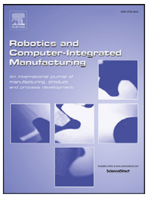
Robotics and Computer–Integrated Manufacturing 51 (2018) 222–229

Contents lists available at ScienceDirect

Robotics and Computer–Integrated Manufacturing

journal homepage: www.elsevier.com/locate/rcim



Review

# Automated material handling in composite manufacturing using pick-and-place systems – a review

Andreas Björnsson[a,*], Marie Jonsson[b], Kerstin Johansen[c]

[a] Manufacturing Engineering, Linköping University, 58183 Linköping, Sweden
[b] Swerea Sicomp, Compraser Labs, Bröderna Ugglas Gata hus 208B, 58188 Linköping, Sweden
[c] Machine Design, Linköping University, 58183 Linköping, Sweden

ARTICLE INFO

*Keywords:*
Automation
Composite materials
Pick-and-place
Prepreg
Review

ABSTRACT

With increasing use of fiber reinforced polymer composites follows a natural pursuit for more rational and effective manufacturing. Robotic pick-and-place systems can be used to automate handling of a multitude of materials used in the manufacturing of composite parts. There are systems developed for automated layup of prepreg, dry fibers and thermoplastic blanks as well as to handle auxiliary materials used in manufacturing. The aim of this paper is to highlight the challenges associated with automated handling of these materials and to analyze the main design principles that have been employed for pick-and-place systems in terms of handling strategy, reconfigurability, gripping technology and distribution of gripping points etc. The review shows that it is hard to find generic solutions for automated material handling due to the great variety in material properties. Few cases of industrial applications in full-scale manufacturing could be identified.

## 1. Introduction

The use of Fiber Reinforced Polymers (FRP) grows steadily as the material properties present an opportunity to design strong, light structures with tailored properties. Passenger aircrafts like the Boeing 787 and Airbus A350 have increased the use of FRP in the aerospace sector and the introduction of electric and hybrid cars like the BMW i3 and i8 has dramatically increased use of FRP in automotive applications. For example the demand for carbon fiber is predicted to grow with more than 10% annually until 2020 [1,2].

In the aerospace sector FRP-products are commonly made by layup of thin sheets of prepreg (fibers pre-impregnated with polymer resin) either directly onto a mold or by layup of a flat laminate that is then subsequently formed. Manufacturing using prepreg materials tend to be a labor intensive operation associated with a lot of material handling. Campbell [3] point out that ply cutting and collation are major cost drivers that can account for 40–60% of the manufacturing cost. Ward et al. [4] note that automated solutions, that can replace manual prepreg layup, have been around since the 80's and that automated systems for dry fiber fabrics descend from the 1950's. Recently early concepts for automated composite handling, so called pick-and-place systems, have been revisited. However, Ward et al. [4] suggest that many of these attempts have been unsuccessful due to a combination of high capital requirements and low output volumes as well as technology barriers like the lack of efficient and reliable end effectors. For automated manufacturing of composite components using prepreg, Ward et al. [4] conclude that realistically, the only commercially available alternatives are Automated Tape Laying (ATL) or Automated Fiber Placement (AFP). However, there are many parts like ribs, spars and brackets that are too small to be efficiently manufactured using ATL or AFP [5]. Geometrical features such as double curvature, tight corners and steep ramps are challenging for ATL and AFP [6] and small parts are difficult to realize due to the minimal course length [7].

Resin Transfer Molding (RTM) and vacuum injection manufacturing require a great deal of dry fiber reinforcements handling. Although these manufacturing processes are sparsely used in aerospace applications they seem to be more established in the automotive sector and for manufacturing of wind turbine blades. Much like prepreg, there seem to be a lack of automated applications for the handling of dry fibers installed in full scale production. Reinhart and Ehinger [8] note that handling and draping of dry fibers to manufacture preforms is still accomplished manually. Dry fiber placement technology, is a growing area with several ongoing research projects [9]. But as for prepreg ATL and AFP there is a need for alternative solutions also for dry fiber placement when it comes to small and complex shapes. Looking at both prepreg and dry fiber based manufacturing Brecher et al. [10] note that "Manufacturing of continuous fiber-reinforced components has so far, except for specialized solutions, been a manual process".

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[*] Corresponding author.

*E-mail addresses:* andreas.bjornsson@liu.se (A. Björnsson), marie.jonsson@swerea.se (M. Jonsson), kerstin.johansen@liu.se (K. Johansen).

https://doi.org/10.1016/j.rcim.2017.12.003
Received 10 May 2017; Received in revised form 9 October 2017; Accepted 21 December 2017

**Table 1**
A mapping of the reviewed sources into material categories.

| Dry fibers | Prepreg | Thermoplastic | Auxiliary |
|---|---|---|---|
| [8,10–12,14,18,20–36] | [13,22,23,37–42] | [10,43,44–46] | [18,19] |

With increased use of FRP there is a growing need to further develop automated manufacturing technologies that cover the gaps where methods like ATL, AFP and automated dry fiber placement are unsuitable. This review paper focus on pick-and-place concepts as a way to automate material handling in composite manufacturing. These concepts can be used for common tasks like clearing the cutter table and layup of flat laminates or layup directly onto contoured molds and, as will be shown, for a wide array of materials. The aim is to highlight the challenges associated with automated composite handling and to analyze the main design principles that have been employed for such systems in terms of handling strategy, reconfigurability, gripping technology and distribution of gripping points etc. An extensive review focused on pick and place solutions of different composite related materials is lacking although several smaller compilations can be found as part of background descriptions for a particular system as for example in [12,15,18]. Also, although the review in [39] covers many of the processes linked to automated composite manufacturing, it can be too broad for the researcher or engineer looking to develop pick and place automation.

This paper reviews a wide range of academic papers, datasheets, product presentations etc. that deal with automated handling of materials used in composite component manufacturing. Most of the papers present solutions for the aerospace industry but there are also descriptions of systems aimed at the automotive sector [11–13] as well as towards the manufacturing of wind turbines [14]. Some of the reviewed papers describe different generations of the same system and these papers have been included if they add something new to the analysis, like stating a challenge, or a technical detail not covered before. Some papers describe several different systems, and thus may show up in different categories. Therefore, direct quantitative comparisons between categories in the tables cannot be made. The presentation of references in the tables is intended as a guide for the reader on where to find more information.

## 2. Handled materials

The term “handling” in manufacturing of composite components implies a very broad range of materials. In the review four main groups emerge; prepreg, dry fiber reinforcements, thermoplastics and auxiliary materials. Apart from papers covering these four groups some papers with more general definitions such as generally limp materials [15] and papers that do not specify exactly the type of composite material the system is designed for [16,17] are also included in the review. Papers that address several different types of materials are found in multiple categories in Table 1. The prepreg-category include both uni-directional (UD) and woven carbon fiber prepreg. For dry fibers different kinds of reinforcements such as woven or UD non-crimp fabrics and materials like carbon fibers and glass fibers are considered. The thermoplastic category includes thermoplastic-infused UD tape and materials just referred to as “thermoplastic composites” in the reviewed papers. The category auxiliary materials include thin and limp materials that are needed in the manufacturing process like tailored membranes for vacuum infusion [18] as well as peel plies, release film and breather materials [19]. The review shows that dry fibers has received a high interest and that auxiliary materials seem a novel, albeit challenging, field for automated handling.

## 3. Challenges associated with automated handling

Many of the reviewed sources account for challenges that must be overcome in order to design a successful system for automated handling of composite materials. The described challenges can be arranged in four categories based on what aspects they cover. The four categories are quality, material, product and system aspects. Table 2 shows what sources cover challenges in each category and below follows a more detailed description of the challenges included in each category. Many of the sources cover numerous challenges and subsequently some sources are cited in several categories.

The quality category includes general challenges posed by the high quality level that many of the systems are designed for. These are usually connected to the strict requirements employed in the aerospace industry. The category also includes more specific challenges related to requirements for contamination-free handling [18,44], positional accuracy in general [8,14,18,20,27,32,37–39] and with specified tolerances for gap/overlap [8,18,20] as well as correct fiber angles after laydown [14,18,21,27] and requirements for damage-free handling [14,26,37], for example, to avoid fiber buckling, distortion and other deformations [14].

The material category includes challenges directly related to the properties of the material that the system is designed to handle. For both prepreg and dry fiber reinforcements the limp material characteristics with highly anisotropic properties [8,24–27,40] and low structural rigidity [12,15,24–27,31,37–40] are frequently acknowledged. The permeable nature of dry fiber reinforcement is also commonly listed as a challenge [8,12,24–27,31]. For prepreg, the dominant challenge is the tack (i.e., the stickiness of the material) [38–40]. The fact that material properties are affected by ambient temperature [15,40] and that protective papers or foils are used for prepreg protection are also mentioned [40]. For thermoplastic materials the high stiffness and rigidity of the material and the subsequent need to maintain material tension in order to avoid distortion is highlighted [10,45].

The product category includes many of the challenges that originate from the shape of the final product, such as the geometry of the mold that the material must be placed on [12,18,19,24,27,38,40,44] and the multitude of different shapes and sizes [8,12,18,24–27,32,45] of material plies that are required to manufacture the product.

Some papers describe challenges associated with the production system that the handling system is part of and that it must interact with. These aspects have been mapped in the system category and it contains aspects such as complexity, weight and power consumption of the end effector [18], cycle-time requirements [8,15] and process related effects on cycle times such as required hold times for powder binder to heat up and cool down [11,35]. It also includes the need to pick up plies from a cutter surface without disturbing adjacent material [15,24] and the need for the handling system to store cut plies to improve nesting efficiency in order to reduce scrap in the cutting operation [45]. The category also includes how different processes affect each other, for example how a stitching-pattern for non-crimp fabrics that simplifies draping can complicate handling [29].

## 4. Handling strategies

The material handling operation can be done in many different ways, which are connected to the manufacturing process that the material handling system is designed for. The selected handling strategy impacts the complexity of the material handling system. For example, the handling operation can be moving the material from a flat surface and deposit it onto another flat surface (2D→2D) or the material can be draped onto the three-dimensional surface like a mold or form tool (2D→3D). A transition from a 2D to a 3D surface is challenging as it yields a more complex layup where draping strategies must be considered [18,44] and the draping has direct influence over the quality of the final product [21]. Table 3 shows what sources present work related with 2D or 3D material handling. Some papers present systems for both 2D and 3D handling and are subsequently listed in both categories. Papers that conclude that their solutions might work for very lightly curved surfaces have been assigned to the 2D category.