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Procedia CIRP 00 (2019) 000–000

www.elsevier.com/locate/procedia

2nd CIRP Conference on Composite Material Parts Manufacturing

Automated fixation of dry carbon fibre fabrics with RTM6 for autonomous draping and sensor-aided preforming

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Abstract

Manual preforming of dry carbon fiber (CF) fabrics is still one of the biggest cost factors for infusion process. Compared to the manual preform process, the difficulty for the automated process lies in pick-and-place system, in gripper deformation depending on component's curvature and in fixation of all the individual CF layers. DLR has developed gripper for fully automated pick-and-place system, which can manage challenges caused by material properties such as low material rigidity and draping for complex geometry. Until now, thermoplastic binding material or double-sided adhesive tape was used for fixing the CF layers. The main focus of this work is the combination of the newly developed fixation method with RTM6 resin and gripper system. Due to subsequent infiltration with the same resin additional binding material can be avoided. For new automated preform process fixing end-effector sprays automatically a thin layer of RTM6 (0,094 g/m) on the surface before placing the fabric. The resin quantity and spray position depends on CF layer size and deformation of gripper. The resin can also be applied during the lay-up process. Thereafter adhesive bonding between fabrics or between fabric and mold is generated by applying a minimum pressure with the gripper. As the gripper is developed for best draping process the fixation area, where pressure must be applied, has been simulated. Only on these simulated positions RTM6 has been sprayed automatically with robot. Afterwards the additional press-on movement for robot was realized with automatic pick-and-place system. This complete automated preform process has been validated on full scale Pressure-Bulkhead demonstrator.

Keywords: Stacking; Fixation of dry carbon fibre layers; Automated CFRP manufacturing; Preforming; Robot

1. Introduction

The Carbon Fiber Reinforced Plastic (CFRP) has an enormous potential to fulfil the requirements of high strength with lower weight, but the complex and manual production processes associated with these materials highly increase the production cost and production time, therefore an automatic and thus an economical production process of these materials is required. To reduce production cost, industry has a growing interest in the manufacturing process automation with robotic systems. The VARI process [1] (Vacuum Assisted Resin Infusion) is a cost-effective manufacturing process. The VARI process developed at DLR-IBK is a resin injection process with a one-sided mould, which takes place under atmospheric pressure. To automate this production process special grippers are developed at DLR to carry out the layup process of the preform. The fixation of the draped carbon fibres cut pieces onto mould succeeds still manually by using a magnet or thermoplastic a binder. Both of these fixing methods are time-consuming and cost-ineffective processes [2, 3]. Furthermore, the influence of the binder's compatibility with the resin (RTM6) to be infiltrated and the effect of added amount of binder on mechanical properties of cured component must also be taken into account [4]. Fixing the first fabric on the mould requires a detachable joining process. After infiltration, the component must be separated from the mould again without damaging to the component or mould. In addition, subsequent layers must be fixed together with the lower layers.

DLR Augsburg has developed a cohesive bond technology by using the matrix material. After applying a controlled quantity of the resin material on some specific spots of a CF ply, pressure needs to be applied to fix this ply with the component or with subsequent plies. Moreover, an infiltration is carried out with the same resin material. Therefore, the fixing spots on the cured component become invisible. The advantages and disadvantages of these suitable selected methods could be proven experimentally [5]. It could be shown that the RTM6 method was the best choice based on cost-utility analysis. Several experiments were conducted on the surface of at component to determine the distribution and the quantity of the resin to be

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used. Based on dispensing requirements Fixing End-effector was developed 1. Experimental results of automated fixing of preform package on component are discussed is short in paper [5]. In this work automated preform process was applied to manufacture a pressure bulkhead with approx. 4 m diameter. Three different gripper system and a fixing End-effector were used for lay-up system. The experimental results are analysed in this work in detail.

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Figure 1: Developed Fixing End-effector

2. Deformable gripper system

A particular challenge in this context is the automated preforming process of double-curved components. In this process, large-area semi-finished fiber products are transferred from a flat state into a three-dimensional state. Three different End-effectors (End-effector for endless lay-up, End-effector for intermediate lay-up and End-effector for cooperating lay-up) were developed at the ZLP Augsburg for this process step. End-effector for intermediate lay-up is the modular gripper, was developed in cooperation with the company Schmalz from DLR. It is capable of transferring its 127 suction surfaces from a flat state to a three-dimensional geometry. This is made possible by a vortex-rib structure. The vortex is realised by two glass fibre rods which are deformed by three linear actuators to create a single curved surface. In addition, the End-effector has 15 independently controllable ribbed modules, which create an additional curvature and thus a double-curved total surface.

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Figure 2: Gripper developed at ZLP Augsburg for preforming large-area, double-curved aerospace components

With this gripper system, it is possible to pick up semi-finished fibre products, shape and drape them and place them in the mould. Figure 2 shows the modular gripper. Due to the double-curved deformation and the resulting path difference, stresses arise along the fiber orientation, resulting in relative movements between the semi-finished product and the suction surfaces. Figure 3 shows this effect graphically. In theory, the slip vectors are zero along the bisectors and maximum along the fiber direction. Since additional friction and adhesion effects must be expected, it cannot be guaranteed that the theoretical case will occur. It must therefore be expected that the fiber cut piece was not optimally draped or its position on the gripper changed and is no longer at the expected position. In order to understand and control this effect, it is essential to record and evaluate the relative movements using sensor systems.

For the automated draping process a new optical sensor system was developed. This system is capable of detecting the relative movement between the fiber material and the active surface and can be integrated directly into the suction surfaces. In this way, the system is able to monitor the draping behaviour and thus draw conclusions about the draping quality and the final position of the semi-finished fiber product on the gripper.

2.1. *Calculation of contact area between gripper and component*

For the offline programming process a software tool was developed. This tool is able to optimize the process parameters of the gripper system, which defines the deformed geometry of the suction surface and the position of the gripper during the placement of the fiber cut-piece. To do so this tool is using a digital twin of the gripper system and the mould to evaluate the given process parameters. The optimization is based on an iterative process by checking the distance of each suction unit and the moulds surface.

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Figure 3: Sliding effects of fiber fabrics during double-curved deformation

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Figure 4: Calculation of the distance or the contact status of between suction surfaces and mould surface

3. Fixation

Several experiments [9] were carried out to determine the influencing factors such as probable distribution and quantity of RTM6 required for holding the plies as well as fixing force. It could be observed that a thin layer of RTM6 and applied pressure plays a major role for higher fixing force. Further details about the fixation process and developed End-effector are published in papers [9, 8, 5]. It could be noticed that fixing force can be increased by increasing applying pressure on CF layers after draping. The End-effector for endless lay-up to be used for draping the lower CF layers can bring enough pressure throughout a contact area of a CF ply. The modular gripper End-effector to be used for draping the intermediate CF layers can also apply enough pressure through the contact area of the specific vacuum grippers. The resin will be applied only on the spots, where the modular gripper End-effector can bring pressure after draping a ply. The End-effector for cooperating lay-up to be used for draping the upper CF layers can apply pressure only through the area as shown in figure 5. These suction cups are very soft compare to other gripper surface. Therefore, for fixing process, the minimum required pressure was determined experimentally with these suction cups, described in next paragraph.

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Figure 5: One of seven module of End-effector for cooperating lay-up

3.1. Parameter study

Experimental setup for the preparation of specimen is illustrated in figure 6. One module of the End-effector was assembled with liner axis (see figure 6). The weighing machine was set to zero after putting the CF plate on it. Due to the structural limitation of the module, soft suction cups could be compressed up to 10 mm. The travelling distance of the module of the end effector was noted from scale. The module was brought down slowly to apply pressure on the ply for 1 minute. The pressure was applied only on the spots on the ply, where the resin has been delivered. When the module travels approximately 5 mm downwards after touching the ply, it can bring 0.8 to 1 kg weight on the ply. For 10 mm travelling distance, this value is 3 to 3.2 Kg. All the prepared specimen were then fixed in a CNC machine to determine the force according to travelling distance of the suction cups. In these experiments, the CF plate was fixed to the base and only CF layers were pulled with a constant velocity until it starts to move from CF plate. A force measuring sensor was installed to determine the force.

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Figure 6: Application of pressure

The experiments were carried out multiple times to get the accurate results by modifying two parameters; number of spots of the resin and weight force to be applied. For performing the same experiments for the 2nd ply, the 1st ply was fixed using the double-sided adhesive tapes in such a way that only the 2nd ply was pulled by the CNC machine. It could be observed that the measured force of the 2nd ply is smaller than the measured force of the 1st ply. Because when the resin is used to fix the 2nd ply on the 1st ply, the resin can flow inside both plies after applying pressure due to capillary effect of the CF layer. When the resin is used to fix the 1st ply on the surface of the CF plate, it will be absorbed by one ply only. The average value of the measured force by the travelling distance of 5 mm for the 1st layer 22.92 N and for the 2nd layer is 16.68 N, which is higher than the value of the force 3.468 N required for holding 10 plies of the size 340 mm x 340 mm on a plane inclined at 45.

3.2. Calculation of fixing area

It could be verified that all grippers can apply sufficient force for the fixation. Furthermore, to apply the force all grippers must be formed according to the double-curved surface of the mould. Due to the rigid gripper surface and vortex-rib structure of the modular gripper, it cannot deform 100% according to the mould surface. Therefore the fixing areas must be calculated beforehand for this gripper. The simulation of fixing area for the modular gripper shows in figure 7, that depending on the contact distance between gripper and mould, different pressure are applied to CF layers. The coloured difference shows the distance to the surface. Red, yellow and green means very good contact, good contact and bad contact accordingly.

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Figure 7: Calculation of fixing area

3.3. Experimental Study at large aerospace component

For all 29 intermediate layers the fixing areas were calculated. The fixing process and End-effector was developed as a part of project ProtecNSR. For the demonstration of the automated fixing process a pressure bulkhead was preformed with help of above mentioned grippers and fixing End-effector. After every lay-up resin was applied automatically. The quantity of resin were calculated according to ply size. By considering the robot speed and the required amount of RTM6, the length of the spray pattern were constructed in *CATIA*. *FASTSurf* offline-program was used to generate the robot program (see in figure 8). Prior to this the base-position of the component and the Tool-Center-Point (TCP) for the fixing end-effector was measured. To fix all 59 CF-layers with different sizes 1.2 kg RTM6 was used. For the infiltration process the same amount was reduced. Total spray time was 11 hrs. It is to be noted that only one nozzle was used for the demonstration and the quantity of RTM6 was not optimised for all the CF-layers. For the optimum case, the resin quantity would be reduced linearly from the first to the last layer. Multiple nozzles and the optimum spray quantity and optimised patterns would significantly reduce the process time. Thus, all the CF-layers could be successfully fixed faster and automatically on the pressure bulkhead. In next section a complete automated preform process is described in detail.

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Figure 8: Offline Robot program

3.4. Patch Preforming

The patch preforming process is started with cutting the carbon fibre fabric regarding the draping simulation result. A vacuum gripper assisted transportation system grips the cut-piece from the conveyor belt and places it on a material carrier. A worker moves the material carrier to the robot cell and positions it to a docking station. The docking station guarantees reproducible material carrier position which is necessary for the following cut-piece detection. On the edges of the material carrier markers are mounted which are calibrated to the robot control and to a cut-piece detection system. The system uses an industrial camera mounted on the gripping End-effector to generate high contrast pictures of the cut-piece and an industrial computer for computer vision. The computer vision software detects the cut-piece edge and matches it to the corresponding contour from the draping simulation [6]. After detection a matching factor is generated to inform if the cut-piece is in the correct shape for gripping or if another cut-piece is needed. Following the position on the material carrier regarding the markers is calculated and a distinct grip point is sent to the robot controls. The grip point describes the placement of the tool center point on the cut-piece and subsequently a parametrized robot program is used to place the End-effector on the cut-piece. To grip the cut-piece all of the vacuum grippers are activated on medium force and the End-effector is lifted up 100 mm. Now a defined pattern for the vacuum gripper forces is activated and the deformation is started. The pattern guarantees that the fabric can deform like the draping simulation calculated. During draping gliding sensors in the vacuum gripper surfaces detect the distance the fabric moved on the surface which is compared to the draping simulation deformations. After draping the vacuum gripper forces are set back to medium gripper force to ensure safe handling without dropping the cut-piece. Since the position of the cut-piece on the material carrier is random due to the manual transportation an inline path planning software (CoCo) is used to calculate the robot path into the tooling. An explicit drop point for the cut-piece and the actual robot position after draping are send to CoCo. The software uses RRT-connect algorithms to calculate a collision free and reachable path [7]. The robot path is described through several frames. The frames are send in the corresponding order to the robot controls. The parametrized robot program is then used to move the robot from frame to frame until a location directly above the drop point is reached. The deformed End-effector with draped cut-piece above the individual prepared drop location is shown in figure 9.

A slow movement into the tooling and onto the drop point completes the cut-piece transfer. The vacuum grippers are deactivated and a holding time of ten seconds ensures that the resin can penetrate the fabric to generate enough adhesion force for the fixation. To finish the preforming cycle the same path for the transfer is used reverse to ensure collision free and reachable transfer back to the material carrier. The last movement of the robot positions the End-effector back to its detection position for the next cut-piece and deforms the End-effector back to its plane configuration. Now the next detection, gripping, draping and placement cycle is started until the patch preforming is finished.

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Figure 9: Draped cut-piece on End-effector above prepared drop position

4. Optimisation of fixing process

The aim of project was to develop an automated fixing process for CF-layers. The advantages and disadvantages of these suitable selected methods was validated experimentally. It could be shown that the cohesive fixing method with RTM6 method fulfils automation criteria. Several experiments were conducted to determine the fixing area and the quantity of the resin to be used. From the experiments conducted to determine the fixing force of a ply increases up to a certain level as the pressure being applied on the ply is increased and the end-effector for cooperating lay-up is also able to bring enough pressure to fix the plies. All the 59 long and intermediate CF-layers were fixed with this new method. It could be observed that the spraying time for the large scale demonstration above was relatively long, compare to other preform process. The time can be reduced by implementing multiple spray nozzles and optimizing the spray quantity. In the scope the project ProtecNSR, for every CF layer the resin quantity was calculated such a way that each CF layer can hold 8 subsequent layer on it. By optimising the this resin quantity, fixing process time can also be reduced. Furthermore the End-effector was developed for portal robot, which resulted that the end effector was extended up to 2 m because of the accessibility to mould.

4.1. End-effector development

Therefore the End-effector was further optimised in order to reduce the time and to achieve better acceptability. Therefore the new End-effector is developed with two nozzles, which were mounted at a 45 degree angle to each other. For the better acceptability a industrial robot was used and the length of the End-effector was reduced to 1 m. Thus the spraying time could be reduced to half. By implementing further nozzle the fixing time could be reduced linearly. It could also be observed that due to the two nozzle with 6 bar pressure small CF layers tend to slip. Another disadvantage of this nozzle is that it has to be cleaned frequently. Otherwise the resin will block the nozzle.

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Figure 10: End-effector with double nozzle spray

5. Conclusions

In this thesis, a cost-effective, reliable and automated fixing method was presented and successfully demonstrated using a preform process. From the experiments conducted by building the test station in the CNC machine, it has been concluded that the fixing force of a ply increases up to a certain level as the pressure being applied on the ply is increased and all grippers are also able to bring enough pressure to fix the plies. Throughout the time period of all experiments, it was noticed that the quantity of the resin dispensed by the dispenser varied slightly even at the normal room temperature fluctuation, therefore the lay-up process of carbon fiber plies must be carried out at a constant room temperature. Moreover, the quantity of the resin dispensed by the dispenser varied with respect to the time of storing the resin at a normal room temperature, therefore it is highly recommended to use the fresh resin, which is preserved at -18C. The distribution of the resin for fixing the intermediate layers with different shapes depends heavily on the ability of the modular surface End-effector to apply pressure through the specific grippers. The Fixing area for each intermediate ply was calculated beforehand. For the optimization of the method, further nozzle types should be investigated in the future on the one hand and the resin quantity should be reduced on the other hand.

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