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Three Dimensional Numerical Study of Contact and Inner Pressures in a Polypropylene Twisted Yarn

[1]I. Maatouk, [1]S. Msahli, [2]M. Zidi and [1]F. Sakli
[1]Textile Research Unit, ISET of Ksar Hellal, BP. 68, Ksar Hella 5070, Tunisia
[2]Laboratory of Mechanical engineering, ENIM, Monastir 5000, Tunisia

Abstract: Yarn twist in spun yarns has the primary function of causing constraints and compressive stresses to be generated. It will be convenient, in the present study, to study the contact and inner pressure in a twisted yarn. The twist behavior of the multifilament was simulated using ABAQUS finite element package by modelling the yarns as 3D continuum elements. The study was conducted on the simulation of a 19 polypropylene filaments assembly with a circular cross section. Factors, such as dimensions and properties of filaments and interactions between filaments are included in the model. To simulate the torsion filament assembly was embedded from one side and twisted from the other. There after, we investigated the inner and contact pressure of all existing filaments inside the yarn. The results of this analysis showed highest level of contact pressure in the yarn surface that decreases while leading to the center as well as for the inner pressure and revealed the existence of migration in the twisted yarn. Moreover, the distribution of the inner pressure according to the radial position showed the presence of compressed and swollen zones in the twisted yarn.

Key words: Filaments assemblies, yarn modelling, twist, filament deformation, radial position

INTRODUCTION

During spinning, the ideal yarn section is composed of a filament surrounded with several concentric layers of filaments whose number increases with the size of the yarn or the filament thickness (Morton and Yen, 1952).

When twisting filaments parallel to the yarn axis, they incline over a defined angle and turn around the yarn axis. The different layers are going to exercise one on the other inwards a controlled pressure, so that creates new friction strength between the layers. This happens at the effective tensile force because of the torsion moment, the filament's rotation around the yarn axis and the compression forces on the filaments towards the yarn core. Filaments become closer, adhesion between the filaments in the yarn increases and yarn fineness decreases (Morton, 1956; Huh *et al.*, 2001).

The movement of filaments during deformation and their final positions after deformation are determined by their need to minimize tensile strain, which is the so-called the shortest-path hypothesis (Liu *et al.*, 2007).

Onder and Baser (1996) concluded that during spinning under conditions of maximum fibre migration, the fibre segments at the surface are at maximum strain. The resulting stress creates a transverse pressure on the yarn, which forces the fibres in contact with one another, thus maximizing contact points. This transverse pressure effect has been discussed by Ismail (1972). In addition, the stress in the surface segments is relieved by movement of the fiber toward the yarn axis. This provides the interlocking of the fibers that Morton (1956) recognized as a necessity for structural cohesiveness in twisted yarns and creates a contact pressure between fibers.

The main work on the mechanics of spun yarns subjected to an axial force is by Shorter (1957). He studied an idealized model for cotton yarns, for which he calculated the mathematically expected strength. In this model, in order to develop any strength, he found that it's necessary to postulate the existence of a small lateral pressure, or average normal stress, at the surface of the yarn.

Other studies was treated by Platt (1950), Gregory (1950), Shorter (1957) and Hearle (1965). Hearle's work (Onder and Baser, 1996) is important in that it sets forward a complete stress analysis, which takes into account both the axial and radial forces acting on fibers without assuming any pressure on the yarn surface. More recent research along the same lines includes work by Van Luijk *et al.* (1985) and Zurek *et al.* (1987). More lately, when developing a geometric model of yarn based on the conical helix paths, Onder and Baser (1996) supposes that the effects of bending and torsional deformations

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Corresponding Author: I. Maatouk, Textile Research Unit, ISET of Ksar Hellal, BP. 68, Ksar Hella 5070, Tunisia
Tel: (+216) 98 55 95 93 Fax: (+216) 73 450 163

suffered by constituent fibers of the yarn and the forces and moments that cause these deformations are negligible.

Literature reveals that researchers have been interested to the axial and transversal forces existing in the yarn and not to the resulting pressures (inner and contact pressure); so far no work has been published.

This necessitates carrying out a research work on pressure phenomenon by using a numerical simulation with finite element technique.

In this study, conducted in the Textile Research Unit of ISET Ksar Hellal in Tunisia between 2005 and 2010, a 3D numerical modelling of filaments assemblies has been developed while using the commercial finite element code, ABAQUS. Pressure phenomenon was analysed using finite element analysis by modelling the yarns as 3D continuum elements. The current work investigated the inner and contact pressure of all existing filaments inside the yarn. For this reason, we will present in this study a numerical model which take into consideration different existing phenomenon in the torsional textile linear structure operation.

MATERIALS AND METHODS

To generate cohesion and strength in yarn, two features are important: the twist which causes transverse forces and the variation in filament position into the yarn. The amount of inserted twist in the yarn can influence many yarn characteristics such as strength, extensibility, appearance, compactness, as well as uniformity of the structure.

By torsion, lateral forces due to filament tensions and local curvatures are created. This increases interfilament pressure and grow contact areas between filaments, which in turn will induce higher friction and contact pressure. Therefore, the pressure phenomenon inside the yarn is therefore important to analyze. In this context we present a numerical study in order to understand different pressures existing in the yarn during deformation and following the torsion.

The accuracy of the model is essentially determined by the accuracy of the input parameters. The number of filaments that can be modelled in a yarn is limited by the computational requirements.

Geometry of twisted yarns: The yarn used in our study is an assembly of 19 polypropylene filaments. The filaments are initially arranged in an open-packed structure with three layers as shown in Fig. 1. The first layer is a single core filament around which six filaments are arranged so that all are touching, this is the second layer. The third layer has twelve filaments arranged so that the filaments first touch the circle that circumscribes the second layer.

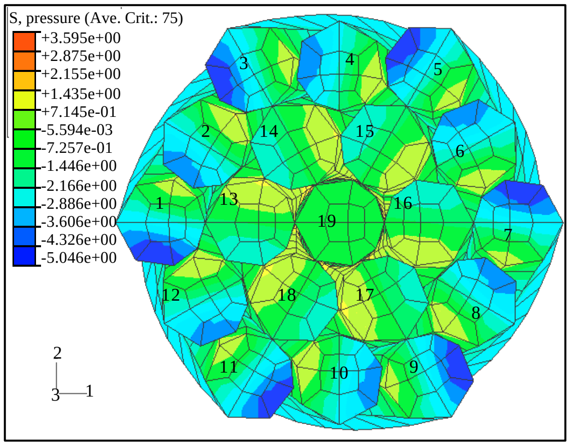

Fig. 1: Cross sections of yarn

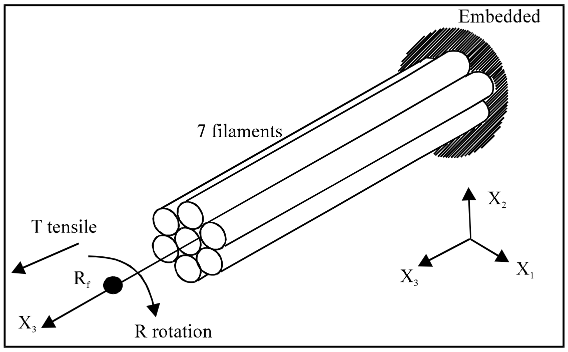

Fig. 2: Boundary conditions of model

In defining the geometry of a single yarn, the model usually adopted is that of an ideal physical form. All the filaments are identical and uniform along their length with a circular cross section of a uniform specific volume. Under tension/twist, all the helices undergo the same amount of extension/rotation. The stress–strain properties of the filaments in the yarn are assumed to be the same. The interactions between filaments within a yarn are processed because they play a significant role in its mechanical properties. The contact force between filaments is assumed to be identical for all contacts and in the same direction as the force applied to the filament assembly. To obtain the twist, the model must be embedded from one side and twisted from the other (Fig. 2). The 3D numerical modelling of filaments assemblies has been developed using 3D finite element simulation which is based on C3D8RH continuous element.

Behavior law: The studied model was a polypropylene yarn. A microscopic study of the PP filament morphology shows that the section is circular with 0.07 mm radius. The law behavior is viscoelastic which is a simple law, identified by the load-extension test added with the relaxation test. These tests have been then implemented in the ABAQUS finite element package.

The Young's modulus of studied PP filament is 171.64 Mpa, its Poisson coefficient is 0.3. The yarn count is 13.8 Tex with initial length of 10 mm. The aim of the present work is the study of inner and contact pressures within a yarn.

RESULTS AND DISCUSSION

Results indicate that during twist insertion the lateral pressure between filaments and inter-filaments frictions increase, thus causing a bigger concentration of filaments in the yarn. Therefore, any tension applied on the yarn due to twist insertion will cause inwards pressures generated by the outside filaments on the interior filaments while forcing them to approach and to form a compact structure. Results based on the present study coincide with the previous study of Morton (1956) when he proposed that twist causes a much greater concentration of fibers in the yam. The fibers cannot escape from one another and any yarn tension leads to an inward pressure from the outer layers on those inside and forces them to approach a close-packed structure.

This cohesion or adhesion between filaments is essentially owed to the contact pressure generated by torsion. These pressures are even maintained when the torsional moment will be null. So, the two phenomena of pressure resulting from the torsional test are the contact pressure and the pressure at the surfaces and inside the filament.

Therefore, torsion induces a complex distribution of tensions in every filament as well as of a filament to the other. These stresses always subsist partially after the twist insertion. We are far from knowing their precisely distribution. So far no work concerning contact and inner pressure has been published.

Study of contact pressure: Yarn twist in spun yarns has the primary function of causing transverse pressure to be generated (Hearle, 1965), which forces the filaments in contact with one another, maximizes contact points and generate a contact pressure between them that spreads all along yarn.

This pressure differs according to the inclination angle and the disposition of the filament inside the yarn. It's therefore important to analyse and quantify the contact pressure of every filament.

The goal, we assign in this part, is to study the contact pressure in the case of torsion equal to 477 turns m^{-1} and tension equal to 0.19 cN/Tex. We are interested to the inter and intra layers contact, so we choose to examine the superficial contact pressure for the 4 sides of the external, internal and central filament (Fig. 3).

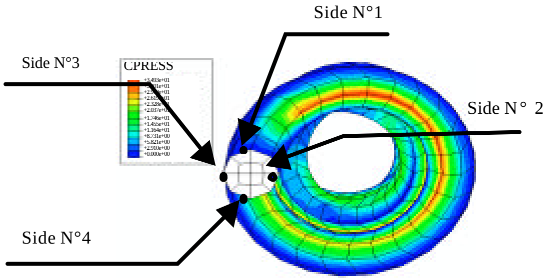

Fig. 3: Presentation of the four filament sides

Theses sides represent respectively:

- For the external filament:
    - The 1st and the 4th sides correspond to the intra layer contact (external-external)
    - The 2nd side represents the inter layers contact (external-internal)
    - The 3rd side presents the surface of the yarn, initially without contact
- Similarly, for the internal filament:
    - The 1st and the 4th sides present intra layer contact (internal-internal)
    - The 2nd side corresponds to the contact between the internal and central layer
    - The 3rd side represents the contact between the internal and external layer
- With regard to the central filament, all sides present the contact between the central and internal layers

The variation of the contact pressure during the insertion of twist in the yarn for every side of the outside filament is presented in Fig. 4. As seen from the Fig. 4, contact pressure is initially equal to zero, it remains null for a time period then it increases until the end of the time step. It's evident to assume that contact stresses are not created since the start of the twisting simulation.

The comparison of contact pressure curves show that strengths between the outside filaments (side N°1) appear the firsts, as well as the pressure is more intense meaning that cohesion between filaments is the highest.

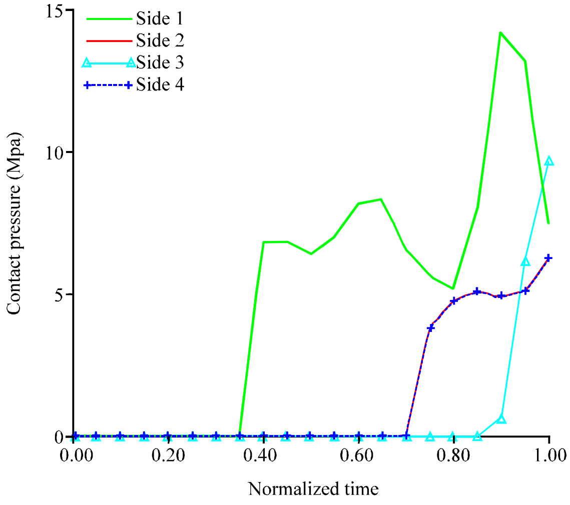

Fig. 4: Contact pressure comparison during twisting

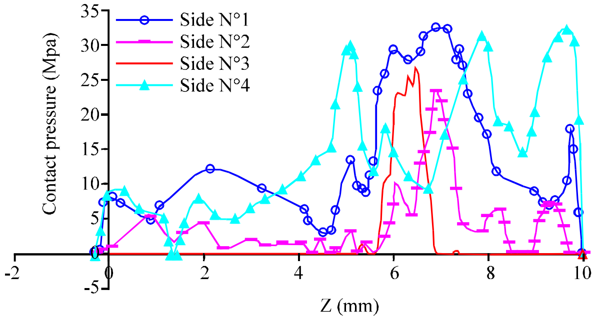

Fig. 5: Contact pressure comparison following the twist operation

In the other hand, we are interested to the contact pressure following the twist operation. Hence we compare the evolution of contact pressure for the 4 sides of the outside filament as illustrated in Fig. 5. These curves indicate that contact pressure isn't uniformly distributed along the yarn.

According to the Fig. 5, we can deduce that contact is more important between the outside filaments (sides 1 and 4).

We notice also that contact pressure for the second side takes values equal to zero what proves that there is no contact in a number of zones along the yarn. This leads to the result of the existence of a free volume in the yarn. This discontinuity of contact is essentially due to the variation of the torsional moment and the inclination angle along the filament.

For the 3rd side, which represents the initially yarn surface, we realize that it enters in contact for an axial position located between 5.7 and 6.9 mm; what shows the existence of migration in the yarn.

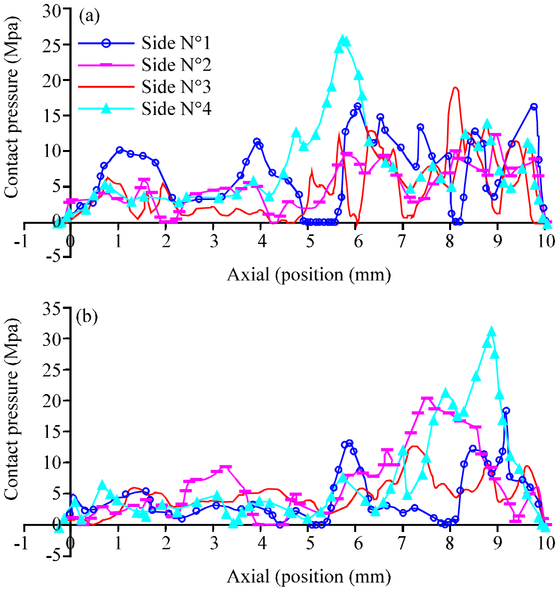

Fig. 6: Contact pressure comparison following the twist operation (a) internal filament and (b) central filament

We are concerned now to the contact pressure for the 4 sides of the internal filament (Fig. 6a) and the central filament (Fig. 6b).

It can be seen from Fig. 6a that pressure is more important in the case of the intra-layer contact. The contact pressure formed by the external filament is greater than the internal filament. This showed very clearly that external filaments are exposed to a more important frictional and contact stresses what forces them to enter in contact while the cohesion is more intense.

For the central filament (Fig. 6b), we notice that contact pressure increases for an axial position higher than 8 mm. It is to mention that central filament underwent buckling for an axial position lower than 8 mm. The following explanation may therefore be advanced to explain the reduction of contact pressure in this zone: the central filament exposed to a compressive and transverse stresses appear to compensate these pressures while changing radial position by buckling.

Study of the inner pressure: During spinning, the different layers of yarn are going to apply one on the other an inwards pressure, thus compresses the interior filaments: they become closer. As a result, adhesion between filaments in the yarn increases and yarn fineness decreases. Every linear textile structure having received torsion undergoes internal pressures that are essentially owed to the contact efforts. Therefore, all along the yarn, it will be swelling and compressed zones.

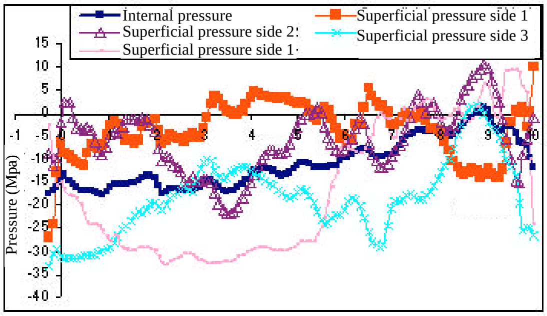

Fig. 7: Comparison of inner and superficial pressures for the external filament

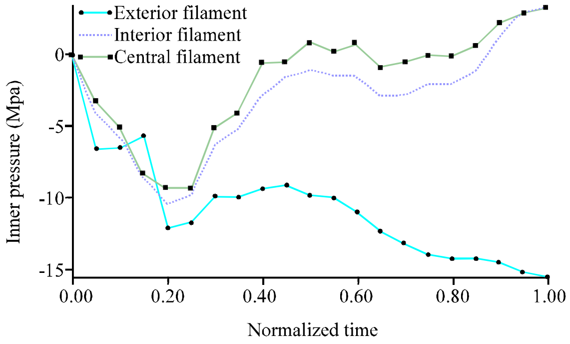

Fig. 8: Evolution of the inner pressure during twisting

In order to study the inner pressure filament, we apply torsion equal to 637 turns m^{-1} and a tension of 0.19 cN/tex to a yarn constituted of 19 filaments. A comparison of the superficial pressure for the 4 sides of the external filament that represent contact inter and intra layer is given in Fig. 7.

As seen from Fig. 7, pressure applied on the yarn extremes is more important for inter layers contact. On the other hand, the intra layer pressure exerted between the external filaments (side 4) is the strongest.

As calculating the superficial pressure average, it reveals that it is equal to the inner pressure. So, we are satisfied in this section with studying the inner pressure represented by the pressure inside the filament.

When comparing the evolution of the inner pressure magnitude during the twist insertion in Fig. 8, we notice that pressure is the strongest for the outside filament during the time step. We remark also that inner pressure is always negative for the exterior filament whereas it is firstly negative at the beginning of twisting operation, thereafter it decreases and becomes positive for the internal and central filaments meaning that during deformation, all filaments are under compression, inner and central filaments buckle or migrate in order to minimize tensile strain which is the so-called the shortest-path hypothesis (Liu *et al*., 2007).

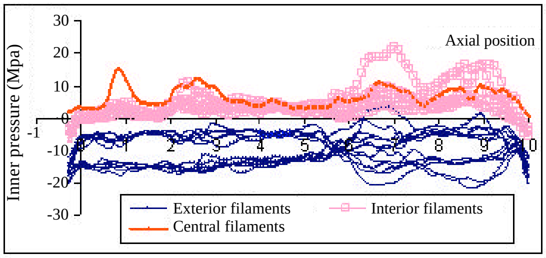

Fig. 9: Inner pressure comparison for exterior, interior and central filaments

Here, we are interested to the internal pressure following the twist operation, so we compare the inner pressure for all filaments in the yarn (Fig. 9).

As shown in Fig. 9 the axial distribution of inner pressure is divided into three disorganized layers. This reveals the existence of migration inward and outward layers.

From these curves, we can affirm also that inner pressure is the strongest for the outside filaments. Furthermore, the outside filaments are the most solicited because they are exposed to important lateral forces and compressive constraints and thus causing inwards transverse forces to be generated (exercised by the external filaments on the internal one).

The exterior filaments are highly stressed, in addition the curvature of their paths is also the largest and they follow a longer path than the internal and central filament. The results presented here confirmed previous results (Morton, 1956; Onder and Baser, 1996) concerning the resultant force acting towards the yarn axis.

To confirm this result, we measure the lengths of external ,internal and central filaments: the length of the outside filament is 14.276 mm whereas, the interior filament length is 11.5475 mm, so they are swollen, as well as for the central filament (10.2887 mm) that may explain the positive internal pressure.

When the yarn is further twisted the filaments near the yarn axis undergo transverse strengths and begin to come under compression. The larger the twist of the yarn, the larger is the region that is under compression. As we know, filament can not sustain significant compression unless there is sufficient lateral pressure. So, under large twist some filaments in the central area of the yarn appear to buckle, bend or migrate to release compression pressure therefore to preserve their length and to decrease the pressure intensity. This finding is different

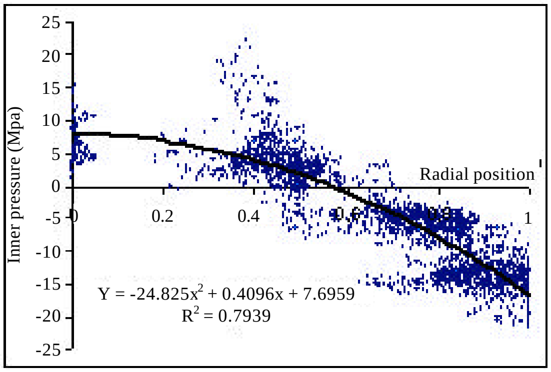

Fig. 10: Radial position distribution of inner pressure

from Liu *et al.* (2007) when he neglected this buckling of fibers in his yarn model and considered that the fibers near the yarn axis are under compression.

The reduced internal pressure can be also understood from lower interfilament friction in the yarn axis.

Therefore, the inner pressure decreases while heading from the surface toward the center of the yarn. The result presented coincides with corresponding result which belongs to Ismail (1972) while studying the distribution of the transverse pressure of filaments, he affirmed that it depends on their radial position.

So, in order to prove that the inner pressure depends on the radial position we visualize in Fig. 10 the inner pressure distribution according to the radial position (r/R) for an assembly of 19 polypropylene filaments. Where r is the helix radius and R represent the yarn radius.

From this figure we can deduce the existence of compressed zones represented by the external layer (negative pressure) and swollen zones represented by the internal and central layer (positive pressure). This result presented here didn't confirm previous study (Ismail, 1972; Liu *et al.*, 2007) while assumed that central zone is under compression.

We remark also that radial position pressure is divided into four layers. The zonal distribution depends on radial position, so we can affirm the hypothesis that yarn is divided into four layers, furthermore, external filaments are divided into two disorganized layers.

It is clear from Fig. 10 that magnitude of the radial pressure in the yarn decreases from yarn surface (r/R = 1) to the internal filament (r/R = 0.6) where it is null then increases while heading to the yarn core (r/R = 0).

This conclusion suggests that the evaluation of pressure phenomenon could be useful where a direct study of pressure over any length of yarn is possible due to numerical simulation.

CONCLUSIONS

Since, the pressure represents the constraints and the compressive stresses generated around the yarn, the present study gives a study of contact and inner pressure. Present research deals with the problem of measuring and defining different pressures existing in a twisted yarn. We have analyzed the pressure during and after twisting, we have proved that the central filament exposed to a compressive and transverse stresses try to compensate these pressures while changing radial position by buckling.

It is clear from the results presented in this analysis that the contact pressure formed by the external filament is greater than the internal filament because they are exposed to a more important stresses what forces them to enter in contact and the cohesion will be more intense. The inner pressure is the most important as the filaments are positioned at surface meaning that they are highly stressed, in addition the curvature of their paths is also the largest and they follow a longer path than the internal and central filament.

The results brought out in this study are of interest in showing the existence of compressed and swollen zones in the yarn. This study is supposed to be a start point to determine the influence of different twist parameters (torsion, tension, friction coefficient …) on the contact and inner pressure.

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