A NUMERICAL STUDY ON TEMPERATURE DISTRIBUTION OF LINE HEATED ANISOTROPIC CARBON FIBER COMPOSITES

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INTRODUCTION

Earlier we have described the various uses of infrared line scanner based thermal nondestructive testing equipment [1]. Time constants of measurements made with these kind of equipment are very suitable for testing carbon fiber composites. Scanning a line heat source over a sample surface causes a nonuniform temperature distribution in the sample. In addition to the heat flow normal to the surface, lateral heat flow exists in the surface plane. In the case of carbon fiber composites with a specific oriented structure, the surface temperature distributions depend on the direction where the line source moves. Generally, this is true of any sample having anisotropic thermal conductivity. In oriented carbon fiber composites the bulk thermal conductivity can be considered anisotropic, because the heat transfer in the composite is different in the direction of the fibers compared to perpendicular directions [2,3]. Varis et al. have discussed these phenomenon briefly with the testing of carbon fiber tubes using numerical methods [4]. Here, we represent a more detailed numerical analysis of the effects of line heating on a sample having anisotropic thermal conductivity.

NUMERICAL METHOD

As mentioned above, the following pages describe a more thorough numerical treatment based on same ideas that have been debated earlier in a preliminary manner [4]. The computational method used for evaluating the heat diffusion equation follows the Cranck-Nicolson finite difference scheme and it has been described on several earlier works also [5-7].
The three-layered numerical model consisted of 20 x 240 x 15 grid points corresponding to a physical size of 28 mm x 50 mm x 3 mm in the x-, y-, and z-directions respectively. A delamination (14 mm x 22 mm) characterized by a thermal contact resistance, $R_c$, was placed either between the first and the second or the second and the third layer (Fig. 1). The depths of these two interfaces were 0.55 mm and 0.85 mm. As usual, the severity of the defect was controlled by using different contact resistance values. In this study two different values were used, $R_c=10^{-4} \text{ m}^2\text{KW}^{-1}$ corresponding to a severe fault and $R_c=10^{-5} \text{ m}^2\text{KW}^{-1}$ corresponding to a weak delamination.

The oriented structure of a carbon fiber laminate was simulated using anisotropic thermal conductivity. A bigger thermal conductivity value was used in the direction parallel to the longitudinal axis of fibers (see Fig. 1 and Table 1). In different layers the fiber directions were perpendicular to each other. By changing the conductivity value from the bigger to the smaller, the fiber configuration of the model could easily be rotated 90 degrees in respect to the scanning direction of the line heat source. The calculations were carried out with all the possible perpendicular combinations of scanning direction, fiber orientation, and delamination depth. The heat source was line-shaped having a gaussian profile in the x-direction and uniform profile in the y-direction. The width of the heating line was 3 mm and the heating power 100 W simulating a hot air jet.

Table 1. The parameters used in numerical calculations.

<table>
<thead>
<tr>
<th>$\rho$ (kg m$^{-3}$)</th>
<th>$c$ (J kg$^{-1}$ K$^{-1}$)</th>
<th>$\kappa_l$ (W m$^{-1}$ K$^{-1}$)</th>
<th>$\kappa_\perp$ (W m$^{-1}$ K$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1400.00</td>
<td>935.00</td>
<td>11.10</td>
<td>0.87</td>
</tr>
</tbody>
</table>
RESULTS

Because of the time it takes for the heat pulse to reach the delamination, the maximum of the surface temperature distribution appears behind the heating point (Fig. 2 a). This is an important result since it dictates where the detection point should be placed. This optimum distance between the heating and the detection point depends on the scanning velocity, v, and to some extent on the fiber orientation. Fig. 2 b shows the dependency between the velocity and the optimum distance in the cases of different fiber configurations. In the studied velocity range (4.2 mm/s - 16.8 mm/s) the optimum distance was found to be a roughly linear function of velocity with a clear distinction between the two delamination depths, whereas the variations due to different fiber configurations played no practical role.

Fig. 3 shows the maximum obtainable contrast caused by the delamination at each point of the surface. When the delamination was placed under the first carbon fiber layer (d=0.55 mm), the delamination boundaries parallel to the fibers were very distinctive. The rapid temperature raise on these edges was caused by the selective heat transfer routes in these areas. The delamination hindered the heat flow in the z-direction. On the other hand the heat transfer from one fiber to another was weaker than through the fibers. In the case of the deeper delamination (d=0.85 mm) no rapid temperature changes were apparent. Again the explanation was in the availability of the heat transfer routes. In this case there were two perpendicular carbon fiber layers above the delamination providing two lateral heat transfer directions instead of one. These results can also be seen from the cross-sections of the three dimensional contrast maps (Fig. 4). The most prominent effect of the fiber configuration was observed between the two cases of delamination at the depth 0.55 mm (Fig. 4). The difference between the temperature contrasts was more than one degree. When the delamination was placed between the second and the third layer the same difference was about 0.1 degrees, which was no longer practically detectable. However, the deterioration of the lateral resolution as the depth increased was evident.
Fig. 3. The three dimensional temperature difference maps. The depth of the delamination is 0.55 mm in cases a) and c) and 0.85 mm in cases b) and d). The thermal contact resistance caused by the delamination, \( R_c \), is \( 10^{-4} \) m\(^2\)KW\(^{-1} \) in all the cases. The arrow shows the carbon fiber orientation of the top layer.
CONCLUSIONS

In cases where the delamination is located under the first carbon fiber layer, the effects caused by the anisotropic thermal conductivity are clearly detectable and significant temperature differences between the two fiber configurations can be obtained. The maximum temperature contrast is highest when the carbon fibers of the top layer are parallel to the heating line. A qualitative feature of interest in these cases is the sharp temperature behaviour near the edges of the delamination. These effects do not appear when the delamination is located under two or more perpendicular layers. The calculations show a dependency between the scanning velocity, the depth of delamination and the optimum detection point. The anisotropy of thermal conductivity has contributions to this dependency, but the practical implications are not crucial to experiments.

REFERENCES