COMPOSITES MANUFACTURING OVERVIEW OF CURRENT ADVANCES AND CHALLENGES FOR THE FUTURE

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Abstract

Lightweight, high-strength and stiffness polymer composites materials have been identified as a key technology in many industries to develop energy efficient, cost-effective and robust solutions. Innovation and improvements in manufacturing for composite materials and structures are needed to meet technical challenges, cost and performance targets in many applications. This goal can be achieved through a thorough understanding of fundamental mechanisms involved in composite processing. This paper provides a synthetic overview of the development of manufacturing technologies and discusses some routes for current and future challenges in composite manufacturing.

1. Introduction

1.1. Polymer composite materials

Lightweight, high-strength and stiffness polymer composites materials have been identified as a key technology in many industries to develop energy efficient, cost-effective and robust solutions. The range of applications of modern composites has progressed exponentially in the last half century. Two of the main drivers are (i) high structural efficiency (strength-to-weight ratio) and (ii) corrosion resistance to a wide range of chemicals.

For instance in the wind energy, the trend is for larger turbines that can produce energy at a lower cost with long-term reliability. This is particularly important for offshore systems that can be three times the size of land-based turbines. In transportation lightweighting can reduce energy consumption through improved fuel efficiency. These improvements will impact all forms of transportation, especially ground transportation where a 10% weight reduction translates to approximately 7%-8% better fuel economy. These improvements can be especially impactful for heavyweight vehicles.

The most intrinsic and distinctive quality of composites is their degree of heterogeneity and anisotropy, which often gives to them a complex range of both physical and chemical properties. Since the characteristic (mesoscopic) scale of the reinforcing material is close to the final product (macroscopic) scale (for instance in the thickness direction), classical fiber reinforced composites are not materials; they are more like small-scale structures. A practical consequence is that manufacturing process will have a strong influence on the part properties.

In this paper we will analyze the manufacturing aspects that are viewed as key for ensuring successful fabrication. The scope of this review is not to propose new technical solutions, but rather to underline key aspects for current manufacturing technologies.

1.2. Manufacturing

An important characteristic property of composite material structures is that both the material and the structure are created during the manufacturing process. It means that as the fibers and matrix are combined and subsequently harden, they also generate the final manufactured component. This manufacturing method is in contrast to the manufacture of elements by deforming or joining an already-existing material into a final shape. The quality of the final part depends on the manufacturing method used to produce it, sometimes as much as the constitutive materials. That is why manufacturing is a crucial step in the development of products made of polymer composites.

Historically many composite manufacturing processes were developed with the specific goal of optimizing a process to meet the economical and technical requirements. For example, the filament winding technique was specifically developed to suit the production of cylindrical shells of revolution (pipes, vessels) and thus is cheaper than using more time-consuming or labor-intensive methods such as hand lay-up, even if the final parts look identical after processing through both routes. The same applies to the pultrusion technique, which is ideally suited for the manufacture of longitudinal parts (beams) whose properties are preferentially aligned in the axis of loading.

2. Classification

Composite manufacturing technologies can be grouped in a variety of ways depending on constitutive materials and manufacturing processes. However, there are no acknowledged hard rules for composites process classification. Relying on material and technological considerations, manufacturing techniques can be divided into three main groups:

i. Molded parts, where processing is conducted on a single or double-sided mold.
ii. Continuous or semi-continuous automated process such as filament winding, fiber placement or pultrusion.
iii. Laminated systems consisting of layers of dry or pre-impregnated tapes or sheets of fiber reinforcement.

Constitutive materials classification consists of two divisions for fibers based on their length: short (discontinuous) or long (continuous) fiber. Each of these can, in turn, be combined with two matrices: thermoset and thermoplastic resins. Although further divisions can be made for most of the classes above, all modern composites fit into some combination of the four classes above.

Relying on the main physical phenomena involved in each process, another classification can be proposed:

i. Transport of discontinuous fibers and liquid/melt resin as a suspension over long distance (example : injection of fiber reinforced thermoplastic pellets)

ii. Long discontinuous or continuous fibers preimpregnated with resin deform together to form the part : Sheet Molding Compound for instance
iii. Flow of relatively low viscosity resin into nearly stationary fiber networks (made of chopped or continuous fibers) : Resin Transfer Molding (RTM) for instance.

3. Main steps

Generally speaking, the basic steps in composite manufacturing include:

1) impregnation of the fiber with the resin,

2) forming of the structure,

3) curing (for thermoset matrices) or thermal processing (for thermoplastic matrices)

4) finishing.

Depending on the process, these steps may occur separately or continuously. For instance, the starting material for many composites is a prepreg i.e., a fiber tape or fabric preimpregnated with resin and partially cured. By contrast, in pultrusion, impregnation, forming, and curing (or thermal processing) are done in one continuous process. As a consequence, modeling of the former technology can be addressed as successive weakly coupled steps, in contrast to the latter process where strong coupling between all mechanisms introduces additional difficulties.

In principle, for good quality, the whole process should be broken down into small steps and each step done at a different time. For low cost manufacturing, many steps may be combined so the process can be done at one time (one-shot process) or a lesser number of steps. Hence, one-shot processes are more challenging to model due to the simultaneity of inter-dependent phenomena.

4. Research & Development Priorities

To design more efficiently and cost effectively and to develop improved materials, it will be necessary to understand and model several important aspects of composite manufacturing processes.

Lower cost manufacturing technologies are required before advanced composites can be used more widely. In addition it is essential to develop a scientific basis for understanding how process variables affect final properties of composite parts.

The primary goal of composite manufacturing science is to be able to control the manufacturing process to ensure complete and uniform curing or solidification, minimize chemical and thermal residual stresses, control fiber/resin content and ensure accurate fiber placement. This requires models that can predict the influences of key process variables and techniques for monitoring these variables so that pressure and temperature can be adjusted accordingly. Such models would also provide useful guidelines for tool design. At present, despite many efforts, modeling is still in an early stage of development. Modeling and simulation tools for processes can speed up the development cycle for new manufacturing processes and innovative designs.

Some research and development priorities are suggested hereafter and in Table 1.

Process	Application	Challenges
Automated fiber placement: tapes, dry tows, prepregs	Aeronautics	• Equipment and material are expensive • Programming the equipment automation • Rate of material placement (kg/hour) • Difficult to make complex shapes
High pressure resin transfer molding (HP-RTM)	Automotive	• Preforming and curing are the rate limiting process steps • Viscosity of thermoplastics • Trade-off between injection speed and fiber volume fraction
Rapid preforming	All	• Production speed • Fast handling and accurate positioning • Material waste
Out-of-autoclave molding	Aeronautics and wind energy	• Void-free parts due to lower consolidation pressure
Stamping of prepregs	Automotive and aeronautics	• Defect-free parts: wrinkles, fiber breakage, tow sliding • Material waste • Rapid heating/cooling
High Performance SMC	Automotive	• Modeling the flow of concentrated long fiber suspensions (transport, orientation and distribution)
Pultrusion	All	• High viscosity of thermoplastics • Multiaxial reinforcement • Curved beams

Table 1: Some key manufacturing processes, their main application area and challenges facing the technology today.

- The development of low-cost manufacturing processes is critical to the use of new low-cost, and high-performance thermoplastics reinforced with continuous fibers. For instance, methods for fabricating complex shapes with double curvature are needed.

- Another important problem is the impregnation and wetting of fiber bundles and fabrics by relatively viscous plastics. A better understanding of effects of processing on microstructure requires further study.
- Similar knowledge is needed of the influence of residual thermal and chemical stresses and geometrical stability of parts, a particular concern for polymers processed at high temperatures.
- Process models are required with limited and easy-to-measure input data.
- Models are often not available or accessible on the shop floor for composite manufacturing
- Methods for high-volume production of automotive components from lightweight materials have not been adequately developed.
- Technologies for high-rate forming and molding of composites for large structural components and high-volume production of continuous fiber preforms are needed.
- Composite processing technologies need to be developed that yield the required component shape and properties in a cost-effective, quick, repeatable, robust and environmentally conscious manner.