Dimensional Control for Composite Manufacturing

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1 Introduction

As the development of industry, composite materials are more and more taking the place of traditional metallic materials. Fiber-reinforced composite materials consist of fibers of high strength and modulus embedded in or bonded to a matrix with distinct interfaces (boundary) between them. They have some better characteristics over metallic materials such as higher combined strength and modulus, lighter in weight, high damage tolerance, better thermal stability, high internal damping and resistance to corrosion.

Dimensional control of composite parts has gained more and more attention in recent years. Good dimensional accuracy can effectively reduce the cost of assembly of large composite structures, ensure part functions, and helps to achieve excellent surface integrity. Thus, it is essential for the precision applications of composite materials.

The problem of dimensional control of composite parts comes from the anisotropic nature of fiber-reinforced materials. Geometric deformation of composite parts can be classified as process-induced and structure-induced. Primary causes include crosslinking, non-uniform thermal expansion, shrinkage, residual stresses induced in curing process, and residual stress induced in the cooling down process.

The preliminary results of dimensional control for composite manufacturing are presented. Using a simple case, it is shown that deformation due to the temperature change in processing can be well predicted and compensated.

2 Finite Element Analysis

The deformation of a flat E-glass/epoxy panel is analyzed. The dimensions of the panel are shown in Fig. 1. The stacking sequence is (0/90)_2(±45)_2(0/90)_2.

![Fig. 1 Flat panel](image)

The fiber volume fraction is about 49%. The mechanical properties and the CTEs of lamina are calculated as:

\[
\begin{align*}
E_{11} & = 37.91 \text{ GPa} \\
E_{22} & = 9.22 \text{ GPa} \\
G_{12} & = 4.94 \text{ GPa} \\
\nu_{12} & = 0.23 \\
\alpha_{11} & = 8 \times 10^{-6} \text{ m/m per } ^\circ\text{C} \\
\alpha_{22} & = 33 \times 10^{-6} \text{ m/m per } ^\circ\text{C}
\end{align*}
\]

The panel is cured at the temperature of 190°C and gradually cooled down to room temperature (21.67°C).
The deformation of the panel is analyzed using MSC.MARC. The mesh of the flat panel is shown in Fig. 2. Quadratic elements are used. The mechanical properties are CTEs of 0° lamina are inputted. The material is defined as composite. For each layer, fiber orientation and thickness are specified. In order to calculate the deformation of the panel, a base point should be defined. In this case, the centroid of the panel is used as the reference point. In calculation, the six degrees of freedom of the point are constrained to eliminate any rigid body movement. The temperature change is defined using boundary conditions and initial conditions.

After calculation, the deformation of the panel is shown in Fig. 3. The peak value is 0.70mm and the valley value is –1.15mm.

### 3 Experiments

For the purpose of verification, several parts are fabricated using the same processing parameters, material parameters.

Two flat panels were fabricated in order to test the repeatability of deformation. These two panels are summarized as follows.

<table>
<thead>
<tr>
<th>mass of fibers (g)</th>
<th>mass of panels (g)</th>
<th>fiber volume fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>122.08</td>
<td>183.14</td>
<td>49.60</td>
</tr>
<tr>
<td>122.25</td>
<td>189.81</td>
<td>47.68</td>
</tr>
</tbody>
</table>

After the panels were fabricated, they were measured on the coordinate measuring machine to obtain the error profiles. The panels are measured in gridded form, as shown in Fig. 4. The grid size is 10mm.
The error profile of part 1 and part 2 are shown in Fig. 5 a) and b), respectively. For the first part, the peak value is 0.96mm and the valley value is –1.19mm. For the second part, the peak value is 0.80mm and the valley value is –0.93mm. Compared with the FEA computation results, they are very close to each other.

4 Error Compensation

The ideal case is to achieve residual stress free process. However, in practice this is very difficult. An alternative approach is to compensate for the geometric errors. After the geometric errors are modeled with an acceptable accuracy, error compensation technique can be used to find a suitable mold design. This approach is shown in Fig. 6.

After 3D error profile is obtained, it can be used for mold design with error compensation. Reverse engineering and surface reconstruction techniques can be used for this purpose. This is shown in Fig. 7.
For the purpose of error compensation, a new design geometric model needs to be built based on the error profile from FEA computation. To test the effectiveness of this method, nine points were chosen to build the new geometric model, as shown in Fig. 8. The surface was generated using cubic spline.

The mesh of the part is shown in Fig. 9. After FEA computation, the actual shape of the part is shown in Fig. 10. The geometric errors were greatly reduced.

<table>
<thead>
<tr>
<th>flatness from FEA computation (mm)</th>
<th>flatness from experiment (mm)</th>
<th>relative error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>flat panel 1</td>
<td>1.85</td>
<td>2.15</td>
</tr>
<tr>
<td>flat panel 2</td>
<td>1.85</td>
<td>1.73</td>
</tr>
</tbody>
</table>

From the FEA computation, it is shown that mold design with error compensation can greatly reduce geometric errors in fabrication. The flatness before compensation is 1.85mm. After compensation is 0.135mm.