Composites Science and Technology 68 (2008) 3093–3098

Contents lists available at ScienceDirect

Composites Science and Technology

journal homepage: www.elsevier.com/locate/compscitech

In situ estimation of through-thickness resin flow using ultrasound

S. Thomas [a,*], C. Bongiovanni [b], S.R. Nutt [a]

[a] Department of Chemical Engineering and Materials Science, University of Southern California, Los Angeles, CA 90089-0241, USA
[b] Cytec Engineered Materials, 1440 N. Kraemer Boulevard, Anaheim, CA 92806, USA

ARTICLE INFO

Article history:
Received 20 February 2008
Received in revised form 16 June 2008
Accepted 8 July 2008
Available online 24 July 2008

Keywords:
Out-of-autoclave
A. Carbon fibres
D. Ultrasonics
D. Optical microscopy

ABSTRACT

Ultrasonic imaging in the C-scan mode was used to measure the flow rate of an epoxy resin film penetrating through the thickness of a single layer of woven carbon fabric. Assemblies, comprised of a single layer of fabric and film, were vacuum-bagged and ultrasonically scanned in a water tank during impregnation at 70 °C. The permeability of the fabric was calculated using Darcy's law. The results demonstrated that ultrasonic imaging in the C-scan mode is an effective method of measuring *z*-direction resin flow through a single layer of fabric. Comparison of ultrasonic and microscopy images yielded consistent results and demonstrated the effectiveness of ultrasonic imaging as an in situ process diagnostic for monitoring through-thickness impregnation and flow rates.

1. Introduction

1.1. Summary of VBO Processing

Traditional processing of high-strength polymer matrix composite materials requires autoclave consolidation and curing at high pressures and temperatures (pressures of several atmospheres and temperatures above 100 °C). A new class of vacuum-bag-only (VBO) prepregs has been introduced for processing at much lower pressures and temperatures. VBO prepregs are intended to yield autoclave-quality parts without the use of an autoclave, and are thus a member of the family of out-of-autoclave (OOA) techniques for composite manufacture. In the VBO process, composite laminates are produced from prepregs by vacuum-bag consolidation followed by curing in an oven at atmospheric pressure. Like resin film infusion (RFI), the VBO prepreg is produced by impregnating dry fabric with a resin film. However, unlike RFI, the VBO prepreg is produced by partial impregnation, leaving vacuum channels for air escape during subsequent consolidation in a vacuum bag. Eliminating autoclave processing simplifies the manufacturing process and greatly reduces operational and capital equipment costs.

One purpose of the autoclave is to apply pressure greater than the vapor pressure of volatile components. Preventing gasses from evolving from the resin during the cure cycle produces a dense structure free of porosity. In RFI and VBO processing, unlike autoclave processing, there is no high pressure to force volatile gasses to remain dissolved in the resin, and the maximum applied pressure is only 1 atm. Therefore, all of the gasses evolved must be removed prior to resin curing, and the cure process cannot produce volatile reaction products. The maximum fiber volume fraction of a composite laminate fabricated from VBO prepregs is limited by the low pressure that is characteristic of the process. Fiber volume fractions s up to 65% for unidirectional composites and 52–57% for composites made with fabrics have been achieved [1].

1.2. In situ methods for measuring resin flow

Understanding resin flow and impregnation of the reinforcing medium is critical to the manufacture of consistent composite laminates free of porosity and flow-related defects. Although resin flow measurements are generally not performed in prepreg processes, they are routinely performed in resin transfer molding and related liquid molding processes. For example, fiber optic sensors, used in the transmission or reflection modes and embedded at various locations in the layers of reinforcing material, have been used to measure resin flow in resin transfer molding (RTM) processes [2,3]. Optical fibers can be fragile, however, and fiber optic sensors are not as sensitive to resin flow inside fiber tows, so alternative approaches are often employed.

Resin flow in RTM processes is often measured by employing a transparent mold, allowing one to visually monitor and record the advance of resin flow fronts as the mold is filled [4–8]. In this approach, the flow rate through and around the stack of fabric or plies is measured directly, while the flow rate through the fiber tows is measured indirectly by a non-linear pressure-time profile [4]. The

* Corresponding author. Tel.: +1 213 235 8341.
E-mail address: slthomas@usc.edu (S. Thomas).

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doi:10.1016/j.compscitech.2008.07.012

video recording method works well for measuring the bulk flow rate in in-plane RTM processes, in which the mold is initially dry (provided also that the mold is transparent). However, video recording methods are not useful for measuring flow rates in prepregs, where impregnation occurs primarily in the through-thickness direction.

Microstructural analysis of composites produced by RTM has also been used to study impregnation kinetics and to provide a basis for model simulations [9]. This work provided the basis for a permeability model for RTM processes [4], as well as two-dimensional elliptic flow models [10,11]. Attempts to measure transverse flow have met with limited success. Wu, Li, and Shenoi demonstrated a simple method of measuring transverse flow in which fibrous material was wound in a coil and resin was injected through the center [12]. By observing the flow front, the flow rate and permeability could be determined. However, if gaps existed between fiber tows, as in most woven fabrics, the rapid flow of resin through the gaps prevented determination of flow rates and permeability. Using a different approach, transverse or through-thickness flow measurements have been performed by pumping fluid through a porous sample at a prescribed rate. Permeability was determined from a linear plot of the pressure drop as a function of flow rate [13,14].

An alternative approach to measuring resin flow during impregnation involves the use of ultrasonic imaging, which has been used in the transmission mode to study the flow front of resin in an RTM process [15]. The samples were cured at different stages of the impregnation process and imaged to determine the flow pattern. In other work, ultrasonic transmission with air coupling was used to measure the impregnation and fill rate of the preform in a resin transfer molding process [16]. The ultrasonic transmitter and receiver were aligned on opposite sides of the mold. The mold fill rates determined ultrasonically were equivalent to those determined visually. This ultrasonic transmission method is well-suited to situations in which the transducers cannot be immersed and do not require immersion in a coupling fluid. The ultrasound signal resolution achieved with air coupling is generally inferior to liquid coupling, however [17].

In the present work, we utilize ultrasonic imaging and reflectivity to monitor the impregnation of fabrics in situ (reflectivity is the amplitude of the reflected signal). An assembly consisting of fabric, resin film, and vacuum bag is immersed in a heated water tank while performing C-scan imaging to produce a density map or profile of the scanned material. The method relies on the acoustic contrast provided by scattering from wet and dry regions of the fabric. As the resin flows into the fabric and permeates the fiber tows, the volume of the material system decreases and the density increases [18]. The volume and density of the material stop changing when the resin stops flowing, and this is detected in sequential C-scan images, which cease to change when fiber wetting is complete and resin flow ceases. The procedure provides a non-invasive, in situ inspection method for monitoring resin impregnation of fiber tows.

The capabilities and limitations associated with this technique are considered and analyzed. The primary intent is to demonstrate the utility and limitations of the method for monitoring through-thickness resin flow in RFI, VBO prepregs, and other non-autoclave processes – not to investigate the effects of process parameters or to detect micro-porosity. (Future work will address the influence of process parameters on resin flow, such as temperature, multiple layers of prepreg, and fiber architecture). The ultrasound data are used to calculate permeability using Darcy's law.

Darcy's law relates the flow rate of a viscous fluid to the permeability of the porous material. The flow rate V (m/s), permeability, K (m^2), pressure gradient, ∇P (Pa/m), and viscosity μ (Pa s) are related by

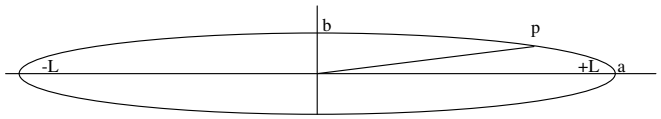

Fig. 1. Diagram of elliptical fiber tow with coordinates.

$$K = \frac{\mu V}{\nabla P}$$

Flow into the fiber tows is two-dimensional. The cross-section of the fibers tows is approximately elliptical and the relationship between elliptical and Cartesian coordinates is well established [19,20]. A diagram of an elliptical fiber tow is shown in Fig. 1.

The sum of distance from the positive and negative values of the foci (L) to any point (p) on the surface of the ellipse is equal to $2a$. The major and minor coordinates of the ellipse (a,b) and their relation to the Cartesian coordinates (x,y) are defined below.

$$a = L\cos h(\xi), \quad b = L\sin h(\xi), \quad x = a\cos(\eta), \text{ and } z = b\sin(\eta)$$

$$\xi = (\overline{+Lp} + \overline{-Lp})/2L = a/L, \eta = (\overline{-Lp} - \overline{+Lp})/2L$$

Values of the elliptical parameters are listed in Table 1.

2. Experimental

The materials selected for the study included a plain-weave carbon fabric (elastic modulus and tensile strength of fibers = 231 GPa and 3650 MPa) containing 3000 fibers per tow (density = 194 g/m^2) and an epoxy resin film (Cycom 5215, density = 102 g/m^2). A single layer of resin film on a single ply of woven carbon fabric was used in all trials. A two-step process was employed in which the resin film was first attached to the fabric by *lamination*, which was followed by *impregnation* in a vacuum bag assembly. The lamination procedure involved removing the release liner from the resin film, placing the resin film and protective paper layer on top of the fabric, placing the laminate on a Teflon® coated flat surface preheated to 50 °C, applying a pressure of 1517 Pa (15 mbar) for 2 s, rapidly cooling to room temperature, and removing the protective paper. The lamination process was followed by the second step of the process – full *impregnation* by vacuum bagging at 70 °C. Preliminary experiments were conducted to determine the depth to which the resin film penetrated the carbon fabric during the lamination step (prior to impregnation).

Lamination: Sections of resin film, 254 mm × 254 mm, were cut from a large roll and lightly pressed onto a piece of plain-weave carbon fabric of equal dimensions at room temperature. Next, lamination was performed using all combinations of the process parameters shown in Table 2. An alternative lamination procedure involved ironing the resin film onto the fabric, although pressure, temperature, and time were not determined during the ironing process.

Laminated samples were cured, sectioned, and polished prior to microscopic examination to determine the resin penetration depth during lamination. When the resin film was laminated to the fabric at 1517 Pa (15 mbar) and 50 °C for 2 s, resin flow through the fabric and into fiber tows was minimal. These conditions were used for lamination of all samples. In samples thus produced, the resin film was lightly laminated to one side of the 0.254-mm thick carbon fabric.

Table 1
Elliptical parameters

a (mm)	b (mm)	±L (mm)	ξ	H	X (mm)	Z (mm)
0.825	0.075	± 0.822	1.00	0.60	1.05	0.55