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# Influence of textile cord tension in cap ply production

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**Abstract**

The deep knowledge about manufacturing processes, as well as their optimization, present themselves as indispensable factors in the search for the best product quality. It is this point of view of continuous improvement that makes companies in profitable and sustainable way. This paper presents a study about unwinding tension of textile cords in the cap ply manufacturing process, using machines called cap-strips for production. In this work, tension can be understood as the tensile force exerted on the cord. This study determines the influence of unwinding tension on the physical and shrinkage properties of the cord, as well as on the properties of cap ply, namely green adhesion and peel adhesion. Furthermore, the impact of cord tension on tire uniformity and the manufacturing process itself was also studied. All conclusions are based on the performed experiments and the execution of statistical tests. This work allows to conclude that the unwinding tension of the textile cords have some impact on the cap ply properties but have no influence on the tire uniformity.

*Keywords:* Quality; Unwinding of textile cords; Textile cord tension; Cap ply; Cap-strip; Manufacturing process; Tire manufacturing.

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## 1. Introduction

The tire is one of the composite structures most complex and most commonly used today. It consists of a series of components or subassemblies, each of which has a specific function for product performance. The typical radial tire is composed of approximately eighteen individual components, ten or more different rubber compounds, one or two

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layers of textile impregnated with rubber, two metal plies and beads [1]. Similar to other automotive industries, the production of tires is the subject of numerous studies, in order to optimize manufacturing processes and gain a deep understanding of manufacturing parameters. Santos *et al.* [2] studied an improvement in APEX machines, a machine used to apply bead rubber inserts, in order to overcome excessive downtime in the production process associated with pneumatic system problems. Costa *et al.* [3] used the Six-Sigma methodology in the process of extrusion of tire side walls and treads, reducing 0,89% of nonconforming material generated.

The cap ply is a material composed of textile yarns (reinforcing material) impregnated with rubber (matrix), forming strip. This strip is then wrapped around the tire, forming a textile ply. These are designed to avoid deformation of the tire at high speeds, due to the centrifugal forces generated [4]. The manufacturing process of cap ply studied in this work is the one used in cap-strip machines. Fig. 1 shows the model of a cap-strip, which is constituted by a creel (a), where the textile cord coils are positioned and tensioned, an extruder and a head (b), where the cords are impregnated with rubber, a cooling circuit of the cap ply strips (c) and a winding section (d), where the strips are wound on reels for later use in the construction of the tires.

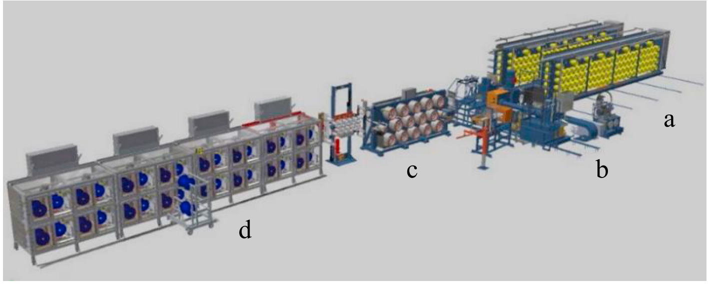

Fig. 1. GfA De Pryck & Co.mbH cap-strip line [5].

The textile is present in the tire in the form of cords or fabrics. The difference is that in the fabrics, the cords (warp) are crossed by yarns (weft), so that the cords keep their spacing between them. The reinforcing textile cords have the function of maintaining the durability of the tire against impact, withstand the inertia load and contain pressurized air in the tire, give rigidity to the tire for acceleration, braking and bend and confer dimensional stability [6]. Although the textile represents a small percentage of the total weight of the tire, its contribution to overall tire performance is significantly high [1].

The most commonly used textile materials in the tire industry are polyamide (nylon®), polyester, aramid and rayon [7]. Polyamides (PA), the textile material used in this study, are among the first synthetic polymers used in fiber applications and may be classified as aromatic polyamides or aliphatic polyamides. PA6.6 is the most used in the tire industry, being a high modulus, low modulus, fatigue resistant and adherent synthetic yarn [8,9]. Due to these characteristics, as well as to its typical hot contracting behavior, it makes this material suitable for the manufacture of cap ply. The textile yarns are twisted individually and then twisted together to form a cord. The twisting of the threads is intended to prevent breakage of the filaments, to confer greater resistance to abrasion damages and to improve the resistance to fatigue [7]. The level of torsion given to the yarns is a fundamental part of their modeling since it has a direct impact on the mechanical properties of the yarns. Aytac *et al.* [10,11] studied the effect of the twist level of the textile cords on their mechanical properties and performance. It concludes that higher twist levels cause a decrease in breaking strength and stiffness, but increase the breaking strain and the absorbed breaking energy.

In the processing of any textile material, the tension represents one of the most important parameters. In the weaving process, for example, the tension in the yarns is an essential parameter inherent in the cloth's shape, technically called fabric, as well as a property related to the efficiency of the looms and the quality of the fabrics [12,13]. During the manufacture of components for textile reinforced tires, there is also a need for the cords, when unwound from the coils, to be tensioned. Without tension, they would fall from their winding position on the coils, causing these cords to break. In addition, the existence of tension causes stability in the unwinding, and along the course that the cords have to travel throughout the manufacturing process. There are several mechanisms of tension control, responsible for generating tension in the unwinding [14]. With the development of machine technology, tension control systems have so far undergone three phases of development, i.e., mechanical, electrical and computerized tension controller [15]. A mechanical tension controller manipulates the stress through a mechanical structure [16]. Durur *et al.* [17] studied cross-yarn coil winding, whereby the tension given to the yarn to be wound was generated by the friction of a belt on the winding drum, and the force exerted on the belt being that of a mass with a weight defined. The electrical tension controller, which usually uses a load transducer to perform real-time detection of the tension of the yarns or cords, feed the result back to the controller. With the development of electronic technology, microprocessors arise. In this way, the computerized tension controller is now used. The microprocessor becomes the core of the control system and therefore reduces the number of circuits in the electronic system, which greatly simplifies the system, improves its reliability and enables the application of advanced control methods [15]. Computerized tension controllers allowed the development of multiple approaches and control algorithms, not only in the textile industry, but also in the production of polymer films [18-20].

While the studies carried out with unwinding tensions of textile products are related to the production of the textile itself, this study addresses the control of unwinding tension when the textile is the raw material of another product, not the final product. Thus, the objective of this study is to understand the impact that these tensions have on the properties of the material to be produced and the uniformity of the tire.

## 2. Materials and methods

In order to carry out this study, the material used was cap ply with polyamide cords as a reinforcement material, since it is the material most used for the effect in the generality of the tires. Each cap ply strip has a defined number of cords. These cords are obtained in coils of 0,27 m in diameter and with 40,000 m of cord each. Fig. 2 shows a textile cord reel already positioned in the creel of the machine.

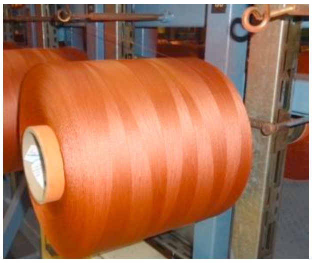

Fig. 2. Textile cord bobbin.

The bobbins are positioned in the creel of the machine in independent drums. Each position has an independent braking system, which is described in Table 1.

Table 1. Description of the textile cord bobbin braking system.

| Description of operation | Braking system |
|---|---|
| System composed of tensile spring, belt and drum. Braking occurs as a result of the frictional force between the belt and the drum, such as in a belt-pulley system. The spring exerts force at one end of the belt, the other end being connected to the machine frame. For this reason, the tension in the cord, when unwound, is directly related to the stiffness and deformation of the spring. | <br>Fig. 3. Illustration of the braking system. |

The unwinding of the cord takes place tangentially by the rotation of the bobbin about a fixed axis, which coincides with the bobbin center of mass. For this reason, the rotation motion of the bobbin can be described by the second law of Newton applied to the rotation, according to equation (1) [21],

$$\sum M_G = I_G \times \alpha \tag{1}$$

where $\sum M_G$ represents the sum of the moments in the center of mass, $I_G$ the moment of inertia of the coil and $\alpha$ the angular acceleration of the bobbin. The bobbin can be considered as a thick-walled tube. For this reason, the moment of inertia can be calculated by equation (2) [21],

$$I = \frac{1}{2} \times m \times (r^2 - r_{final}{}^2) \tag{2}$$

where $I$ is the moment of inertia of the bobbin, $m$ the mass of the bobbin, $r$ the outer radius of the bobbin and $r_{final}$ the inner radius of the bobbin. The angular acceleration is the derivative of the angular velocity as a function of time. By calculating the angular velocity along the unwinding time, generating a function, it is possible to calculate the angular acceleration by deriving this function. As in this type of process the linear velocity of the cord is constant, and for each unwinding time a given radius of the bobbin corresponds, it is possible to calculate the angular velocity by equation (3) [21],

$$v_{linear} = \omega \times r \Leftrightarrow \omega = \frac{v_{linear}}{r} \tag{3}$$

where $v_{linear}$ is the linear velocity of the cord and $\omega$ the angular velocity of the bobbin. In practical terms, angular winding acceleration has little impact on the tension variation in the cord, since the cord windings have many meters of cord (some tens of thousands) and the increase of the angular velocity is very slow and gradual. In this study, the linear unwinding speed was 55 m/min. During the unwinding, there are two moments present, the moment of unwinding and the moment of braking. The tension present in the cord is responsible for unwinding the bobbin. As the cord has to rotate the bobbin, the cord is subjected to high tension variations. At the beginning of unwinding, a high tension is imposed on the cord to overcome the friction between the bobbin and its support, as well as overcoming the effect of the steady inertia of the bobbin. These two factors can vary between materials because they depend on the weight of the package. After the bobbin begins to rotate, the tension decreases. When, for some reason, the unwinding of the cord suddenly stops, it does not stop immediately because of its inertia, which causes a significant reduction in cord tension. This system is therefore not very suitable for high speed unwinding [14]. Thus, the unwinding moment induced by the tension in the cord can be calculated by equation (4),

$$M_{unwinding} = T \times r \tag{4}$$

where $M_{unwinding}$ is the moment of unwinding, $T$ tension in the textile cord and $r$ is the bobbin radius. The braking moment described in Table 1 is obtained by equation (5),

$$M_{braking} = (T_3 - T_2) \times r_2 \tag{5}$$

where $M_{braking}$ is the moment of braking, $T_2$ is the load exerted by the spring $T_3$ is the force exerted by the belt on the machine-attached end and $r_2$ is the radius of the circular surface where the belt is applied to the drum. The load exerted by the spring is calculated by equation (6),

$$T_2 = P + k \times x \tag{6}$$

where $P$ is the preload on the spring caused by its manufacturing process, $k$ the elastic spring constant and $x$ the displacement of the spring. The spring used in this study has an elastic constant of 600 N/m, an initial length of 0,09 m and a preload of 5 N. According to the equation of friction between circular surfaces, also known as the Euler-Eytelwein formula, the load exerted by the belt at the machine-attached end can be calculated by equation (7) [13],

$$T_3 = T_2 \times e^{\mu \times \beta} \tag{7}$$

where $\mu$ is the coefficient of dynamic friction between the belt and the circular surface and $\beta$ the angle between the belt and the circular surface of the drum, which corresponds to 2,44 rad. Substituting equations (4, 5, 6 and 7) into equation (1), it is possible to calculate the tension present in the textile cord when unwinded by equation (8).

$$T = \frac{\left[(P + k \times x) \times e^{\mu \times \beta} - (P + k \times x)\right] \times r_2 + I \times \alpha}{r} \tag{8}$$

Once all the variables of the proposed model are known, it is possible to estimate a dynamic friction coefficient, so that the value of the real tension is coincident with the theoretical value calculated by equation (8). For this, with a tensiometer, the tension was measured in a cord during unwinding, for a given radius of the bobbin and a certain elongation of the spring. Thus, a coefficient of dynamic friction of 0,35 proved to be the value able to become the real tension closer to the theoretical tension.

Currently, the unwinding tensions present in the textile cord are, in average, 3,18 N. This value was obtained by the analysis of the unwinding tensions in the current manufacturing process of cap ply. For this tension value, the properties of the textile cord and the cap ply are already characterized by a previous study, where thirty samples of material manufactured with this tension value were taken and the laboratory tests were carried out. Thus, the experience described in this work is to increase the unwinding tension of the textile cords and rehearse the tests that analyze the properties of the already characterized material, in order to understand if there are behavior changes in some of them. For this purpose, the following samples were taken:

- 6 samples of cap ply with a tension in the cords of 15 N;
- 4 samples of cap ply with a tension in the cords of 20 N.

For the latter, only four samples were taken, since 20 N of tension means an increase of 6,3 times in relation to the current unwinding tensions. The tension was measured in four cords in each strip, and the tension value that characterizes the sample is the mean of these four measurements. These tension measurements were performed with the cord tension measurement tensiometer.

The properties of the material to be analyzed are those that are most likely to undergo changes with increasing unwinding tensions. Of these properties, some characterize the textile cord and others the own cap ply. In relation to the textile cord, tensile properties, namely strength (N) and elongation (%) at breakage, as well as its contraction with increasing temperature (air at 180°C) are studied, which quantifies the sensitivity of the cord to thermal cycles. The properties that characterize the contraction of the cord are as follows:

- Contraction (%): consists of the reduction of the initial length of the sample, caused by heating, time and pretension;
- Residual contraction (%): consists of the reduction of the sample length that remains after the test, while the sample remains in the conditioned environment and the pre-load is maintained;
- Contraction force (cN): force resulting from changes in temperature, time and pretension, for a constant length of the cord;
- Residual contraction force (cN): residual force after cooling in conditioned environment.

In order to obtain the tensile properties of the cord, a cord sample is mounted on clamps in a tensile testing machine. The cord is stretched at a constant strain rate until it reaches breakage. To determine the contraction properties of the cord with increasing temperature, the cord samples are placed in the test machine which heats the samples with hot air at 180°C, with a certain tension caused by a weight gripped at one end of the sample.

Regarding the properties of cap ply, the green adhesion is studied, which consists of the force (N) necessary to separate the textile cord from the unvulcanized rubber compound, as well as the peel adhesion, which consists of the force (N) necessary to separate the textile cord of the vulcanized rubber compound. Both properties are obtained with a tensile testing machine. For the peel adhesion property, the sample is first prepared and then vulcanized.

In order to detect the influence of the cord increased tension on the cap ply properties, statistical tests were performed, namely ANOVA with one factor, to detect significant differences between the means of the samples and the test of the standard deviations, as well as to detect significant differences between the standard deviations of samples.

The uniformity of the tire refers to the analysis of the dynamic mechanical properties of the tire. Thus, the ability of the tire to rotate smoothly and free of vibrations is analyzed to meet customer specifications. Uniformity testing simulates what actually happens between the tire and the road. These tests are performed on machines designed and constructed only for the purpose of controlling the uniformity properties of the tires. In order to understand if the unwinding tensions of the textile cords have any influence on the uniformity of the tire, tires with cap ply fabricated with different cord stresses were constructed. For this study, a tire 205/65 R15 type was chosen because it is a tire that represents, in a good way, the generality of all the tires for vehicles, and because it is a stable tire in terms of uniformity, which makes more visible the possible changes that the cap ply with high tension can produce. The following tires were manufactured:

- 79 tires with cap ply made with unwound cords with the current tensions of 3,18 N;
- 55 tires with cap ply made with unwound cords with a tension of 20 N.

The parameters analyzed for tire uniformity were those that are more controlled and significant in the tire industry, being the peak-to-peak radial force, the amplitude of the 1st and 2nd harmonics, and the peak-to-peak lateral force the selected ones. With the uniformity data of the test tires, the *t-student* test was performed to detect significant differences in the means of the two samples, and the standard deviations test to detect significant differences amongst the standard deviations of the samples.

## 3. Results

The six samples used for the first level of the experiment have presented a mean unwinding tension of 14,17 N - Fig. 4 (a). The four samples used for the second level of experiments have shown an average unwinding tension of 21,32 N - Fig. 4 (b). The cap ply strips with cords at the current tension values (3,18 N) have shown excellent rubber impregnation, no cord being seen on the surface of the material. For an average cord tension of 14,17 N, small rubber gaps on the strip can be already detected. When 21,32 N values are reached, the rubber failures in the strip are clearly visible, especially at the ends of the strip.

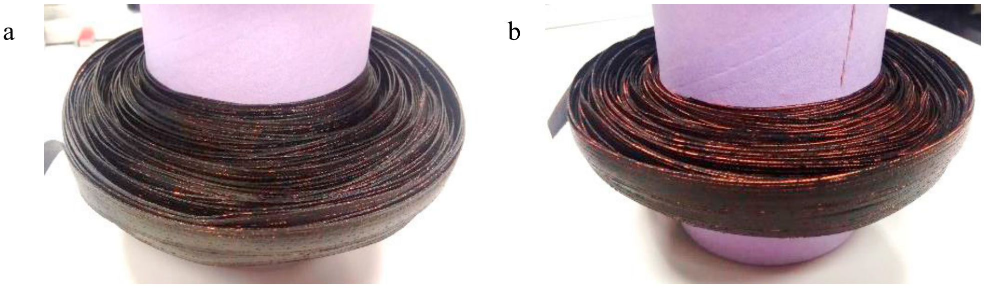

Fig. 4. (a) sample with an average unwinding tension of 14,17 N ± 0,38 N; (b) sample with an average unwinding tension of 21,32 N ± 0,59 N

In the laboratory, the test methodologies established by the company where the study was performed were applied, in order to obtain the values of the eight previously mentioned properties. Table 2 presents the means and standard deviations of the properties tested, corresponding to the three values of unwinding tension of the string to be compared.

After performing the statistical tests in Minitab® software, it is possible to detect significant differences, at a significance level of 5%, in the mean tensile strength and shrinkage force. Regarding the tensile strength, there was a slight gradual reduction with the increase of the unwinding tension of the textile cords used to fabricate the samples of material. While a 3,18 N unwinded polyamide cord has a mean breaking strength of 147,89 N, the same unwind material with a tension of 21,32 N has an average breaking strength of 141,00 N, which corresponds to a 5% reduction. By analyzing the shrinkage force, a significant difference is observed between the samples unwinded with 3,18 N and 14,17 N, because the ranges of values corresponding to these samples have a high probability of differing. However, there is only a 2% reduction in contraction force. To determine if samples with 21,32 N also differ significantly from the rest, it was necessary to increase the number of samples for this unwinding tension.

Table 2. Average and standard deviations resulting from laboratory testing of sample properties.

| **Property** | **Cord tension (N)** | **Average value** | **Standard deviation** |
|---|---|---|---|
| Tensile strength | 3,18 | 147,9 N | 4,02 N |
| | 14,17 | 144,0 N | 1,55 N |
| | 21,32 | 141,0 N | 2,94 N |
| Deformation at break | 3,18 | 21,05% | 0,90% |
| | 14,17 | 21,35% | 0,73% |
| | 21,32 | 20,25% | 0,60% |
| Shrinkage force | 3,18 | 517,2 cN | 21,1 cN |
| | 14,17 | 508,1 cN | 6,39 cN |
| | 21,32 | 532,3 cN | 16,9 cN |
| Residual shrinkage force | 3,18 | 9,64 cN | 11,8 cN |
| | 14,17 | 9,17 cN | 5,09 cN |
| | 21,32 | 19,2 cN | 8,28 cN |
| Shrinkage 180° | 3,18 | 4,18% | 0,18% |
| | 14,17 | 4,23% | 0,16% |
| | 21,32 | 4,41% | 0,34% |
| Residual shrinkage 180° | 3,18 | 1,81% | 0,17% |
| | 14,17 | 1,90% | 0,12% |
| | 21,32 | 2,11% | 0,25% |
| Green adhesion | 3,18 | 24,02 N | 3,08 N |
| | 14,17 | 23,83 N | 3,87 N |
| | 21,32 | 20,75 N | 3,50 N |
| Peel adhesion | 3,18 | 143,6 N | 8,64 N |
| | 14,17 | 138,9 N | 7,81 N |
| | 21,32 | 155,3 N | 8,43 N |

Although there are no significant differences between the means of the residual shrinkage force, there is a significant increase in the force of residual contraction of the cords with 3,18 N relatively to the cords with 21,32 N (50% increase). If the number of samples for the cords with more tension was higher, this difference was most probably noticed in the statistical test. The same happens for the residual shrinkage, because comparing the obtained means of this property, a gradual increase occurs as the unwinding tension of the samples increases. Among the samples with a tension of 3,18 N and 21,32 N there was an increase of 14%. It is also noticeable that the green adhesion decreases with the increase of the samples' tensions. This reduction was expected, since with increasing unwinding tensions the cap ply strips have a lower quality of rubber impregnation.

The different unwinding tensions have little impact on the variability of the test results, since only a significant difference in the standard deviations for the shrinkage property was observed.

The test tires constructed with the cap ply made with the unwinding tension of polyamide cords described in Section 2 were analyzed for their uniformity. Table 3 shows the value of the means and standard deviations of the uniformity parameters analyzed.

Table 3. Average and standard deviations of uniformity parameters.

| **Uniformity parameter** | **Cord tension (N)** | **Average (daN)** | **Standard deviation (daN)** |
|---|---|---|---|
| Radial force peak to peak | 3,18 | 3,64 | 0,81 |
| | 21,32 | 3,72 | 0,85 |
| Amplitude of the 1st harmonic of the radial force | 3,18 | 2,11 | 0,99 |
| | 21,32 | 2,03 | 0,97 |
| Amplitude of the 2nd harmonic of the radial force | 3,18 | 1,02 | 0,44 |
| | 21,32 | 1,01 | 0,39 |
| Lateral force peak to peak | 3,18 | 2,69 | 0,74 |
| | 21,32 | 2,53 | 0,66 |

From the statistical tests performed on the Minitab® software, no significant difference was found in both means and standard deviations of the uniformity parameters analyzed for a significance level of 5%. Analyzing the results obtained from the uniformity tests, the stability of the data is notorious. The largest variations were in the lateral force peak to peak, with a 6% reduction with the increase of the unwinding tension of the cords and in the amplitude of the 1st harmonic of the radial force, with a reduction of 4%. These are slight changes which, according to the statistical tests, cannot be considered as real changes caused by the different unwinding tension of the textile cords. With this, it can be stated that the unwinding tension of the textile cords in the manufacture of cap ply have no influence on the uniformity of the tire.

## 4. Discussion and conclusions

The aim of the study was to increase knowledge about the cap ply manufacturing process in cap-strip machines, namely on the influence of the unwinding tension of the textile cords on the properties of the material, the cap ply manufacturing process and the uniformity of the tire.

Similar to the study developed in this work, Dorgham [22] studied the influence of tension and speed of unwinding of yarns in the process of preparation of warps, for later manufacture of textile fabrics. The range of test tensions used by the author is around 4 N, close to the current stresses of the cap ply manufacturing process presented herein. However, in the study developed here, it was possible to increase tensions up to the order of 20 N, because, while Dorgham studied the unwinding of yarns, this work aimed to study the unwinding of cords.

The tensile properties of the material that showed the greatest change with increasing tension were: tensile strength (5% reduction), residual contraction force (50% increase) and residual contraction (14% ). These differences are between the lowest tension level (3,18 N) and the highest level (21,32 N). In this way, it can be concluded that the unwinding tension can make the textile cords more sensitive to thermal cycles, and reduce the mechanical resistance thereof. In addition to the properties of the material, it has been found that the unwinding tension of the textile cords have no influence on the uniformity of the tires. Thus, the unwinding tension shows to be an important parameter to be controlled, but not critical, since the properties of the cap ply only underwent changes for tension values 6,3 times higher than the working tensions used. It is also important to refer that the execution of this study has also demonstrated that controlling unwinding tensions with mechanical systems is difficult because control accuracy is low and limited. It may thus be found that it is more important to control the tension in the cords than to try to optimize any other parameter of the manufacturing process, given the current state of the same process.

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