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Surface porosity during vacuum bag-only prepreg processing: Causes and mitigation strategies

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ABSTRACT

In this study, we employ a parametric approach coupled with surface analysis to identify the source(s) of surface porosity and to develop effective mitigation strategies. Results confirmed that surface porosity was primarily associated with air that was trapped at the tool–prepreg interface during layup. The magnitude and distribution of surface porosity was affected by multiple parameters, including vacuum hold time, freezer and out time, and material and process modifications that affect air evacuation. The results indicated that prepreg out time (and thus tack) and vacuum quality were the primary drivers of surface porosity; for example, surface porosity decreased by 83% after just four days of out time and by 99% after 14 days of out time. These factors were used to formulate guidelines to mitigate surface porosity by (a) increasing the driving force for air evacuation and/or (b) increasing the permeability of the tool–prepreg interface.

1. Introduction

In recent years, the manufacturing of fiber-reinforced polymer (FRP) composites has shifted from autoclave processing toward out-of-autoclave (OoA) approaches [1]. Autoclave processing is robust, utilizing above-ambient pressures during high temperature cure to suppress the formation of defects, particularly voids. However, the high capital and operating costs, long cycle times, and process flow restrictions motivate the demand for more cost-effective and flexible alternatives. Vacuum bag only (VBO) prepreg processing is one such approach. VBO prepregs are vacuum bag-cured in conventional ovens, and are therefore compacted only by an atmospheric pressure differential of 101.3 kPa (1 atm, compared to ~5 atm typical in autoclaves). To achieve autoclave quality levels under this reduced processing pressure, VBO prepregs feature a partially impregnated microstructure (by design) that allows the evacuation of a majority of the air extant between and within the laminate plies. This distinctive characteristic, along with several bagging arrangements and cure cycle modifications, enables the manufacture of defect-free parts with high microstructural quality. Nevertheless, the lack of positive pressure during processing renders laminates cured through VBO methods more susceptible to certain defect-causing phenomena.

Surface porosity often arises on the tool-side surface of composite laminates made from VBO prepregs. While it is generally not detrimental to mechanical properties, surface porosity degrades the aesthetic quality of the part and must often be remedied, incurring additional time and cost. Several solutions to eliminate it currently exist. For example, during layup, a resin-rich surfacing ply can be added between the first prepreg ply and the tool plate to produce a smooth, resin-rich surface. However, this adds parasitic weight to the final product and may not be viable in weight-critical applications. Post-cure operations include gel coating and painting, which also add weight to the final product as well as time and cost to the manufacturing process. The ability to consistently produce void-free surfaces without unnecessary materials or process steps, while much needed, is presently unavailable.

Surface porosity has been addressed in previous studies, but the primary causes are not comprehensively understood, and few truly effective mitigation strategies have been proposed, particularly for non-autoclave processes. Herring et al. reported that when using a non-autoclave process based on bladder-induced consolidation (the Quickstep method), a decrease in compaction pressure resulted in an increase in surface porosity, indicating that resin pressure is an influential process parameter and pointing to why surface porosity arises more often in non-autoclave than in autoclave processes [2]. Darrow et al. used a design of experiments (DoE) approach to identify sources of surface porosity in autoclave-processed parts [3]. Several factors were considered including prepreg supplier, moisture on the tool surface, and loss of vacuum during autoclave staging. None of the parameters were identified as primary sources of surface porosity, but the authors inadvertently discovered that use of a release film at the

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tool-part interface resulted in a void-free surface. This solution works well for flat laminates and is commonly used for such applications [4,5], but is not viable for contoured parts due to the difficulty of draping a polymer film over tooling with multiple curvatures.

Recent studies have suggested that surface porosity results from air that becomes trapped between the prepreg and tool plate during layup [6–8]. In a previous study, we reported that composite laminates made from woven prepreg exhibit more surface porosity than laminates made from unidirectional (UD) prepreg, an observation attributed to the initial morphology of the prepreg [6]. Air entrapment is less likely with UD prepregs because of the more uniform surface topography. In the same study, we investigated the effect of tool surface roughness on surface porosity to determine if a rougher tool plate created a more permeable tool-part interface, but results showed no identifiable trend.

Grigoriev et al. attempted to reduce surface porosity during VBO processing by manipulating other tool plate properties. First, they studied the effect of tool surface energy on surface porosity by treating tool plates with atmospheric pressure plasma [7]. The results did not indicate a relationship between surface energy and surface porosity, but tool plates with higher surface roughness resulted in laminates with reduced surface porosity. Then, the same group investigated the effect of tool topography on surface porosity [8]. Different microstructural patterns were created on the tool surface, confirming that surface topography, microstructural spacing, and material cure cycle have an effect on the resulting surface porosity quantity. While our study showed no relationship between tool roughness and surface porosity, this study suggested that surface porosity can be reduced by optimizing the shape and size of microstructures present on the tool surface.

A review of the literature indicates that surface porosity may be governed by both prepreg material properties and tool properties, but does not clarify the relative importance of each factor. The literature also contains numerous studies focused on the nucleation, growth and migration of bulk porosity [9,10], as well as on the material and processing factors governing internal voids [11]. However, none of these works consider surface defects. In addition, few studies have directly considered the role of other process parameters, including pressure and room temperature vacuum hold time, on such surface defects. The mitigation strategies that have been proposed thus far are either only viable in specific cases (e.g. the use of a release film) or remain relatively exotic (e.g. tool surface patterning) and unlikely to be quickly implemented in an existing production environment.

1.1. Objectives

In this work, we clarify the fundamental causes of surface porosity during VBO prepreg processing and identify avenues for mitigating surface defects that avoid adding significant manufacturing time or part weight. We describe a systematic experimental study consisting of material characterization, manufacturing trials and surface porosity quantification. The resulting data clarify the dominant material–process-property relationships, and identify science-based approaches for effectively and consistently reducing surface defects.

2. Experimental procedures

2.1. Test matrix

Table 1 outlines the factors considered, the ranges investigated, and the prepreg material used. These factors include both material properties and manufacturing parameters.

The fiber bed architecture we considered included typical woven fabric and unidirectional product forms to determine the influence of prepreg surface topology on surface void formation during VBO processing. Prepregs were conditioned in humid ambients to determine the effect of absorbed moisture within the resin on surface porosity. Prepreg plies were conditioned for 30 h on a tray within a sealed bell jar partially filled with water below the tray. The water gave rise to a constant relative humidity level of 99%, confirmed by a digital humidity sensor. A four-hour vacuum hold at 20 °C was performed before cure to allow sufficient time for all air trapped during layup to be evacuated, thus ensuring that any surface defects present were a result of moisture, not trapped air. A wide range of out times was selected to determine the effects of increased resin viscosity and decreased prepreg tack on the formation and evolution of surface pores. Prepreg plies were aged at ambient conditions while stored within sealed plastic bags, as well as after being placed on the tool, to determine whether the state of the prepreg at the moment of layup was significant. Finally, the influence of the freezer storage time was investigated by fabricating laminates with material at the beginning and end of the stated life (12 months). In all cases, frozen prepreg was stored in sealed bags provided by the material manufacturer at a temperature below −23 °C (−10 F).

Layup was performed using both liquid and film release methods. The room temperature (RT) vacuum hold time was varied by subjecting parts to vacuum for zero to sixteen hours prior to high temperature cure to evaluate the influence of air evacuation on surface pore formation. In addition to RT vacuum holds, two additional methods of extracting air from the tool-part interface were performed: a ten-minute intermediate debulk on the first ply and spiking of the first ply. Debulking involved assembling a temporary vacuum bag around the first ply and applying vacuum consolidation before laying up the remaining plies. Spiking entailed rolling a spiked roller tool to create a regular pattern of transverse

Table 1
Parameters, ranges, prepreg choice and number of repeat tests included in parametric study.

Parameter	Range	Prepreg	Number of repeat tests
Material			
Prepreg fiber bed architecture	Unidirectional; woven	UD; woven	3
Prepreg humidity conditioning	99%RH	Woven	3
Prepreg out time	0–49 days	Woven	3
Out time aging method	On tool; off tool	Woven	2
Prepreg freezer time	0–12 months	Woven	3
Processing			
Release method	Liquid agent; film	UD; woven	3
Room temperature vacuum hold	0–16 h	Woven	3
Debulk 1st ply down	0–10 min	Woven	3
Spike 1st ply down	None; spiking	Woven	3
Reduced vacuum level	80–99 kPa	Woven	3