Exercise 6: Solution

OUT-OF-AUTOCLAVE PROCESSING

Source: http://www.virgingalactic.com/multimedia/album/graphics-and-illustrations

Exercise responsible:
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**Task 1: Laminate thickness in Out-of-Autoclave conditions**

Material data (OOA prepreg system):

- **Resin:** MTM®44-1 cytec
- **Fabric:** CF5804-A, 2x2 twill woven, HTA 40 fibers, 6K
- **Fiber density** $\rho_f = 1.76 \text{ g/cm}^3$
- **Resin density** $\rho_r = 1.18 \text{ g/cm}^3$
- **Fabric areal weight** $A_w = 284 \text{ g/m}^2$
- **Number of layers** $N = 6$
- **Mass ratio** 40 \% resin weight

Assumptions:
- Zero bleeding condition: no resin is flowing out from the prepreg laminate during the processing
- 2\% of void content in the final laminate
Questions

a) Estimate the final thickness of the laminate manufactured in an OOA process. Which will be the thickness of a laminate if cured in an autoclave with 8 bar pressure? Motivate your answer.

Mass ratio to volume ratio

\[
\frac{m_{resin}}{m_{fibre} + m_{resin}} = 0.4 = \frac{V_{resin} \cdot \rho_{resin}}{V_{fibre} \cdot \rho_{fibre} + V_{resin} \cdot \rho_{resin}}
\]

Volume ratio to resin volume content in one layer of prepreg

\[
u_{resin} = \frac{V_{resin}}{V_{resin} + V_{fibre}} = \frac{1}{1 + \frac{V_{fibre}}{V_{resin}}} = 0.498 \approx 0.5
\]

Volume contents calculations considering void content:

\[
u_{voids} = 2%
\]
\[
u_{resin} = 49%
\]
\[
u_{fibre} = 49%
\]

Laminate thickness

\[
t = \frac{N \cdot A_w}{\rho_{fibre} \cdot \nu_{fibre}} = 1.975 [mm]
\]

Other method
Prepreg areal weight (from 40% resin weight) = 473 g/m²
Resin areal weight = 189 g/m²
Thickness = Areal weight / density
Thickness of resin content = (189 g/m²) / (1.18 g/cm³) = 0.160 mm
Thickness of fiber content = (284 g/m²) / (1.76 g/cm³) = 0.161 mm
Single layer thickness = 0.160+0.161= 0.321
Single layer thickness including 1% in volume of voids = 0.321/0.99= 0.324
Laminate thickness = 6*0.324= 1.945 mm

If cured in an Autoclave, the thickness of the laminate will not change! The resin is uncompressible; therefore if no bleeding take place, the laminate thickness remains be the same. However the pressure in the resin will be higher.
b) Calculate the bulk factor of the OOA prepreg laminate, considering a fiber volume content before cure (after debulking) of 40%.

\[
\text{Bulk factor} = \frac{\text{uncured ply thickness} - \text{cured ply thickness}}{\text{cured ply thickness}}
\]

Laminate thickness in uncured state:
\[
t = \frac{A_w \times N}{\rho_f \times \nu_f} = 2.42 \text{ [mm]}
\]

Bulk Factor:
\[
\text{Bulk factor} = \frac{2.42 - 1.945}{1.945} = 0.24
\]

c) Explain the problem occurring with female tools during the consolidation of OOA laminate. Suggest some solutions to ensure a homogenous compaction in the corner region.

Due to the high bulk factor of half impregnated OOA prepreg systems, the vacuum bag may not be able to follow the shape change which takes place during the consolidation of the laminate. For this reason in the corner, there may be a lack of pressure in the resin which will take to uncontrolled voids growth. Due to the small compaction pressure ensured by the atmospheric pressure, the vacuum bag will not deform or slip. Possible solutions are rigid or semi rigid counter-molds (mechanical load introduction).

d) Estimate the resin pressure in OOA (1 bar) and Autoclave (8 bars) conditions considering Terzaghi’s law.

According to the compaction curve of the fabric, the textile at 50% fiber content carries almost 0.35 bar of compaction pressure. Therefore the resin pressure in OOA condition will be around 0.65 bar and in Autoclave condition around 7.65 bar.
e) Why is it critical in OOA processing to maintain maximum vacuum throughout the cure cycle?

The level of vacuum throughout the cure cycle is critical for three reasons:

- Minimize residual air content
- Ensure evacuation of the moisture at high temperature
- Ensure the compaction of the entrapped gases
  (a small pressure variation correspond to an important variation of the void size)
**Task 2:** Void Mitigation

As 1 bar applied pressure in OOA prepreg processing is insufficient for void mitigation, the extraction of entrapped gases by internal laminate gas transport is essential to produce OOA prepreg laminates with a low void content.

a) Using the 1-D gas transport model presented in [1], calculate and plot the gas evacuation times for the UD and fabric prepreg materials for a laminate length of 2, 6 and 10 meters.

\[
time = \frac{\mu}{P_0 k} \left( \frac{L^2}{0.9} \right) \left[ -1 \ln \left( \frac{m}{m_0} \right) \right]^{0.6}
\]

**Assumptions:**
- Edge breathing is occurring only at the far ends of the laminate; therefore, the length of evacuation is \( \frac{L}{2} \) of the entire laminate length.
- Gas permeability in the prepreg remains constant under debulking conditions.

**Material Permeabilities (in-plane):**
- Carbon fiber prepreg fabric:
  - Air permeability:
    \( k = 5E-13 \, \text{m}^2 \)
- Carbon fiber prepreg uni-directional tape:
  - Air permeability:
    \( k = 2E-14 \, \text{m}^2 \)

**Reference:**
The length of structure corresponds to double of the evacuation length. Notice how the evacuation time of a structure of 2m made in prepreg UD tape requires the same evacuation time as a structure of 10 meters made with prepreg fabric.

b) Determine the size limit of a structure that can be produced in Seattle compared to one produced in Clearfield, if 90% of the entrapped air is to be removed within a 36 hour maximum debulking window prior to the cure process.

\[ L^2 = \frac{t * k * P_0}{\mu} \left[ -\frac{1}{0.9} \ln \left( \frac{m}{m_0} \right) \right]^{\frac{1}{0.6}} \]

With 90\% air removal and a 36 hour maximum debulking window...
The maximum evacuation length in Seattle is: 8.6209 meters, and so, the size limit of a structure is: 17.2418 meters.
The maximum evacuation length in Clearfield is: 8.0152 meters, and so, the size limit of a structure is: 16.0303 meters.

A comparison of evacuation times is also visualized in the graph. The curve are calculated for a prepreg fabric material.