EVALUATION OF THE KLINKENBERG EFFECT IN PREPREG PROCESSING

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Introduction

Out-of-Autoclave processing of composite structures, utilizes special partially saturated prepregs, designed such that gases can be evacuated at room temperature, prior to oven curing. The unsaturated regions of the fiber reinforcement maintain an open porosity, which serve as pathways for gases within the laminate to be extracted at the edges; this is schematically represented in Fig. 1. Success of the gas evacuation process is essential for achieving low void content within the cured composite material. This study aims to predict how resin saturation of the prepreg will influence the time required during the gas evacuation process [1]. A close inspection of the governing equations and experimental results reveals that the gas permeability will increase as gas pressure decreases. This is known as the Klinkenberg effect, it is analogous to the presence of a slip velocity in the gas flow at the solid pore walls. An experimental technique in conjunction with an analysis of the governing equations is outlined in order to evaluate the permeability and Klinkenberg parameter for Out-of-Autoclave prepregs. It is shown that when resin saturation is high, the Klinkenberg effect becomes more pronounced.

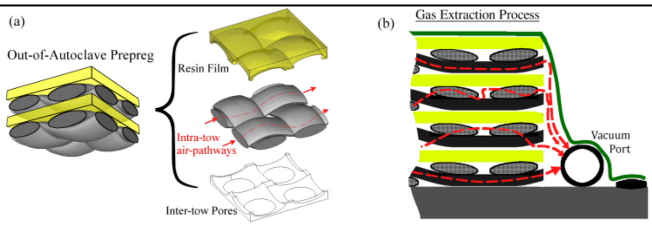

Figure 1: *Left: Schematic of an Out-of-Autoclave prepreg structure. Right: Schematic of the gas evacuation process.*

Theory

The permeability of a porous medium (in units of area) is defined to be a geometric property of the medium which depends on the pore structure; decreasing pore diameter and increasing tortuosity will reduce its permeability. Gases, however, unlike liquids, will yield a different measured permeability depending on the pressure used during testing. In 1941, Klinkenberg [2] explained that this was due to gas rarefaction which causes a slip velocity on the pore walls. The measured gas permeability, K_g, is related to the 'intrinsic' (liquid) permeability, K_i, by the relationship

$$K_g = K_i\left(1 + \frac{b}{P}\right) \tag{1}$$

where P is the absolute gas pressure - which is often taken as a mean value instead of an instantaneous value, and b is the Klinkenberg parameter in units of pressure. The Klinkenberg parameter is purely a function of the pore diameter of the medium (varying inversely). Including the relationship in Eq. (1), the partial differential equation describing the gas pressure P is

$$\frac{\partial P}{\partial t} = \frac{K_i}{\phi\mu}\frac{\partial}{\partial x}\left[(P + b)\frac{\partial P}{\partial x}\right] \tag{2}$$

where ϕ is the volumetric porosity, μ is the gas viscosity, t is time, and x is the spatial coordinate of the domain. To determine K_i and b from experimental data, Eq. (2) is non-dimensionalized and solved numerically with finite differences to produce dimensionless master curves. A least squares fit of the experimental data to the model predictions yields both parameters.

Experimental

Intrinsic permeability and the Klinkenberg parameter were measured with a transient pulse-decay (or draw down) technique. The method consists of abruptly changing the gas pressure at one end of the sample while the gas pressure is recorded as it equilibrates over time. The data collected is fit the model prediction in order to determine the permeability. Traditionally, when the pulse-decay method is used for geological samples, the Klinkenberg parameter is evaluated by retesting the sample multiple times while varying the initial and boundary pressure to show how the pressure used effects the recovered permeability. Since testing prepreg samples with various initial and boundary pressure conditions is impractical the method of analysis was reworked

In accordance with the Out-of-Autoclave processing conditions, prepreg samples were tested with atmospheric air pressure initially filling the lamina. Vacuum pressure was abruptly applied to one edge of the sample while a pressure transducer inserted at the opposite edge recorded the gas pressure as it decayed over time. As the gas pressure approached vacuum pressure over time, the change in gas permeability was detectible during a single test (see Eq. (1)), which allowed extraction of the Klinkenberg parameter from the '*shape'* of the pressure decay curve.

Results

Gurit ST94-RC200T Out-of-Autoclave prepreg was used to demonstrate the test methodology, and show how permeability and the Klinkenberg parameter vary with resin saturation. Resin saturation was monitored by viewing the area of resin which covered the side of the prepreg which was initially dry [3]. As the saturation increased, gas flow was constrained to travel through in interstitial space between fiber where the pore diameter is roughly 5mm. With the decreasing average pore diameter, the Klinkenberg parameter increases (from 0kPa) to significant values 5-22kPa – reducing the predicted time for gas evacuation by up to a factor of 3.

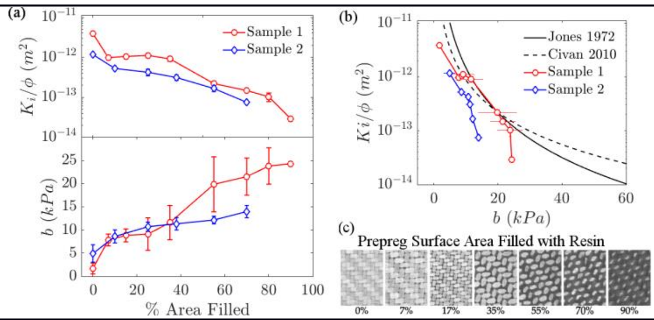

Figure 2: *(a) Recovered material parameters w.r.t. resin area filled. (b) The relationship between permeability and Klinkenberg parameter are consistent with literature models.(c) Prepreg surface area covered with resin.*

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