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Estimation of the winding tension to manufacture full section parts with robotized filament winding technology

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Abstract—Winding tension is a very critical parameter to be controlled during the manufacturing of composite parts by robotized filament winding technology. In fact, the winding tension influences directly the defects and the mechanical properties of composite parts.

The nominal value of the winding tension that has been set in order to obtain a good roving alignment and compactness inside the composite part is not equal to the actual value acting on roving during the winding. The difference between the nominal and actual value of the winding tension is due both to the typology of the winding trajectory that has been set and to the agents that are external to the technological process and consequently hardly controllable. Therefore, once the value of the nominal winding tension has been set and the geometry of the part to be wound has been fixed, it is necessary to act on the geometric parameters of the winding trajectory in order to guarantee that tension acting on the roving during the winding is as near as possible to the nominal value.

The present work shows how using a unique parameter, the actual trajectory angle characterizing the planned winding trajectory, it is possible to estimate quickly and easily the average value of the tension acting on the roving once the nominal winding tension and the geometry of the part to be wound have been chosen. In this way it is possible to decide which winding trajectory typology is prefereable in order to manufacture a composite part of good quality.

Keywords: Winding tension estimation; winding trajectory; filament winding; robotized cell; full section parts.

1. INTRODUCTION

Robotized filament winding technology coordinates the relative motions of a feed-deposition system and a winding die in order to manufacture a composite part by an industrial robot.

Winding tension needs to be controlled for robotized filament winding technology, since it influences directly the compaction and the alignment of the fibres [1].

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Composite resistance against loads applied along roving deposition direction of the resulting part is due both to the presence of defects in the work-piece and to its fibre percentage [2, 3]; the higher the fibre percentage per unit volume, the greater is the work-piece mechanical resistance. It is possible to adjust the amount of fibre for a unitary volume by means of winding tension that influences fibre compactness.

The choice of the value of the winding tension and the need to keep the winding tension constant at the chosen value are two aspects strongly connected to the geometry of the part to be wound. The present work focuses on full section parts. It is impossible to manufacture these kinds of parts by traditional technology, while it is possible, even if complex, to obtain them by robotized filament winding technology. The deposition system should move along a critical winding trajectory. A critical winding trajectory means a trajectory where bending and sharp direction shifts cause fibre unfastenings or speed variations during the roving fibre winding that provoke remarkable inhomogeneities of a manufactured part [4]. The winding trajectory should take account of winding tension loosening, or insufficient fibre compactness, which is particularly evident along rectilinear segments, and roving location inaccuracy. A proper value of the winding tension has to be chosen and kept constant along the whole winding in order to limit the two problems described previously. If the applied winding tension is insufficient, the fibre may present wrinkling or folds along the deposition direction, causing defects in the final composite part (known as 'marcels'). At the same time a very high winding tension value may cause both a fibre damaging and a strong inhomogeneous compactness of the roving along the underlying surface.

Solving this trade-off means to determine the value of the winding tension that allows to minimise the empty spaces, the wrinkling and the folds, and to have a component with a good structural uniformity. Moreover, to guarantee a constant winding tension during winding implies to reduce the roving slippage and loosens of roving that alter the fibres alignment inside the part.

In the literature, some studies exist on the influence of winding tension on composite part quality, even if they are referred to symmetric part shapes that may be obtained by traditional filament winding [5–8]. In previous works we have discussed the problem to set the winding tension value that gives the best performances in terms of roving alignment and compactness [2, 9]. Once the winding tension value has been set, it is necessary to assure that the tension acting on the roving during winding is as near as possible to the set nominal value. In a previous work we have demonstrated how to act on the main winding parameters of the robotized filament winding technology in order to maintain the average value of the winding tension on the roving near to the nominal value that has been planned to have good composite parts [10]. The effect of these main winding parameters on the winding tension may be expressed by a unique parameter, the actual trajectory angle.

The present work shows how using an unique parameter, the actual trajectory angle, characterizing the planned winding trajectory, it is possible to estimate quickly and easily the average value of the tension acting on the roving once the nominal winding tension and the geometry of the part to be wound has been chosen. In this way it is possible to decide which is the winding trajectory to prefer in order to manufacture a composite part of good quality.

The actual trajectory angle, whose value is planned by a CAD/CAM software, is correlated to the average value of the winding tension: increasing the actual trajectory angle involves an increase in the average tension value. The actual trajectory angle allows to choose the winding trajectory whose tension value during the winding is the nearest one to the nominal value of tension. Moreover, the actual trajectory angle may be set by means of the geometric parameters and of the winding trajectory speed, such as the number of points used to approximate the trajectory, the trajectory angle and the safety distance.

The objectives of this work are: (1) to show the relationship among the actual trajectory angle and the geometric parameters of the winding trajectory, (2) to study the relationship between the average value of the winding tension and the actual trajectory angle.

2. TRAJECTORY GEOMETRIC PARAMETERS AND ACTUAL TRAJECTORY ANGLE IN ROBOTIZED FILAMENT WINDING

The method of planning a winding trajectory, which is discussed in detail in Ref. [11], considers a set of geometric parameters that strongly depend on the structural constraints of the robotized cell and on the technological requirements of the process. Those geometric parameters are easy to numerically compute and graphically visualize. They are the number of points (n) used to approximate the winding trajectory, the trajectory angle (θ) and the safety distance (d).

The winding trajectory is constituted by the sequence of points (n), ordered in space, along which the deposition head moves in order to deposit the composite roving on the die. It represents the image of the points of the base path, i.e. points A, A_1, A_2, ... in Fig. 1 that represent the path of the roving to deposit on the winding die. This means that when the deposition head, i.e. the robot end-effector, performs the winding trajectory, it approximates the continuous path by points. The number of points used to approximate the continuous winding trajectory influences the regularity of the deposition head movement. In fact, an increase of the number of points makes the movement of the deposition head more continuous and more harmonious during winding, since it avoids the sudden change in the head's direction. A more and more continuous movement of the deposition head makes the occurrence of tension loosening during winding unlikely and it increases the accuracy and the repeatability in performing the winding trajectory.

The deposition head moves from one point to the following one of the trajectory during winding. The angle that the vector of the deposition head movement from

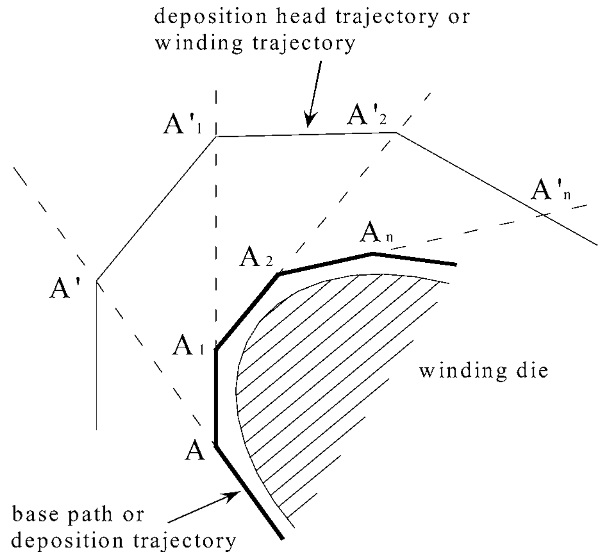

Figure 1. Number of points (n) used to approximate the winding trajectory.

point to point forms with the roving direction is very critical for winding. It is called the trajectory angle and is indicated by θ. The trajectory angle is responsible of tension control of roving during winding. It aims to avoid decrease in the tension value of the roving during winding, i.e. roving loosening. Figure 2 shows the deposition of the roving from point A_1 to point A_2 on the winding die: on the left the roving is placed on point A_1, while on the right it is on A_2. To deposit the roving between points A_1 and A_2, the deposition head moves from point A_1' to point A_2'. During its movement from A_1' to point A_2', the trajectory of the deposition head $A_1'A_2'$ has to form with the roving direction A_1A_1' a θ angle greater than or equal to 90°, in order to satisfy the condition $A_1A_2' \geqslant A_1A_1'$ that avoids loosening of the roving.

The deposition head moves along the trajectory points by keeping at the safety distance (d) from the die in order to avoid collisions with it during winding (see Fig. 3). An increase of the safety distance may avoid collisions between the deposition head or the robot arms and the winding die during winding, especially for small parts. To plan the winding trajectory, the minimum value of the safety distance is fixed; if the distance of the deposition head from the die during winding is equal to or higher than this minimum value, there are no collisions.

The value of the safety distance strongly depends on the value of the trajectory angle. If the value of the safety distance does not satisfy the condition for the value of the trajectory angle previously introduced ($\theta \geqslant 90°$), the value of the safety distance should be increased as far as the trajectory angle can satisfy its constraint. In fact, during its moving from A_1' to point A_2'' along the control volume in Fig. 2 on the right, the trajectory of the deposition head $A_1'A_2''$ does not form with the roving direction A_1A_1' an angle greater or equal to 90°, such as happened when the

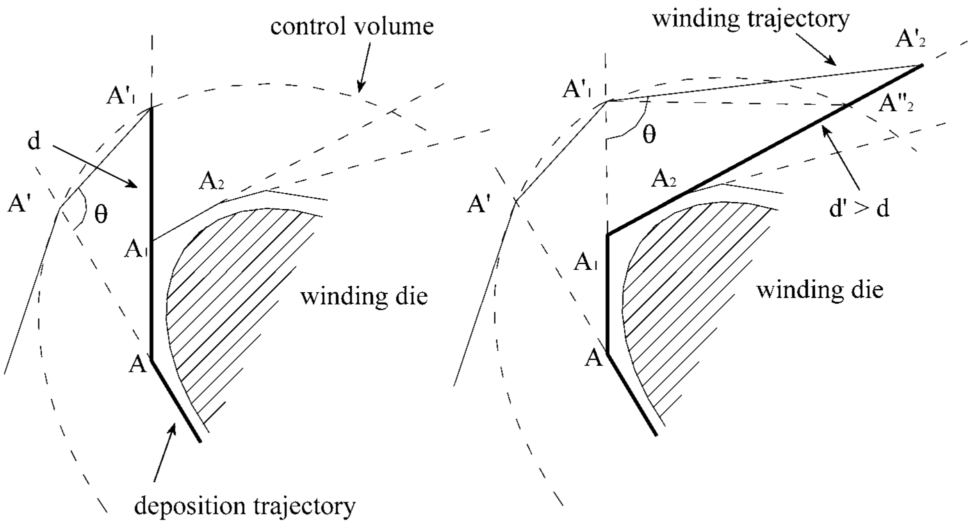

Figure 2. Trajectory angle (θ).

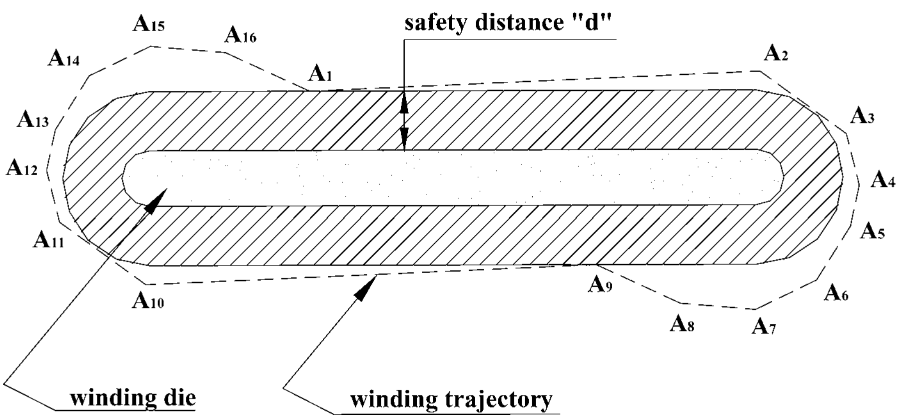

Figure 3. Safety distance (d).

deposition head moves from point A'_1 to A'_2 in Fig. 2 on the right. Therefore, the safety distance must be increased to $d' > d$ in order to have a trajectory angle (θ) at least equal to 90°.

The present work aims to plan the winding trajectory that assures a value of winding tension during winding nearer and nearer to the nominal one, which has been planned to assure roving alignment and compactness. Once the geometric parameters (n, θ, d) have been set, the winding trajectory is planned by means of a software, called Filocad v.4 r.5 [12]. The software generates the part program the robot has to execute together with the values of the actual trajectory angle in each point of the winding trajectory.

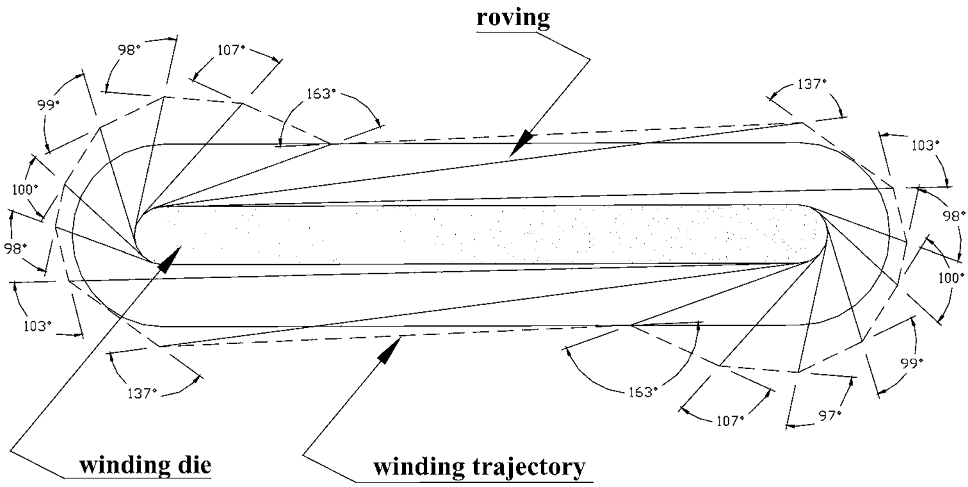

Figure 4. Values of the actual trajectory angle θ^* for each point of a winding trajectory characterised by the following nominal geometric parameters: n = 16, d = 25 mm and $\theta = 95°$.

The analysis of the file generated by the CAD/CAM software underlines how the values of the actual trajectory angle θ^* for each point of the planned winding trajectory are different from the value of the nominal trajectory angle θ that has been set initially. The values of the actual trajectory angle of the planned winding trajectory depend on the number of points, n, that are used to approximate the trajectory, and by the safety distance d. The values of the actual trajectory angle are higher than the value of the nominal trajectory angle θ, which represents a minimum limit.

The nominal trajectory angle θ is the smallest value of the trajectory angle that the trajectory planning should satisfy from point to point. The actual trajectory angle θ^* is the value of the trajectory angle along each point of the trajectory planned by means of a CAD/CAM software. The actual trajectory angle θ^* depends on the two geometric parameters, n and d, whose nominal values are set before planning the winding trajectory.

Figures 4 and 5 show an example of winding trajectory for a benchmark described herein. The present work aims to model the influence of the actual trajectory angle θ^* on the average value of the winding tension characterizing the whole winding trajectory, once the nominal winding tension and the geometry to be wound have been chosen. The average value of the actual winding tension is calculated by averaging the values of the tension measured along the points of the winding trajectory. The relationship obtained may be used to easily set the actual trajectory angle and, therefore, the geometric parameters characterizing the winding trajectory, in order to keep the tension value during the winding near the nominal one that has been planned to have good composite parts. In fact, the nominal winding tension is the value of the tension that has been fixed in order to manufacture work-pieces

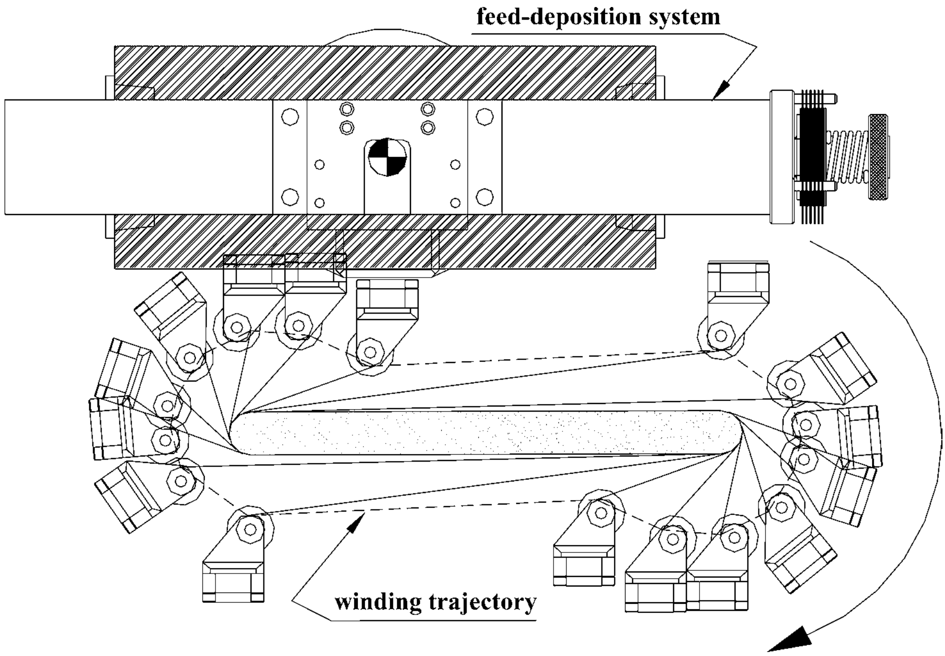

Figure 5. Movement of deposition head along a winding trajectory (n = 16, d = 25 mm, $\theta = 95°$).

characterized by good mechanical resistance performances and few defects inside the part. This value is applied by the clutch on the roving. The actual winding tension is the value of the tension on the roving that is measured when the roving is wound on the die.

3. INFLUENCE OF ACTUAL TRAJECTORY ANGLE ON THE AVERAGE VALUE OF THE WINDING TENSION

In order to understand better the influence of winding tension as a function of actual trajectory angle θ^*, a benchmark has been defined and a set of winding trajectories has been planned by a CAD/CAM software. The benchmark is an irregular ring, shown in Fig. 6. It is commonly used by an important Italian aeronautic company to test alternative composite manufacturing technologies and systems. The material used for the experimental tests is carbon roving impregnated by epoxy resin. The slip roving consists of 12 thousand (12k) filament-count tows. Polyacrylonite (pan) precursor graphite fibres are used. The slip roving has a 3.2 ± 0.8 mm width and a 0.76–0.85 g/m yield. This benchmark will be used for both numerical tests and experimental tests.

A set of winding trajectories has been planned by the designer of a factorial experimental plan. The number of points n, the safety distance d, and the trajectory angle θ have been considered variable parameters; the values of the geometric parameters are shown in Tables 1 and 2. Twenty trajectories of the deposition

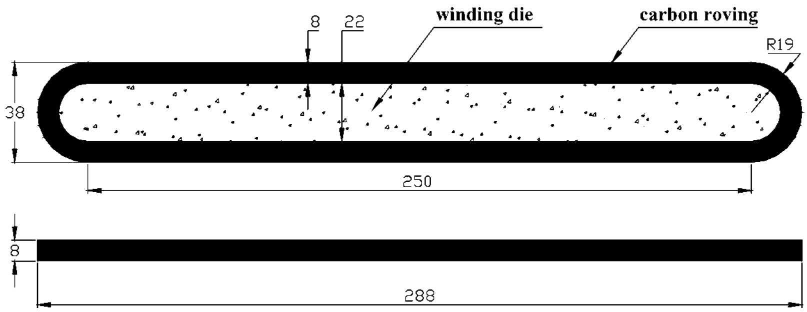

Figure 6. Dimensions (in mm) of the irregular ring — benchmark.

Table 1.
Experimental plan

Trajectory variables	Number of levels	Values
Number of points (n)	3	14–30–44
Trajectory angle ($\theta°$)	2	90–100
Safety distance (d, mm)	4	50–70–90–150
No. of winding trajectories planned	20	

Table 2.
20 trajectories planned by CAD/CAM software

Trajectory	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
n	14	14	14	14	14	14	30	30	30	30	30	30	30	44	44	44	44	44	44	44
θ (°)	90	90	90	90	100	100	90	90	90	90	100	100	100	90	90	90	90	100	100	100
d (mm)	50	70	90	150	50	70	50	70	90	150	50	70	90	50	70	90	150	50	70	90

head have been planned instead of twenty-four, since for some combinations of the trajectory variables the software does not converge towards a valid trajectory. A trajectory is considered valid if it satisfies the constraints described in the previous section. The CAD/CAM software does not find a valid trajectory, since it increases indefinitely the safety distance in order to satisfy the constraints on the trajectory angle. Figures 7–9 show examples of winding trajectory for different values of both the number of discretized points and the safety distance.

The actual trajectory angle θ^* has been calculated for each of the 20 planned trajectories. Each trajectory has been implemented 3 times, by a robotized filament winding cell, yielding 60 wound benchmarks.

The cell is composed of an anthropomorphic robot shown in Fig. 10a that is opportunely equipped with an unique and innovative feed-deposition system, shown in Fig. 10b. A dynamometer has been mounted under the winding die as shown in Fig. 10c. 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 $<\pm 0.15$ mm [2].

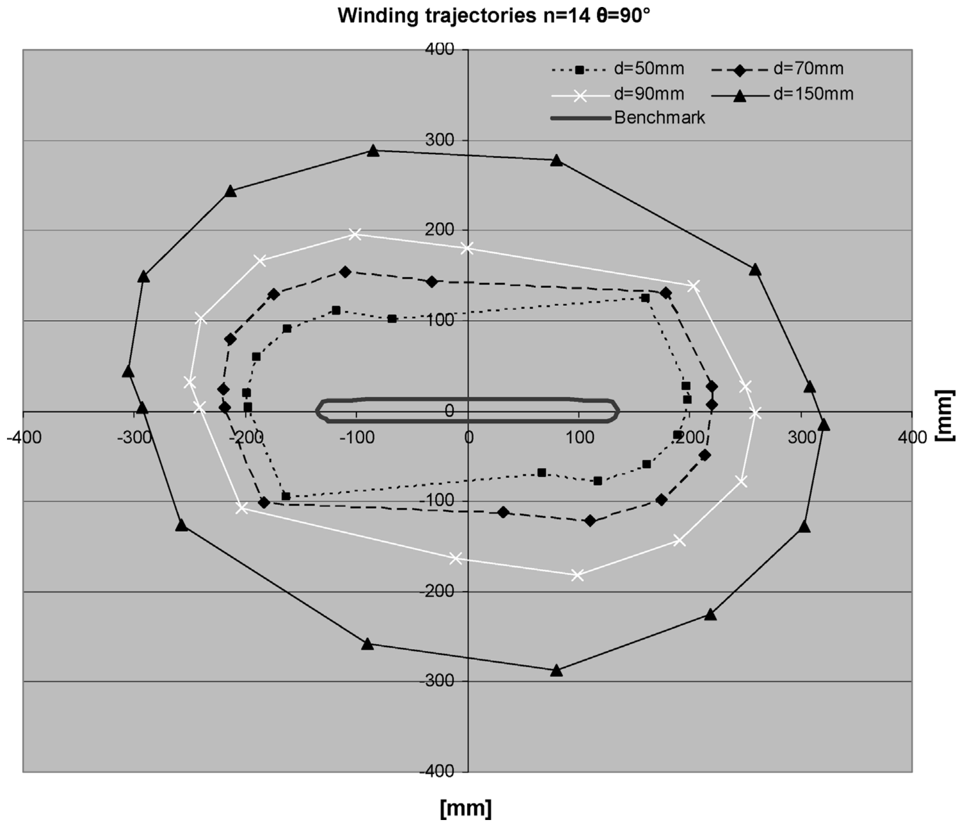

Figure 7. Winding trajectories for n = 14 and $\theta = 90°$.

The winding device, already described in previous works [3], has been designed and built on the basis of compactness, structural lightness, stiffness and functionality principles, in order to guarantee both the maximum dexterity of the robot, to minimize the probability of crashes between the winding die and the components of the cell, and to improve the control of the process parameters for accuracy and repeatability. The feeding device shows a modular structure constituted by four critical subgroups or modules: the main frame, the roving-guide system, the roving tensioner and the deposition system. The winding die is mounted on a circular plate by means of a tie rod. The plate allows us to mount the tie rod in different locations as required by the shape of the winding die. The length of the tie rod is reduced in order to avoid collisions during winding.

The nominal winding speed of the deposition head has been fixed on three levels (50%, 75% and 100% of maximum linear speed value of robot, which is equal to 2 m/s). The value of the nominal winding tension has been set to 70 N, which assures good mechanical resistance of the manufactured work-pieces and defects inside the part [9]. The value of 70 N is the tension applied to the roving in static friction conditions before unwinding. The actual winding tension has been

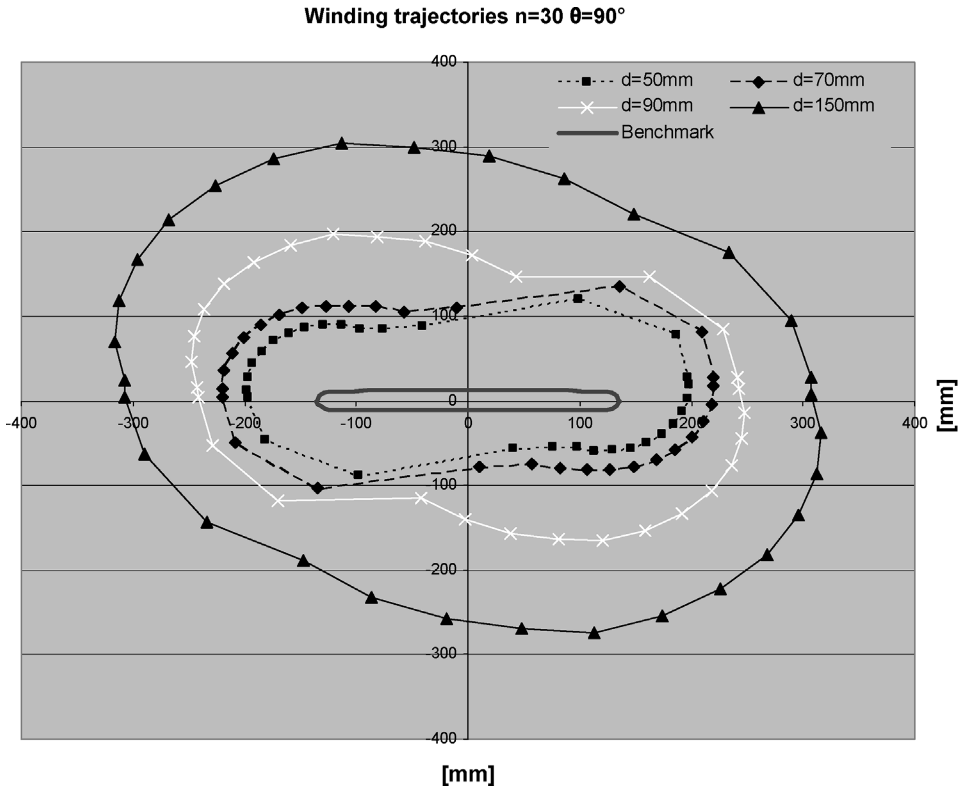

Figure 8. Winding trajectories for n $=30$ and $\theta=90°$.

measured along the winding trajectory of each benchmark by a dynamometer mounted under the winding die.

The average value of the actual winding tension has been calculated by averaging the actual tension values measured along the whole winding trajectory. It increases significantly with θ^* up to the nominal value 70 N, as shown in Fig. 11. Since the average value of the actual winding tension does not depend on the winding speed, the relationship between the average value of the winding tension and the average value of the actual trajectory angle may be expressed by means of the following equation, once the nominal winding tension and the geometry of the part to be wound have been chosen:

$$\log(\mathrm{T}) = \mathrm{a} + \mathrm{b} \cdot \log(\theta^*), \tag{1}$$

where a and b are two constants that have the value of 1.4 and 0.6 respectively. The determination coefficient is equal to 85%, the lack of fit test demonstrates that equation (1) is adapt to describe the collected data with a I type error (α) equals to 0.01. The hypotheses to apply the regression theory are completely satisfied.

This means that it is possible to estimate the average value of the actual winding tension related to a winding trajectory by the equation (1), once the CAD/CAM

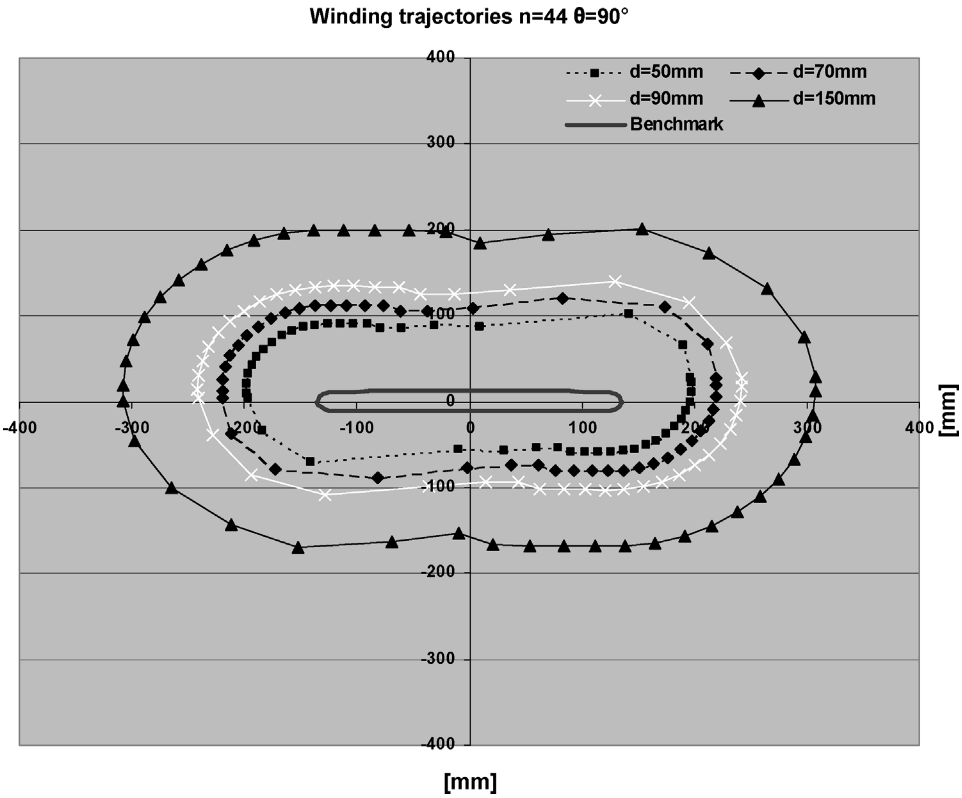

Figure 9. Winding trajectories for n = 44 and $\theta = 90°$.

software that plans the winding trajectory has calculated the average value of the actual trajectory angle connected with the planned trajectory.

If the estimated value of the average actual winding tension is lower than the nominal tension value that assures a good roving alignment and compactness inside the composite part, it is possible to increase the value of the actual trajectory angle θ^* by opportunely setting the values of the geometric parameters (n, θ and d). In fact, non-parametric tests show how the actual trajectory angle is significantly influenced by the geometric parameters n, θ and d. The actual trajectory angle, as shown in Fig. 12, increases with the increase of both the number of points used to approximate the winding trajectory (n) and the nominal trajectory angle (θ); while it decreases with the increase of the safety distance (d). This means that different sets of values of the geometric parameters, characterizing the winding trajectory, may determine the same value of the actual trajectory angle. It is possible to choose the most promising set from a technical and an economical point of view as a function of the specific geometry to be wound. The technical requirements depend on the working space available to wind the part without collisions, while the economical specifications are connected with the time to wind the composite part.

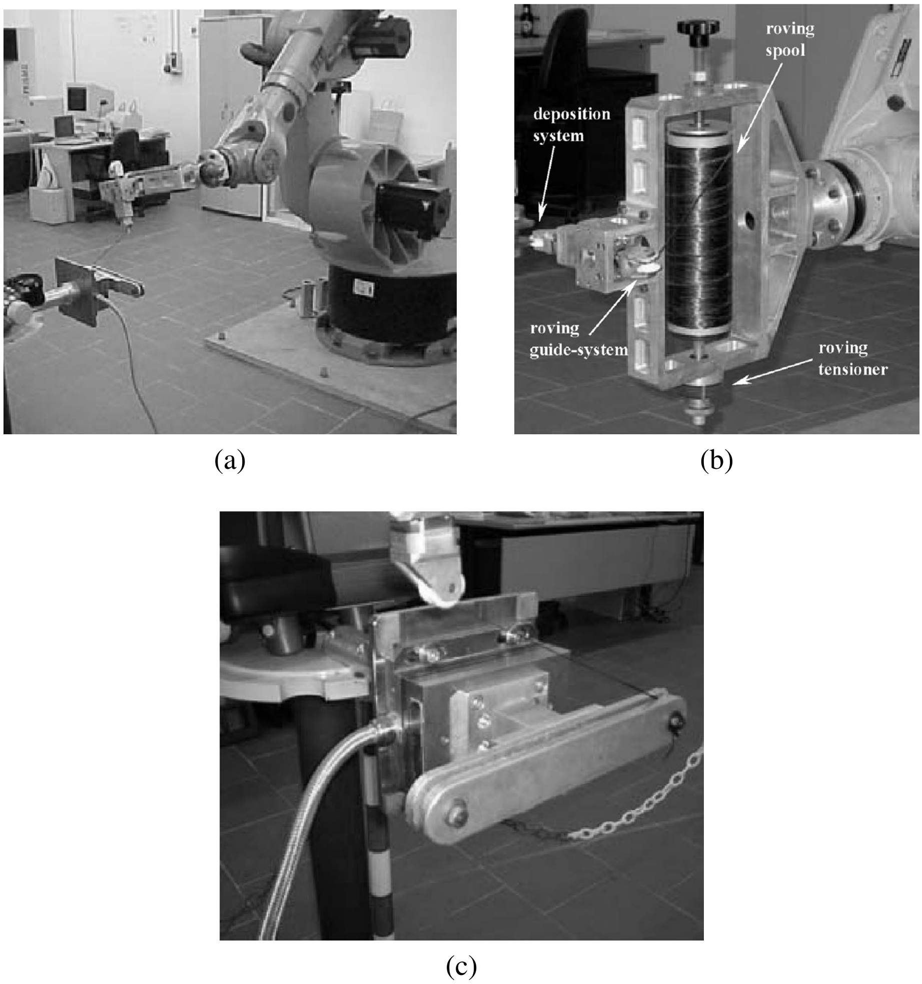

Figure 10. (a) New robotized filament winding cell; (b) feed-deposition system; (c) dynamometer and winding die.

4. CONCLUSIONS

The present work shows how to have a quick and easy estimation of the average value of the actual winding tension by means of a unique parameter connected with the planned winding trajectory, the actual trajectory angle, once the nominal winding tension has been set and the geometry of the part to be wound has been fixed. Moreover, it is possible to maintain the average value of the winding tension near to the nominal one that has been planned to have good composite parts, by opportunely setting the value of the actual trajectory angle. The value of the actual trajectory angle may be set by means of the geometric parameters characterizing the winding trajectory. Increasing the number of points, n, used to approximate the winding trajectory or the trajectory angle θ over 90° makes the movement

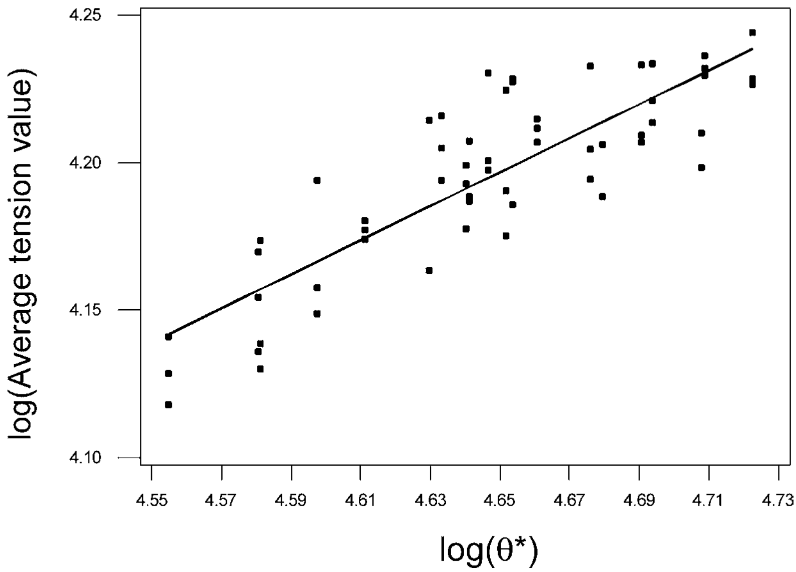

Figure 11. Average winding tension *vs.* actual trajectory angle.

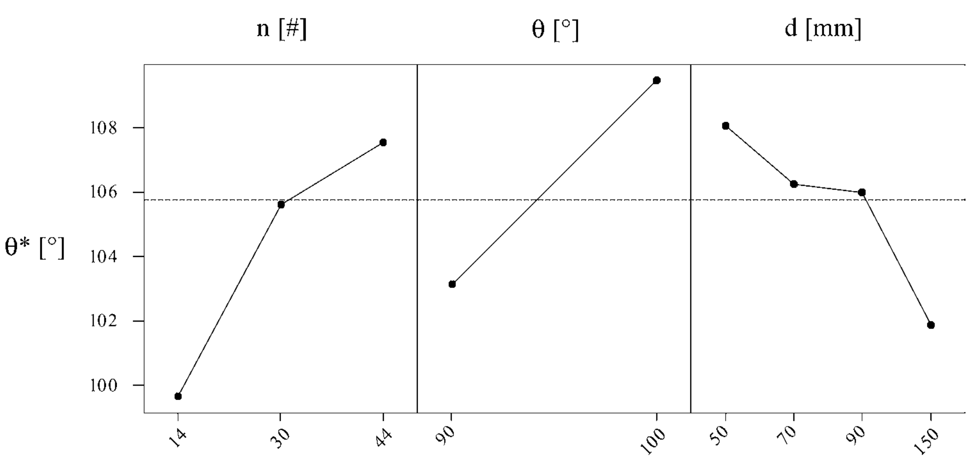

Figure 12. Influence of geometric parameters (n, d and θ) on actual trajectory angle (θ^*).

of the deposition system more continuous thus making the occurrence of tension loosening unlikely during winding. The reduction in tension loosening implies the tension average value to maintain near to the nominal value. Increasing the safety distance, d, involves a longer roving that is unwound between the die and the deposition system and, therefore, an average value of tension lower than the nominal one.

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