Emerging Technologies for Processing Structural Composite

Rose, T
Advanced Processing Technology, Inc. (AvPro), Norman, OK USA

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Abstract

Although there have been many efforts to improve the quality and reduce the cost of processing composites, these efforts have provided only marginal improvement, primarily in the area of void reduction. Even with these efforts, excessive voids remain one of the major causes for scrapping a part and are a significant risk if undetected requiring the continued use of costly post process inspections. Voids, in turn, are most often caused by a deviation from the process or a change in materials that could be addressed by a change in the process if the state of the material were known.

This paper discusses the advances in cure characterization, cure modeling, temperature sensing and controls that are now available. These technologies have proceeded well beyond the proof of concept stage, however remain unavailable for extended use by manufacturing and engineering because of lack of investment for later stages of manufacturing readiness. AvPro, the NRC of Canada and UBC have been leaders addressing these issues and helping to implement modern technologies.

1 Introduction

The goal of this paper is to examine why the industry has adopted its current approach and discuss emerging technologies for processing structural composites using processes that more directly manage properties critical to performance.

The first truly high modulus commercial carbon fibers were invented in 1964, when Bacon and Wesley Schalamon made fibers from rayon using a new ‘hot-stretching’ process. High performance carbon fibers were first commercially available in the late 1960’s and PAN-based fibers entered significant commercial use in the 1970’s [1].

The first 'all composite' aircraft, the LearFan, was first flown on 1 January 1981. Specifications were written to accommodate the technology available at the time. Figure 1 is a 1976 illustration from the encyclopedia of the time noting that "the result of a modern chemical analysis is often a graph from a strip-chart recorder" that save the labor of reading the dial and recording data by hand.

Thus, the best sensors available at that time were a clock, a thermometer and a pressure gauge. 'Modern' laboratories would include a chart recorder to document the process.

While great progress has been made in structural analysis, finite element models and sophisticated software, the curing of composites remains essentially the same as in the 1970's with the exception that computers have replaced the chart recorder for monitoring the time and temperature changing the control settings.

Cure Control Basics

A basic teaching of six sigma and similar approaches is to *determine the properties critical to performance* and to *establish control over these properties.* It is empirically obvious that the following properties are critical to the performance of the resin matrix. Resins must be at a low viscosity to infuse into the fiber yarn or tow. The resins: must have proper viscosity (tack and drape) critical during prepreg layup; must also exhibit viscous flow during consolidation; flow stops at gelation and takes on an elastic behavior; and become elastic when cured and is the definition of cure for a structural composite.

However, for historical reasons, specifications generally ignore the viscoelastic state of the resin. The exceptions are measuring the initial viscosity of the resin prior to infusion into the yarn, and measuring glass transition temperature after cure has occurred.

This is not an oversight. The criticality of the viscoelastic state of the resins during processing was known from the beginning; however, during the early years of advanced composite production was not possible to cost effectively measure the viscoelastic state at the point of manufacture. Even the 'off line' measurements required careful preparation and expert interpretation. It was therefore necessary to compensate for this lack of capability with strict control over the formulation and the time-temperature records following formulation.

Figure 1. Picture from 1976 Encyclopedia Britannica depicting emerging technology of the chart recorder eliminating the need to manually record data

This has resulted in an infrastructure and material qualification scheme that is based on rigorous control on the temperature history of the matrix that achieves an unknown but acceptable viscoelastic behavior during processing. Extensive coupon level testing and progressively more sophisticated sub element tests leading to a full-scale test of the aircraft or weapons system. A large statistical database has been established which provides confidence in the structural integrity of the design but greatly limits options for process improvement since the process itself defines cure and storage time-temperature defines the materials shelf live. For example (a specified two-hour cure time cannot be shortened without a specification change). This is further constrained by the fact that the temperature within the part is not measured and relies on a correlation between a thermal survey done prior to releasing a part to production and the temperature of sensors placed in a trim area near the part. Raw materials for the part are assigned a specified shelf life and storage temperature and must be retested or scrapped based on exceeding a time or temperature limit.

While this approach achieves the goal of making good parts, it also leads to the rejections of structurally sound parts for specification deviations that are ultimately unrelated to the structural soundness of the part. These constraints on process improvement and scrapping of sound parts are not caused by overzealous quality assurance or arbitrary regulations but rather the necessary constraints to assure quality and safety when the properties criterial to the performance are not easily determined at the point of manufacture. A similar issue exists with the storage of uncured materials i.e., prepregs and resins. These materials often remain capable of producing sound structures but are scrape solely for exceeding a specified time based on worst case storage that is seldom the case.

Opportunity and Approach

Since the early days of building advanced composite structures, there have been many changes. Cure system now use computers to manage the process and new analytical capabilities have emerged.

Figure 2 illustrates the control room for autoclave and ovens in a typical production shop. Although the software is currently used to only monitor and manage legacy cure cycles, they are in fact capable of implementing real time cure models and communicating with offsite laboratory instrument to validate the models in near real time.

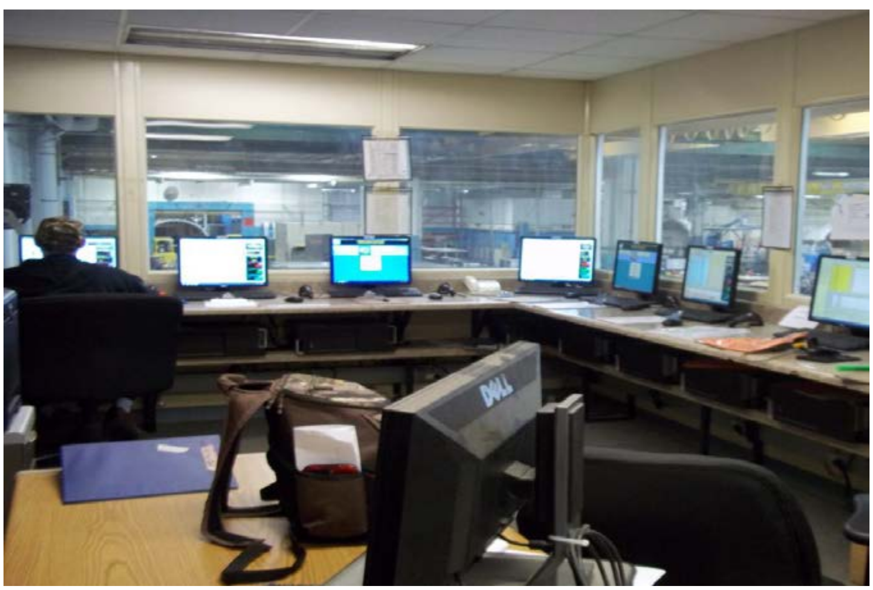

Figure 2. Modern Control Room for Composite Processing

Figure 3 illustrates some of the instrumentation that can be networked with the production shop using cure models manage the process and instrumentation to validate or update the viscoelastic state of the material used to manage the process.

Emerging Capability and Constraints

The reason production specifications for processing composites mostly ignore the viscoelastic state during processing was not a lack of foresight but rather because the capabilities to measure these properties simply did not exist. Regardless of the cause, the result is an infrastructure that does not include viscoelastic state as a specified value to build parts which are acceptable to existing applications or certification requirements.

As noted in Figure 2 and Figure 3, new capabilities have emerged that are currently underutilized because they are not compatible with existing specifications. Further, their use will require data and an infrastructure that does not currently exist and therefore, cannot be used without the active participation of engineering and the development of a database correlating viscoelastic properties with production operations and final cure state. It will be necessary to revise the definition of cure from time at temperature constraints to the viscoelastic state the specifications were intended, albeit indirectly, to control. Even the recording of temperatures within the part will require testing and possible specification revision since the part interior temperatures often differ those specified and measured in the trim area.

The development of the required data would permit removing unnecessary limits imposed by the indirect relationship of temperature and time with viscoelastic state and provide the necessary data to promote the development of critical requirement that are, as yet, undefined but that relate far more directly to the properties critical to performance of the resulting structure.

Figure 3. Test Equipment that can communicate with production controls

Examples

Cure models

Multiple mathematical models of cure state are available from multiple sources. One of the more noted are the models developed at the University of British Columbia and used by design engineers to predict processing outcome. These predictions could be integrated into the cure management systems to both aid in the cure management and permit further optimization of the models with feedback from the process itself.

Process control software

The National Research Council located in Ottawa and multiple sites within the USA currently own control system software that is compatible with this technology. Implementation of the available software tools remains limited but is available to support development.

Interior Laminate Temperatures

The success of cure models based on temperature rely on accurate temperature measurements within the laminate itself. New technology is in the later stage of development which use a magnetic field to interrogate small sensors interior to the laminate. A prototype of this system is show in Figure 4. The focus of current research is on demonstrating equivalency to thermocouples for accuracy and precision as well as examining the effect of defect sensor interior to the part. Since legacy methods do not typically measure temperature within the laminate but rather estimate interior temperature from heat transfer trials during ‘tool proofing’ of the part, even the temperature requirements of current specification will need to be reviewed as this technology is implemented.

It is possible that the interior temperature measurements would fail the current quality assurance requirements if tested against existing temperature boundaries. The point being that legacy methods have been designed to overcome the limitations impose by the ‘then unavailable data’ and ‘new’ data cannot be simply substituted for the legacy requirements.

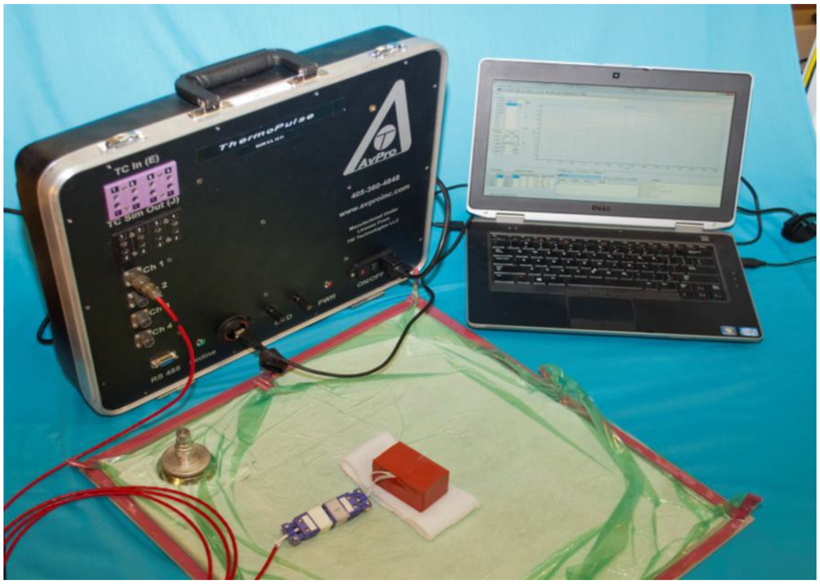

Figure 4. Interior laminate temperature sensing

Viscoelastic Measurements

The ability to quantitatively obtain the viscoelastic properties of a curing prepreg (resin and fiber) is a recent development. Figure 5 illustrates the viscoelastic behavior using the Standard Test ASTM 7750-12 *Method for Cure Behavior of Thermosetting Resins by Dynamic Mechanical Procedures using an Encapsulated Specimen Rheometer.*

The test method was released in 2012 and provides cure information as the composite transforms from a viscous prepreg to an elastic solid. While this data provides the engineer, production and quality assurance with the properties critical both process and performance, the task of redefining the current time and temperature definition of cure remains.

Conclusions

Multiple new capabilities have emerged since specification were first written to process composite. These specifications were written to overcome the limitations on measuring the viscoelastic state of cure in the last century while enabling safe use of composite materials at that time. While these specifications achieved their objective, they do not directly support the emerging technologies and will require review and revision of current specifications to achieve the attainable goal of cost reduction with greater assurance of product quality.

References

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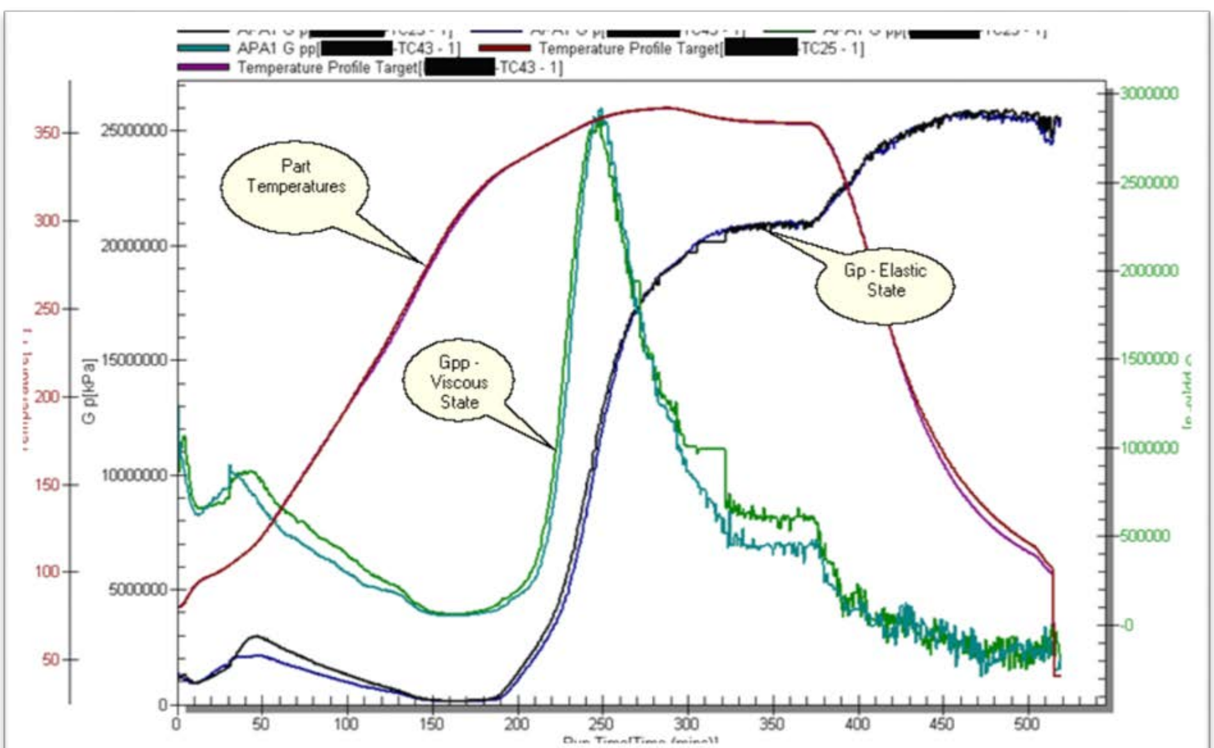

Figure 5. Viscoelastic Trace of Cure