1 Introduction

Historically, research on composite manufacturing technology has focused on performance rather than cost considerations. As a result, only a handful of industries, e.g., aerospace, have been able to afford the use of composite structures in their products. Nowadays, however, as composites are increasingly being incorporated in a wide variety of applications, performance is no longer the only consideration. Composites are also required to be cost effective. Automation of manufacturing processes along with resin infusion techniques has been regarded as the solution to produce improved quality at low cost. However, compared with metal industry, where manufacturing process automation is widespread, composites industry has a limited variety of automated processes. The industry is evaluating new manufacturing technologies and investing in research to develop them [1-3]. In this context, the present paper reports the development of a novel process to manufacture preforms using dry fibres. This technology has been named as Robotic Dry Fibre Placement (RDFP). Before presenting the work developed with RDFP, it is convenient to make a brief review of other three processes which are very closely related.

- Automated Tape Laying (ATL).
- Automated Fibre Placement (AFP).
- Tailored Fibre Placement (TFP).

The first designs of ATL and AFP machines can be traced back to patents issued in the early 1970's. Both processes have many characteristics in common. They use a manipulator under computer control which drives a delivery head to lay-up prepreg tape under controlled conditions. The machines on both processes allow the rapid deposition of prepreg to either a flat or curved mould to manufacture complex structures, Figure 1. The heads used on ATL and AFP are quite complex pieces of machinery. The heads have the capability to unwind the prepreg tape from the roll, peel off the backing material, place the prepreg on the mould using a pressure roller, cut off the prepreg at the end of the trajectory and then restart the process all over again.

The main difference between ATL and AFP machines is the width of the tape being handled [5]. ATL process deposits a single, wide, unidirectional reinforced tape [4]. Due to the width of the tape, the ATL machines are limited to the manufacturing of flat or single curvature structures. AFP uses multiple individual narrow tows of tape to form a band. Each tow can be stopped, cut, and restarted individually during the manufacturing. This allows the head to deliver each tow at its own speed, making possible to lay-up over moulds with complex geometries and to deposit the material following curvilinear paths [4].
At the present, ATL and AFP have achieved a high degree of maturity. Both processes are the main technologies used to manufacture large composite structures in aerospace industry. Lukaszewicz, Ward and Potter [5] make an exhaustive literature review of these two processes citing up to 111 sources. They point that the quantity of research being developed to improve existing thermoset lay-up processes is indeed increasing.

The TFP process, Figure 2, uses an embroidery head which stitches a single carbon tow or a glass roving onto a thin substrate. This process offers the possibility to lay-up in the orientations of the principal stresses expected to be developed by the structure once subject to load [6].

The RDFP process use a flat tool with pins implanted on it. The delivery head passes a tow of dry fibre reinforcement around two pegs to form a straight segment of fibre. This process is repeated to deposit several segments, each one, parallel to the other in order to form a layer, Figure 3. The use of pins is necessary to hold together the layers being manufactured because unlike a prepreg material the dry fibres do not have any tackiness [8][9][10][11]. The operation is accomplished by a 4-DOF Cartesian manipulator with a work envelope of 3m x 2m x 0.6 m. The manipulator is based entirely on FESTO electrical drives and controls, Figure 4.

The robotic dry fibre placement process has already some degree of development as it has been used previously to manufacture flat and rectangular shaped reinforcements [10][11]. However further success of this method in an industrial or commercial environment depends on the feasibility of its application on manufacturing preforms with complex shapes. The handling problems associated with long and continuous dry fibres mean that the progress in the development of machinery to manufacture preforms from dry fibres has been comparatively slow.

2. Objectives

This study pursues the following objectives:

- Develop the RDFP manufacturing process to make composite structures form dry fibres.
- Produce preforms with a large number of layers in 0, 90 and ±θ orientations and with single or double curvature geometries for aerospace applications.
- Incorporate through the thickness reinforcement using robotic tufting technique.
3. **Experimental**

3.1. **Ply-book design.**

A ply-book is a collection of layouts which contain information about the shape, orientation of the fibres and thickness of each one of the layers comprising the preform [12]. The ply-book layouts help to determine the positions where the pins will be mounted on the pin board.

The ply-book generation technique is based on the mathematical concept of level curves [13]:

**Definition 1.** If \( f(x, y) \) is a scalar-valued function of two variables, \( f: \mathbb{R}^2 \rightarrow \mathbb{R} \) then its graph is the surface formed by the set of all the points \((x, y, z)\) where \( z = f(x, y) \).

**Definition 2.** A level curve of a function \( f(x, y) \) is the curve of points \((x, y)\) where \( f(x, y) = c \).

As an example, the Figure 5 shows the graph of the function \( f(x, y) = -x^2 - 2y^2 \), an elliptic paraboloid. It can be noticed that when the plane \( z = c \) intersects the surface \( z = f(x, y) \), the result is the curve with eq. \( f(x, y) = c \). Such intersection is the trace of the graph of \( f(x, y) \) in the plane \( z = c \) or contour curve. The set of points \((x, y)\) in the xy-plane that satisfy \( f(x, y) = c \) is called the level curve of \( f \) at \( c \), and the entire family of level curves is generated as \( c \) varies over the range of \( f \) [13].

Applying the above discussion to composites manufacturing, the graph of the function \( z = f(x, y) \) represents the composite to be manufactured. The trace of the graph of \( f \) in the plane \( z = c \) represents one ply. The family of contour curves represents the ply-book.

The ply-book creation is a standard tool to develop reinforcements from a variety of manufacturing processes such as hand layup, ATP or AFP. These processes, along with the RDFP process, can be visualized as the inverse of CNC milling processes because they create a tri-dimensional object by laying-up and stacking layers of material instead of cutting and removing material [4][10]. Indeed these processes can be regarded as a form of 3D printing.
3.2. Tooling design.

The wrist of the manipulator was equipped with a lay-up head built completely in aluminum as shown in Figure 6. The lay-up head was conceived to have a slim and modular design. This makes the tool easy to maintain and minimizes the inertia of the arm, allowing the robot to deposit fibre at speeds as high as 600 mm/s.

3.3. Development platform.

During this research the FESTO Configuration Tool, FCT, and the FESTO teaching language, FTL, were employed as development platforms.

FCT is a tool for configuring and commissioning electrical drives manufactured by FESTO. FCT provides a friendly environment to configure devices with minimal effort. FCT also works as an IDE from where projects written in FTL can be edited, managed and uploaded to the controller’s memory.

FTL is an interpreted programming language used to program the FESTO CMXR controllers. The FTL includes a library of functions to control the kinematics of the 4-DOF Cartesian robot in a transparent way. A set of functions to move the kinematics in linear and circular arc paths and to define and reference new coordinate systems are included.

Previous researchers [10][11] used CoDeSys as development platform. CoDeSys is a software development tool which converts any PLC into a IEC 61131-3 controller. CoDeSys includes and Integrated Development Environment (IDE). Also implements the four programming languages defined by the IEC 61131-3 standard [15]. CoDeSys can generate machine code for a wide variety of CPU’s in a development PC. However, with CoDeSys is responsibility of the programmer to write code from scratch to control the kinematics of the manipulator. FCT and FTL help to reduce significantly the development times by allowing the programmer to concentrate on application coding.

3.4. Path planning.

Previous to the fibre deposition, the manipulator must be programmed to follow a predetermined trajectory. This trajectory must avoid collisions with any obstacles present in the path of the tool. Ideally, the trajectory must also maximize the speed of the fibre deposition process. During the earlier stages of this research, the trajectories were determined manually with the aid of a CAD program. For example, to produce a layer for a preform of rectangular shape, the trajectory shown in Figure 7 was drawn using a commercial CAD program. This path only passes the carbon fibre tow around the first set of pins. However, the mould has 40 sets of pins. To create the trajectory around the 39 remaining sets, a loop in the program makes a translation of all the points in the horizontal direction to the next set of pins and then the robot makes the travel through
all the newly generated points. The operation is repeated until the robot reaches the last set of pins. This approach is not suitable for the manufacturing of a double curvature preform because it requires the manual definition of an individual trajectory per each set of pins. The lay-up of a complete layer requires the definition of hundreds of points. Even the relatively simple trajectory shown in Figure 7 is composed by approximately 30 points for one set of pins. The computer calculates the trajectories for the other 39 sets of pins. In total 1560 points per layer are defined. Another drawback of the manual path planning approach is that if the configuration of the pins change then a whole set of new points must be determined.

The algorithm requires feeding the computer with precise information about the obstacles present along the trajectory of the robot, i.e. a map of the position of the pins in the middle of the mould. Because the robot has full “knowledge” of its environment, the whole process of path planning is a one-time, off-line operation. This means that for a particular configuration of pins it is necessary to run the program only once. The output is a file containing source code in the language of the controller with the declaration of all the points and the sequence in which those positions must be executed to form a trajectory. Then the source file is uploaded to the memory of the controller.

Therefore, a path planning with complete information algorithm, also known in the literature as the “piano movers problem” [16][17], was programmed in a PC. The aim is to determine automatically the trajectory which the robot must follow to deposit the fibre while avoiding colliding with the pins in the middle part of the mould.

During this research work, Toray 12K T700S carbon fibre with linear density of 800 tex and 7 micron filament diameter was used to manufacture the preforms.

Previous to the infusion process, it is necessary to remove the preform from the pin-board. To keep the fibres arranged, adhesive tape was used to consolidate the borders while a commercial adhesive spray was employed for the ply drop area.

According to the manufacturer, Aerofix 3 is a spray adhesive which has been formulated to hold glass/carbon fabrics and core materials in place in the moulds during the resin infusion process. The
The manufacturer also states that this adhesive is compatible with both polyester and vinylester resins without affecting the mechanical performance of the preform and not compromising or inhibiting the polymerisation of the resin.

Removing the preform form the pin-board leave some gaps between the fibres.

![Figure 9. Sample consolidated by applying Aerofix 3 spray adhesive.](image)

The SCRIMP method was used to infuse the preforms. Araldite LY-564/Hardener XB3486 system produced by Huntsman was employed to form the matrix.

4. Observations and discussion.

The maximum deposition rate at this moment is 0.7 kg of carbon fibre per hour. This rate has been achieved by programming the robot to follow a smooth path. However, the accelerations involved in guiding the carbon tow around the pegs limit severely the rate of deposition.

To the moment, a few components with sculpted surfaces have been manufactured. Several samples were cut from each composite to inspect the quality of the final composite visually and with the aid of the microscope.

The experiments have shown that the use of the adhesive spray Aerofix 3 helps to keep the carbon yarns in place, to minimise the shrinking of the fibres and the expansion of the loops, and to add stiffness on the fibres when they are released by removing the central pins, Figure 11.

![Figure 10. Gaps in between the tows left after pin-plate removal.](image)

![Figure 11. Preform treated with the adhesive in spray.](image)

All the composites presented dry fibres in their thickest region. This is the result of an inadequate technique of infusion. The vacuum bagging method followed in the laboratory works fine for preforms not exceeding 5 mm thickness. But from these experiments is evident that the standard
methodology employed does not work well with preforms with more than 10 mm thickness.

Applying and excessive quantity of Aerofix 3 on the surface of the preform produces holes around the loops where is expected a resin rich pocket.

In the sample AH1N2, figure 14, a reduced quantity of Aerofix 3 adhesive was used and the resulting quality of the surface improved significantly however there was some fibre misalignment after removing the central pin plate of the mould.

**Figure 12.** Microphotography of the sample showing voids in the ply-drop region.

**Figure 13.** Defects on the surface of a preform caused by excessive application of Aerofix 3 product.

**Figure 14.** Preform without surface defects due to the application of a less quantity of Aerofix 3.

### 5. Conclusions and future work

Automated manufacturing of composites from dry fibres is an area with great potential for future research. This work has demonstrated that it is feasible to manufacture composite structures with the RDFP process. However, there is a considerable amount of work to be done to take the RDFP process to a level of development that allows its use in industry for mass production of composite parts.

The pin frame must be redesigned to minimize the waste of fibres in the borders of the preform.

The pin frame must allow a quasi-isotropic configuration with the next orientation and lay-up sequence 0/+45/90/-45/-45/90/+45 (8 layers).

A tool for extracting the pins in the middle part of the mould must be designed and built to ensure and even extraction and minimize the damage on the fibres, help to remove the sample form the mould in a clean an efficient way when using less adhesive.
The algorithm must be improved to avoid any potential for collision. At this point there are still some collisions between the tool and the pins. And the yarn is not uniformly distributed leading to gaps.

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References