THE INVERSE PROBLEM IN ZERO LINEAR ABLATION OF ALUMINIZING CARBON COMPOSITES UNDER HIGH HEAT FLUX

by

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The concept of zero linear ablation is introduced to describe the mass ablation without shape change, and it is employed to design thermal protection materials under an extreme thermal environment. Aluminizing carbon composites are used as a sample to study numerically the heat response. As indicated in the numerical results, the shape of the composites did not change under a high heat flux because the phase transition (melt or evaporation) of aluminum can absorb a lot of energy before the ablation of carbon, and the zero linear ablation depends on not only the volume fraction of aluminum, but also the heating period and the heat flux.

Key words: *zero linear ablation, aluminizing carbon composites, thermal response, inverse problem*

Introduction

Due to the viscosity and shock wave, an extreme thermal environment is formed in front of the aircraft. For the safety of aircraft, researchers proposed a number of thermal protection schemes such as ablation and transpiration cooling [1], which are damaged to some extent due to severe reentry heating. Although ablation, which absorbs heat by loss of mass, can protect the spacecraft against danger, losing a part of materials will change the shape of the spacecraft and then affect its aerodynamic property [2]. And the forced transpiration cooling is a technique in which a coolant fluid (such as water or air) is sent through a porous medium in order to protect that surface from heat, but it is too complex and uncertain to be used in aerospace [3]. For the sake of keeping a good aerodynamic performance in hypersonic flying, it is very important to design the zero linear ablation which does not change in shape but a phase transition (melt or evaporation) occurs inside materials. Gori *et al.* [4] evaluated the effective thermal conductivity of an ablative composite material in the state of virgin material and in three paths of degradation. Ferraiuolo and Manca [5] developed analytical and semi-analytical procedures to solve thermal problems. Huang *et al.* [6] presented the reverse-quadtree scheme for solving the convection equation in aerodynamics. Kunihiko [7] gave a thermal analysis for re-entry vehicle structure using the CFD/FEM coupling method. Palaninathan and Bindu [8] gave a model for mechanical ablation in thermal protection systems. Though an effective self-transpiration cooling model was presented for studying thermal response of the heat resistant layer [9], there has never been a model for estimating the zero linear ablation, which cannot be avoided in the aircraft design. In order to optimize the design of thermal protection materials under a high heat flux, we will develop the model of zero linear ablation which is composed of aluminum and carbon.

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Model

When working in a high-temperature environment, aluminizing carbon composites (Al/C) can be cooled by itself-sweating (phase transition of low-melting aluminum). Aluminum begins to absorb some heat by melt when the temperature increases to its melting point (933 K). Under the low gas pressure, the melted aluminum continues to evaporate, fig. 1(a). However, the melted aluminum cannot evaporate under the saturated vapor pressure, fig. 1(b). Alumina layer is easily generated on the surface of carbon in order to protect the carbon from being oxidized, so the zero linear ablation appears below the melting point of alumina.

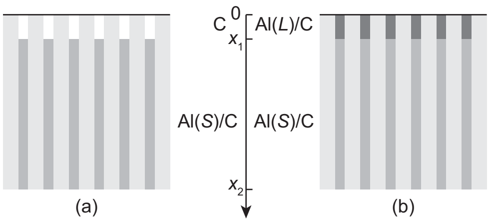


Figure 1. Models for zero linear ablation of Al/C

We will consider the following two kinds of models for zero linear ablation:

Under the low gas pressure, two layers – carbon layer and Al/C layer – should be calculated. The heat conduction equations for Al/C layer and carbon layer, respectively, can be written:

$$\rho_{\mathrm{Al}(S)/\mathrm{C}} C_{p,\mathrm{Al}(S)/\mathrm{C}} \frac{\partial T}{\partial t} = k_{\mathrm{Al}(S)/\mathrm{C}} \frac{\partial^2 T}{\partial x^2} \tag{1}$$

$$\rho_{\text{C-layer}} c_{p,\text{C-layer}} \frac{\partial T}{\partial t} = k_{\text{C-layer}} \frac{\partial^2 T}{\partial x^2} + \dot{m}_r c_{p,\mathrm{Al}(L)} \frac{\partial T}{\partial x} + \dot{m}_g c_{p,\mathrm{Al}(g)} \frac{\partial T}{\partial x} \tag{2}$$

The boundary conditions are:

$$-k_{\text{C-layer}} \frac{\partial T}{\partial x} = q_{(w)} - \varepsilon\sigma T_w^4 \qquad x = 0 \tag{3}$$

$$-k_{\mathrm{Al}(S)/\mathrm{C}} \frac{\partial T}{\partial x} = -k_{\text{C-layer}} \frac{\partial T}{\partial x} + \dot{m}_r \Delta H_r + \dot{m}_g \Delta H_g \qquad x = x_1 \tag{4}$$

$$\frac{\partial T}{\partial x} = 0 \qquad x = x_2 \tag{5}$$

where m and ΔH are the phase transition mass and the latent heat of aluminum, respectively; subscripts r and g denote the melt and evaporation, respectively.

Under the saturated vapor pressure, Al/C layers with liquid Al and with solid Al should be considered. The heat conduction equations for Al/C layer with solid Al and Al/C layer with liquid Al are, respectively:

$$\rho_{\mathrm{Al}(S)/\mathrm{C}} C_{p,\mathrm{Al}(S)/\mathrm{C}} \frac{\partial T}{\partial t} = k_{\mathrm{Al}(S)/\mathrm{C}} \frac{\partial^2 T}{\partial x^2} \tag{6}$$

$$\rho_{\mathrm{Al}(L)/\mathrm{C}} C_{p,\mathrm{Al}(L)/\mathrm{C}} \frac{\partial T}{\partial t} = k_{\mathrm{Al}(L)/\mathrm{C}} \frac{\partial^2 T}{\partial x^2} \tag{7}$$

The boundary conditions are given as:

$$-k_{\mathrm{Al}(L)/\mathrm{C}} \frac{\partial T}{\partial x} = q_{(w)} - \varepsilon\sigma T_w^4 \qquad x = 0 \tag{8}$$

$$-k_{\mathrm{Al}(S)/\mathrm{C}}\frac{\partial T}{\partial x}=-k_{\mathrm{Al}(L)/\mathrm{C}}\frac{\partial T}{\partial x}+\dot{m}_r\Delta H_r \qquad x=x_1 \tag{9}$$

$$\frac{\partial T}{\partial x}=0 \qquad x=x_2 \tag{10}$$

The initial conditions of two kinds of models are both:

$$T(x,t)\big|_{t=0}=303\ \mathrm{K} \tag{11}$$

Numerical calculation and results

In the two kinds of models with thickness 30 mm, the volume fraction of aluminum varies from 15-60% and the heating flux is divided into two groups: 1.0-10.0 MW/m^2 and 0.25-2.5 MW/m^2. In addition, the physical properties of aluminum are assumed that: $\rho_{\mathrm{Al}(L)}\approx\rho_{\mathrm{Al}(S)}$, $k_{\mathrm{Al}(L)}\approx k_{\mathrm{Al}(S)}$, $C_{p,\mathrm{Al}(L)}\approx C_{p,\mathrm{Al}(S)}$.

The density and specific heat of Al/C are, respectively:

$$\rho_{\mathrm{Al/C}}=\rho_{\mathrm{Al}}\phi_{\mathrm{Al}}+\rho_{\mathrm{C}}\phi_{\mathrm{C}} \tag{12}$$

$$C_{p,\mathrm{Al/C}}=C_{p,\mathrm{Al}}\phi_{\mathrm{Al}}+C_{p,\mathrm{C}}\phi_{\mathrm{C}} \tag{13}$$

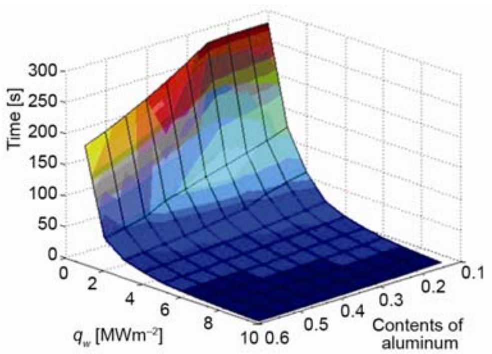
where ϕ is the volume fraction.

The density of carbon layer is:

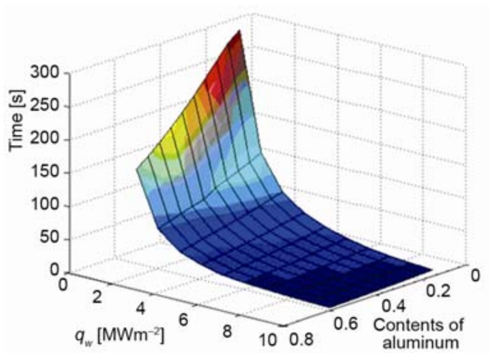
$$\rho_{\mathrm{C-layer}}=\rho_{\mathrm{C}}\phi_{\mathrm{C}} \tag{14}$$

Based on eqs. (1)-(14), the thermal response of Al/C has been calculated with dt = 0.001 using the FORTRAN codes. When q_w = 1-10 MW/m^2, the inversion solutions of zero linear ablation on model 1 and on model 2 are shown in figs. 2(a) and 2(b), respectively. The zero linear ablation time becomes longer with the smaller heat flux under the same volume fraction of aluminum, and the longer zero linear ablation time needs decreasing the content of aluminum under the same heat flux. When q_w = 0.25-2.5 MW/m^2, the inversion solutions of zero linear ablation on model 1 and on model 2 are shown in figs. 3(a) and 3(b), respectively. The zero linear ablation time on two models above is longer than 600 s when the heat flux is not more than 0.75 MW/m^2.

Taking the melt, evaporation and radiation of Al/C with the volume fraction 15% of



(a) Model 1



(b) Model 2

Figure 2. Inversion of zero linear ablation when q_w = 1-10 MW/m^2
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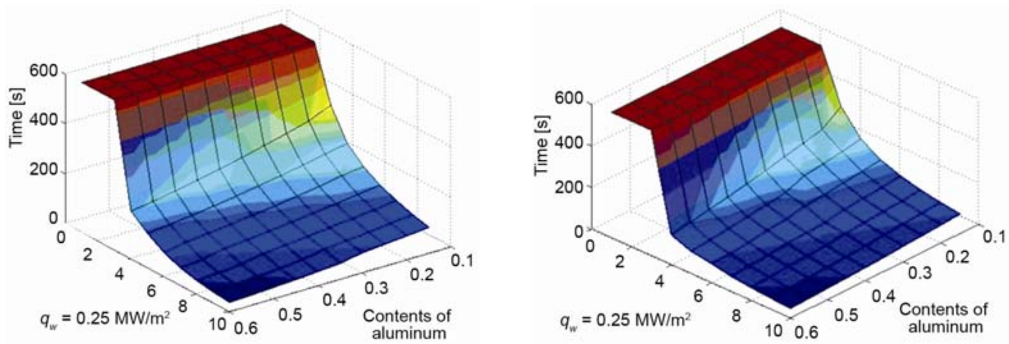

(a) Model 1 (b) Model 2

Figure 3. Inversion of zero linear ablation when q_w = 0.25-2.5 MW/m^2
(for color image see journal webslite)

aluminum into consideration, the inversion solutions of the temperature on the back and the wall under the low gas pressure are shown in figs. 4(a) and 4(b), respectively. The results show that the absorbing heat at the melt and evaporation is not obvious when the heat flux is larger.

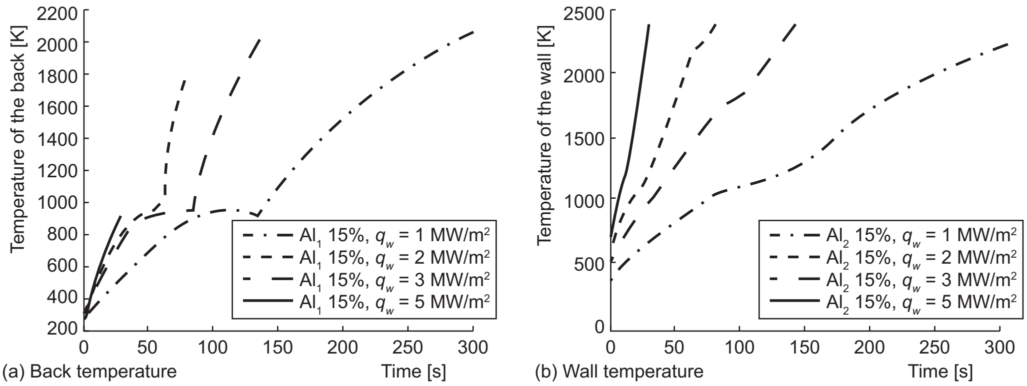

Figure 4. Temperature *vs.* heating time

Namely, the temperature on the wall rises rapidly to the melting point 2323 K of alumina when the heat flux is over 5 MW/m^2 and zero linear ablation of Al/C may not appear. However, the temperature on the back has a longer horizontal line in fig. 4(a), and it is obvious that the absorbing heat is numerous when the heat flux is less than 3.0 MW/m^2.

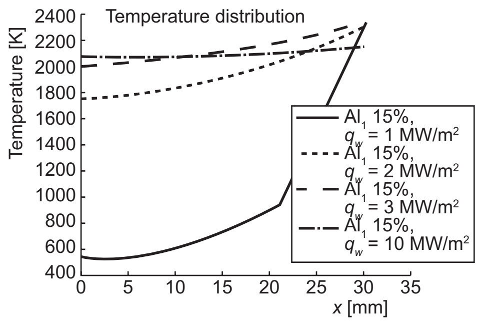

Figure 5. Temperature distribution in the thickness direction when t = 300 s

In addition, fig. 5 shows the temperature distribution in the Al/C thickness direction at the heating time 300 s. At this moment, there is only solid carbon left without solid aluminum when the temperature reaches 2000 K under a higher heat flux, but the transpiration cooling effect of aluminum can make the growth rate of temperature on back surface slow under a lower heat flux.

Conclusions

Based on the Fourier heat equation, the model of zero linear ablation of Al/C under a high heat flux has been developed in this paper. By using the FORTRAN codes, the inversion on heat response is performed with a finite difference approach. The numerical results show that:

- The phase transition (melt or evaporation) of aluminum can absorb a lot of heat before the ablation of carbon, and the shape of Al/C may not change under a high heat flux;
- The zero linear ablation of Al/C is dependent not only on the volume fraction of aluminum, but also on the heating time and the heat flux.

Acknowledgment

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Nomenclature

C_p – specific heat, [kJkg^{-1}K^{-1}]
ΔH_g – latent heat of evaporation, [MJkg^{-1}]
ΔH_r – latent heat of melt, [MJkg^{-1}]
k – thermal conductivity, [Wm^{-1}K^{-1}]
$\dot{m}_g$ – mass rate of evaporation, [kgs^{-1}]
$\dot{m}_r$ – mass rate of melt, [kgs^{-1}]
q_w – heat flux on the wall, [Wm^{-2}]
T – temperature, [K]

Greeks symbols

ε – radiation factor of the wall, [–]
ρ – density, [kgm^{-3}]
σ – Stefan-Boltzmann constant, [Wm^{-2}K^{-4}]
ϕ – volume fraction, [–]

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