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A SOLUTION TO MANUFACTURE STRUCTURAL PARTS WITH CONCAVE SURFACES BY ROBOTIZED FILAMENT WINDING

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Abstract: The present work shows how to manufacture composite full section parts with concave surfaces by robotized filament winding technology. It considers the family of structural parts whose shape may be obtained by sweeping a full section along a closed not auto-intersecting 3D curve.

The part used to introduce the manufacturing method has concave surfaces where the roving deposition is hardly accurate. It has been produced by a robotized cell where pneumatic devices, that are automatically synchronised with the movements of the deposition system, allow to wind the roving on concave surfaces by avoiding fibre bridging and by favouring fibre compactness. Those solutions have been designed and implemented in a cell adopting an anthropomorphic robot.

Some tests have been carried out to evaluate the physical and mechanical properties of the composite parts manufactured by adopting the proposed technical solution. The obtained results show that it is possible to control the strength of the manufactured composite part by accurately setting the process parameters used during winding, such as winding tension and air pressure of the auxiliary devices, since in this way the percentage of composite constituents (resin, fibres and voids) is accurately set.

1 INTRODUCTION

The present work shows all the steps to manufacture composite full section parts with concave surfaces by robotized filament winding technology.

Robotized filament winding technology implies a robot that winds a roving impregnated by resin on a die along the directions of stresses the work-piece is submitted to in exercise. The robot moves a deposition system along a winding trajectory in order to deposit roving. Then, the part on the winding die is coupled with the closed die and put into the furnace. This process is characterised by a high repeatability, flexibility and quality for small batch production of parts, not only for aeronautic and aerospace industrial fields. The robotized cell configuration aims to minimise deposition time and, then, to spread this process in fields near mass production [1-5].

The present work considers the family of structural parts whose shape may be obtained as a result of the sweeping of a full section along a closed not auto-intersecting 3D curve. In particular, this 3D curve represents the path to move the full section barycentre (i.e. called barycentre path) in order to build the part shape. The composite roving used to manufacture the component has an approximate rectangular section smaller than part full section. Therefore, the part full section filling can be obtained by moving the roving section inside the part full section. The roving wound on the die is oriented as the barycentre path that is the direction of stresses applied to the part in exercise. Independently by stratification, the path along which the roving has to be wound is generated by offsetting the barycentre path up to the barycentre of the roving section; it is called base path. Each coil is due to the sweeping of the roving section along the base path. Then, the trajectory along which the deposition system should move in order to wind the roving along the defined base path needs to be defined; it is called winding trajectory. To guarantee an accurate winding of the roving on the support, the winding trajectory must be planned in order to keep the tension on roving as constant as possible and to avoid collisions among the deposition head and the robot arms. The constancy of the tension allows to align the roving on the die along the direction of stresses applied to the part in exercise [6-9]. The collisions are avoided by defining a proper value of the safety distance between the deposition system and the winding die.

The present work focuses the attention on the structural parts, belonging to the previously introduced family, with concave surfaces. A concave surface may imply defects inside the manufactured part, due to the formation of bridges during winding. A bridge forms for a no mating constraint between the roving and the concave surface of the die during winding, due to the tension applied on the roving. The bridge generates a no uniform stress applied to the roving, when the part is closed between the dies; it carries out a residual stress inside the part when the polymerization is ended. This residual stress causes delaminations that may bring the part to crack.

This work aims to present the technological solutions introduced in a robotized filament winding cell to manufacture the parts shown in Figure 1 without defects due to bridging. Those solutions have been designed and implemented in a cell adopting an anthropomorphic robot [10-12]. Many tests have been carried out to evaluate the presence of marcel, delamination and porosity inside the manufactured samples.

The obtained results show that it is possible to have defects (marcel, delamination and porosity) inside the manufactured parts by accurately setting the process parameters used during winding, such as winding tension and air pressure of the auxiliary devices.

2 CASE STUDY: A PART WITH THREE CONCAVE SURFACES

A component of the tail rotor hub of an helicopter has been considered to exemplify the effectiveness and efficiency of the proposed method. It is a plane ring of 10 mm thickness, whose boundary surface has three concave zones, as shown in Figure 1. It is subjected in exercise mainly to a tensile stress along the direction of ring main dimension. Therefore, the roving needs to be oriented along the direction of the applied tensile stress.

The robotized filament winding technology needs to be used in order to place the roving oriented according to the direction of the tensile stress that is applied to the ring in exercise. The plane ring has been manufactured in carbon roving (width of 3.175 mm) impregnated by epoxy resin.

The plane ring includes a bush constituted by glass fibres, shown in Figure 2, that allows to couple the ring with the blade of the helicopter. A further component, constituted by moulding compound, called filler and shown in Figure 3, fills the zones of the ring whereas it is no possible to place the roving in a right way. The 3D model of the considered ring may be built as the sweeping of a rectangular section along a closed not auto-intersecting 2D curve. This 2D curve is called barycentre path; it has three zones with a concave curvature. The composite roving has an approximate rectangular section smaller than ring rectangular section. The winding of the ring is obtained by moving the roving section from one place to the other, after a while round around the die, inside the ring rectangular section through coils. A coil represents the movement of roving section on the winding die along a 2D curve obtained by offsetting the barycentre path (see Figure 3). A continuous deposition is implemented from coil to coil up to constitute a roving layer deposited on the die and, then, from layer to layer.

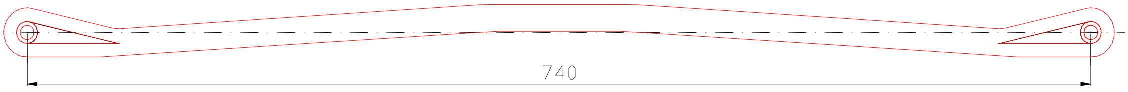


Figure 1: Dimensions of the plane ring in mm

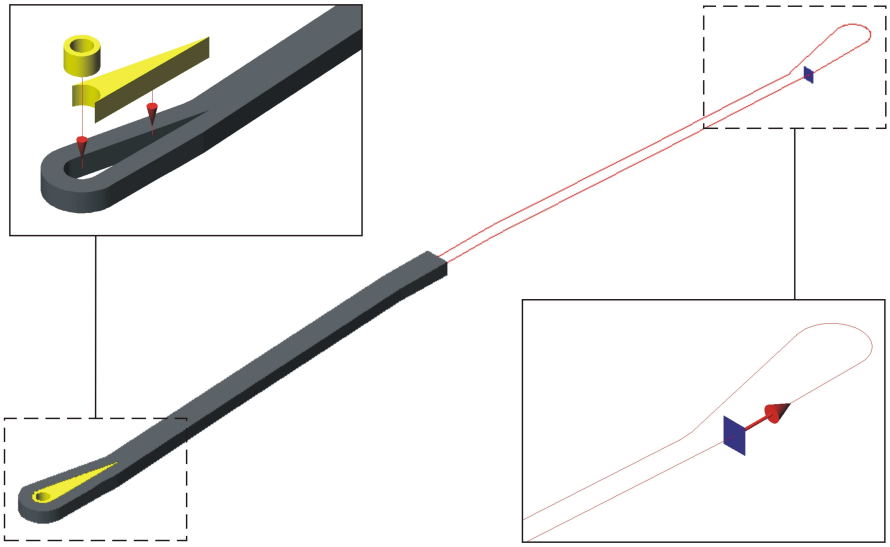


Figure 2: 3D-view of composites part considered

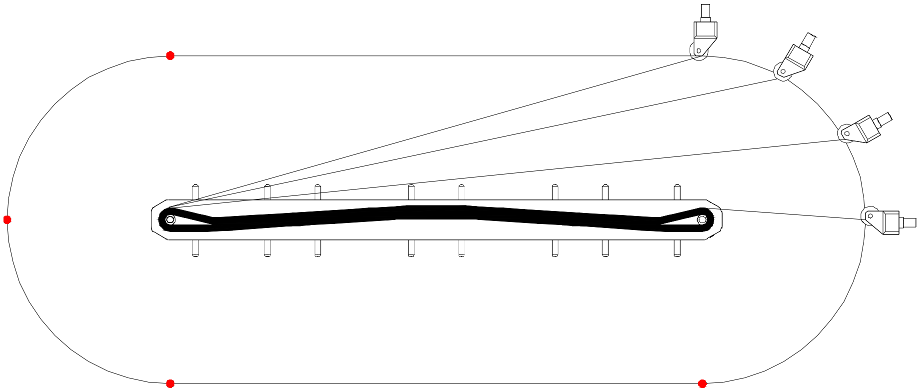


Figure 3: Roving movement to wind the plane ring

3 ROBOTIZED FILAMENT WINDING CELL

The considered part has been wound by a robotized cell constituted by an anthropomorphic robot, a unique and innovative feeding device and a winding die [10-12], as shown in Figure 4.

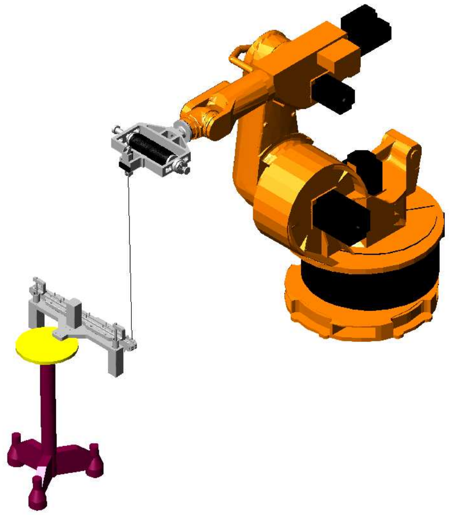


Figure 4: Robotized filament winding cell

The robot is an anthropomorphic Kuka, with 6 d.o.f., payload 45 kg, max. reach 2041 mm, work envelope volume 24 m^3, repeatability <± 0.15 mm. The feeding device shows a modular structure constituted by four critical subgroups or modules: the main frame, the roving-guide system, the winding tensioner and the deposition system. It is compact, light and stiff in order to favour the maximum dexterity of the robot and to reduce the probability of crashes among the components of the cell. The winding die is constituted by two plates that are kept distant by the bushes of the plane ring previously introduced [10-12], as shown in Figure 5. The accuracy of the winding die influences the shape and the mechanical performances of the composiste workpiece.

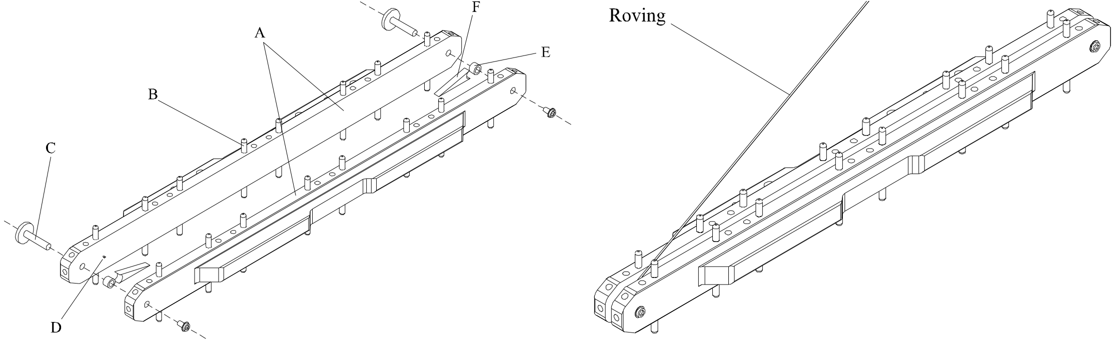


Figure 5: Winding die: A: plates to contain the fibre; B: reference pin; C: flanges; D: bushes; E: filler; F: pin to position the filler

The winding die has been equipped with three pneumatic devices to force the roving, once it is placed on the die, to adhere to the three concave surfaces of the die (see Figure 6); thus avoiding the forming of fibre bridging during roving deposition (see Figure 7a). These pneumatic devices allow to keep the roving pressed on the die too. The tension, that is applied to the roving during winding to avoid its torsion, allows to press the roving on the die where the die presents convex surfaces. This pressing action is as higher as lower is the value of the bending radius of the surface where the roving is placed. It is practically null when the roving is placed on planes or concave surfaces. These devices may rotate around an axis and may translate along the same axis by means of pneumatic actuators in order to approach or to go away the concave surface of the die on which the roving needs to be placed, as shown in Figure 7a.b. The movement of these pneumatic devices is synchronised with the movement of the feeding device that is mounted on the robot arm by means of the robot controller.

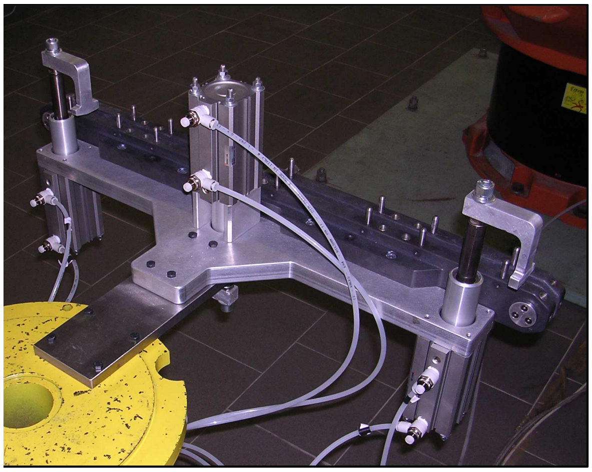


Figure 6: Winding die equipped with three pneumatic devices

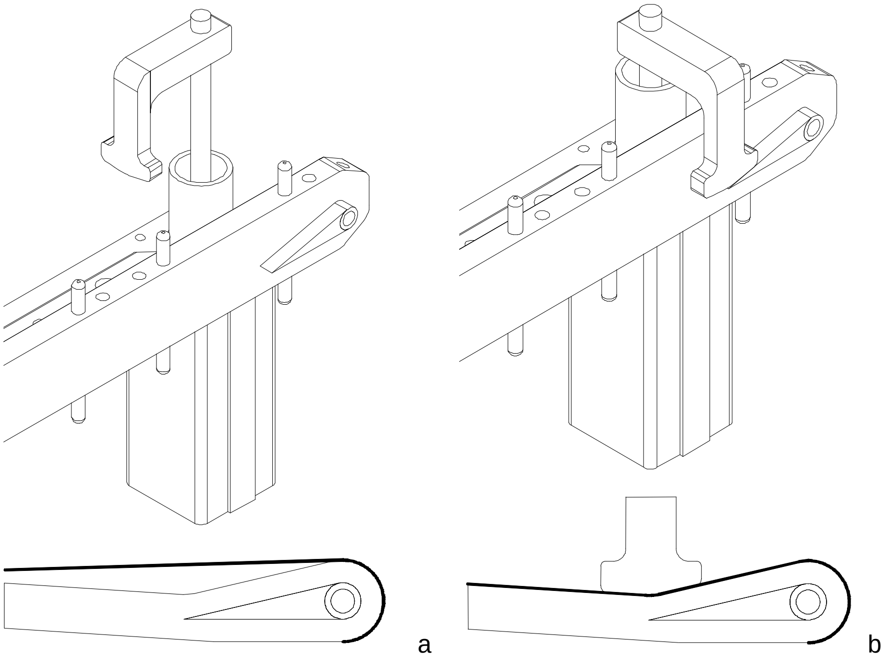


Figure 7: Movement of pneumatic device: a, open; b, closed on the die

4 ROVING WINDING PROCESS

The planning of the process to wind the plane ring has involved the definition of the trajectory to wind a single coil and, then, the identification of the sequence of coils to define the layers that constitute the work-piece section. For each coil the trajectory of the deposition head has been planned by offsetting the barycentre path at a distance of 200 mm from the winding die, as shown by the continuous line in Figure 8. The obtained trajectory is a sequence of straight and circular curves, i.e. a regular path, that avoids the sudden change in deposition head’s direction and, therefore, makes the occurrence of tension loosens unlikely. In the same time, this kind of trajectory allows to decrease strongly the winding time, if compared with alternative logics of trajectory planning.

The value of the winding tension has been fixed to 70 N, since we have demonstrated in previous works on convex parts that this value of tension assures good performances of manufactured composite parts 11, 12]. The value of the air pressure of the devices used to keep in position the roving placed on the die during winding is equal to 5.5 bar, since this is the lowest value assuring to avoid fibre bridging. The nominal winding speed of the deposition head, that is expressed as the percentage of the maximum linear speed of the robot arms (equal to 2 m/s,) has been fixed to 75%. The movements of the three pneumatic devices have been synchronised with that of the deposition system to wind each coil of roving on the die (see Figure 8).

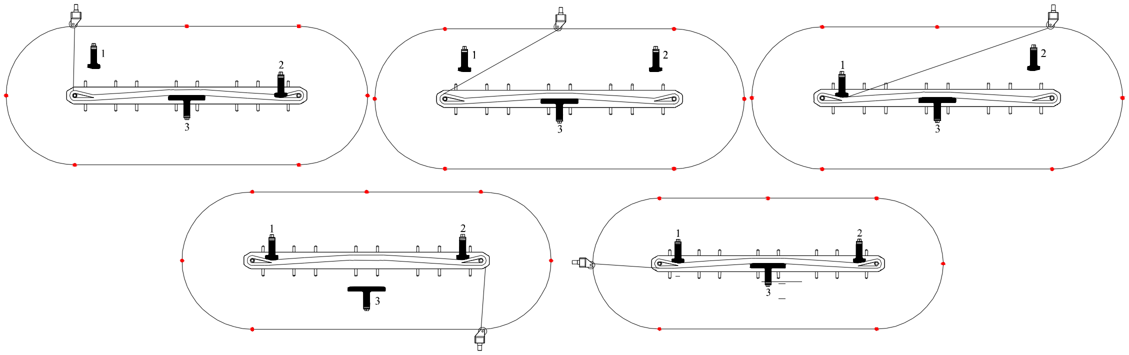


Figure 8: Movements of the three pneumatic devices during a single coil winding

Once defined the winding trajectory to obtain a single coil, it has been planned the number and the sequence of the coils to deposit on the die in order to obtain a part with the designed shape and mechanical performances. Analysing the relationship among the ratio between fibres and matrix, the number of wound layers of roving and the density of the part after compactness, of convex parts manufactured by robotized filament winding process, three values of the number of layers to wind have been defined, 27, 28 and 29, in order to assure a porosity inside the part that does not compromise the mechanical performance of the part, as presented in the following. Two rings have been manufactured for each value of the number of layers, since each ring involves a long time to wind and to polymerize the composite material inside the autoclave (about 3 hours). Since the tape is wide 3.175 mm, 5 coils have been used to fill the width of the benchmark of 10 mm with an overlap of 1.475 mm between two following coils. Figure 9 shows the sequence of coils to place on the die in two sections of the part. Table 1 shows the winding time.

The analysis of the defects inside the manufactured parts has underlined that the possible causes may be the stress on roving when it is placed on the winding die and the scarse pressure on the roving to make it adhere to the die. Therefore, the tension value has been decreased to 60 N, while the air pressure has been increased to 7 bar in order to experimentally verify if the part quality improves. Further three rings have been manufactured with the new values of tension and air pressure; one ring for each number of layers (27, 28 and 29 respectively). In the following paragraphs the results of non-destructive and destructive tests on the manufactured rings are deeply described.

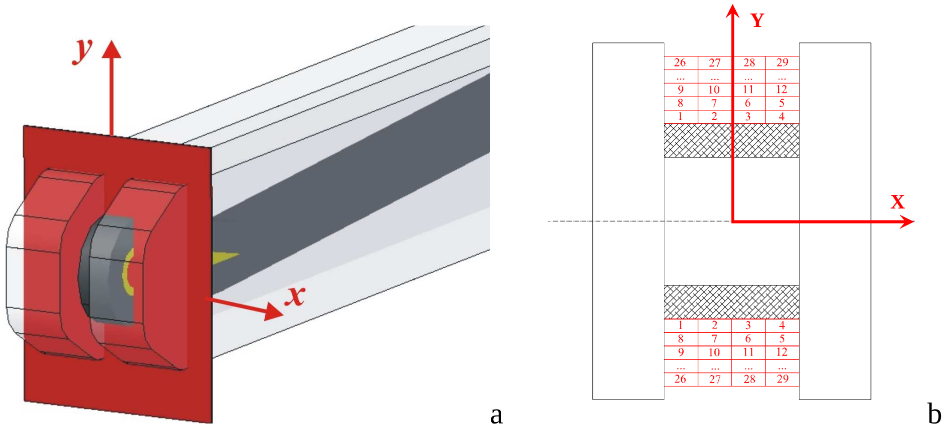


Figure 9: Coils sequence in eye section

Table 1. Winding time

Deposited Layers [#]	Winding time [s]
1	**298**
27	**640**
28	**663**
29	**687**

5 CLOSURE OF DIES AND POLYMERISATION

Once the winding process is ended, the winding die has been coupled with the closed die by means of reference pins in order to compress the work-piece, as shown in Figure 10. The design of the closed die has provided a set of plates to couple with the winding die in order to simplify the assembly stage, but in the same time improving the homogeneity of the part, decreasing the voids presence and increasing its density. The alignment of the dies is very important to assure the alignment of the fibres and to avoid pinching and wrinkles.

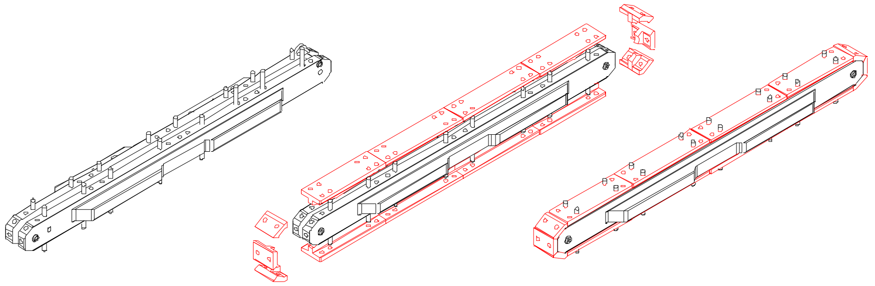


Figure 10: Closure between winding and closed dies

Once the component have been closed between the winding die and the closed die, it has been placed inside an autoclave to carry out the curing process. Curing conditions have used a heat up rate of 2÷3°C/min, a temperature of 125±3°C for a time of 90 min and a pressure of

2.7bar, a cool at 60°C. Finally, the benchmarks have been pulled out the die (see Figure 11) and they have been subjected to tests in order to identify the quality and therefore the acceptability of the part.

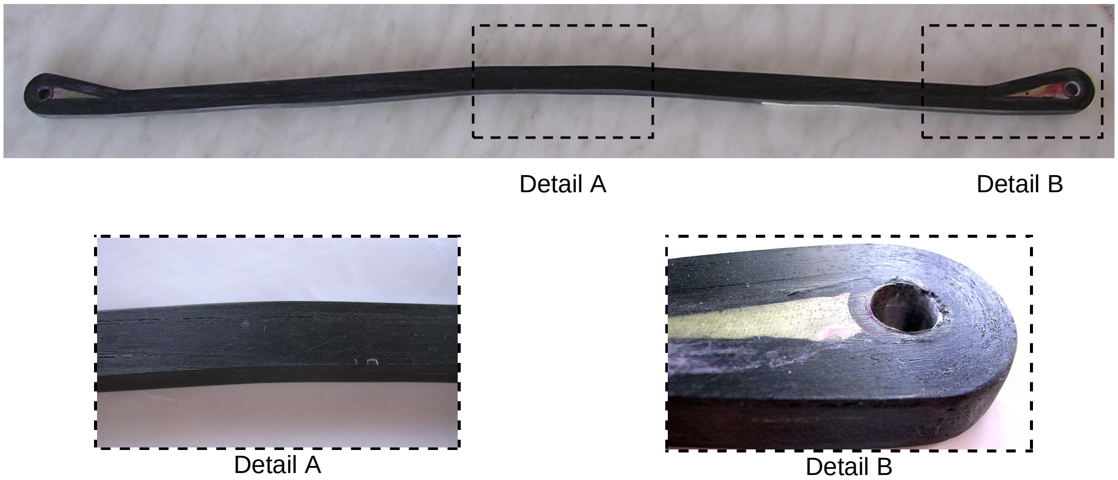


Figure 11: Manufactured part

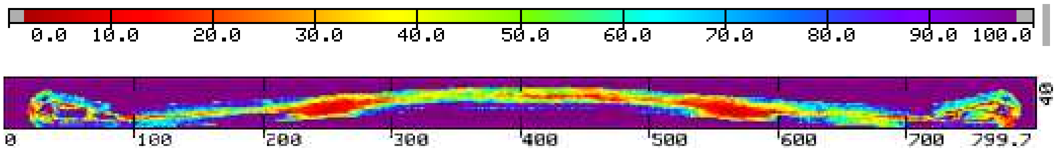
RESULTS DISCUSSION

A first visual inspection of the manufactured rings has underlined that their boundary surfaces do not present any wrinkle or pinching. To notice the presence of marcel and delamination a X-rays inspection has been carried out. No marcels are present inside all the manufactured rings that they have been classified inside the class 1. However, the presence of delaminations inside the rings manufactured with a tension value of 70N and an air pressure of 5.5 bar has led to classify them in classes 3 and 4 connected with a scarce quality level according to radiographic standards defined by aeronautic firms. These standards take into account the type, the dimension and the location of defects inside the part.

The decrease of the winding tension to 60N and the contemporary increase to 7 bar of the air pressure of the devices used to force the roving to adhere to the die surface carry out the absence of delamination inside the manufactured rings that are classified inside class 1. In fact, these two correlated actions, the reduction of stresses on roving during winding and the increase of the pressure on roving, when it is placed on the die, seem to improve the homogeneity and the compactness of component.

Finally, the presence of porosity inside the manufactured rings has been investigated by a test that uses ultrasounds. The part is plunged into water and it is invested by ultrasounds; the presence of porosity inside a part reflects the ultrasounds and carried out to generate a signal on an oscilloscope with an attenuate modulus. The rings manufactured with a roving tension of 70N and an air pressure of 5.5 bar include an amount of porosity such that the resulting composite strength assumes an unacceptable value. Those rings belong to the classes 2, 3 and 4 of the scale commonly used to qualify aeronautic parts, according to the number of layers used to wind them, 29, 28 and 27 respectively (see Figure 12). The ring constituted by 29 layers include the lowest amount of porosity.

To evaluate the effect of the process parameters' variation (tension decrease to 60 N and air pressure increase to 7 bar) on the amount of porosity included inside the ring, a further ring has been submitted to ultrasounds analysis. This ring is constituted by the number of layers that has previously carried out to have the lowest porosity, i.e. 29. The analysis has underlined no porosity inside the ring that has been included in class 1, as shown in Figure 12.



27 layers – Class 4, T=70; p=5.5bar

28 layers – Class 3, T=70; p=5.5bar

29 layers – Class 2, T=70; p=5.5bar

29 layers – Class 1, T=60; p=7bar

Figure 12: Chromatic map of three rings manufactured with a winding tension of 70N

6 CONCLUSIONS

The present work shows how to plan and to carry out the manufacturing process of a structural part in composite material with concave surfaces. The roving winding process involves the use of pneumatic devices together with the control of the pressure exerted by these devices on the roving that is wound on the die. Once the winding process is ended, the obtained component has been closed between the winding die and the closed die and it has been placed inside an autoclave to carry out the curing process. The developed process has been implemented for different values of the winding tension and of the pneumatic devices air pressure to manufacture some samples that have been submitted to non-destructive tests.
The results show that no marcels are present inside all the manufactured samples. However, the presence of delaminations inside the samples manufactured with a tension value of 70N and an air pressure of 5.5 bar has led to classify them as unacceptable according to radiographic standards defined by aeronautic firms. The decrease of the winding tension to 60N and the increase to 7 bar of the air pressure of the pneumatic devices carry out the absence of delaminations inside the manufactured samples, since the homogeneity and the compactness of the samples are improved. Finally, the presence of porosity inside the manufacturing samples has been investigated by a test that uses ultrasounds. The samples manufactured with a roving tension of 70N and an air pressure of 5.5 bar include an amount of porosity to result unacceptable, while those due to a roving tension of 60N and an air pressure of 7 bar are characterised by no porosity.
Further destructive tests to evaluate the percentage in volume of fibres, resin and voids, the composite density and strength are current matter of study.

7 ACNOWLEGEMENTS

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