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Numerical prediction of temperature distribution in thermoset composites during laser curing process*

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Abstract: The temperature distribution in the advanced thermoset composite during the laser curing process was predicted with the use of the two-dimensional thermo-chemical model presented in this paper which also gives the governing equations based on the thermal history of the curing process. The finite-difference method was used to get the temperature distribution. This paper also deals with the effect of some factors (such as the winding velocity, the tape thickness and the laser heat source) on the temperature distribution.

Key words: Thermoset composites, On-line curing, Temperature distribution, Degree of curing, Laser heat source
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INTRODUCTION

Large thermoset filament-wound or fiber-tape-wound composite structures are widely used to form rigid, lightweight aerospace components, underground pressure vessels, and tubing. In manufacturing such structures, the fiber is firstly wound and then batch-cured in an oven or autoclave in the traditional method. During the curing process, the resin network grows into longer chains with branches and cross-linkings.

In the on-line laser curing method, a laser heat source is directed incident to the local area of the wound structures to initiate resin curing during the winding process. This method offers the possibility of a more uniform degree of cure and hence less severe residual stresses distribution in the finished structure. Moreover, this process is expected to have greater energy efficiency, higher productivity, be less size restricted and use less floor space compared with the standard batch-oven curing. Studies related to this on-line curing are limited. A thermo-chemical model was developed by Chern et al. (1995). A thermo-chemical model of self-sustaining curing process was developed and numerical results for a glass/polyester composite were obtained by Kim et al. (1995). However, their analyses were based on the steady state and there was no open report on the on-line laser curing process.

A two-dimensional thermo-chemical model for the on-line laser curing of thermoset composite is presented in this paper. A moving laser heat source and moving boundary are adopted in the analysis. Temperature within the composite during processing is predicted numerically and the effects of process parameters on the temperature distribution are analyzed.

ANALYSIS

In the analysis, a rectangular, transversely isotropic tape of width w_{ply} and thickness t_{ply} is considered and shown in Fig. 1. The tape is wound circumferentially at a constant 90° winding angle (hoop winding) at a feed rate of U onto a cylindrical mandrel of diameter D rotating with angular velocity $2U/D$. Due to the accretion of ply layers during the winding, this condition is not strictly satisfied for long time winding; but for a practical

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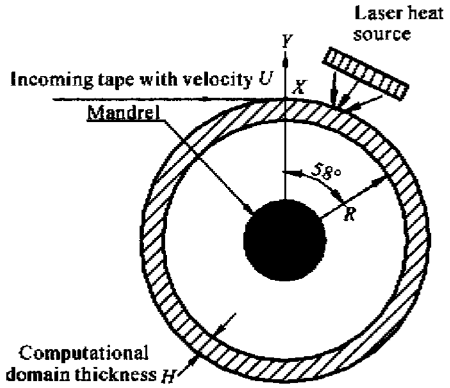

Fig.1 Physical geometry

winding situation, it is satisfied provided $2H/D \ll 1$. A cylindrical-coordinate system (R, θ, z) having its z-axis coincident with the mandrel's axis is used to describe the mandrel and the composite geometry. For typical plies used in tape winding, $t_{ply}/w_{ply} \ll 1$, so that variations in the axial (z) direction are negligible; the problem is thereby reduced to two dimensions: R and θ. The laser energy is assumed to be incident upon a given arc length of the cylinder's periphery. All the radiant energy deposition and primary heat transfer are assumed to occur in a thin surface layer of radial thickness H ($\ll D/2$) comprised of the n outermost plies. It is further assumed that $2H/D \ll 1$, so that the curvature of the surface layer can be neglected and the annular physical domain can be simplified into the rectangular computational domain (X, Y) (Fig.2). In the model, the composite is wound onto the mandrel ply by ply and the laser heat source movies with velocity relative to the mandrel, so the computation domain and the boundary condition change with time.

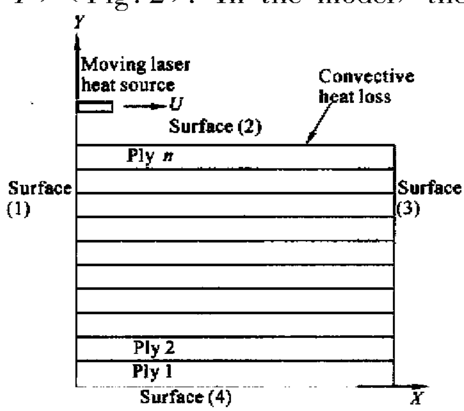

Fig.2 Computation domain

1. Energy equation

Under these assumptions, the governing equations are as follows.

For the thermoset composites, the energy equation is:

$$\rho_c C_c \frac{\partial T}{\partial t} + \rho_c C_c U \frac{\partial T}{\partial x} = k_{c,l} \frac{\partial^2 T}{\partial x^2} + k_{c,t} \frac{\partial^2 T}{\partial^2 y} + \rho_c \frac{\mathrm{d}Q}{\mathrm{d}t} \quad (1)$$

where ρ is mass density, C is specific heat, U is tape speed, k is thermal conductivity. Subscript represents thermoset composite, l represents along fiber axis direction. The two terms on the left-hand side of Eq.(1) are the unsteady term and the energy transport by advection due to ply motion, respectively. The first two terms on the right-hand side of Eq.(1) are energy transport by thermal diffusion along the fiber and transverse fiber directions, respectively. The last term on the right-hand side of Eq.(1) is the rate of heat released by chemical reaction.

The boundary conditions for Eq.(1) are assumed as described below.

Surfaces (1) and (3) are connected to each other, so:

Adiabatic condition of Surfaces (1) and (3):

$$\frac{\partial T}{\partial x} = 0 \quad (2)$$

Convective condition of Surface (2):

In the grid with laser heat input:

$$k_{c,l} \frac{\partial T}{\partial y} = -h(T - T_{air}) + sq \quad (3)$$

where sq is rate of laser heat input, h is convective heat transfer coefficient.

In the grid without laser heat input:

$$k_{c,l} \frac{\partial T}{\partial y} = -h(T - T_{air}) \quad (4)$$

Adiabatic condition of Surface (4):

$$\frac{\partial T}{\partial y} = 0 \quad (5)$$

2. Cure kinetics equation

Due to its wide use in industry and the

availability of a cure kinetics model (Loos et al., 1983), the Hercules AS/3501-6 resin system is used in the present study. Loos' model is used to estimate the heat release dQ/dt as a function of the degree of cure α and temperature T. In this model α is defined to be the ratio of the exothermic heat released Q_{ch} until some intermediate time to the total exothermic heat released Q_{tot} when all cross-linking reactions are complete. The incoming tape is assumed to be totally uncured: $\alpha = 0$.

3. Numerical method of the model

Control volume formulation is employed to solve the energy equation. Detailed derivation of the two-dimensional discretization equation was given by Patankar (1980). The resulting algebraic equations were solved by SLUR method. After obtaining the new temperature fields, the degree of cure is determined by solving the cure kinetics equations.

RESULT AND DISCUSSION

The most primitive results of the analysis are the ply-by-ply temperature profiles during the curing process. In Figs. 3-6, the horizontal axis shows the grid points of composite ply along X-axis. The values of the Y-axis indicate the temperature of the ply when its layout has just finished. The unit for the parameters are as follows: convective heat transfer coefficient h: $W/(m^2 \cdot K)$; ply thickness (in y direction) t_{ply}: m; rate of laser heat input sq: W/m^2; thermal conductivity along fiber axis direction kl: $W/(m \cdot K)$; tape speed U: m/s. The steep ramp-up on the right-hand of each ply is primarily due to the laser heat input because the last two points along the X axis are the points that have just got the laser heat input under the moving laser heat source assumption. It can also be seen from Fig.3 that the temperature of the later-wound ply is higher than the previous ply temperature; and that the transverse-fiber diffusion is less. The relatively higher temperature on the left side of the first ply is due to the symmetrical matching condition for the first ply. The effects of some process parameters on the temperature distribution are considered here and shown in Figs.4 - 6. When one parameter is considered, others are kept constant. The temperature in the ply decreases with the increase of the tape speed (Fig. 4) and the increase of the tape thickness (Fig.5). It can be seen from Fig.6 that the greater the laser heat input, the higher is the temperature in the ply. Yet too great heat input will cause material degradation, which must be prevented. The effect of the convective heat transfer coefficient between the air and composite on the temperature is relatively small.

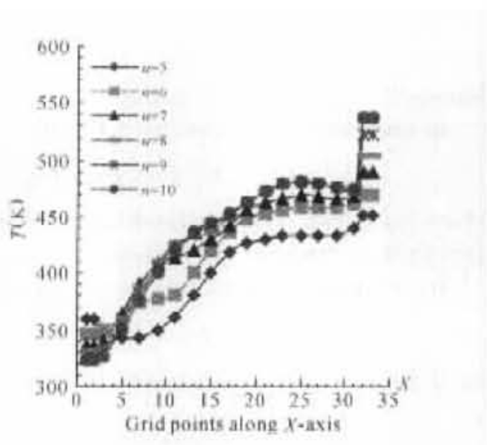

Fig.3 Temperature distribution in the plies
$t_{ply} = 1 \times 10^{-4}$, $sq = 0.5 \times 10^6$, $h = 5$, $kl = 6$, $U = 0.15$

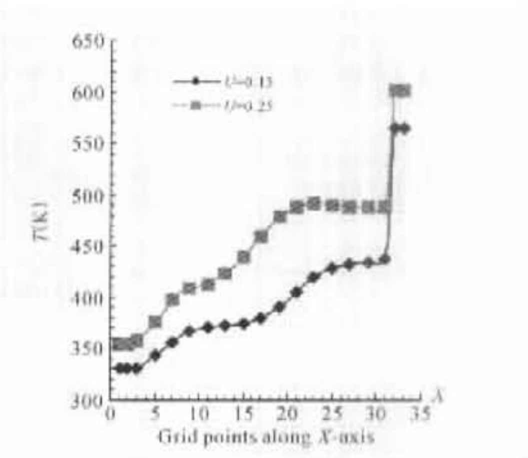

Fig.4 Effect of tape speed on the temperature
$t_{ply} = 2 \times 10^{-4}$, $h = 5$, $sq = 1 \times 10^6$, $kl = 6$

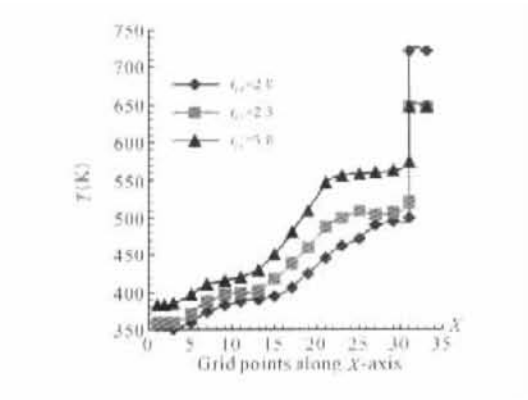

Fig. 5 Effect of tape thickness on the temperature

$sq = 0.75 \times 10^6$, $h = 5$, $kl = 6$, $U = 0.1$

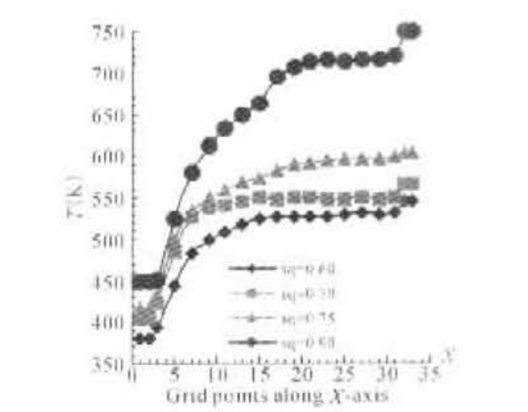

Fig. 6 Effect of laser heat input on the temperature

$h = 5$, $kl = 6$, $U = 0.1$, $t_{ply} = 1.194 \times 10^{-4}$

CONCLUSIONS

A numerical thermo-chemical model for the on-line curing of thermoset composite is established. The temperature distribution in the composite is presented. The effects of various process parameters on the temperature are also discussed. Since the model can predict the temperature distribution in the composite during the curing process, the method developed can serve as design tool for the on-line laser curing of thermoset composite.

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