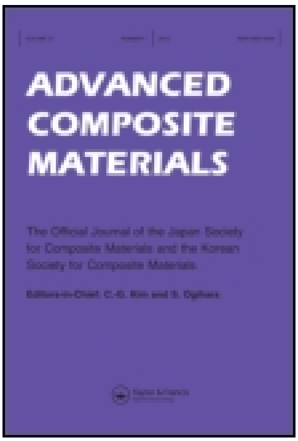

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Low-cost fabrication of advanced polymeric composites by resin infusion processes

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Abstract—The resin infusion processes RTM, RFI, and VARTM have been identified as cost-effective fabrication techniques for the manufacture of complex-shape composite structures. Dry textile preforms are resin-impregnated, consolidated, and cured in a single step process that eliminates costly prepreg tape manufacture and ply-by-ply lay-up. The principles of the three infusion processes are discussed along with the advantages of each technique compared with traditional composite fabrication methods such as prepreg tape lay-up and autoclave cure. The large number of processing variables and the complex material behavior during infiltration and cure make experimental optimization of the infusion processes inefficient. Three-dimensional computer models have been developed which can be used to simulate the resin infusion processes. The model formulation and solution procedures are presented and the material property input data required for solution of the model are discussed. Potential benefits of the model include reduced manufacturing cost and risk.

Keywords: Composites; manufacture; resin infusion; process modeling.

1. INTRODUCTION

Advanced composites offer performance characteristics that are superior to those of conventional materials. Although advanced composites have been attractive materials for high-performance aerospace applications, due to their high strength and stiffness and light weight, the use of these materials in commercial aircraft and other industries has been limited due to high manufacturing costs. Composite manufacturers recognize that new fabrication techniques that reduce material and assembly labor costs will lead to wider composite applications.

Resin transfer molding (RTM) and resin film infusion (RFI) have become popular cost-effective processing techniques for the manufacture of advanced composite structures [1]. The resin infusion processes lend themselves to the use of near

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net-shape textile preforms manufactured through a variety of automated textile processes such as knitting and braiding [2]. Often, these advanced fiber architecture preforms have through-the-thickness stitching for improved damage tolerance and delamination resistance [3]. The challenge facing users of the resin infusion techniques is to design a robust process that will consistently ensure complete infiltration and cure of a geometrically complex-shape preform with the high fiber volume fraction needed for structural applications.

One major disadvantage of the RTM and RFI processes is that they require expensive molds or tools that allow high-pressure resin infusion. In addition, long-duration, high-temperature cure cycles are required to fully cure the resin-saturated preforms. The vacuum-assisted resin transfer molding (VARTM) and the patented SCRIMP (Seemann composite resin infusion molding process) [4, 5] processes have been developed as alternative low-cost methods for the manufacture of composite structures.

This paper reviews recent research and development activities related to advanced composite manufacture by the low-cost resin infusion processing techniques RTM, RFI, and VARTM. Many of these programs are focusing on the development and verification of process simulation models to eliminate the costly trial-and-error procedures that are frequently used in tool design and cure cycle development. The development of computer simulation models of the resin infusion processes is reviewed. The material property input data that must be measured for use in the model and the type of information that can be generated by the model are discussed.

2. RESIN INFUSION PROCESSES

A schematic diagram of the RTM process is shown in Fig. 1. A dry, net-shape, textile preform is placed into the lower cavity of a two-part mold assembly. The mold assembly is closed, which compacts the preform to the desired thickness and fiber volume fraction. A liquid thermosetting resin is injected into mold, which flows into the preform. Once resin has completely filled the mold, injection is terminated and the part is cured either at room temperature or at elevated temperature. The exact cure temperature depends on the resin system. Upon completion of the cure,

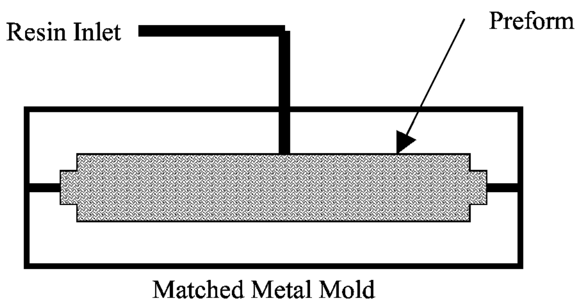

Figure 1. Schematic diagram of the RTM process.

the composite part is removed from the mold. The major advantages of RTM over the traditional composite manufacturing techniques include:

- near net-shape molded parts;
- short cycle time;
- close dimensional tolerances;
- void-free, structural quality parts;
- low pressure and temperature process;
- closed mold process, reduced volatile emissions;
- smooth surface finish on both sides of the part (class A surface possible); and
- cores, ribs, and inserts can be encapsulated into the part.

Today, the RTM process is used to fabricate both primary and secondary structural parts for commercial and military aircraft industries. RTM is the dominant composite manufacturing process for the F-22 Raptor. Three hundred and sixty individual parts are produced by RTM, which accounts for 45% by weight of all non-skin composites [6]. In addition, RTM is used extensively in the sports and recreation, marine, and transportation industries.

RTM requires the use of matched metal heated tools which must be properly designed to allow the resin to flow into and completely wet-out the compacted preform. Hence, the tooling material and fabrication costs can be prohibitive for large structural composites. In addition, the ability to completely saturate high fiber volume fraction complex-shape preforms at low to moderate injection pressures requires the use of low-viscosity (< 0.3 Pa s) resin systems. This limits the selection of resin systems to the lower performance polyesters, vinyl esters, and low T_g epoxies. Higher performance, low-viscosity resins are available, but the cost is quite high.

In order to address the disadvantages of RTM for the fabrication of large composite structures, the RFI process is being developed by the aerospace industry. The RFI process combines the advantages of RTM with the flexibility of traditional prepregging processing technology. An example of the RFI manufacturing technique for a two-blade stiffened panel is shown in Fig. 2.

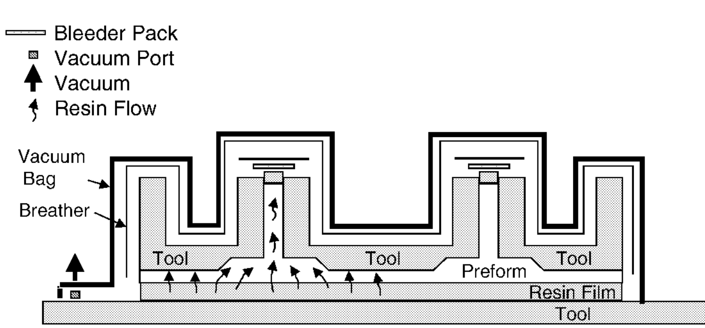

Figure 2. Schematic diagram of the RFI process.

The RFI process is similar to the RTM process, except that a hot-melt resin film is used to infiltrate the dry textile preform instead of a liquid resin. The hot-melt film is placed on the surface of the base plate. The thickness of the resin film depends on the mass of resin required to completely infiltrate and wet-out the preform. The dry preform is placed on the top of the resin film and the metallic tool blocks and bleeder packs are located in place. A vacuum bag is placed over the tool and the entire assembly is placed into an autoclave for infiltration and cure. At some point in the processing cycle, consolidation pressure is applied to the assembly. The pressure compacts the fabric preform to the specified fiber volume fraction and forces resin into the preform. The tool assembly is heated according to the prescribed temperature cycle, which decreases the resin viscosity, allowing for infusion and fiber wet-out, and cure of the resin-saturated preform.

NASA and the Boeing Company have developed the RFI process to fabricate cost-effective wing structures for commercial transport aircraft [7, 8]. A 13 m long wing cover panel was fabricated by Boeing using the RFI process [9]. The preform was infiltrated with a reduced catalyst Hexcel 3501-6 resin system. The resin is similar to the well-characterized 3501-6 prepreg system, except that the amount of catalyst is reduced to lengthen the flow time. The melt viscosity of the 3501-6 resin is much too high for a traditional RTM process. However, in RFI, the resin flow into the preform is predominately in the through-the-thickness direction, which shortens the resin travel distance and allows the use of higher-viscosity resin systems.

In the VARTM process, the vacuum bag is used for one tool surface. Liquid resins are infused into the dry preform using only vacuum pressure. The key to successful resin infiltration of the preform is the design and placement of the resin distribution medium, which allows complete wet-out of the preform and elimination of voids and dry spots. Since resin infiltration is in the through-the-thickness direction, race tracking and resin leakage around the preform are eliminated. An illustration of the VARTM process is shown in Fig. 3.

VARTM is ideal for the fabrication of very large composite structures since an autoclave or an oven is often not required. VARTM has been used to successfully fabricate marine composites for both military and commercial applications [10–12] and structural laminates for ground combat vehicles [13]. The ability of the VARTM

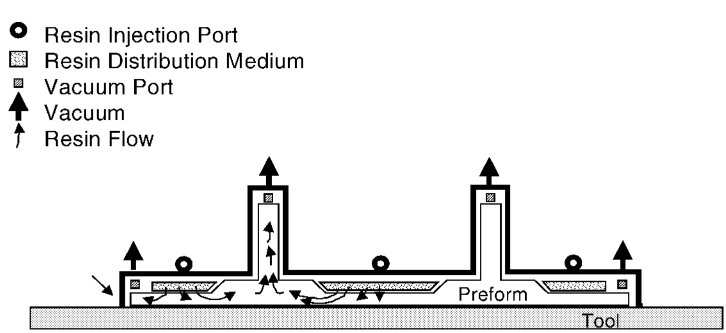

Figure 3. Schematic diagram of the VARTM process.

processes to fabricate aircraft-quality stiffened composite structures still needs to be established. However, recently developed stitching and debulking methods are being used to produce near net-shape preforms, which require no additional compaction during manufacture [7].

3. PROCESS SIMULATION MODELS

The large number of material properties and processing parameters that must be specified and controlled during resin infiltration and cure of textile composites make trial-and-error procedures of determining the processing cycle extremely inefficient. Analytical simulation models are clearly far superior alternatives for the determination of a processing cycle that will result in complete resin infiltration and cure of the textile preform. Furthermore, process simulation models are useful in mold design and in specifying the location of resin injection and vacuum ports in the tool for the liquid resin molding processes.

Three-dimensional models have been developed to simulate the manufacture of complex-shape composite structures by the resin infusion processes [14, 15]. The models are comprehensive and include modules that describe resin flow, heat transfer, resin cure kinetics, preform compaction, and residual stress and warpage. For a specified compaction and temperature cure cycle, the model can be used to predict the following parameters during infiltration and cure:

(1) resin flow front position during infiltration and total infiltration time;

(2) temperature distributions in the preform and tooling components;

(3) resin viscosity and degree of cure of the resin-saturated preform;

(4) final cured thickness and fiber volume fraction of the preform; and

(5) residual stresses and the final shape of the cured part.

A schematic diagram of the model construction is shown in Fig. 4. The user provides the geometries of the preform and tooling and the time–temperature–processing cycle. The governing equations are solved numerically by the finite element technique. Input and output format for the model is generated using a solid modeling package such as PATRAN. Input to the code includes the finite element mesh, boundary conditions, choice of materials, and various control parameters. Two important material characterizations are required inputs into the model.

The first includes the flow characteristics of the preform materials. The textile preforms are deformable and anisotropic porous materials. Hence, the permeability depends on both the direction of flow and the degree of compaction of the preform. The compaction characteristics and the permeabilities in the principal material directions must be measured for each textile preform. Test methods that can be used to measure the compaction behavior and permeabilities of textile preforms have been developed [16]. Permeability test fixtures have been constructed and used to measure transverse and in-plane permeabilities by both the advancing front and the steady-state techniques. A cure kinetics model and resin viscosity model must be developed for each new resin system used in the process [14, 15]. The cure kinetics model relates the cure rate to the temperature and degree of cure. The data are obtained by differential scanning calorimetry (DSC). The procedure is to use DSC to measure the heat evolved as a function of time at constant temperature (isothermal mode) and the heat evolved as a function of temperature at constant heating rate (dynamic mode). These measurements are made on small resin samples. From the scans, the cure rate, degree of cure, and heat of reaction are measured. The cure rate and degree of cure data are fit to a mathematical equation using a nonlinear regression analysis program. The resin viscosity model relates the temperature and cure of the resin to its viscosity. A series of isothermal viscosity tests are performed which give the viscosity as a function of time at temperature. Using the cure kinetics model, the viscosity as a function of the degree of cure is determined and fit to a mathematical expression. Once the material properties are determined, the model calculations are performed and the desired output parameters are displayed as shown in Fig. 4.

A full three-dimensional computer simulation of the non-isothermal mold filling process coupled with preform compaction and residual stress calculations usually requires large amounts of computer memory. In addition, it can take many hours to run a complete process simulation on a high-end workstation. This limits the size of the composite part that can be modeled. Further research must be performed to develop new algorithms, improvements in matrix assembly and storage processes, and parallel processing techniques that will result in significant reductions in memory and CPU requirements and computation time.

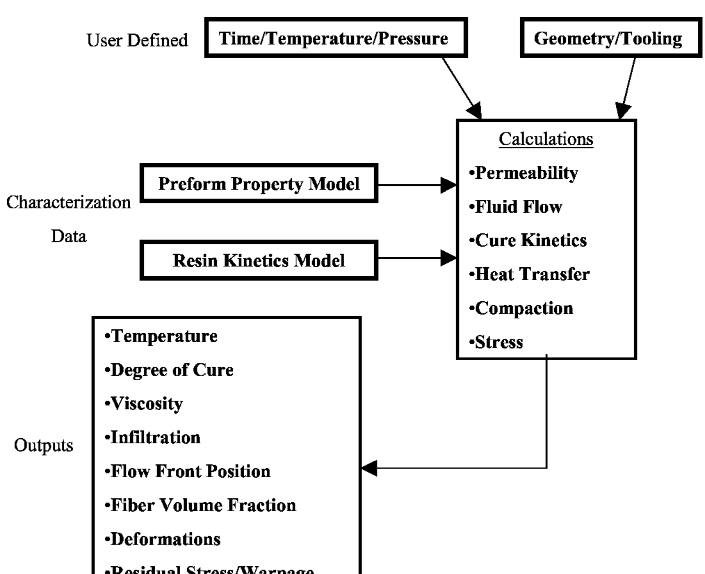

Figure 4. Computer model structure.

4. CONCLUSIONS

The three resin infusion processes, RTM, RFI, and VARTM, have become popular low-cost techniques for the manufacture of high-quality composite structures. Dry fibrous preforms, produced by highly automated textile processes, are rapidly infused to produce void-free, near net-shape composite parts. Post-fabrication machining and assembly requirements are reduced, compared with conventional composite fabrication methods.

Comprehensive three-dimensional computer models of the resin infusion processes have been developed. The physical processes modeled include the flow of resin through a three-dimensional anisotropic preform, heat transfer in the preform and tooling components, cure kinetics of the resin, and the residual stresses and final shape of the part. Process simulations have been used for mold and tool design and to optimize processing parameters to ensure proper infiltration and cure of the preform. The simulation model can be used to model manufacturing uncertainties and reduce manufacturing cost and risk.

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