Automated Composite Manufacturing Using Off-the-shelf Automation Equipment – A Case from the Space Industry

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AUTOMATED COMPOSITE MANUFACTURING USING OFF-THE-SHELF AUTOMATION EQUIPMENT – A CASE FROM THE SPACE INDUSTRY

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Abstract

A novel approach to the manufacturing of composite products using off-the-shelf automation equipment is explored in this article. A manufacturing concept for a specific product is developed and analyzed, from a technical perspective, in order to find areas where off-the-shelf automation equipment can be used. The article also highlights areas where case-specific solutions need to be developed. In this particular case, off-the-shelf automation equipment can be used for most of the tasks that the manufacturing system needs to perform. The most challenging process is identified as the application of adhesive. The manufacturing concept described in the article shows that it is possible to build a system for the manufacturing of composite components using a high degree of off-the-shelf automation equipment.

1. Introduction

In high-performance applications for space and aerospace, polymer fiber composite materials offer an appealing combination of low weight and high strength. Traditionally, the manufacturing of high performance composite components has been costly. The raw material is expensive, and in many cases the manufacturing methods, especially for low and medium-sized production volumes, are labor intensive. Many of the automated manufacturing solutions that are commercially available for manufacturing composite components are developed for medium and large production volumes, and are associated with high investment costs. Further development of automated manufacturing systems is important in order to develop cost-efficient alternatives for low and medium production volumes. In order to lower the cost for developing automated manufacturing systems, commercial off-the-shelf equipment can be used. A few examples of areas where the use of off-the-shelf equipment in automation of composite manufacturing have been explored are automation of RTM preform manufacturing [2] and pick and place of prepreg [1, 7]. The purpose of this article is to analyze the possibility to utilize commercial off-the-shelf equipment, systems or processes to develop an automated manufacturing system for a composite product. In the described case, the product and the manufacturing system are developed in parallel with an integrated product and manufacturing development approach. The product design enables a novel manufacturing approach based on adhesive joining of standardized building blocks.

2. Theoretical framework

2.1 Manufacturing system and automation

There is a long-term trend in manufacturing towards a greater use of automated processes instead of manual labor [10]. There are several reasons to implement automation in a manufacturing system, such as increased labor productivity, reduced labor cost, improved product quality and reduced manufacturing lead-time [10]. In working with automation it is important to acknowledge that some tasks, for instance tasks that require manual dexterity, can be technologically difficult to automate [10]. According to Groover [10] there are five levels of automation. The levels range from the least comprehensive level, the device level through the machine level, the cell, or system level, to the plant level, all the way to the most comprehensive level, the enterprise level [10]. Here, the focus is on the third level, the manufacturing cell or manufacturing system.

2.2 Robotic manipulation and accuracy

Industrial robots are used for a great variety of tasks in automated manufacturing systems. Two key parameters in robot manipulation are repeatability and volumetric-accuracy or simply accuracy [5]. The accuracy can be explained as a robot's ability to attain a commanded pose with respect to its base reference frame [11]. The accuracy is typically below one mm, and is dependent on the robot structure as well as where in the robot's workspace the Tool Center Point (TCP) is located [5]. According to Slamani et al. [11], repeatability can be explained as a robot’s ability to return to a previous position in the workspace. Most robot manufacturers present the value for unidirectional repeatability, that is, the ability to return to one point from the same direction. The multidirectional repeatability can be more than twice the value for the unidirectional repeatability [11]. Both the accuracy and the repeatability vary greatly between different types of robots, but also within the workspace for one robot. Siciliano et al. [5] refer to an example where a robot with a maximum reach of 1.5 m has an accuracy that varies from 0.2 mm – 1 mm within the workspace. For the same robot, the repeatability varies from 0.02 mm – 0.2 mm [5]. Tests performed by Slamani et al. [11] on a standard robot resulted in repeatability varying from 0,022 mm – 0.037 mm [11]. According to Saund and DeVlieg [4], there are a number of technologies that can enhance robotic accuracy and repeatability. One type of method to improve accuracy is real-time guidance via metrology systems. Another type relies on vision systems that locate part features and sync with the robot controller. Programming the robot by directly teaching the positions can also improve accuracy. Increased accuracy can also be achieved by adding a secondary feedback system from each robotic joint to the controller unit. [4]

2.3 Gripping technologies

In a review of gripping technologies, Björnsson et al. [1] identify a number of different examples. Two of the most common technologies are vacuum grippers and clamping grippers. Examples of the two technologies are shown in Figure 1. For these two technologies, there are a large number of commercially available designs on the market. For the vacuum grippers, there are two main technologies for generating vacuum: the vacuum pump and blowing compressed air through an ejector system.

Figure 1. A vacuum cup with an ejector system (left). Two examples of clamping grippers (right).

2.4 Adhesive joining

In adhesive joining, two or more parts, called adherends, are joined by a chemical bond. In order to form a strong bond, the adherend surfaces must be free of contaminates; therefore, careful preparation of the adherend surfaces is of paramount importance [6]. According to Crossley et al. [13], some aspects related to adhesive bonding are important to consider. A two-component adhesive must be accurately mixed and the pot life must be managed. The pot life is the maximal time from mixing until the adhesive no longer should be used. It is related to the change in resin viscosity over time because the curing starts immediately after mixing. Furthermore, Crossley et al. [13] point out that automated mixing equipment is becoming increasingly available, and is a good alternative to cartridge-based systems. In automated mixing systems, the substances to be mixed are kept in large containers and mixed with high control just before application; this reduces the resin waste. The systems are easy to automate and can be mounted on robots as a part of a completely automatic adhesive dispensing system. [13] In large-scale manufacturing, specialized equipment for dispensing the adhesive is necessary [12]. When the adhesive is crosslinking, or curing, the joined parts must, in most cases, be supported in order to ensure geometric stability of the joint [6]. This is usually done by the use of dedicated bonding fixtures, or jigs.

2.5 Surface preparation

Polymers have inherently lower surface energy compared to metals, and therefore tend to form poor adhesion bonds without some kind of surface treatment [14]. Polymer fiber composites have, in many cases, smooth surfaces from molding processes, and the surface regions tend to be mainly composed of polymer matrix material [8]. From the previous manufacturing steps, the composite material surface can be contaminated by silicones from release agents, fluorocarbon release sprays, machining oils and fingerprints [8]. The cleaning of the adherend surfaces is important; failures in adhesive joints are generally attributed to poor surface and adhesive preparation [13]. There are a great number of methods available for surface treatment before bonding. They can be grouped into four main categories, based on [8] and [14], as shown in Table 1. The different methods are suitable for different cases of contaminants, surfaces and materials.

Mechanical	Energetic	Chemical	Bulk
Alumina gritblast	Corona discharge	Solvent cleaning	Additives
Cryoblast	Plasma	Detergent wash	Blending
Sodablast	Flame	Acid etch	Recrystallization
Peel ply	Excimer laser	Primer	
Silicon carbide abrasion			

Table 1. Methods for surface preparation of composite materials. Based on [8] and [14].

3. Method

The theoretical framework in this paper is based on a literature review in the fields of automatic application of adhesives, surface preparations for adhesive joining, robot accuracy and gripping technologies. The review of academic publications has been complemented with studies of commercially available equipment from different manufacturers. The product information and the background information for the case have been collected in close cooperation with industrial partners. For the development of technical solutions to sub-problems, as well as the development of a concept for the complete manufacturing cell, a generic product development method proposed by Ulrich and Eppinger [9] has been used. Digital simulations of the complete manufacturing cell have been used to evaluate the cell layout and robot reachability. Some preliminary physical tests of key tasks, such as adhesive application, have been carried out in order to increase the understanding of the task and to identify challenges associated with adhesive application. A transparent plastic material was used for the physical tests in order to simplify the evaluation of the adhesive application tests.

4. Industrial case

The case, which forms the basis for the analysis, concerns a product from the space industry. The product is a structure that consists of two major parts. The first part is a large truncated cone made from carbon fiber reinforced plastic. On the top surface, the section of the truncated cone with the smallest diameter, the second major part, a ring, is assembled. The ring also consists of polymer fiber composite material. The two parts, the cone and the ring, cannot be integrated into one product. Due to the angle on the truncated cone and the shape of the interface between the ring and the cone, the ring cannot be manufactured in one piece and then assembled on the cone. Instead, the ring is built on the cone by adhesively joining many standardized building blocks (here simply called blocks) together until they form a complete ring. The geometry of the block and the cone, as well as a picture and a schematic view of how they are attached to each other, are illustrated in Figure 2.

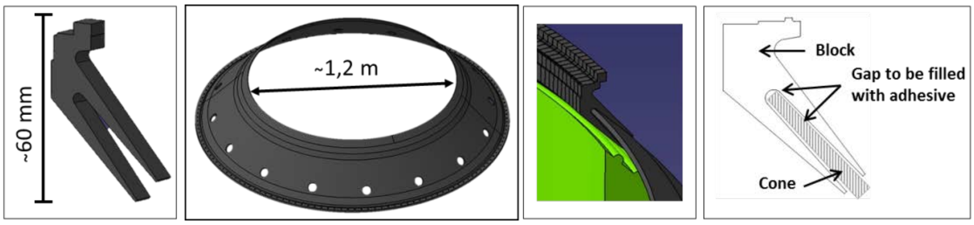

Figure 2. The two leftmost illustrations are a 3D CAD representation of the block and a picture of the truncated cone, while the two illustrations to the right show how a block is assembled on the cone.

The blocks are manufactured by first producing flat laminates and then, by means of two-dimensional water jet cutting, cutting out several blocks from the flat laminate. All blocks are cut to the same size and thickness. The angle that is needed between the blocks in order to form a rounded shape when joining the blocks to each other is accomplished by varying the thickness of the adhesive joint from the inner to the outer diameter of the circle. The area between two adjacent blocks and the distance between the block and the cone must be completely filled with adhesive and no air is allowed to be trapped in the adhesive joints. The assembly of blocks onto the cone continues in a repetitive sequence until all blocks are assembled and a full ring is achieved. Then, the assembly cures for several days. When it is completely cured the assembly is moved to a large vertical mill and machined to the correct shape and tolerances. The workflow sequence is illustrated in Figure 3. Only the assembly of blocks on the cone is in the scope for the developed manufacturing concept; the manufacturing of the blocks and the machining of the assembly are not considered in this article.

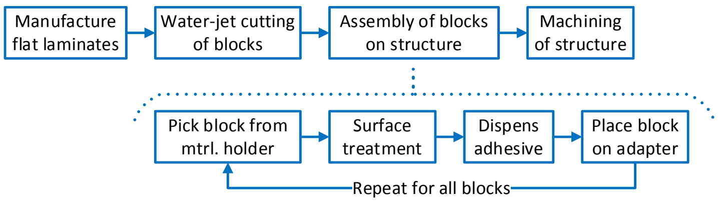

Figure 3. The process flow for the manufacturing of blocks and the assembly of blocks on the cone.

Two pictures of the manufacturing concept developed for the assembly are shown in Figure 4. The entire system is composed of a transportation system for feeding new blocks into the manufacturing cell, and a cleaning station where the surfaces of the blocks are prepared for adhesive joining. A standard robot picks up the blocks after the cleaning procedure and moves them to a stationary adhesive dispensing unit. The robot positions the block for the correct application of adhesive, and then moves the block to the fixture and places the block on the cone that is located on an indexing rotary table. The block is supported by a fixture during the curing in order to assure geometric stability and positional accuracy. In order to handle the block, the robot is equipped with a gripping device.

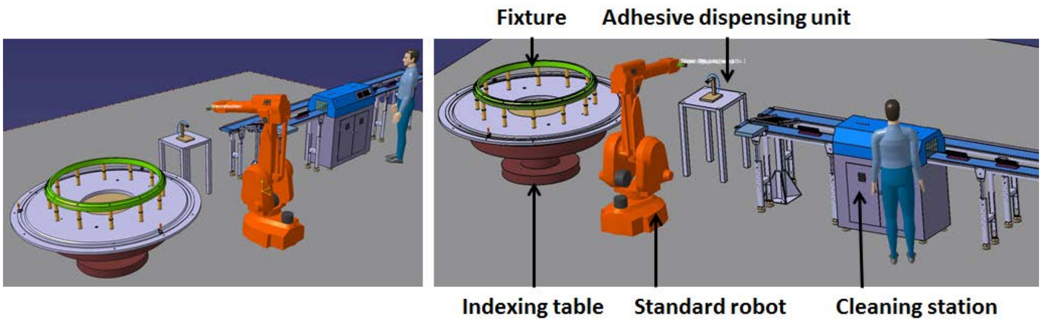

Figure 4. A view of the proposed manufacturing concept for the automatic assembly of blocks on the cone.

For the manufacturing concept analyzed in this article, the adhesive selection is limited to one type of paste adhesive. This type of adhesive has a high viscosity, approximately 160 Pa·S, and the pot life is 90 min. In working with the space and aerospace industries, it is important to acknowledge that they are subject to rigorous quality standards. New manufacturing processes or changes to existing manufacturing processes must be qualified before they are implemented, and all manufacturing processes must be stable, with highly repeatable output. Therefore, the requirements for process control are high [3].

5. Evaluation of each work element

In order to evaluate different areas of the automated manufacturing concept, it is divided into five separate areas. The possibility to utilize off-the-shelf solutions for each area is discussed below.

5.1 Robotic manipulation

The complete assembly process can be programmed to be a sequence of robot motions that is repeated for each block. By using an indexing table, the position where the robot assembles a block can be exactly the same each time. This means that the accuracy in the assembly sequence is mainly dependent on the repetition accuracy that, for most robot types, will be able to comply with the tolerances in the current case. If improved accuracy still is requested, there are a number of off-the-shelf solutions for improving robotic accuracy, such as teach-in programming or real-time feedback via metrology systems. In the manufacturing sequence, the assembly of blocks on the structure is followed by a machining operation and the final product shape, with tight tolerances, is shaped during the machining operation. By using oversized blocks, with working margin, in the assembly process and machine the final shape of the ring the need for accuracy in the assembly process is reduced. The conclusion is that robotic manipulation is an area where off-the-shelf equipment can be used.

5.2 Robotic gripping

To facilitate the adhesive application process, one side of the block must be fully exposed for adhesive application, while the other side can be used for gripping. Therefore, a vacuum cup gripper is considered to be a good solution for robotic gripping. A suitable vacuum cup design is easy to find, but the material used for the cup must be compatible with the material to be handled. The cup material must not affect the surface of the block, and there must be no risk of transferring any contamination from the cup to the surface of the block. In this case, vacuum cups containing silicone must be avoided, as there is a risk that the silicone traces can transfer to the block surface and thereby affect the adhesive joint. The most suitable system for vacuum generation in this case is a pump, since ejector systems exert compressed air that can stir up dust. The exhaust air from the ejector systems can contain lubrication oil that can be a source of contamination in the manufacturing cell. To conclude, all the equipment needed for robotic gripping is commercially available, off-the-shelf equipment.

5.3Cleaning and surface preparation

For cleaning and surface preparation there are a wide range of methods to choose from; some examples are listed in Table 1. Most of the methods available today are developed for manual operations. There is no universal method for cleaning and surface preparation that works for all types of contaminates and gives the desired surface for all types of materials. The most suitable method for cleaning and surface preparation must be found by testing different methods on the current material. Some of the methods, listed in Table 1, can be considered to be more suitable to be incorporated in an automated manufacturing concept. For example, corona treatment can be quite easily incorporated in an automated manufacturing cell since the equipment is small and easy to install. Other techniques, such as detergent or solvent wiping, must be considered far less adapted for automation. For these techniques, an automated solution would require dedicated equipment and an isolated environment, making it difficult to integrate as a part of a manufacturing cell. To summarize, a series of tests is necessary in order to find the cleaning and surface preparation method that gives the best result for the adhesive bonding. Depending on what method is determined to be most suitable, the task of automating the cleaning and surface preparation will vary greatly. Some methods, such as corona treatment, are easily included in an automated solution, but for many methods, such as detergent and solvent cleaning, new automation equipment must be developed.

5.4 Fixturing

Naturally, the fixture used for locating and supporting the blocks when they are adhesively joined to each other and to the cone must be developed for the current product. The fixture must be adapted to the adhesive joining process in a way that there is no risk of adhesively joining it to the rest of the assembly. This can be avoided by choosing materials that the adhesive does not bond to. It is also important to carefully consider where the adhesive can leak out from the assembly during the assembly process. To conclude, some off-the-shelf equipment such as fasteners can be used for the fixture, but the majority of the fixture must be developed for the current product.

5.5 Adhesive dispensing

The dispensing of adhesive can at first glance seem to be a simple process. There are a number of off-the-shelf automatic dispensing units that can be used. If the dispensing unit is stationary, the robot can easily position the block under the dispensing unit. However, even if the equipment for dispensing the adhesive can be considered to be off-the-shelf equipment, the process itself is not. The dispensing process must be developed to fit the current product, materials and also the fixture and gripping solutions. The paste adhesive used in this case has a high viscosity, and tends to form long strings of adhesive between the point of application and the nozzle when the application is completed and the block is removed from the application nozzle, as seen in Figure 5. The tendency to form strings seems to be dependent on how the application is performed and how the nozzle is removed. It has also been shown to be influenced by the nozzle diameter. A challenge for an automated adhesive application is that the string must either be eliminated or controlled in a repeatable way. The areas between the two blocks, as well as the area between the blocks and the cone, must be completely filled with adhesive, and no entrapped air can be allowed. The application pattern has, during testing, shown to clearly affect the risk of entrapped air as well as the risk for areas that are not covered with adhesive paste.

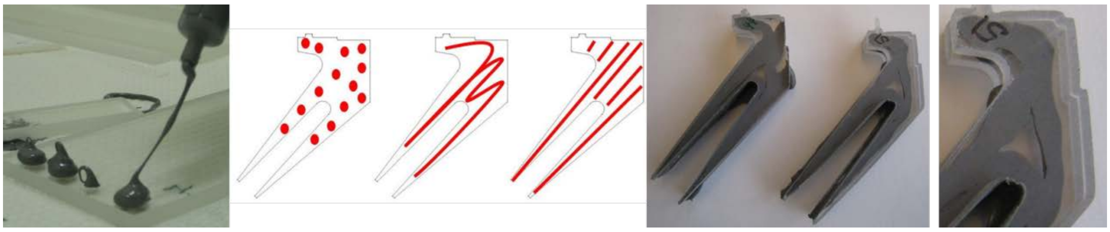

Figure 5. To the left are a picture of an adhesive string and illustrations of different patterns for the application of adhesive; to the right, two pictures showing air trapped between joined blocks.

The method for how two blocks are positioned beside each other on the cone also affects the joint result, as it has a great influence on how the adhesive is smeared on the surface. A block that is to be joined to the cone and to other blocks already assembled on the cone can be threaded onto the cone and then moved sideways into contact with previously assembled blocks. Another possible solution is to put the block into contact with previously assembled blocks, and then thread it straight down on the cone. Preliminary testing identifies several difficulties in creating a good joint between the blocks, as well as between the block and the cone. Off-the-shelf equipment can be used for the adhesive application, but it might be necessary to complement it with a system that can take care of the string that can form between the point of application and the applicator nozzle. In conclusion, the method for adhesive application must be developed to fit the material and geometry of the product. The application process is identified as the key area to focus on in order to succeed in developing an automated manufacturing system for this case.

6. Conclusions

The analysis of the developed automated manufacturing system shows that, for this novel approach to manufacturing composite products, off-the-shelf equipment can be used for automating several of the tasks in the system. Robotic manipulation and gripping of blocks can be carried out by the use of off-the-shelf equipment. However, it is important to select a material for the contact surface between the gripper and the block that does not contaminate the block surface. The correct method for cleaning and surface preparation must be investigated by further testing. Some methods for cleaning and surface preparation are suitable for automated manufacturing, while other methods need to be developed further in order to be implemented in an automated manufacturing solution. The adhesive application is identified as a key process that needs further development. The application can be accomplished by off-the-shelf equipment, but the method must be adapted to the current case.

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