \) were taken from the literature [5], and the properties of the materials from the literature [5, 6]. Very thin layers do not significantly affect the results. Therefore, they were omitted in the analysis. For the adopted materials, it was assumed that the thickness of aluminum skin is 0.00254 m, SIP 0.00406 m. In the first stage of calculations, the undamaged tile model was analyzed, and in the second, the damaged tile model, whose damage size changed for an insulation thickness of 0.0775 m. Model of damage was made for the case, where the defect in insulation is formed by an impact with small object moving at a hypersonic speed. The damage shape is characterized by the parameter \( D \), which is 0.0155 m (20% of thickness), 0.02325 m (30% of thickness), 0.031 m (40% of thickness), respectively. The lower part of the damage forms a semicircle with a radius \( D/2 \). All calculations were made for the axisymmetric model in FreeFem ++ non-commercial environment. Figure 2 presents the shape of the model.

![Figure 2. Numbering of layers and walls: \( \Omega_{11} \) – layer of insulation, \( \Omega_{12} \) – layer of strain insulation pad SIP, \( \Omega_{13} \) – layer of aluminium alloy](image)

Heat exchange with the environment at the edge of a damaged tile is a complex issue, in the description of which radiation in the entire damage area should be taken into account. Therefore, the coupled issue of heat conductivity in the area of the tile \( \Omega_1 \) and the area of damage \( \Omega_2 \) should be considered, figure 3.

In the area of \( \Omega_1 \) the heat conductivity equation is in the form

\[
\rho c_p \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( k_r r \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial T}{\partial z} \right)
\]  

(1)

with boundary conditions on the wall \( \Gamma_1 \)

\[-k_z \frac{\partial T}{\partial r} = q(t) + \varepsilon \sigma \left( T_w^4 - T_f^4 \right)\]

(2)

and walls \( \Gamma_3, \Gamma_4, \Gamma_5 \)

\[
\left( \frac{\partial T}{\partial r} \right) = 0
\]

(3)

The quantities present in the formulas (1) – (2) mean respectively: \( \rho \) – density, \( c_p \) – specific heat at constant pressure, \( k_r, k_z \) – heat conductivity in the directions \( r \) and \( z \), \( q(t) \) –heat flux, \( \varepsilon \) – thermal emissivity, \( \sigma \) –Stefan–Boltzmann constant , and \( T_w \), \( T_f \) – the temperature of the wall and air surrounding the panel.
The problem of thermal radiation is related to the $\Omega_2$. Therefore, radiative transfer equation must be solved. The conservation of the radiative energy along a ray path of direction $\hat{s}$ can be written as [7]

$$\mathbf{s} \mathbf{V} I (\mathbf{r}, \mathbf{s}) = -\kappa l (\mathbf{r}, \mathbf{s}) + \kappa_a n_l^2 \frac{\sigma T^4}{\pi} + \frac{\kappa_s}{4\pi} \int I (\mathbf{r}, \mathbf{s}') P (\mathbf{s}' \cdot \mathbf{s}) d\omega'$$  \tag{4}

where $I (\mathbf{r}, \mathbf{s})$ – radiative intensity at a point with coordinates $\mathbf{r}$ ($\mathbf{r} \in \Omega_2$), and direction determined by the unit vector $\hat{s}$, $\kappa$ – extinction (or attenuation) coefficient, $\kappa_a$ - coefficient of absorption, $\kappa_s$ - coefficient of scattering, $P (\mathbf{s}' \cdot \mathbf{s})$ – scattering phase function, $n_l$ – refractive index, $d\omega'$ - solid angle.

$P_1$ approximation method was used to solve the above equation. In the $P_1$ model, it is assumed that the radiative intensity can be expressed as a Fourier series which is variable separated into a function depending on coordinates and another on the direction as follows

$$I (\mathbf{r}, \mathbf{s}) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} I_l^m (\mathbf{r}) Y_l^m (\mathbf{s})$$  \tag{5}

where $I_l^m (\mathbf{r})$ – corresponds to the position coefficients, $Y_l^m (\mathbf{s})$ – corresponds to the spherical harmonics.

If the series in equation is truncated beyond $l = 1$, there is the lowest-order ($P_1$ approximation).

Using governing equations for the $P_1$ approximation

$$\nabla \cdot \mathbf{q} (\mathbf{r}) = 4\kappa_a n_l^2 \sigma T^4 - (\kappa - \kappa_s) G (\mathbf{r})$$  \tag{6}

and

$$\nabla G (\mathbf{r}) = -(3\kappa - A\kappa_s) \mathbf{q} (\mathbf{r})$$  \tag{7}

where $\mathbf{q} (\mathbf{r})$ – radiative heat flux, $G$ – incident radiation, $A$ – proportionality coefficient associated with anisotropy of the medium in the range.

Boundary conditions in the area $\Omega_2$ are

- at the edge $\Gamma_11$ (assumed $\varepsilon = 1$)

$$\frac{2}{3} \frac{\partial G (r_w)}{\partial n} + G (r_w) = 4n_l^2 \sigma T_w^4$$  \tag{8}

- at the edge $\Gamma_12$

$$\frac{(2-\varepsilon)}{\varepsilon} \frac{2}{3} \frac{\partial G (r_w)}{\partial n} + G (r_w) = 4n_l^2 \sigma T_w^4$$  \tag{9}

- at the edge $\Gamma_13$ (condition of symmetry);

$$\frac{\partial G}{\partial n} = 0$$  \tag{10}

In the medium $\Omega_2$, heat exchange occurs only through thermal radiation. The effect of convection has been ignored. The assumed ambient pressure and temperature are those at sea level according to the reference atmosphere. The heat flux $q(t)$ as a function of time was assumed on the basis of the heat transfer in the spacecraft for a specific flight trajectory during the return from orbit to Earth. It takes into account the changing environmental conditions during the flight.

3. Results

Due to the lack of access to the AETB properties, the thermal conductivity in the direction of the $r$ axis was unknown. There was assumed that the percentage changes in the thermal conductivity coefficient of the $z$ axis to the $r$ axis for the same temperature and pressure for the AETB-8 material were the same each time as the changes in these coefficients for the LI900 material. The second assumption was to adopt the same (as in LI900) emissivity factor as a function of temperature at the defect location, i.e. on the edge $\Gamma_2$. The calculation results are presented in Figure 3 and 4. The maximum temperature for each dimension of damage significantly exceeds the permissible operating temperature of the insulation material. In extreme cases the difference is 697°C. In any case, the maximum
temperature appears 850 seconds after the start of the heating process. This situation is significantly different for the skin surface. The maximum temperature for a damaged panel model with the largest dimension D compared to no damage appears 810 seconds faster.

![Figure 3. Maximum temperature distribution in function of time on the surface of insulation](image1.png)

![Figure 4. Maximum temperature distribution in function of time on the surface of aluminium alloy](image2.png)

The equation searched for describing the temperature rise for an increasing dimension of damage at the edge of the aluminum alloy \( \Gamma_4 \) describes a third-degree polynomial

\[
T_w = 447562D^3 + 160250D^2 - 784.95D + 149
\]

4. Conclusions

Using \( P_1 \) approximation radiative transfer equation was solved in the AETB damage area. A polynomial was determined for temperature and damage oriented in the central part of the panel. The size of the insulator defect significantly increases the temperature on the surface of the aluminum alloy, the damage of which is associated with the danger of destroying the entire structure of the orbiter. The analysis shows that during the landing for the largest adopted dimension D, the temperature on the skin surface increases by about 75 °C. The resulting equation allows to quickly estimate the temperature. The next step may be to perform a number of calculations, that will allow to create a graph of skin temperature characteristics for different sizes of damage and different thicknesses of AETB panel layers.

References

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