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3 Design and Process Integration for Low Cost Manufacturing

11 Fabrication and Mechanical Properties of In-Situ Synthesized (TiB+TiC/Ti-6242 Metal Matrix Composites

16 S2Glass/Vinyl Ester Polymer Nanocomposites: Manufacturing, Structures, Thermal and Mechanical Properties

28 Photopolymerization Kinetics in Near Infrared Sensitive Liquid Crystalline Materials

33 Indention Damage Detection in Thermoplastic Composite Laminates by Using Embedded Optical Fibers

38 Fatigue Behavior of Sandwich Foam Core Materials - Comparison of Different Core Materials

43 A Novel Forming Methodology for the Deep Drawing of Powder-Based Rice-Husk/Polyvinyl-Alcohol Composite

49 Structural Characterization and Thermal Behavior of Ni/Mg/Al Layered Double Hydroxides

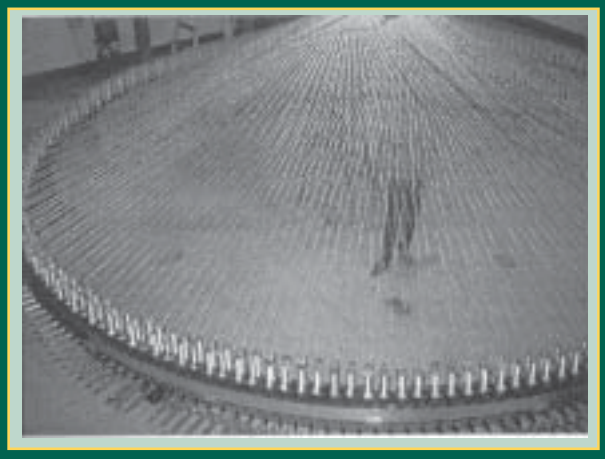
53 Manufacturing and Tensile Characteristics of Integral Sandwich Tee Joints

61 Dynamic Local Mechanical and Thermal Strength Prediction Using NDE for Material Parameters Evaluation of Aerospace Components

67 Journal of Advanced Materials Order Form

68 Book Store Form

Inside and Back Cover Technical Notes



See Article on Page 3

Photograph of A&P Technology's MEGABRAIDER™

Society for the Advancement of Material and Process Engineering

Design and Process Integration for Low Cost Manufacturing

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Abstract

Between 1998 and late 2000, Lockheed Martin Aeronautics Company conceived, designed, tooled, and fabricated a unitized, fastenerless, all-composite vertical tail using resin transfer molding. The structure was a full-scale component sized for realistic fighter aircraft requirements. Skins were complex mixtures of very lightly impregnated fabric and fully impregnated unidirectional broadgoods. Understructure was formed from an array of complexly configured, dry-braided torque tubes. Costs were collected, analyzed, and compared against the conventional approach, where design and construction of a vertical tail requires mechanical fastening together of pre-cured skins and numerous understructure details. The project produced three high quality fastenerless assemblies produced by resin transfer molding. It also validated a cost savings of 61% and a weight savings of 12% from the conventional approach. At its annual national conference in September 2001, the Composite Fabricators Association recognized this achievement with its Process Innovation Award. This article describes some aspects of the project, with emphasis on the rheological characterization work necessary to support process model studies used to select the optimum injection sequences and process parameters.

Introduction

Pursuit of lower cost composite structures has intensified during the past decade. Except for a few special situations, pursuit of performance at any cost has given way to maintaining performance while delivering at lower cost.

A variety of methods have been exploited to achieve lower production costs. The majority of methods have involved application of refined or new manufacturing methods such as fiber placement or resin transfer molding. Typically these applications have been made for production of specific parts. The F-22 program, for example, uses RTM to fabricate over two hundred different parts such as spars and other such individual components. Similarly, the newly awarded JSF program intends to use fiber placement for fabrication of wing and inlet duct skins.

In each such case, structural design is tailored to account for the mechanical properties provided by the chosen material after application of the chosen process. Thickness, ply-drop locations, and similar details are adjusted as necessary for these properties and for nuances of the process. Otherwise, the structural design concept is largely independent of the processing approach taken.

Significant production cost savings can result from application of such new and improved manufacturing methods. Building individual parts by better methods does not represent a paradigm shift in approach, however.

Under its self-funded Advanced Affordability Initiative, AAI, Lockheed

Martin chose to investigate new and potentially revolutionary approaches to very large manufacturing cost reductions. This was perceived to require new design and assembly approaches as well as new manufacturing approaches. Assembly easily can account for half of the total cost of a completed composite structure.

Design concepts were studied which could enable structural unitization: formation of a completed structural assembly without drilling holes and installing mechanical fasteners. A variety of concepts were developed, studied, and traded. From these emerged a concept for building structures such as tails, edges, and control surfaces that appeared to have potential for very large cost savings. This concept required careful design and process integration to yield unitized structural assemblies produced by resin transfer molding (RTM).

RTM had received increased attention recently for fabrication of aerospace structures[1-3]. It had been used extensively in other manufacturing industries[4]. However, use of RTM typically had been addressed to substantially smaller parts, and generally not to highly complex, integrated structural components. Nevertheless, it was concluded that a viable structural design and manufacturing concept involving RTM could produce a large, complex, integrated structure.

Specifically, the concept that was developed involved uniting unimpregnated or uncured external skins using an array of braided torque tubes. The torque tubes would be braided of dry carbon fibers, and RTM would be used to impregnate the braids and unite the torque tubes with the skins.

Small-scale trials using a simple box section validated that the concept offers significant cost savings. Under the AAI program funding, a vertical tail structure was chosen and used as a demonstration component. A full-scale structure was designed and analyzed to match the attachment and structural loading requirements for a realistic aircraft application. Anticipated JSF configuration and loading requirements were used.

Full-scale tooling was purchased and three vertical tail components were built and inspected. Costs were collected and analyzed. These data validated that the approach delivers large cost savings.

In September 2001, the Composite Fabricators Association, CFA, recognized the accomplishment at its national meeting in Florida. CFA gave its Process Innovation Award in recognition of the tail's low-cost structural simplicity enabled by sophisticated design and process integration.

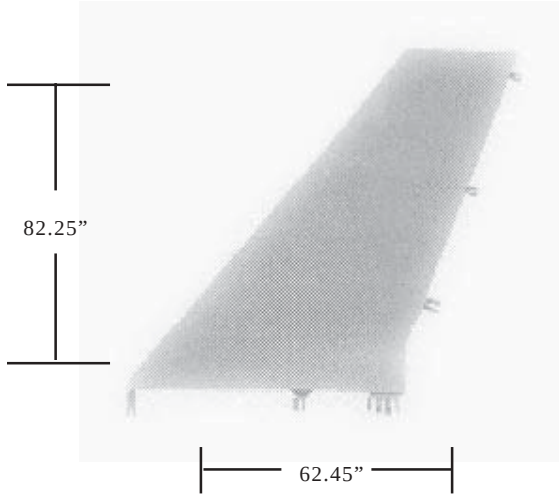

Figure 1. Diagram of the JSF based design for the unitized, fastenerless vertical tail.

Design and Process Integration

Design and process integration began with the structural design of the vertical tail, using planned aircraft attachment locations and geometries and sized to realistic flight loading requirements. To create a realistic and relevant structure, anticipated requirements for the new Joint Strike Fighter (JSF) established the baseline.

A metal attachment structure was planned for connection to the aircraft. The composite tail was to be connected to the metal attachment structure using mechanical fasteners. Leading and trailing edges also were to be attached with mechanical fasteners. Otherwise, the composite tail box was planned to be a unitized structure made without mechanical fasteners. Figure 1 illustrates the size of the tail box component without leading or trailing edges and shows the attachment locations.

Torque tubes were selected to form the internal structure of the tail box. Transverse rib stiffening of the tail box would have dramatically complicated tooling requirements. Detailed design studies were performed to identify approaches that would enable use of the torque tube design approach without having to incorporate a transverse rib to stiffen the tip of the tail box. This was accomplished by careful tailoring of a tip "C" channel that would be used for attaching a closeout edge.

Skins were made from combinations of fabric and unidirectional materials. Figure 2 illustrates the complex design of the skins. Skin thickness ranged from 0.845" at the root down to 0.198" at the tip.

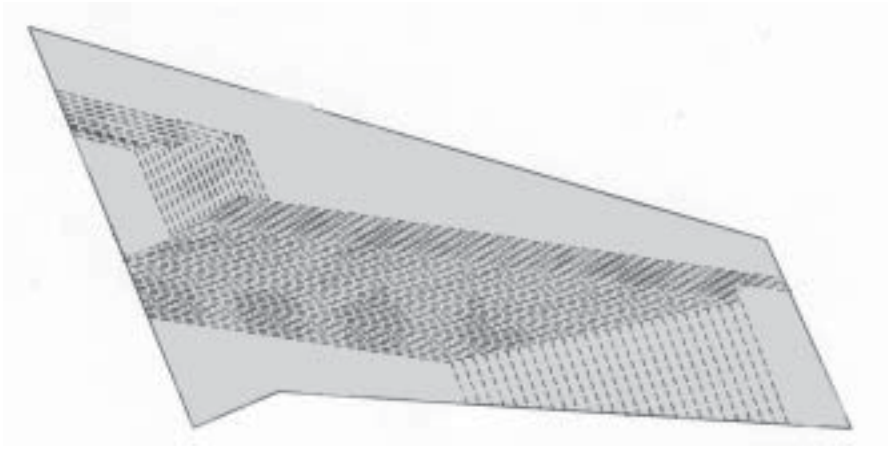

Figure 2. Vertical tail box skin layout involved 32 plies of lightly impregnated Hexcel IM7 5HS fabric and 70 plies of fully impregnated unidirectional IM7 broadgoods.

IM7 carbon fibers were selected for the skins. For lowest structural weight, unidirectional material was concluded to be essential for substantial portions of each skin.

Instead of spending time and money to obtain a "unidirectional fabric" material, fully impregnated unidirectional material was selected. Fabric materials, chosen for use in buildup areas, were very lightly impregnated to provide ~9% resin content. Cytec developed a special process to accomplish this. The result was a fabric that had just enough tack to aid layup with enough unimpregnated fibers to allow resin movement during the RTM process.

A critical cost driver for the program was determined to be the preforming approach for the torque tubes. Experience showed that prepreg cutting and plying of torque tubes was not a low cost preforming approach and would complicate the RTM unitization process. Although compatible with the RTM unitization concept, trying to create the torque tubes by laying up dry fabric was not an option because of the difficulty of handling, controlling, and debulking dry material. After reviewing a number of approaches, Lockheed Martin selected braiding as the process to form the torque tubes. Unimpregnated T300 carbon fibers were selected for the braiding operation. Braiding also was selected to form the "noodle" or radius filler material. Figure 3 illustrates the relationships of torque tubes, radius fillers and skins.

With respect to braiding, the vertical tail presented many new challenges due to the requirement for constant fiber volumes down the length of the narrowing torque tubes. For some of the torque tubes, the effective root end diameter was five or more times the effective tip end diameter. It was quickly surmised that standard biaxial braiding would create an unacceptable level of variation in sleeve thickness and/or fiber volume due to the severe taper of the tubes.

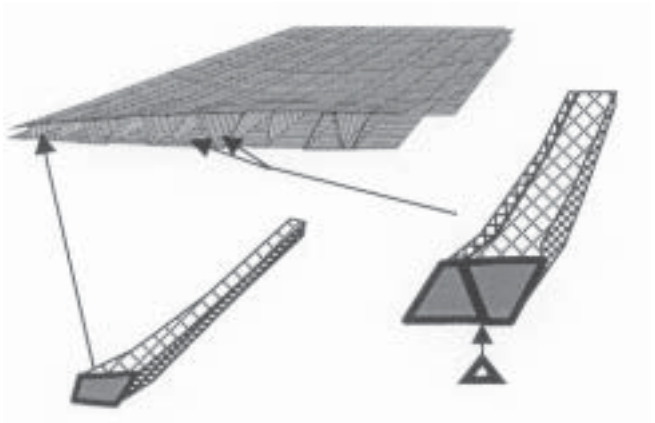

Figure 3. Relationships of torque tubes, radius fillers, and skins.

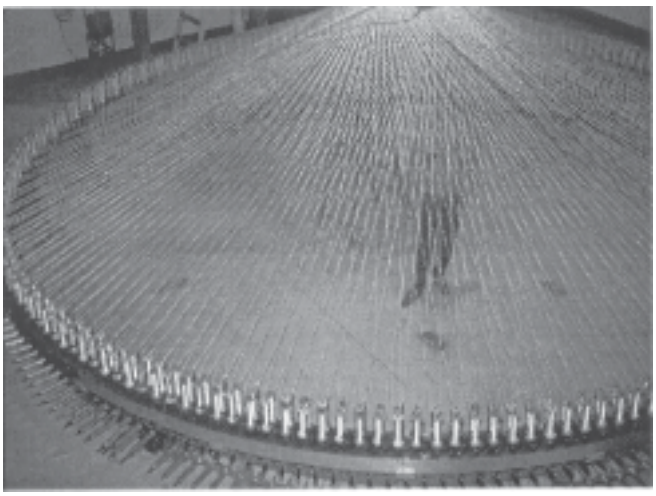

Figure 4. Photograph of A&P Technology's MEGABRAIDER™.

Lockheed Martin presented this challenge to A&P Technology. A&P Technology's large MEGABRAIDERS™ (Figure 4) enabled the use of small fiber bundles to be braided to the appropriate diameters and thickness while still achieving good coverage. Numerical controls on the braider were programmed to automatically adjust the braid angles down the length of the sleeves. As the diameter narrowed, this variation in angle translated into the required cured ply thickness of 0.014"

Figure 5. Application of braided sleeves to mandrels.

Figure 6. Placement of spooled triaxially braided "noodle" filler.

and 50% fiber volume. Initial setup was tedious due to 14 spar configurations ranging in ply count from 2 plies to 12 plies. Each sleeve was cut to the appropriate length and carefully marked to show layup direction and position. Wooden mandrels were fabricated to test fit the sleeves prior to shipment.

Lockheed Martin received from A&P Technology a kit of over fifty contoured sleeves for each tail. The layup process for the torque tubes involved simply pulling the sleeves over the appropriate mandrels to create the torque tube preforms. Figure 5 illustrates this operation.

In addition to the contoured braided sleeves, A&P Technology supplied braided triaxial, triangular-shaped "noodles" to be used as radius fillers. The reduction in touch labor using braid was beyond expectations and a key contributor to exceeding the cost reduction targets for the program. Placement is indicated in (Figure 6).

To meet both elevated temperature performance requirements and the need for a large processing window, Cytec's 5250-4 bismaleimide (BMI) resin was selected. After exposure to high humidity environments, the resin can be used at

temperatures up to 165°C. This met the service environment requirement. A long time to gel at temperatures below 130°C indicated an acceptable processing window.

Cost risk increases as component size, complexity, and degree of structural unitization increases. Failure to achieve acceptable component quality early in a program can jeopardize chances of continuation. In difficult economic times, failure to succeed on the first try can cause postponement and even termination of a program in order to shift support to important projects judged to have a higher probability of immediate success. To reduce risk, accurate location of resin injection ports and proper sequencing of resin injection steps was critical.

From the beginning, it was planned that the finite element structural design model would be used as the base for process modeling. A key objective of such modeling was to confirm tooling injection port locations and to develop process parameters for resin transfer molding of the structure. Accomplishing this required numerous transitions through various computer model tools. Shown below are the series of design transition steps taken to go from the initial structural design model to the final processing model.

1. Perform CAD Structural Modeling Using CATIA
2. Cleanup into Meshable Geometry
3. Improve Meshing Using SDROC IDEAS
4. Establish Port Nodes Using C-VIEW
5. Set Inlet Boundary Condition Node Groups Using PATRAN
6. Translate Into Computational Engine Code Using VT INFIL
7. Perform Resin Flow Modeling Using FlyerFlow©
8. Complete Post Processing Using C-VIEW

- SDROC IDEAS is a FEM program providing solid model import.
- C- VIEW is a Lockheed Martin Aeronautics code providing a graphical interface.
- VT INFIL is a Lockheed Martin Aeronautics computational engine based on FORTRAN.
- FlyerFlow© is a flow front modeling program used by University of Dayton Research Institute.

Mechanical property data already were available from previous work at Lockheed Martin Aeronautics. This set of information was adequate for the structural design work, but flow front modeling required rheological data to describe the resin's behavior during the intended RTM process. Providing this required extensive testing.

Experimental

Cytec's Rigidite 5250-4 modified BMI resin was obtained from the supplier in a sealed five-gallon bucket and stored in the freezer. A piece of resin large enough for at least 20 rheological experiments was chipped out of the bucket. This sample was stored in a sealed polypropylene container in another freezer. Small pieces were broken off for each experiment, and the container was returned promptly to the freezer to minimize "outtime" which might interfere with the thermal history of the sample.

A detailed rheological analysis of 5250-4 BMI resin was completed using a Rheometrics Dynamic Analyzer RDA II, Rhesource Series steady shear rheometer. The rheometer was equipped with a precisely controlled oven so that sample temperature could be carefully controlled. Initial experiments were done with 25 mm parallel plates, but it was found that a better response could be obtained using 50 mm parallel plates. Most of the data were collected using the 50 mm parallel plates. The oscillatory frequency was 20 Hz and the strain level was 10-50% depending upon the temperature of measurement. At lower measurement temperatures the viscosity of the resin was relatively higher and a strain of 10% was sufficient to generate a measurable rheological response. At higher measurement temperatures the viscosity of the resin was relatively lower and a greater strain was required to generate a measurable response.

The first rheology experiment was measurement of complex viscosity during a dynamic temperature sweep from 190°F to 390°F at 5.4°F/min. This experiment was designed to gain a general understanding of the "process window" of the BMI resin. The results from the dynamic temperature sweep also provided important data for selecting the parameters of subsequent investigations. The next rheology experiments were a series of isothermal measurements at specific temperatures within the "process window" to more carefully examine the rheological processing behavior of 5250-4 BMI resin.

A series of isothermal rheological measurements were made at temperatures of 217°, 238°, 248°, 275°, 284°, 293°, 302°, 320°, and 350°F. In order to most precisely measure the isothermal response of the resin, the parallel plates of the rheometer oven were preheated to the desired measurement temperature. Then the oven was opened and the sample of resin was quickly placed between the parallel plates. The plates were moved together to a gap setting of approximately 1.0 mm and the excess resin was wiped away with a lint-free lab wipe. The oven was then closed and the experiment was started. The duration of the isothermal hold was dependant upon the measurement temperature. In general, the duration of every experiment was long enough to allow the complex viscosity to increase above 10,000 cp. The thermal response of the resin was measured using a Perkin Elmer Differential Scanning Calorimeter model DSC 7 with standard aluminum pans in a nitrogen atmosphere. Cure kinetics of samples of 5250-4 resin were examined by DSC under two different thermal cycles: (i.) dynamic scan 212°F to 752°F at a rate of 18°C/min (ii.) isothermal hold at of 266°F for 193 minutes followed by rapid cooling to room temperature, then dynamic scan of 212°F to 752°F at a rate of 18°C/min.

Discussion

The first experiment was measurement of complex viscosity during a dynamic temperature sweep from 190°F to 390°F at 5.4°F/min. This experiment was designed to gain a general understanding of the "process window" of the BMI resin. The results from this experiment are shown in (Figure 7) as complex viscosity vs. temperature. As seen in (Figure 7), the complex viscosity is less than 1,000 cp in the temperature range of 210°F to 375°F, and less than 100 cp in the temperature range of 280°F to 365°F, how-

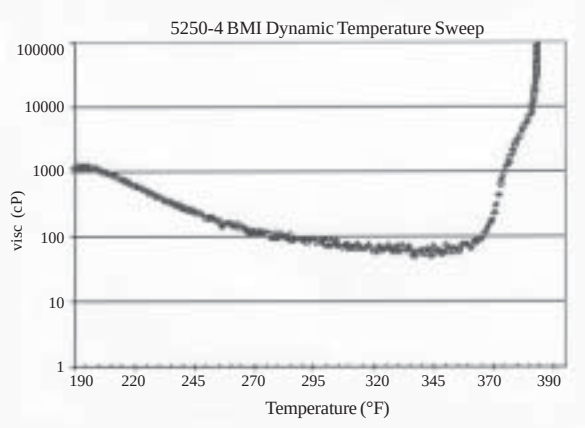

Figure 7. Complex viscosity of 5250-4 BMI resin during dynamic temperature sweep.

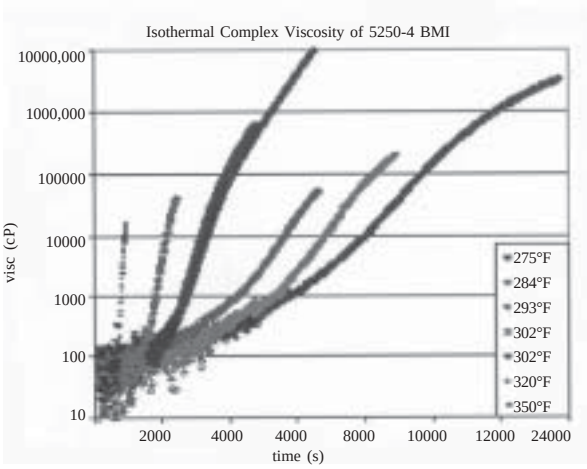

Figure 8. Isothermal complex viscosity of 5250-4 BMI resin at temperatures 275° - 350°F.

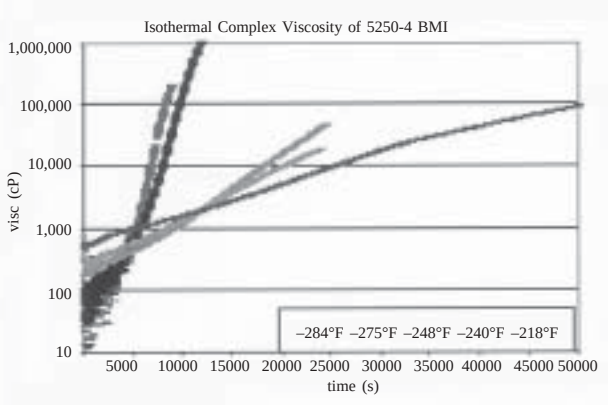

Figure 9. Isothermal complex viscosity of 5250-4 BMI resin at temperatures 218°-284°F.

ever the viscosity increases rapidly at temperatures above 350°F.

For the RTM resin flow process 10,000 cp was used as an upper limit in viscosity for RTM flow in a compacted carbon fiber preform. This limit is considered to be conservative since Loos and Springer used 100,000 cp as the "gel point" for the compaction flow of AS4/3501-6 prepreg[5]. The results from the dynamic temperature sweep were used to define the general "process window" for the 5250-4 resin system. From the results shown in (Figure 7) it appears that the temperature of the resin must be at least 210°F to begin a resin injection procedure. Although the dynamic nature of the experiment does not allow conclusions to be made on the optimum processing temperature because thermal history varies, it can be seen in (Figure 7) that the complex viscosity reaches a minimum value around 345°F.

The results from the dynamic temperature sweep provide important data for selecting the parameters of subsequent investigations. The next rheological experiments were a series of isothermal measurements at specific temperatures within the "process window" to more carefully examine the rheological processing behavior of 5250-4 BMI resin. A series of isothermal rheological measurements were made at temperatures of 217°, 238°, 248°, 275°, 284°, 293°, 302°, 320°, and 350°F. The results from the isothermal hold experiments at temperatures of 275° and greater are shown in (Figure 8).

The complex viscosity increases during the isothermal experiments, as shown in (Figure 8). At 350°F, the complex viscosity very rapidly exceeds 10,000 cp. At 275°F the increase in complex viscosity is more gradual and allows for a processing duration of approximately 8000 seconds (133 minutes). An analysis of how the rheological properties are affected by the curing reaction will be used to develop the mathematical rheological model in a following section.

Figure 9 shows the complex viscosity of 5250-4 BMI resin measured at isothermal temperatures of 218°, 240°, 248°, 275° and 284°F. As seen in (Figure 9) the initial complex viscosity is greater for lower temperatures, however the increase in complex viscosity is very gradual. The "process window" is approximately 20,000 seconds (~5 1/2 hours) at an isothermal temperature of 238°F. This time duration is suitable for the RTM fabrication of the vertical tail component.

The isothermal rheological data is very useful for selecting process temperatures for the RTM fabrication procedure. However, a more detailed analysis is necessary for the purposes of modeling the RTM flow process. The vertical tail component is an extremely complex geometry structure. Therefore, it is desirable to mathematically model the flow process so that process conditions such as specific local temperatures, locations of injection inlets and exit vents can be determined with confidence. The RTM flow models require a mathematical model describing the viscosity of the resin as a function of thermal history. The isothermal rheology data was used to develop the mathematical rheological model as a function of time and temperature. The kinetics and the rheology of the resin system are both time/temperature dependant. At very low molecular weights, the viscosity of a polymer melt is proportional to the molecular weight[6]. One can assume that the molecular weight is within this range for the low viscosities required for RTM processing. Since the molecular weight is also proportional to the extent of reaction[7], it follows reason that the viscosity measurements should provide a very good representation of the reaction kinetics in the low viscosity region.

As mentioned earlier, 10,000 cp is defined as the upper limit of viscosity for RTM flow process. The extent of reaction, represented by "α" is a kinetic term typically defining the progression of a curing type reaction from an arbitrary beginning state (α =0), to an arbitrary state of cure completion (α = 1)[7]. By defining 10,000 cp as the upper limit viscosity this also defines a condition for α =1. For the purposes of the RTM process this is the most important extent of reaction. Therefore, the kinetic behavior up to this point is of most interest. The

complex viscosity was normalized with respect to this upper limit (10,000 cp) which essentially converts the complex viscosity data to a measurement of extent of reaction.

Representative data shown in (Figure 10) for the 302°F isothermal condition is then plotted as ln (α) vs. time. The data was truncated to include only the extent-of-reaction data up to the condition of α =1.0. The curve becomes linear with a constant slope at time greater than 2400 seconds. At times less than 2400 seconds the data suffers in accuracy of measurement due to viscosities below the lower detection limit of the rheometer.

The linear region is most meaningful for modeling the behavior during the RTM process because it describes the rheological behavior of the resin as the complex viscosity approaches and passes though the upper limit viscosity of 10,000 cp. A linear expression was fit to the ln (α) vs. time data in the region of constant slope, as seen in (Figure 11). A linear regression was used to find the slope and intercept for each isothermal experimental data set. The data from these regression analyses were then plotted vs. absolute temperature to determine an empirical expression that could be generally applied to viscosity predictions of 5250-4 BMI resin within the temperature range suitable for RTM flow processes. The data from the regression analyses of slope and intercept are shown in (Figure 11).

The regression slope data were plotted on a log scale vs time and another analysis yielded the empirical expression:

$$r = 2x10^{-17} e^{0.0773T} \qquad [1]$$

where r is the regression slope data and T is temperature in Kelvin.

The regression intercept data were plotted vs. time and a regression analysis yielded the empirical expression:

$$q = 0.2348\,T - 86.803 \qquad [2]$$

Finally, from these expressions, the extent of reaction can be calculated empirically using:

$$\alpha = e^{q\,t} - r \qquad [3]$$

where t is time in seconds. Of course, since the extent of reaction is proportional to the complex viscosity, the viscosity can be calculated by multiplying a by 10,000. This empirical model was used to predict the viscosity of 5250-4 BMI over a range of isothermal hold temperatures to validate the model. Figure 12 shows a comparison of model predictions to actual complex viscosity data from three isothermal conditions (320°, 284° and 238°F). In general, there is good agreement between experimental data and predictions at all temperatures suitable for RTM.

The accuracy of the empirical model suffers slightly at small times for temperatures lower than 230°F. For these conditions, the model initially predicts negative extent of reaction due to a relatively high initial complex viscosity. However, this minor error effects viscosity predictions at small times and for the purposes of modeling the RTM process for 5250-4 BMI,

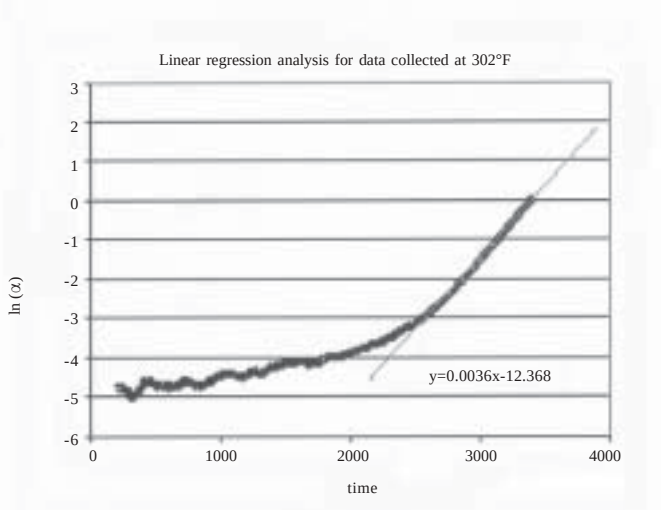

Figure 10. Plot of ln (α) vs. time for 302°F isothermal data showing a linear regression analysis of the most significant region of the curve for RTM flow model development.

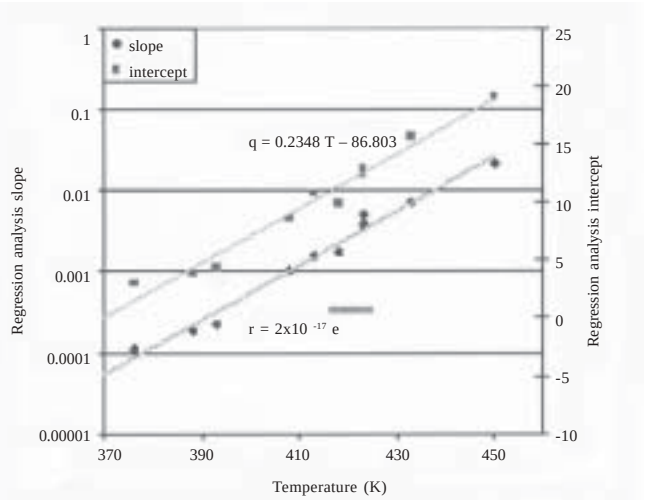

Figure 11. Regression analysis data vs. absolute temperature fit to expression.

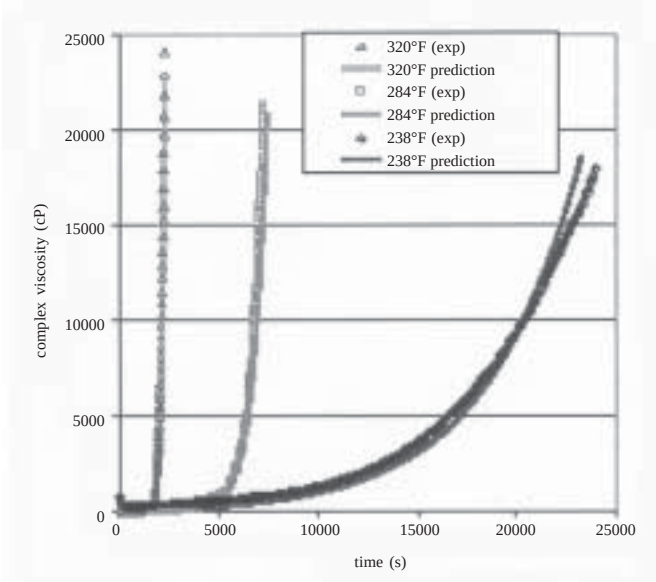

Figure 12. Actual complex viscosity data from 320°, 284° and 238°F isothermal conditions compared to predictions of empirical rheological model.

accurate results for small times are not as important as accurate results at large times, especially times approaching the completion of the mold filling process. Nonetheless, these problems were addressed in the finite element code for modeling the RTM flow process. Whenever a negative extent-of-reaction was calculated for a given time segment, the incremental change in total extent of reaction was set to zero. This empirical rheological model was used in finite element analysis for predictive flow modeling.

Thermal Analysis of 5250-4 BMI Resin

The thermal response of 5250-4 BMI was studied using Differential Scanning Calorimetry (DSC). DSC measurements were made in triplicate and the averages of important thermal response data are shown in Table 1.

The thermal response of the first sample of "as received" resin was used as a baseline to measure the heat of reaction for full cure. The resin sample with the thermal history of 266°F for 193 minutes represents an important condition for the RTM process which has a calculated extent of reaction of 1.0 from the empirical model described above. It was intended to also measure the viscosity at the 266°F isothermal condition to verify a viscosity of 10,000 cp after 193 minutes. However, the Rheometrics instrument had an oven failure before this data could be collected.

The DSC scans were all neat and free of unexplained exotherms or endotherms. The thermal response data were all reproducible and the averages of the data shown in Table 1 represent the raw data very well. The values T1 and T2 are the temperatures that the Perkin Elmer analysis software selected for the starting point and end point of the exothermic peak, respectively. The value T peak is the temperature for which the exotherm reached a maximum value. The value .H is the exothermic heat normalized by sample weight that is typically described as the "heat of reaction". The Onset Temp is the temperature selected by the Perkin Elmer analysis software from the tangent of the front leg of the exothermic peak extrapolated to the peak baseline.

The values for T1, T2, and T_{peak} are all quite consistent for samples (i.) and (ii.). The most significant information from the DSC data is the heat of reaction, ΔH. Sample (i.) is considered to be the baseline condition with no progression of cure. From the discussion in the previous section, the kinetic extent of reaction, a, is zero. Therefore, the total heat of reaction to fully cure 5250-4 BMI is 227.0 J/g. For sample (ii.) the heat of reaction is 183.3 J/g. Using the equation:

$$\text{extent of cure} = [\Delta H(i) - \Delta H(ii)] / \Delta H(i) \quad [4]$$

the calculated kinetic extent of full cure for sample (ii.) is 14.6%. It: should be noted that this extent of cure is defined differently that the extent of reaction in the previous section. The extent of reaction from the previous section was strictly based on the completion of reaction which would result in the viscosity reaching the maximum allowable viscosity for the RTM process. The extent of cure defined here by the thermal response data is representative of the more traditional definition.

A more complete study, which was not possible under this program, would include DSC measurements for samples throughout a range of extent of reaction values. This data could be correlated with the rheological measurements and predictions of cure kinetics to validate the assumptions of the theory.

RTM Fabrication of Vertical Tail Component

Three vertical tail components were made under this program. The first was a tool-proof article with fiberglass skins and carbon fiber spars. The second and third articles were made entirely with carbon fiber reinforcement.

Labor hours were recorded for each of the all-carbon components, and materials costs for each were added. Total costs were calculated and analyzed for comparison against the conventional baseline approach to vertical tail design and fabrication. After minor trimming and inspection, each tail was dimensionally measured and weighed. Inspection was made using Lockheed Martin's new Laser Ultrasonic Inspection System, and dimensions were measured using a laser based inspection setup. Quality was found to meet all requirements.

Weight of the completed tail was found to be 12% less than that of a conventionally designed and assembled tail. Although weight savings was not an original objective of the project, it had been determined that elimination of mechanical fasteners and improved unitization efficiencies from the torque tube unitizing approach would enable lower weight.

Reduced cost was the original objective, and the results measured exceeded original project expectations. A net cost reduction at T_1 of 61% was validated.

Table 1. Thermal response data from DSC scans of 5250-4 BMI samples.

	(i.) as received	(ii.) after 266°/193 min
T_1 (°F)	329	331
T_2 (°F)	630	639
T_{peak} (°F)	502	502
ΔH (J/g)	214.7	183.3
Onset Temp (°F)	390	405

Conclusion

Rheological characterization of 5250-4 BMI resin was used to develop an empirical model for predicting the resin viscosity in the regions of time and temperature significant to the RTM process. This mathematical model was used in finite element simulations of the process to define process conditions such as local temperatures, inlet locations, vent lo-

cations and injection sequences. The simulation modeling was critical to the successful fabrication of the full scale, unitized vertical tail. Complete resin infusion with no dry spots detected was accomplished for all three articles that were made. NDE evaluation using the LM Aero Laser UT system verified a high quality part.

Analysis of material and labor costs confirmed that the chosen design and process approach offers great benefits. Total cost was compared against conventional fabrication of a tail box using mechanical fasteners to unite individually fabricated skins and understructure details. The measured results validated a 61% cost reduction for the assembled tail box.

Successful fabrication of the vertical tail using an RTM process is an "industry first" for a unitized, fastenerless structure this large in size and with such a complex design. This project represents cutting edge manufacturing technology development for the RTM process. The accomplishment has been recognized by the Composite Fabricators Association's Process Innovation Award, presented in September 2001 at its national meeting in Tampa, Florida.

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