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A review of out-of-autoclave prepregs – Material properties, process phenomena, and manufacturing considerations

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ABSTRACT

Out-of-autoclave (OoA) prepreg materials and methods have gained acceptance over the past decade because of the ability to produce autoclave-quality components under vacuum-bag-only (VBO) cure. To achieve low porosity and tight dimensional tolerances, VBO prepregs rely on specific microstructural features and processing techniques. Furthermore, successful cure is contingent upon appropriate material property and process parameter selection. In this article, we review the existing literature on VBO prepreg processing to summarize and synthesize knowledge on these issues. First, the context, development, and defining properties of VBO prepregs are presented. The key processing phenomena and the influence on quality are subsequently described. Finally, cost and environmental performance are considered. Throughout, we highlight key considerations for VBO prepreg processing and identify areas where further study is required.

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1. Introduction

Advanced composite materials based on carbon fiber-reinforced thermoset polymers have become common in primary aerospace structures, as well as high performance sporting goods, and marine and wind energy structures. As these composite parts grow in number, size and complexity, the need for faster, more cost-effective and more versatile manufacturing comes into conflict with the limitations of traditional processing methods.

Most high-performance structural composites for aerospace applications begin as layers of prepreg, or carbon fiber beds pre-impregnated with a catalyzed but uncured resin [1]. Traditionally, prepreg layers are stacked on a tool to form a laminate, enclosed in a vacuum bag assembly, and placed in an autoclave (pressurized oven). The autoclave temperature is then raised, partial or full vacuum is drawn in the bag, and the vessel is pressurized. The consolidation pressure differential compresses the fiber bed, conforms the laminate to the shape of the tool and, in some cases, forces out excess resin. The applied pressure also suppresses porosity, the main manufacturing defect in prepreg-based parts, by driving resin into dry areas and collapsing bubbles of entrapped air and/or cure-generated volatiles. Concurrently, the elevated temperature reduces the resin viscosity, allowing resin to flow and wet the reinforcement before curing into a stiff, strong solid.

Autoclave processing is robust and well-understood, having benefited from significant research and experience gained from widespread industrial use, and remains a benchmark for competing processes [1,2]. However, autoclaves involve significant costs for acquisition, operation, and tooling, particularly for large parts. Autoclaves also impose a relatively inflexible manufacturing environment, in which potential part designs are constrained by available vessel sizes, production rates are restricted by scheduling, large autoclaves must sometimes be used inefficiently for small parts, and subcontractor options are limited. Given the predicted market growth for composites and the aforementioned limitations of autoclave processing, out-of-autoclave (OoA) manufacturing techniques, particularly those that yield autoclave-quality parts, are required to meet future demand.

Recently, a new generation of out-of-autoclave prepregs has been introduced, and experience with these prepregs has demonstrated that it is possible to produce autoclave-quality parts using vacuum bag-only (VBO) consolidation. By avoiding the use of autoclaves, such materials significantly reduce acquisition and operating costs, and are compatible with a diverse range of lower-cost cure set-ups, including conventional ovens, heating blankets, and heated tooling. In addition, the lower cure pressure supplied during VBO cure can eliminate autoclave-induced defects such as honeycomb core crush, allowing the use of lighter (and less expensive) cores. Questions remain, however, as to the ability to produce void-free primary structural parts out-of-autoclave and the true economic benefits of VBO cure. In 2011, High Performance Composites magazine published an article entitled "Out-of-autoclave Prepregs: Hype or Revolution?" [3]. Here, we revisit this question by considering over two decades of publications on OoA processing, compiling, for the first time, the relevant literature on the topic.

1.1. Background

Initial work on out-of-autoclave prepregs was performed by prepreg manufacturers and their industrial partners. Research carried out in an industrial context is often only selectively published because of intellectual property considerations. The development of VBO prepregs, therefore, is documented in a series of patents and conference proceedings [4–15]. These publications discuss the context and rationale behind VBO prepregs and describe general characteristics. In recent years, research universities throughout the world have undertaken efforts aimed at a fundamental understanding of VBO cure. There is, at this point, sufficient published data on VBO cure to warrant a comprehensive review of the topic, relevant to both academia and industry.

Early-generation VBO prepregs were designed for low-temperature initial cure (~60 °C), followed by high-temperature post-cure, and intended for low production runs or load-limited structures [4,5,7]. The main advantages of these materials were the ability to use lower cost tooling, combined with an increase in dimensional accuracy because of reduced tool thermal expansion. However, these benefits were outweighed by three major drawbacks: (1) relatively high porosity resulting from low applied pressure or inconsistent resin bleed, particularly for high fiber volume fraction reinforcements [4,8]; (2) out-times, or allowable room temperature storage times, of only about a week [4,8,16]; and (3) relatively low mechanical performance, particularly in terms of toughness [4,16]. Resin formulators noted, however, that in typical practice, such systems were cured in the 80–100 °C temperature range [4]. This hotter, wider process window, coupled with developments in resin chemistry and an increasing understanding of optimal matrix properties, enabled the development of a new generation of VBO resins. When properly integrated into appropriate fiber bed architectures and correctly processed, these materials were competitive with autoclave systems on multiple fronts, including porosity [5,6,11], mechanical performance [5,10], and out-time [11]. Several such resin systems are shown in Table 1, most of which can be coupled with a range of reinforcements, including woven carbon and glass fiber fabrics and unidirectional (UD) tapes. While a diverse range of VBO prepregs are commercially available, commonalities exist across all low-pressure curing prepregs.

Repecka and Boyd [8] and Ridgard [5] outline several features commonly encountered in VBO prepregs, and emphasize important layup, bagging and cure characteristics. The key requirement for low porosity VBO-cured parts is the removal of air entrapped during lay-up. To this effect, VBO prepregs are "breathable," featuring partially impregnated microstructures consisting of both dry and resin-rich areas (Fig. 1A, from [17]). The dry areas, sometimes denoted as "engineered vacuum channels" or "EVaCs," form a relatively permeable vascular network that allows gas migration towards the laminate boundaries in early processing. When the temperature is increased, resin flows into and infiltrates these channels, leading in principle to a void-free part.

To allow gases to escape from the prepreg into the breather, vacuum bag assemblies must include permeable boundaries that connect the laminate to the breather cloth without allowing excessive