Influence of winding speed on winding tension in robotized filament winding of complex-shape parts

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ABSTRACT

Filament winding is a composite technology: it winds fibres, which are impregnated with resin, on a winding die. Robotized filament winding appeared in order to wind more and more complex asymmetric parts. A robotized cell for filament winding is composed of an industrial robot opportunely equipped with a feed and deposition system.

In filament winding, the stratification technique strongly influences the whole manufacturing process. As far as the stratification phase of filament winding technology is concerned, the critical process parameters are the winding trajectory, the winding tension and the winding speed.

In order to manufacture complex-shape parts complex winding trajectories need to be planned and implemented. The design of those complex winding trajectories should take into account geometric constraints in order to keep constant the winding tension. Guarantying a constant roving tension during winding implies to reduce the roving slippage and loosens of roving that alter the fibres alignment inside the part. Tension constancy is influenced by the winding speed: during winding those trajectories may involve hard changes of the direction in the deposition head therefore the winding speed may cause a inconstant value of the winding tension.

The aim of the present work is to evaluate the influence of the winding speed on the winding tension during the manufacture of complex-shape parts. A set of experimental tests have been carried out by a robotized filament winding cell where a robot reproduces the human behaviour to wind a part. The cell consists of a robot, a fixed support, a fiber supply spool, a fiber tensioner and a deposition system. An irregular ring has been chosen as benchmark, which is used to test robotized filament winding process by a well-known aeronautic company. Different values of the process parameters have been considered by means of design of experiment (D.O.E) technique.

1. INTRODUCTION

Filament winding is a composite technology: it winds fibres, which are impregnated with resin, on a winding die. Robotized filament cells appeared in order to wind more and more complex asymmetric parts [1-4]. A robotized cell for filament winding is composed of an industrial robot opportunely equipped with a feed and deposition system.

The set of pre-impregnated fibres (called roving) is located along the main force direction and the achieved filling coefficient, that is defined as the ratio of fibre volume to resin volume, is generally very high. In filament winding, the stratification technique strongly influences the whole manufacturing process. In fact, it may significantly increase the time required to manufacture a composite part. Moreover, it is responsible of both the roving alignment and the amount of fibres in a unitary volume and, therefore, of composite mechanical properties. As far as the stratification phase of filament winding technology is concerned, the critical process parameters are the winding tension, the winding speed and the winding trajectory.

The winding tension influences directly the compaction and the alignment of the fibres [5]. The composite resistance against applied loads is mainly due to its fibres: the higher is the fibre percentage in a unitary volume, the greater is the material mechanical resistance. The winding tension determines the force squeezing the roving on the winding die or on the roving layers during winding. Therefore, it is possible to adjust the amount of fibres for a unitary volume by regulating the value of the winding tension. Moreover, increasing the tension value implies improving fibre unfolding on the mandrel and, therefore, fibre's alignment along the direction of the applied load.

The winding speed influences the accuracy and the repeatability to perform the winding trajectories: the locating error of the deposition head in every point of the winding trajectory increases with the winding speed [6]. High values of the winding speed imply the robot joints to jerk along the winding trajectory by increasing stresses on roving that is unfolded from the spool and vibrations on robot joints. The manufactured part will have fibres distribution that will be different from the designed one; consequently there will be a deterioration of the structural characteristics.

In order to optimise the winding process and to reduce the manufacturing cost, it is necessary to attain the objectives: i) to control and to plan the winding trajectories in order to enlarge the geometrical range and to increase the complexity of the producible parts; ii) to maximise the winding speed, in order to reduce manufacturing times; iii) to carefully control the winding tension, in order to improve the mechanical properties of the parts.

The present work focuses on the influence of the winding speed on the winding tension in order to manufacture complex shape parts. When geometrically complex parts, with strong curvatures are manufactured, two main problems may arise: a) insufficient fibre compactness, particularly evident along rectilinear segments, b) tension losses of the roving during winding. In order to solve these two problems, a proper value for the winding tension has to be selected and kept constant along the whole winding. In fact, if the applied tension is not enough, fibre may present wrinkling or folds along the deposition direction, causing defects in the final composite part (i.e. “marcels”). At the same time a very high 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 tension that allows to minimize the empty spaces, the wrinkling and the folds, and to have a component with a good structural uniformity. Moreover, to guarantee a constant roving tension during winding implies to reduce the roving slippage and loosens of roving that alter the fibres alignment inside the part.

In previous works we have discussed the problem to set the value of the tension that gives the best performances in terms of roving alignment and compactness [7, 8]. Once the tension value has been set, it is needs to assure that this value remains constant along the whole winding trajectory, as discussed before. This work studies the influence of winding speed on tension constancy during the production of compact and complex parts.

Complex shape parts need complex winding trajectories that should be planned and implemented. The design of those complex winding trajectories should take into account geometric constraints in order to keep constant the winding tension. At the same time, this design stage should put into evidence the existence of hard changes in deposition head direction during winding, where the winding speed may cause an inconstant value of the winding tension.

The present work deals with the method to identify the value of the winding speed that preserves the constancy of the winding tension, thus assuring an acceptable quality of the manufactured composite parts. The winding speed may be put into relationship with the geometric parameters introduced to compare alternative winding trajectories [9].

This work follows an experimental approach by means of a robotized cell that consists of a robot, a fixed support, a fibre supply spool, a fibre tensioner and a deposition system. An irregular ring has been chosen as benchmark; this ring is used to test robotized filament winding process by a well-known aeronautic company, benchmark. Different values of the nominal speed of deposition head have been planned and, then, measured along each winding trajectory. Both of them have been put into relationship with tension constancy.

Firstly, the considered complex shape parts are shown. Then, the winding speed is introduced together with the parameters of the winding trajectory. Finally, the experimental approach is presented and the obtained results are deeply discussed.

2. COMPLEX SHAPE PARTS IN COMPOSITE MATERIAL

A part obtained thanks to the extrusion of a section along a closed not auto-intersecting path is the family of complex shape work-pieces that have been considered in the present work. The closed path is formed by 3D curves, the part is automatically produced through a sweeping operation. The composite tape has an approximate rectangular section smaller than part section. Therefore, the part section filling can be obtained through a continuous location of the tape section. A grid is positioned on the straight section of the part: it has cells with dimensions equal to the tape ones in the straight section, positioned over it (see Figure 1). The cells represent the various coils of the tape, necessary to define the layers of the whole part section. A continuous deposition is realised starting from one place (such as 1) and ending, after a while winding round, in a new one (such as 2) from which a new winding coil starts. The support gives the supporting walls for the most external of the reinforcement, and because of the shape of the section, it is possible to take two or three retaining surfaces into consideration. It is possible to define two main directions: the first one Y (versor U_1) determines the growth of each single layer by approaching single coils while the second main direction X (versor U_2), which is perpendicular to the first one, constitutes the direction where the multiplication of the layers takes place. The two directions are associated to the supporting surfaces and, in particular, to the sides of the product section to be analysed.

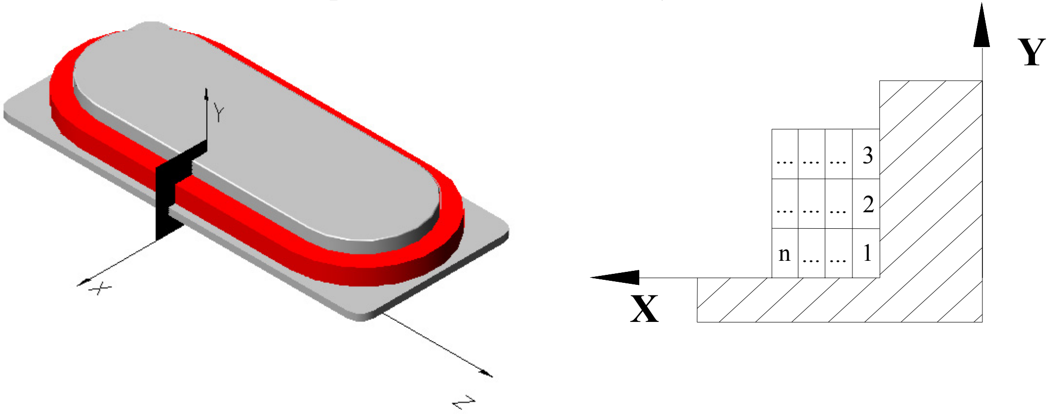

Figure 1. Irregular ring section.

A possible deposition strategy is the continuous layering that allows to align layers that are generated by the deposition of the filament according to opposite directions along Y axis.

This strategy allows to avoid that voids and bridges are present inside the part. Independently by stratification, the path along which the tape has to be wound must be generated; it is called base path. Then, the trajectory along which the deposition head should move in order to wind the tape along the defined base path needs to be defined. The trajectory of the deposition head is a set of points ordered in space; it represents the image of the points of the base path. The existence of a relation of biuniqueness between the points of the base path and the winding trajectory ones, is absolutely necessary. It is possible to generate the winding coils through extrusion along the base path of the cells belonging to the straight section of the workpiece. To guarantee an accurate winding of the tape on the support, the winding trajectory must be tangent to the tape trajectory along each contact point between the winding tape and the already wound tapes. Moreover, the tape tension must be as constant as possible, the deposition head and the robot arms should be moved on collision free trajectories, the free tape must not interfere with the support and the whole environment. A control volume is generated to calculate the impacts, in order to keep the path outside the considered volume. The control volume is a positive offset of the solid model related to part-support assembly. The end-effector has to respect the security distance which is defined by the user, the bearing and by the deposited fibre.

3. WINDING SPEED IN ROBOTIZED FILAMENT WINDING TECHNOLOGY

The actual winding speed (Ws_i) is the speed of the deposition head when it moves from point A’ (on the left) to point A_1’ (in the middle) and, then to point A’$_2$ (on the right) in Figure 2. It may be calculated by dividing the trajectory length by the winding time.

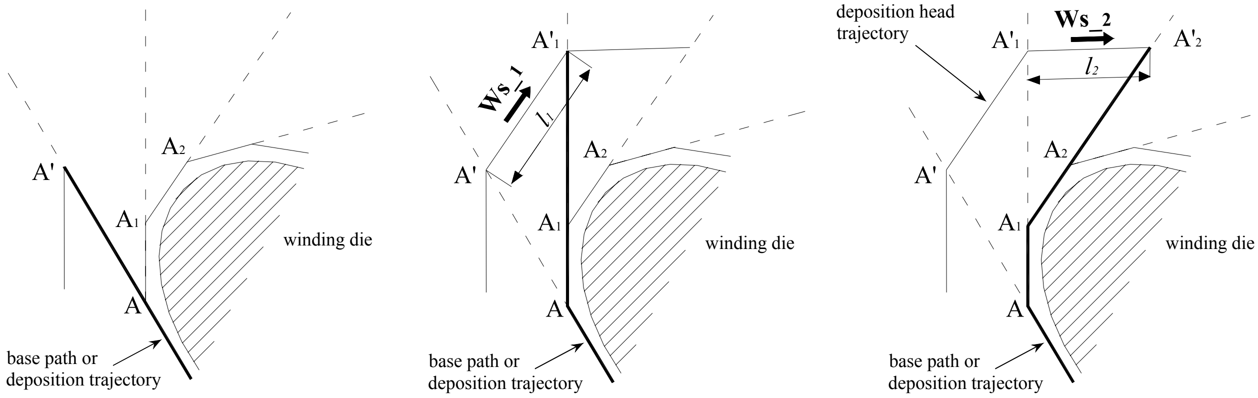

Figure 2. Winding speed (Ws)

The length of the winding trajectory is easily calculated by the distance of each couple of points constituting the winding trajectory (A’, A’$_1$, A’$_2$, ..). The winding trajectory is constituted by the sequence of points, 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. point A, A_1, A_2,… in Figure 3. This means that when the deposition head, i.e. the robot end-effector, performs the winding trajectory, it approximates the continuous path by points (A’, A’$_1$, A’$_2$, …).

The number of points (n) used to discretise the 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 during winding, since it avoids the sudden change in head’s direction. A more and more continuous movement of the deposition head makes less probable the occurrence of tension loosen during winding 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 point to point forms with the roving direction is very critical for winding. It is called trajectory angle and is indicated by “θ”. The trajectory angle is responsible of roving tension control during winding. It aims to avoid decrease in the tension value of the roving during winding, i.e. roving loosens. Figure 4 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 moving 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 or equal to 90°, in order to satisfy the condition $A_1A'_2 \geq A_1A'_1$, that avoids roving loosens.

The deposition head moves along the trajectory points by keeping at the safety distance (d) from the die in order to avoid collisions with the die during winding. 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. The value of the safety distance strongly depends by the value of the trajectory angle. If the value of the safety distance does not allow to satisfy the condition on the value of the trajectory angle previously introduced ($\vartheta \geq 90°$), the value of the safety distance should be increase as far as the trajectory angle satisfy its constraint. In fact, during its moving from A’$_1$ to point A’$_2$ along the control volume in Figure 5 on the right, the trajectory of the deposition head

$A'_1A'_2$ does not form with the roving direction $A_1A'_1$ a angle greater or equal to 90°, such as happened when the deposition head moves from point $A'A'_1$ in Figure 5 on the left. Therefore it is needed to increase the safety distance to d'>d in order to have a trajectory angle (θ) at least equal to 90°.

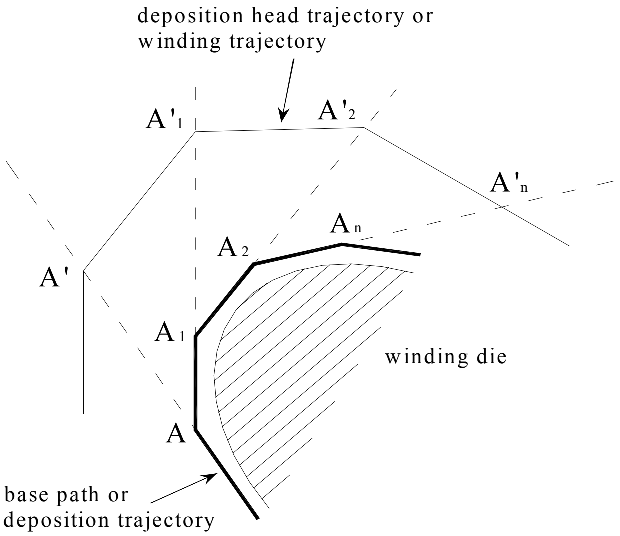

Figure 3. Base path and winding trajectory

The actual winding speed (Ws), which has been calculated as the average of Ws_i values along the winding trajectory, may result very different from the nominal one (S). The difference between the value of winding speed (S) set by PC before moving the robot and that measured as ratio between trajectory length and winding time (Ws) is due to the ramps of acceleration and decelerations that may significantly increase the time required to wind the part. It is possible to increase the winding speed (Ws) by opportunely setting the values of the geometric parameters that characterise winding trajectory and that, in the same time, preserve tension constancy.

In the following paragraph the influence of nominal and actual winding speed on tension constancy is deeply discussed in order to address the choice of the values of the geometric parameters of winding trajectory.

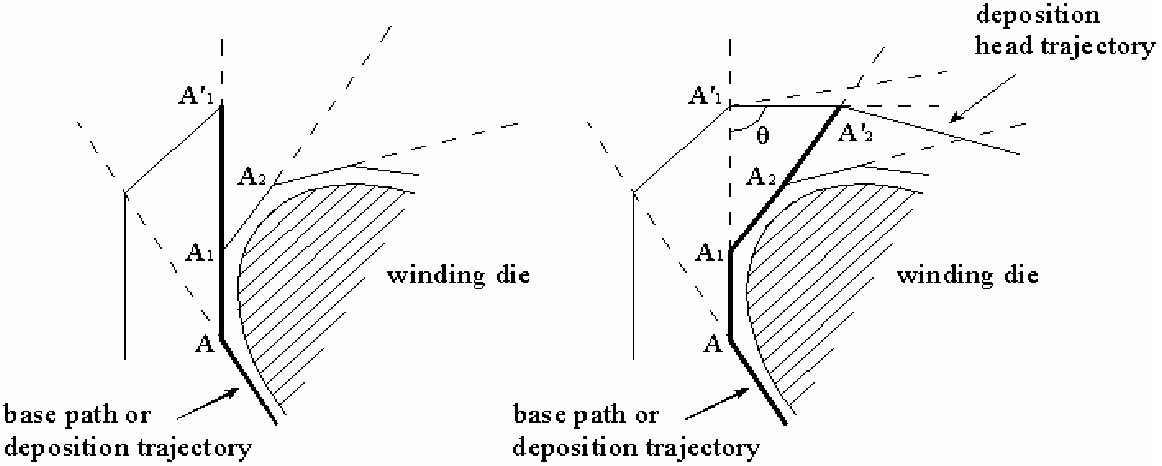

Figure 4. Trajectory angle (θ)

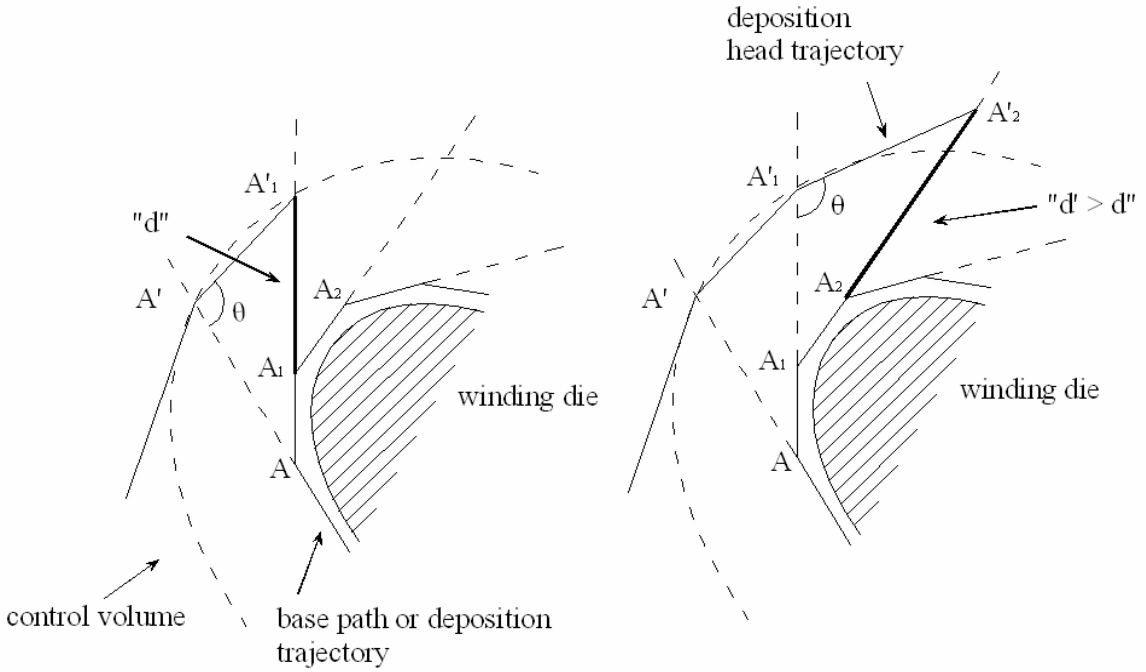

Figure 5. Safety distance (d)

4. EXPERIMENTAL TESTS

To evaluate the influence of the nominal winding speed (S) and the actual winding speed (Ws) on the tension constancy, experimental tests have been carried out by a robotized filament winding cell. The benchmark, the composite material and the robotized cell are presented in the following together with the experimental plan.

4.1 Benchmark

The chosen benchmark for experimental test is an irregular ring, which is commonly used by an important Italian aeronautic company to test alternative composites manufacturing technologies and systems, shown in Figure 6. The material used for the experimental tests is carbon roving impregnated by epoxy resin, conformed to MIL-R-9300 requirements. The slip roving consists of 12 thousand (12K) filament-count tows. Polyacrilonite (PAN) precursor graphite fibres are used. The slip roving has a 3.2±0.8mm width and a 0.76÷0.85 g/m yield. The part usually requires about 90 revolutions around the supporting die.

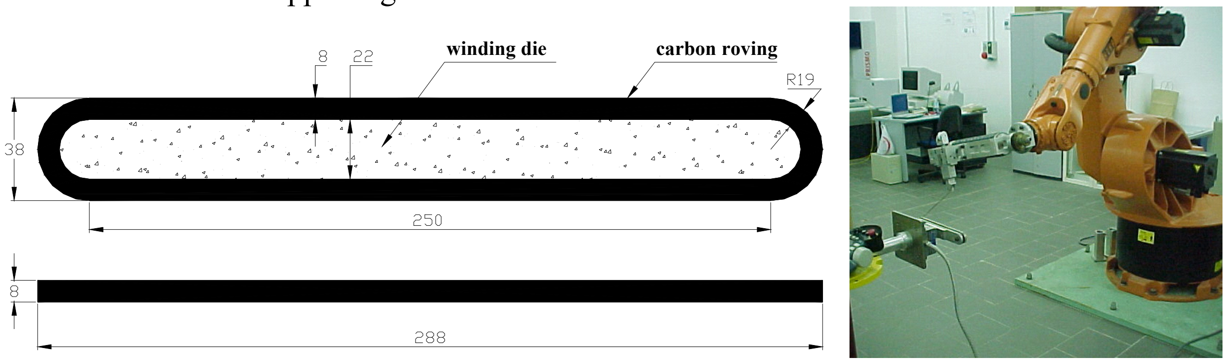

Figure 6. Dimensions (in mm) of the irregular ring – benchmark and robotized filament winding cell

4.2 Robotized filament winding cell for complex shape parts

The cell used for experimental test is composed of an anthropomorphic robot, opportunely equipped with an unique and innovative device, a winding die and a dynamometer. 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 winding device, already described in previous works [10, 11], 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 minimise 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 dynamometer, mounted under the winding die, is connected to circular plate by means of a tie rod. The plate allows 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.

4.3 Experimental plan

Eight winding trajectories have been planned by changing the values of discretized points (n), of safety distance (d), of trajectory angle (θ) and of nominal speed of the deposition head (S[1]), as shown in Table 1. Tension has been set to a value of 70 N that assures reduction of loosens [7, 8]. The winding trajectories have been planned by a CAD/CAM software for robotized filament winding cell [12]. Each of the eight trajectories has been implemented by using three values of the nominal winding speed S for three times yielding 72 manufactured benchmarks. Each benchmark involves 6 coils, thus 432 coils have been wound for 72 benchmarks.

The time to wind each benchmark has been measured by a chronometer. The time to wind each single coil constituting the benchmark has been calculated by dividing the measured time by the number of coils (6). The trajectory length of each coil has been numerically calculated as described in section 3 and it has been divided for the calculated value of time in order to calculate the winding speed Ws.

5. RESULTS DISCUSSION

The tension constancy has been evaluated by calculating the difference between the nominal value of tension (70 N) and the values of tension measured for each coil (the variable DeltaT). It has been put into relationship with the nominal winding speed S by means of analysis of variance technique. We have found that winding speed does not influence tension constancy, as shown in Figure 7/a.

Table 1. Experimental plan

Trajectory [#]	1	2	3	4	5	6	7	8
Discretized points, n, [#]	14	14	14	14	44	44	44	44
Safety distance, d, [mm]	50	50	150	70	50	50	150	90
Trajectory angle, θ, [°]	90	100	90	100	90	100	90	100
Nominal winding speed, S, [%]	50, 75, 100							
Replications [#]	3							
Wound coils [#]	432							

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[1] The nominal winding speed or nominal speed of the deposition head (S) is indicated like percentage value of maximum value of the robot linear speed equal to 2mm/s

However, tension constancy seems to be significantly influenced by actual winding speed (Ws), as shown in Figure 7/b. An increase of actual winding speed (Ws) causes a tension variance from the nominal value of 70 N with a consequent worsening of tension constancy.

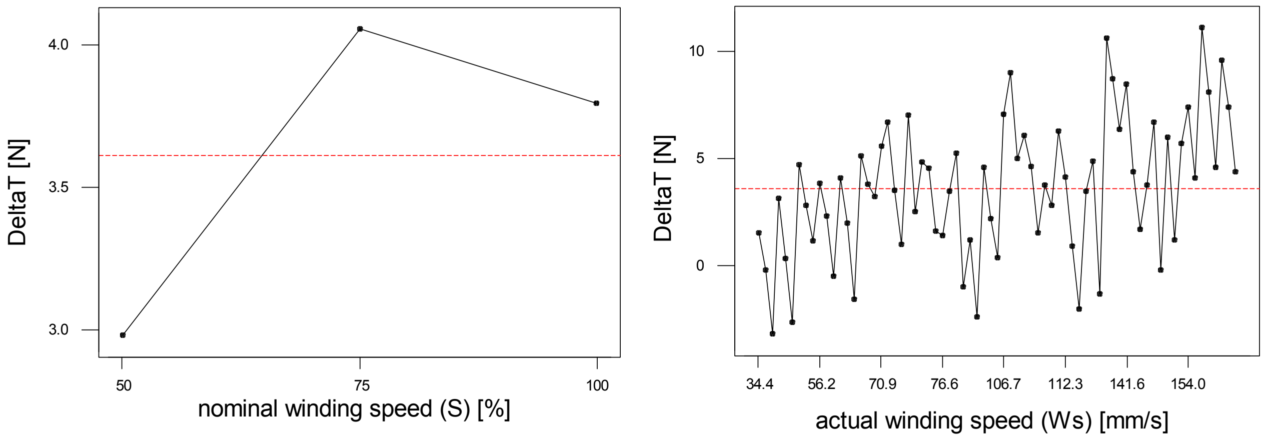

Figure 7. Main Effect Plots of DeltaT vs.: a) nominal winding speed (S); b) actual winding speed (Ws)

This is due to the fact that actual winding speed Ws depends on the geometric parameters characterising the winding trajectory and, in particular on the safety distance (d). In fact, it is possible to describe the strong relationship among winding speed Ws, geometric parameters and nominal winding speed (S) by a simple equation.

$$\mathrm{Ws} = -57.3 + 2.06 \cdot \mathrm{S} + 0.698 \cdot \mathrm{d} - 0.0236 \cdot \mathrm{n} \cdot \mathrm{S} \tag{1}$$

that is characterised by a coefficient of determination of 95.5%. Moreover, it depends on the interaction between the number of discretized points (n) and on the nominal speed (S): increasing the number of points involves to increase the ramps of acceleration and deceleration, the winding time and, therefore, to decrease the actual winding speed (Ws). To try to recover the time lost in the ramps, it is possible to increase the nominal winding speed (S); that's why the interaction between the number of discretized points and the nominal winding speed is statistically significant.

To take into account eq. (1) it the relationship among the tension constancy, the geometric parameters and the winding speed has been studied by the analysis of variance. The significant variables are the trajectory angle (θ), the number of discretized points (n), the safety distance (d), together with the interactions between the trajectory angle (θ) and the nominal winding speed (S) and between the number of discretized points (n) and the nominal winding speed (S), as shown in Figures 8-9. An increase in trajectory angle causes a decrease in the distance of tension value from the nominal value; the higher is the nominal winding speed (S), the higher is the magnitude of distance decrease. An increase in number of discretized points involves a decrease in the distance of tension value from the nominal value; higher is the nominal winding speed (S), lower is the magnitude of distance decrease.

Finally, we can conclude that an increase of nominal winding speed (S) causes an increase of actual winding speed (Ws) and, therefore, a reduction in tension constancy. An increase in the number of discretized points (n) or a decrease of the safety distance (d) cause a decrease of the actual winding speed (Ws) and, therefore, an improvement in tension constancy. A decrease in trajectory angle value seems to have no effects on actual winding speed (Ws), while it improves tension constancy.

All the analyses of variance and regressions that have been carried out satisfy the hypothesis concerned with both the normality and the homogeneity of variance of the residuals.

6. CONCLUSIONS

The present work has shown the influence of winding speed on roving tension constancy. The actual winding speed is influenced by the nominal winding speed and by the geometric parameters characterising the winding trajectory. At the same time the actual winding speed seems to significantly influence the tension constancy. An increase in the safety distance or in the nominal winding speed causes an increase in the actual winding speed and, then, it provokes the tension on the roving to move away from its nominal value. Therefore, a good planning of the winding trajectory and of the nominal winding speed allows to preserve the tension constancy and to reduce the winding time yet.

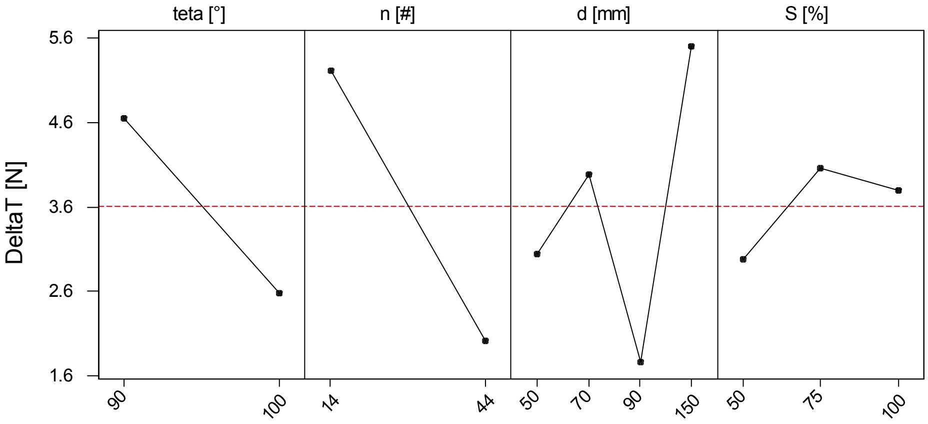

Figure 8. Main Effect Plot of DeltaT vs. nominal (S) and geometric parameters (n, d, θ)

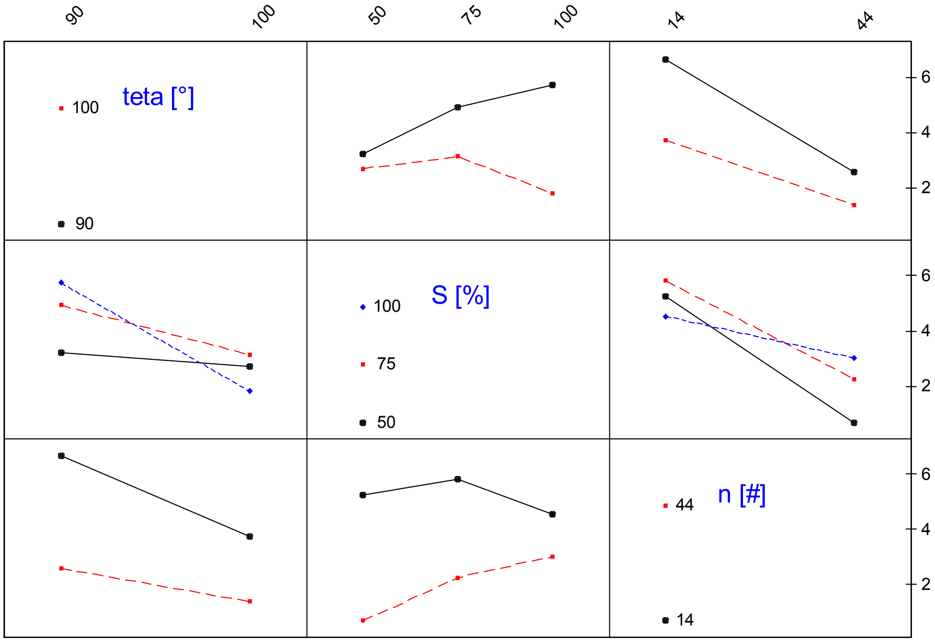

Figure 9. Interaction Plot of DeltaT vs. nominal (S) and geometric parameters (n, d, θ)

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