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Modeling ablation of laminated composites: A novel manual mesh moving finite element analysis procedure with ABAQUS

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ABSTRACT

The recent improvements of the commercial, general purpose Finite Element Analysis (FEA) software have allowed them to be used for modeling ablation problems. ABAQUS for example, provides a user-subroutine UMESHMOTION along with the Arbitrary Lagrangian-Eulerian (ALE) adaptive remesh algorithm that enable the users to couple the heat transfer with the progressive surface recession (i.e., ablation). However, such a numerical capability is limited to model ablation problems when the ablation front (i.e., receding surface) is confined within a single material domain (e.g., homogenous material). For ablation problems when the ablation front proceeds from one material domain to another (e.g., laminated composite materials that consist of multiple laminate layers with different material orientations), such a numerical capability is insufficient, since the mesh is not allowed to flow from one material domain to another when the UMESHMOTION subroutine is used. In this paper, a novel computational procedure that sequentially performs the general heat transfer analysis and the general static analysis in ABAQUS, is proposed enabling the capability of ABAQUS for modeling ablation of laminated composites. The proposed procedure is verified by comparing the predictions of temperature and ablation histories of a two-dimensional isotropic panel (i.e., with single material domain) with those obtained using the traditional UMESHMOTION + ALE method. In addition, a case study of applying the proposed procedure to predict the thermal and ablation response of a laminated carbon fiber reinforced epoxy matrix (CFRP) composite panel subjected to a high-intensity and short-duration radiative heat flux is demonstrated.

1. Introduction

Laminated composite materials experience surface material removal (i.e., ablation) due to oxidation, nitridation, and vaporization when exposed to extreme heating conditions such as during lightning strike [1–3], laser machining process [4], and hypersonic reentry [5]. Although the thermal and ablative response of the laminated composite materials have been identified and characterized in some experimental studies [5,6], developing an accurate predictive model is still lagging behind due to the tight coupling between the heat conduction and the progressive surface material removal. In particular, a moving boundary condition due to the progressive material removal needs to be considered in the formulation of the heat conduction problem. One of the prevalent approach to develop such models is to use the commercial, general purpose finite element analysis software ABAQUS with the user-subroutine UMESHMOTION and the Arbitrary Lagrangian-Eulerian (ALE) adaptive remesh algorithm (UMESHMOTION + ALE method) [7]. However, when using the UMESHMOTION subroutine, the mesh is not allowed to flow from one material domain to another, and hence, such a method is not applicable for predicting the ablation of laminated composite materials, for which the material may recede from one layer to another (with different material orientations) during ablation. To enable ABAQUS with the capability of modeling ablation for laminated composites, in this paper, we propose a novel computational procedure, which performs the heat transfer analysis and the general static analysis in parallel and solves the temperature and ablation depth sequentially after every a few time increments. Here, we present the verifications for the proposed computational procedure by comparing the predictions of the recession and temperature histories of a two-dimensional (2D) homogenous isotropic panel with those predicted using the existing UMESHMOTION + ALE method. Note that, the choice of an isotropic panel allows us to use the UMESHMOTION + ALE method. Finally, a case study is presented to demonstrate the application of the proposed computational procedure to the prediction of the thermal and ablation response of a lami-

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nated carbon fiber reinforced epoxy matrix (CFRP) composite panel subjected to a high-intensity short-duration radiative heat flux. Note that, for such a case, the traditional UMESHMOTION + ALE method is not applicable.

2. Heat transfer equations considering material surface removal

The heat conduction in solid materials considering the material surface removal is typically governed by the following equation:

$$\rho C_p \left(\frac{\partial T}{\partial t} - \dot{s}\frac{\partial T}{\partial z} \right) - \nabla \cdot (k\nabla T) = \dot{q} \tag{1}$$

where ρ is the density, C_p is the specific heat, T is the temperature, t is time, $\dot{s}$ is the surface recession rate, z is the coordinate normal to the recession surface (i.e., for ablation problems when surface recedes in the through-the-thickness direction), k is the thermal conductivity, and $\dot{q}$ is the rate of energy input (e.g., from laser or plasma irradiation or aerodynamic convection). Here, the surface recession rates $\dot{s}$ (i.e., the ablation rate) of the solid material under extreme irradiation and convection heating conditions are strongly related to various chemical reactions that can occur on the surface of the material. Those possible reactions include evaporation, sublimation, oxidation, as well as nitridation. The surface recession rate is often determined through either experimental tests or theoretical predictions. For example, the ablation rate of the Thermal Protection System (TPS) material under hypersonic re-entry conditions is obtained through the Arc Jet test [8]. However, such experimental tests are restricted and the availability of the experimental data is quite limited. Meanwhile, a few gas-surface predictive models have been proposed to predict the mass fractions of the ablation products and, thus, the ablation rate of the TPS material [9–11]. Another typical example of the heat conduction problem with progressive material removal is the pulsed laser ablation (PLA) of solid materials [12]. Such a problem is quite common in the applications include laser surface processing and laser machining. In the case of PLA, the ablation mechanisms usually consist of two stages: the rapid material evaporation stage under low laser fluence conditions and the material phase explosion stage under high laser fluence conditions [12]. The ablation rate of solid materials during the evaporation stage is typically expressed using the Hertz-Knudson equation:

$$\dot{s} = \beta \sqrt{\frac{m}{2\pi k_B T}} \frac{P_b}{\rho} \exp\left[\frac{m L_v}{k_B} \left(\frac{1}{T_b} - \frac{1}{T} \right) \right], \tag{2}$$

where β is the vaporization coefficient, m is the atomic mass of the solid material, k_B is the Boltzmann constant, L_v is the latent heat of vaporization of the material, and T_b and P_b are the boiling temperature and the boiling pressure, respectively.

The material removal during the material phase explosion stage of PLA is quite complicated and no available explicit expressions are available to predict the ablation rate to the authors' best knowledge. The determination of such ablation rates during material phase explosion still typically relies on extensive experimental tests. Generally, for common solid materials, the surface recession rate is dependent on the enthalpy of the material, temperature, and pressure [9–11]. In the case of laminated solid materials, the surface recession rate may also depend on the material orientations of the laminate layers. In other words, the surface recession rate may also vary, when the material recedes from one laminate layer to another (assuming the material orientations of those layers are different).

3. Numerical implementation

Numerically, traditional methods to model ablation problems utilize moving grid systems with finite difference (or volume) analysis, which allow to predict the ablation and temperature histories by considering the coupling between the heat conduction and the progressive material removal. However, the ablation analysis tools developed based on these methods are often restricted, such as the Fully Implicit Ablation and Thermal Analysis (FIAT) tool developed by NASA Ames [8]. Moreover, the capability of such codes for modeling ablation of laminated composite materials, for which the ablation front may develop from one laminate layer to another (with different material orientations), has barely been reported. In addition to the existing approach with finite difference (or volume) method, the recent improvements of the commercial, general purpose Finite Element Analysis (FEA) software, have also allowed them to be used for modeling ablation problems considering the progressive material removal. ABAQUS for example, allows the users to model ablation problems for homogenous materials (i.e., ablation front is confined within a single material domain) using a provided user subroutine and the remeshing algorithm. However, this approach is not applicable to model ablation problems for laminated composite materials. To overcome this limitation, in this paper, a novel computational procedure based on a manual mesh moving (MMM) approach is proposed to model ablation for laminated composite materials in ABAQUS. The detailed procedures of the traditional UMESHMOTION + ALE approach (for modeling ablation of homogenous materials) and the proposed MMM approach (for modeling ablation of both homogenous and laminated composite materials) are discussed in Sections 3.1 and 3.2, respectively.

3.1. Traditional mesh moving method with adaptive remeshing algorithm in ABAQUS

The commercial, general purpose FEA software, ABAQUS, provides a user subroutine UMESHMOTION and the Arbitrary Lagrangian-Eulerian (ALE) adaptive remesh algorithm, that enables the users to model ablation problems by coupling the general heat transfer analysis with the progressive surface material removal. In particular, the surface recession rate of the material can be prescribed in the UMESHMOTION subroutine as a function of surface temperature or time. After each time increment, the UMESHMOTION subroutine is used to calculate the corresponding ablation depth,

$$\Delta h = \int_{t_1}^{t_1+\Delta t} \dot{s}dt, \tag{3}$$

where t_1 is the time at the end of the previous time increment and Δt is the current time increment. Meanwhile, the surface nodes are moved to their new locations according to the calculated ablation depth. Next, the ALE remesh algorithm generates the new mesh after the surface nodes are moved to their new locations. Note that, the boundary conditions (e.g., surface heat flux) can also be automatically updated. This UMESHMOTION + ALE method has been recently used in Ref. [13] for the analysis of ultrashort pulse laser-material interaction and in Ref. [14] for modeling ablative behavior and thermal response of carbon/carbon composites. Meanwhile, such a method has also been validated for PLA of aluminum under the low laser fluence regime [15]. However, as mentioned previously, this method is not applicable when the ablation problem includes multiple material domains (e.g., laminated composite materials, which are showing promising applications in the aerospace industry) due to the fact that ABAQUS does not allow mesh to flow from one material domain to another. Therefore, in the case when the material recedes from one layer to another layer with different orientations, the analysis will be terminated due to severely distorted mesh near the boundary of the two layers.