Processing Mechanics of Alternate Twist Ply (ATP) Yarn Technology

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DEDICATIONS

First and last of all, I dedicate this Ph.D. thesis to Almighty ALLAH SWT for giving me the strength to finish this thesis and for all his blessings to me.

Secondly, I dedicate this work to my parents Prof. Said Elkhamy and Eng. Sanna Seif Eldin for their love, support, for encouraging me to go to my limits and to achieve my goals. You’ve sacrificed a lot to see me get to where I am today and for that I’ll be forever grateful.

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Ply yarns are important in many textile manufacturing processes and various applications. The primary process used for producing ply yarns is cabling. The speed of cabling is limited to about 35m/min. With the world’s increasing demands of ply yarn supply, cabling is incompatible with today’s demand activated manufacturing strategies.

The Alternate Twist Ply (ATP) yarn technology is a relatively new process for producing ply yarns with improved productivity and flexibility. This technology involves self plying of twisted singles yarn to produce ply yarn. The ATP process can run more than ten times faster than cabling. To implement the ATP process to produce ply yarns there are major quality issues; uniform Twist Profile and yarn Twist Efficiency. The goal of this thesis is to improve these issues through process modeling based on understanding the physics and processing mechanics of the ATP yarn system.

In our study we determine the main parameters that control the yarn twist profile. Process modeling of the yarn twist across different process zones was done. A computational model was designed to predict the process parameters required to achieve a square wave twist profile.

Twist efficiency, a measure of yarn torsional stability and bulk, is determined by the ratio of ply yarn twist to singles yarn twist. Response Surface Methodology was used to develop the processing window that can reproduce ATP yarns with high twist efficiency. Equilibrium conditions of tensions and torques acting on the yarns at the self ply point were analyzed and determined the pathway for achieving higher twist efficiency. Mechanistic modeling relating equilibrium conditions to the twist efficiency was developed. A static
tester was designed to zoom into the self ply zone of the ATP yarn. A computer controlled, prototypic ATP machine was constructed and confirmed the mechanistic model results. Optimum parameters achieving maximum twist efficiency were determined in this study. The successful results of this work have led to the filing of a US patent disclosing the method for producing ATP yarns with high yarn twist efficiency using a high convergence angle at the self ply point together with applying ply torque.
CHAPTER 1: INTRODUCTION

Plied yarns are widely used in tire cords, cables and many textile products as well as industrial applications. Of particular interest in this thesis is the use of plied yarns in the carpet industry where the plied yarns are either looped or cut. Commercially available ATP processes have been able to supply yarns to the loop pile carpet market, however none of them has succeeded to supply yarns to the cut pile carpet market due to major quality issues. Plied yarn structures intended for use in the cut pile carpet are currently prepared by the cabling process. This cabling process is time consuming and is often the bottleneck in the carpet industry. The speed of cabling process for ply yarn production is limited to about 35 m/min due to the aerodynamic drag as one yarn is whirled around the other by a flyer guide.

The Alternate Twist Ply (ATP) yarn technology is a new process for producing ply yarns. An ATP yarn is a self twisted plied yarn, where the twist direction alternates every few feet. To ensure yarn stability at the twist reversal locations, the fibers must be interconnected or bonded. The ATP process can run up to ten times faster than conventional ply twisting. The speed advantage results from the fact that the paths taken by the individual fibers are topologically equivalent to that of a simple parallel array. This geometric feature permits the process to be run without capturing or rotating either the feed or output yarn packages; thus eliminating completely the limiting factors to productivity.

Current commercial ATP processes (Repco, Gilbos, Belmont) have limited applications in the carpet industry. They can only be used for loop pile carpet yarn production and not for cut pile carpet yarns. This is mainly due to the quality of the ATP yarn produced. Yarns produced by the current ATP technologies have a long zero twist region at the twist reversal, lack a uniform square wave twist distribution along the yarn
length and adequate twist efficiency. Non-uniformity in the twist will create sections of substandard twist and appear as defects in the carpet. The twist efficiency is defined as the ratio of the ply yarn twist to the singles yarn twist. High twist efficiency is needed to ensure that the yarns do not unravel after being cut.

There are still no disclosures which enable one skilled in the art to operate a process at a speed greater than that of conventional cabling while making a satisfactory product with good twist uniformity and twist stability suitable for use as cut pile carpet yarns.

Alternate twist plying involving the self plying of a fibrous assembly is a complex physical phenomenon. Little work in the literature has been done on the modeling of the self plying process. The goal of this thesis was to understand the physics and the processing mechanics of the Alternate Twist Ply yarn system. Through this understanding and process modeling, achieving a square wave yarn twist profile and an improved twist efficiency of the yarns produced on the Drexel ATP process was made possible.

Several parameters in the ATP process control the yarn twist profile. The ATP process is a time dependant process where the coordination of the yarn velocity profile and the twist insertion rate as a function of time is very crucial to produce a uniform ply twist distribution. Thus process modeling of the yarn twist across the different process zones was needed. This was done through establishing the equations of state for the different zones using a set of differential equations. A solution for these differential equations was obtained using a stiff integrator. This process modeling has also shown that the lengths of the twist insertion zone and the self plying zone on the machine greatly affect the twist propagation and distribution along the yarn length. Process Optimization using this process model together with a computer simulation of the time dependant velocity and rotation
profiles was done. The optimum process profiles and machine zone lengths required to achieve a square wave twist profile were determined.

A major goal of this thesis was to improve the twist efficiency of the ATP yarns. Aside from the yarn twist profile, the yarn twist efficiency is considered the main limiting factor to the use of ATP yarns in cut pile carpets. Conventional cabling produces ply yarns with 100% twist efficiency, while the maximum twist efficiency achieved in yarns produced by current commercial ATP processes is 65%. Twist efficiency is a measure of the tip stability of the yarn structure after it is cut to be used in the cut pile carpet. The yarn twist efficiency also affects the bulk properties of the yarn. Higher bulk yarns would provide a greater coverage in square footage per yard of the carpet which in turn has a huge impact on the economics of the carpet manufacturing industry.

This thesis has systematically studied the effect of the ATP process variables on the yarn twist efficiency. This research has also included the upgrading and modifying the Drexel ATP process to ensure that the experimental results are reliable and reproducible. Response Surface Methodology (RSM) was applied for the first time to the ATP process, to develop the processing window that can reproduce ATP yarns with the highest possible Twist efficiency. Results from RSM have shown that a maximum twist efficiency of 73% could be obtained with current machine setup. To further improve the yarn twist efficiency, a detailed study focusing on the self plying zone of the ATP process was conducted. The equilibrium conditions of the tensions and torques acting on the singles and ply yarns at the self ply point were analyzed. This analysis determined that the pathway for achieving higher twist efficiency is through the use of a wide yarn convergence angle at the point of self ply together with the addition of torque to the self ply yarn. A mechanistic model relating these equilibrium conditions to the yarn twist
efficiency was developed. This thesis has additionally designed and built a static tester to simulate the self plying process. The static tester has allowed us to study the effect of a large range of yarn convergence angles and ply torques on twist efficiency, which was not possible on the Drexel ATP process due to the restricted machine design. The results of the static tester were used to verify the mechanistic model results. This thesis has successfully identified the optimum process parameters needed to achieve maximum twist efficiency.

The production of ATP yarns with a square wave twist profile and high twist efficiency is of vital importance to the carpet industry. Successful modeling and application of the ATP process to produce cut pile carpet yarns would revolutionize the carpet yarn manufacture and the global carpet market will be transformed to a much higher level performance.
2.1 Ply Yarn and Its Applications

Plied yarn structures, occurring widely in science and engineering. Yarns are seldom being used in the form of single twisted strands. A conventional plied yarn shown in figure 1 is made from two or more twisted single yarns which have been combined together in a second twisting operation. The plying process generally improves the yarn strength and abrasion resistance to be able to withstand the stresses they are subjected to during subsequent processing operations.

![Figure 1 Conventional Ply Yarn](image)

Plied yarns have numerous applications. They are widely used in tire cords, cables, sewing threads and many textile products. Knitwear is almost always made from plied yarns in which the twist must be balanced as any residual torque in the yarn causes loop distortion. Ply yarns are also used in many industrial applications including filtration and geo-textiles. High performance technical yarns and hybrid yarns are also made from ply yarn constructions. A novel interest also is the use of ply yarn structures in biomedical applications.
2.1.1 Ply Yarn Application in Carpets

Of particular interest to this thesis is the use of plied yarns in the carpet industry. Carpets account for 65% of the floor covering market. The US market for carpet and rugs is a huge market with a good growing potential. As shown in Table 1, the carpet and rug supply demand is projected to rise 1.6% per year, through 2009, to more than 22 billion square feet. The US carpet and rug industry consists of about 200 companies. The key companies include Mohawk with 5.9 billion dollars in 2004 annual revenues with the carpet accounting for 70%, Shaw Industries with 5.2 billion dollars in 2004 revenues, Beaulieu and Interface. [1]

<table>
<thead>
<tr>
<th>Item</th>
<th>1999</th>
<th>2004</th>
<th>2009</th>
<th>% Annual Growth 04/99</th>
<th>% Annual Growth 09/04</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carpet &amp; Rug Demand</td>
<td>17230</td>
<td>20370</td>
<td>22100</td>
<td>3.4</td>
<td>1.6</td>
</tr>
<tr>
<td>+ Net Exports</td>
<td>90</td>
<td>-1040</td>
<td>-1700</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Carpet &amp; Rug Shipments</td>
<td>17320</td>
<td>19330</td>
<td>20400</td>
<td>2.2</td>
<td>1.1</td>
</tr>
<tr>
<td>Tufted</td>
<td>15715</td>
<td>17420</td>
<td>18100</td>
<td>2.1</td>
<td>0.8</td>
</tr>
<tr>
<td>Woven</td>
<td>325</td>
<td>580</td>
<td>850</td>
<td>12.3</td>
<td>7.9</td>
</tr>
<tr>
<td>Other</td>
<td>1280</td>
<td>1330</td>
<td>1450</td>
<td>0.8</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Carpets are usually made from two ply or three ply yarns. Over 90% of residential carpet is manufactured as tufted carpet. The two main types of tufted carpets are loop pile carpets and cut pile carpets. Loop pile carpets shown in figure 2 have yarns that are looped and uncut on the carpet surface. Loop pile carpet has excellent durability, strength and soil hiding capabilities.
Figure 2 Loop Pile Carpet [2]

However, loop pile have limited appeal for most home owners because of their low profile and reduced cushioning. Cut piles shown in figure 3 are used far more widely in residential applications and comprise the largest share of the residential market. Cut pile consists of yarns that are cut at the ends.

Figure 3 Cut Pile Carpet [2]

Quality construction of the cut pile carpet will affect the durability, appearance and price of the carpet and is most influenced by the twist of the fibers and the density of the tufts. Twist is especially important in cut pile carpet because the yarn tips are exposed and can become untwisted, giving the carpet a matted and worn appearance. There are five basic styles of cut pile carpet: Velvet, Saxony, Frieze, Shag, and Cable, each providing a different look and texture. The primary difference among these styles is the amount of twist in the yarns that will ultimately influence the carpet's durability.
Ply yarns used in cut pile carpets should have a uniform level of twist along its length. Non uniformity in the yarn twist level would affect the carpet appearance producing streaks and defects in the carpets. Ply yarns intended for use in cut pile carpets should have balanced structures with zero residual torque in the singles yarn i.e. 100% Twist Efficiency. The twist efficiency is defined as the ratio of the ply yarn twist to the singles yarn twist. The presence of any residual twist in the singles yarns would drive the yarns to unply once it is cut for pile insertion. The plied yarn are also exposed to hot air or steam to set the fibers in the twist ply configuration to ensure that they retain that form after the plies are cut. A certain degree of twist is required to hold the twisted heat-set yarns together and provide tuft definition during normal floor wear on a cut pile carpet. Frieze carpet has the highest twist level at about 7-9 twists per inch, whereas most cut pile carpet styles have between 3-6 twists per inch. [2]

2.2 Development of Ply Twisting Processes

Yarn spinning has probably been around almost as long as people have. Every group of people known on earth at least knew how to pick some animal hair and roll it back and forth along their leg or between their hands until the hair all twisted together and made a stronger piece of twine or twisted yarn. Later by around 5000 BC, a stick, called a spindle, shown in figure 4, was used to add the twist and hold the twisted fiber. Usually a whorl or weight stabilizes the spindle. The spindle is spun and twists the fiber until it becomes yarn.[3]

Figure 4 shows the major developments that took place in the yarn ply twisting processes over the years. The first major improvement in spinning technology was the spinning wheel, which was invented in India between 500 and 1000 A.D. It reached
Europe via the Middle East in the European Middle Ages. It replaced the earlier method of hand spinning with a spindle. The first stage in mechanizing the process was to mount the spindle horizontally in bearings so that it could be rotated by a cord encircling a large, hand-driven wheel. A series of improvements occurred in the 1700s and culminated in the first ring spinning mill for ply yarn production in the United States in 1970. Newer technologies that offer faster ply yarn production including two for one twisting and the yarn cabling process were also developed. In the 1970’s a new way for producing ply yarns was also introduced. This new method produced alternate twist ply (ATP) yarns using a self twisting process. Several ATP processes were introduced including the Repco, Gilbos, Dupont and Belmont offering much higher production speeds than conventional plying but mostly at the expense of yarn quality. The following sections will provide a brief description of the main developments main in ply twisting processes.
2.2.1 Conventional Two Stage Ply Twisting Process

Conventional ply yarns are produced by a two stage process. The first stage is to produce unidirectional twisted singles yarns on the ring spinning machine. Ring spinning is still the most dominant spinning system for producing high quality twisted singles yarns. The ring spinning machine simultaneously twists fibers into yarn using a ring-traveler system as shown in figure 5. The yarns are then wind onto a bobbin for storage. The production speed of the ring spinning machine is about 10 yd/min. The primary technological limitation of ring spinning lies in the speed of the ring-traveler system. Twist insertion is also limited by the rotation speed of take up package, where the higher the rotation speed the higher are the tensile forces acting on the yarn due to ballooning. This limits the size of the take up package and thus requires frequent process stoppage for package exchange.

Figure 5 Ring Traveler System on the Ring Spinning Machine [4]
The second stage is the plying of the twisted singles yarns together on the plying machine. The plying machine also has the similar speed limitations as the ring spinning machine due to ballooning and frequent process stoppage. With the speed limitations of both the yarn spinning process and the plying process, the conventional two stage ply twisting process is a very expensive one and represents a serious production bottleneck problem.

2.2.2 Two for One Twister

![Two for One Twister](image)

Figure 6: Volkmann Carpet Two for One Twister [5]

The Two-for-One twisting process is characterized by the fact that each mechanical spindle revolution imparts two twists to the yarn. This ensures a particularly effective up-twisting process for single yarns. This two for one principle allows two or more single yarns to be wrapped around each other while twisting thus eliminating the need for the
time consuming two step process of single yarn twisting followed by yarn plying. The two untwisted singles yarns are either preassembled onto one yarn package or two superposed yarn packages are used, each with one single yarn end. The untwisted feeding arrangement is placed into the stationary spindle pot as shown in figure6. The yarn passes from the feed package to the apex of the spindle and enters the yarn channel and multi-tension device. It then enters the spindle and exits at the spindle rotor. Between the tension device in the hollow axle and the exit in the spindle rotor, the yarn receives its first turn of twist. The yarn then follows the groove of the reserve disc and balloons around the stationary spindle pot. The second turn of twist is given within the balloon between the spindle rotor and the balloon thread guide. The yarn then passes around the deflection rolls of the yarn sensor to the pre-take-up roll. Finally the traverse guide lays the yarn onto the rotating yarn package driven by the take-up roll. [5]

2.2.3 Yarn Cabling Process

The cabling process shown in figures7&8 is the primary process currently being used for producing ply yarns for cut pile carpet. In the direct cabling process, two yarns are twisted around each other in a single operation without the individual strands themselves being twisted. One of the two untwisted yarn packages is fed in an overhead creel, while the second yarn package is located above the rotating spindle, in the cabler spindle pot. Both yarns are controlled by tension devices. This ensures that both yarns are cabled with uniform tension. The untwisted yarn end from the creel package wraps around the storage disc and forms a balloon around the pot package. At the balloon apex, both yarns meet and wrap around each other, which thus dissolves the false twist in the balloon yarn.
At the meeting point, both yarns must have the same tension in order to form a balanced ply yarn with no residual torque and equal lengths of component yarns. [5]

The most important feature of the cabling process is that it produces yarns with 100% twist efficiency. This is simply due to the fact that the single yarns do not receive any twist during the cabling process provided that the singles yarn tension is exactly equal on both yarns. In practice, the precise setting of the tension is determined by experiment. Whenever the spindle speed is altered, the pot-yarn tension must be adjusted to compensate for a consequent increase or decrease in balloon tension. The most accurate test for balanced conditions is to measure the lengths of both ends after unplying and detwisting.

In comparison with the Two-for-One twisting process, the yarn balloon in the cabling process contains only one yarn with a correspondingly low level of air resistance.
Energy consumption levels are thus also considerably smaller for the cabling process. Because only one yarn is drawn from the pot, double-length feed packages can be processed in one loading. This ensures long operating times and the manufacture of substantial knot-free lengths of cabled yarn.

The major disadvantage of the cabling process is its speed limitation. The speed of cabling process for ply yarn production is limited to about 35 m/min due to the aerodynamic drag as one yarn is whirled around the other by the flyer guide. The cabling process is often the bottleneck in the carpet industry. The cabling process also has limited product flexibility where only two ply yarn constructions could be produced.

2.2.4 Alternate Twist Ply Process

An ATP yarn shown in figure9 is a ply yarn where the twist reverses in direction every few feet. [6]

![Figure 9: Alternate Twist Ply Yarn Structure](image)

The ATP yarn is produced by the self plying of the singles yarns in one direction of twist for one half of the cycle and self plying in the opposite direction of twist for the second half of the cycle. The concept of self plying arose from the consideration of the use
of alternating twist. In the conventional two stage ply twisting process, mentioned in section 2.2.1, in order to be able to insert unidirectional twist, it is necessary to rotate the take-up packages. This is the short coming of the process. Thus, if it were possible to accept twist alternating in S and Z directions; it would be necessary only to rotate the singles yarn rather than the associated take up package. Since the singles yarn mass and diameter are small, it thus should be possible to rotate it at high speeds with the expenditure of very little energy.

2.2.4.1 Basics of the ATP Process

An ATP yarn [6] is produced by applying torque in the same direction to two singles yarns under low tension as shown in figure10. This applied singles yarn torque is the main driving force of the ATP yarn system. The singles torque generates twist in the singles yarns which in turn leads to the build up of the tensile and torsional strain energies in the singles yarns. Once these singles yarns are allowed to converge together, the yarns immediately release the energies stored in the system through a spontaneous self plying process. This is because the unwinding torques developed in the individual singles yarns, before they are allowed to converge, do not counter balance one another but urge the singles yarn to rotate in the same direction and thus self ply. The self ply yarn produced has an opposite direction of twist to that inserted in the singles before self plying. As the self plying process proceeds the strain energy in the singles yarns gradually decreases and tensile, torsional and bending strain energies are developed in the ply yarn. The bending strain energy increases due to the yarn curvature in the ply structure and the tensile strain energy increases due to ply twist contraction. Ideally, the self plying process stops when all
unwinding torque energy saved in the singles is released, i.e. when the singles yarn have zero residual twist.

In the second half of the process cycle, the torque applied to the singles yarns must then reverse its direction and twist is inserted in the singles yarn in the opposite direction. This is because continuing to apply torque in the same direction all throughout the process will result in the buildup of a very high twist level and tension in the singles yarns which would lock the singles yarn structure and halt the self plying process.

The region in the ATP yarn created when the torque applied to the singles yarns reverses its direction is known as the zero twist region. This is because, at this region, portions of the ATP yarn with opposite directions of twist meet together and cancel each other creating a region of zero twist in the yarn. This zero twist region greatly affects both the ply yarn appearance and strength. In order to minimize the length of the zero twist region, a method of bonding the ply yarn at the zero twist region must be used. This bond serves to capture the twist in each region of opposite twist and prevents the yarns from unraveling. The distance between two zero twist regions in an ATP yarn is defined as the
twist reversal length.

An optimum ATP yarn should have a uniform level of twist along the yarn length, known as a square wave **Twist Profile**, a minimum bond length of about 0.1” and a twist reversal length of a few feet.

The ATP yarn should also be a balanced ply yarn structure. A balanced ATP yarn is one that will maintain its configuration without the application of external tension or torque. This means that the torque applied to the singles yarns, before they are allowed to self ply, must all be translated to the ply yarn structure leaving zero residual twist in the singles yarn. The measure of this translation efficiency is called the **Twist Efficiency**. The twist efficiency is defined as the ratio of the ply twist to the singles twist.

Table 2 shows a comparison between the ATP process and the cabling process. The ATP process could be run at much higher speeds than the cabling process. The speed advantage results from the fact that the paths taken by the individual fibers are topologically equivalent to that of a simple parallel array. This geometric feature permits the process to be run without capturing or rotating either the feed or output yarn packages, thus eliminating completely the limiting factors to productivity. Moreover, the winding tension, which is often very high on conventional plying systems, is replaced by a much lower, controlled winding tension; reducing end breaks and virtually eliminating the emission of fly and dust at the plying operation. Production of ATP yarns at speeds reaching 600 yd/min to be used in cut pile carpets would completely revolutionize the carpet industry and its economics.

Unlike the cabling process, the ATP process also offers a very large flexibility in the range of products it can produce. The number of plies in the ATP yarn structure is theoretically unlimited. Current commercial ATP processes can produce ply yarns with up
to six plies. This feature offers a great advantage over the cabling process, where ATP yarns constructed with various yarn colors, diameters and types could be made use of in the producing of numerous fancy effects in carpets.

A major advantage of the cabling process over current commercial ATP processes is the yarn twist efficiency. Compared to the 100% twist efficiency yarns produced by the cabling process, the ATP yarns produced in the current commercial market have a maximum twist efficiency of 65%. This means that the singles yarn still have about 35% residual twist in their structure after self plying. Although this feature of twist liveliness of the singles yarn could be made use of in various applications such as to provide different surface looks and texture in loop pile carpets, but it is unacceptable for use in cut pile carpet yarns.

Table 2 Comparison between the ATP process and the Cabling process

<table>
<thead>
<tr>
<th></th>
<th>Cabling</th>
<th>ATP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Speed Limited by</strong></td>
<td>Inertia</td>
<td>Unlimited</td>
</tr>
<tr>
<td></td>
<td>Aerodynamic drag</td>
<td></td>
</tr>
<tr>
<td><strong>Max. No. of plies</strong></td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td><strong>Twist efficiency</strong></td>
<td>100%</td>
<td>65%</td>
</tr>
</tbody>
</table>
2.2.4.2 Modeling of the ATP Process

Very little work in the literature has been done on the modeling and understanding of the Alternate twist plying process. This is in most possibly due to that the ATP process, never really gained a world wide acceptance commercially when it was first introduced in the 1970’s.

In 1971, Henshaw [7, 8] reviewed the basic concepts of ATP and the different methods of inserting alternating twist with a description of the associating machine components and the resulting ATP yarn properties, with an emphasis on the Repco ATP process. The Repco ATP process is described in section 2.3.1. In this study, Henshaw, also provided a simple model to derive the relationship between the singles yarn twist and the ply twist in the ATP yarn. This model was based on the analysis of the internal forces set up in the ATP yarn structure when it is subjected to stress. The theory behind the model was that the ATP yarn is a stable structure on its own account without needing any setting treatment. Thus, in order to obtain that stable structure, a balance must be maintained between the untwisting forces, due to tension applied on the yarn, and the binding forces, due to the compression forces generated between the two plies of the ATP yarn. This model yielded the relationship between the ply and singles twist shown in equation 1.

\[ 6D = -(S_1 + S_2) \]  

(2.1)

Where D is the ply yarn twist, \( S_1 \) and \( S_2 \) are the twist in each of the singles yarn respectively. Thus, if the two singles yarns have the same twist level, the ply twist would be opposite and equal to one third of the singles yarn twist, i.e. yielding a yarn twist efficiency of 33%. The results of the theoretical model where much lower than the experimental results which showed that the ply twist is equal to or higher than two thirds
of the singles yarn twist. [8] This was attributed to the extremely crude approximations to the actual yarn used in the theoretical model.

The work done by Tayebi and Backer, [9-11] on the analysis of the mechanics of parallel self plying structures is one of the most significant reviews available in literature. Their research was directed towards the theoretical prediction of the equilibrium ply twist in the ATP yarn on the basis of singles yarn twist and properties. Both monofilament and multi-filament singles yarn were considered in their research. The procedure adopted in that study was to express the total strain energy of the ply yarn system as a function of the initial singles twist, singles yarn diameter and physical properties, and the ply twist helix angle. The prediction of the ply twist helix angle was based on the theory that a stable equilibrium condition is reached when a minimum strain energy system is obtained and that any further externally imposed change in ply twist will result in an increase in the total strain energy and develop a restoring torque which tends to drive the system back to the minimum strain energy configuration.

The tensile strain energy of the singles yarn was neglected in this model because contraction of the singles yarns during alternate twisting was judged negligible. The total strain energy was expressed as the sum of the shear strain energy (SSE), bending strain energy (BSE) and tensile strain energy (TSE). In order to obtain the value of the ply twist helix angle corresponding to the stable equilibrium configuration, the strain energy expression was minimized as a function of the ply twist helix angle. Figure11 shows the results of the Tayebi monofilament rubber model, illustrating how the total strain energy of the ATP yarn system and its components vary with the ply twist helix angle. Figure11 shows that as the ply twist helix angle increases the rate of increase of both the tensile and
bending strain energies increases and that the total strain energy possesses a minimum at a certain value of ply twist helix angle.

Experimental verification of the predicted ply twist values was done by simulating the self plying process on a simple laboratory static device. The self ply yarn was prepared by following stages 1-3 shown in figure12.

![Figure 11: Strain energy and its components as a function of ply helix angle in Tayebi monofilament rubber model [10]](image)
Figure 12: Stages of producing an ATP yarn using a static laboratory device [9]

Stage (1): Twisting of Component Strands in Alternating Directions

Stage (2): Attaching of Individually Twisted Component Strands Together

Stage (3): Spontaneous Flying of Component Strands

Figure 13: Theoretical and experimental results of Tayebi monofilament rubber model [10]
Figure 13 illustrates the results of the Tayebi monofilament rubber model. [10] The experimental and theoretical results are in good agreement at low values of singles twist which validates the minimum strain energy model. At higher values of singles twist, the experimental results showed higher values of ply yarn twist than the theoretically expected. This was attributed to the nature of the stress-strain behavior of the rubber yarns used, where if the strain in the rubber exceeds the linearity region on the stress-strain curve, the actual tensile strain energy developed in the singles rubber yarn would be less than the theoretical value, thus resulting in the continuation of the self plying process to a higher ply twist angle until the equilibrium position of minimum strain energy is reached. [9]

As shown also in figure 13, as the singles yarns twist increases, the rate of increase of ply twist decreases. In other words, this shows that as the singles twist increases, the yarn twist efficiency decreases. From example, it can be seen that at a singles yarns twist of 2 turns per inch (TPI), only a yarn twist efficiency of about 55% is obtained.

Renewed interest in the modeling of ply yarn structures has been seen over the past few years [12-15]. This is due to the applicability of these models to the modeling of supercoiled DNA plasmids, i.e. closed pieces of DNA. In 2003, Heijden et al [14] used a variational approach to derive the equilibrium equation and boundary conditions for a parallel self ply structure under tension. The total potential energy of the self ply was expressed as the sum of the bending energy, due to curvature in the ply, the torsional energy, due to twist, the potential energy, due to applied tension, and the potential energy, due to applied torque. Numerical results were presented for a balanced self ply structure approaching lock-up, i.e. when self plying stops.
Figure 14 shows the ply solution obtained numerically by solving the equilibrium equations subject to the boundary conditions that the initial singles twist in the two parallel strands is zero and the final singles twist is three turns of twist. The numerical solution yielded a self ply yarn with 2.29 turns of ply twist, i.e. the yarn twist efficiency is 76%. The results of the numerical model are in close agreement with the experimental results obtained by Tayebi et al [9-11].

The results of Tayebi and Backer [9-11] and Heijden et al [14] have provided key insight to the nature of one of main problems associated with alternate twist plying. Both models have shown that the self plying process involved in the ATP process does not yield ply yarns with 100% twist efficiency. However, these results were only illustrated at very low values of singles yarns twist from 0-3 TPI, whereas ATP yarns intended for use in cut pile carpets should have twist in the range of 3-9 TPI depending on the carpet type. Of the major goals of this thesis is to improve the twist efficiency of ATP yarns, actually produced on a commercial ATP machine, within the required twist level of cut pile carpet yarns. In addition to that, both models have only considered the self plying of parallel yarn
structures which is not the actual case in all commercial ATP processes where the yarns converge together at an angle termed “Convergence Angle” at the point of self ply.

### 2.2.5 Sirospun Process

The Sirospun process shown in figure 15 is another method of producing a two ply yarn in a single spinning operation. In this process, the two singles yarns are drafted either on the same or adjacent drafting systems and then combined and twisted together on the same spindle. Sirospun yarns are used mainly in the worsted industry because of its improved weaveability over its singles yarn counterpart. In 1982, Plate and Lappage [16-18], published a series of papers on the introduction of the sirospun process. In their work,
the basis of the sirospun process was discussed and the theoretical model underlying the process was presented.

Plate et al [16-18], have shown that the convergence angle (α), shown in figure16, at which these two singles yarns will converge is determined by a force-and-torque balance at the convergence point. Above the convergence point, the singles yarn will contain some twist that is in the same direction as the ply twist and of a magnitude that is again determined by torque balances. In a static modeling of the process, as ply twist is being inserted, the position of the convergence point of the two strands will move upwards which is approximately equivalent to the normal spinning situation, in which the convergence point remains stationery in space while the two strands are moving downwards. In spinning, once equilibrium is reached, the twist in the strands above the convergence point

![Diagrammatic Representation of the Force Balance at yarn convergence point in the Sirospun process](image)
will remain constant. As the strands move downwards, the twist would run up the strands so as to retain a constant position in space and the ply yarn below the convergence will have no residual singles twist.

The sirospun model results [16, 17] showed that the level of twist generated in the singles yarns above the convergence point at equilibrium relies solely on the ply twist and the helix radius of the yarns inside the ply. This model was based on the idealizing assumptions that the singles yarns are perfectly elastic and that the flexural rigidity of the singles yarns are the same above and below the convergence point. Experimental verification using rubber monofilaments showed good agreement with the theory. [18]

Miao et al, [19] also adopted an experimental procedure to investigate the steady-state sirospun spinning geometry and the effect of some major machine variables on the process. The experiments were conducted on a ring spinning frame and a high frequency stroboscope in a single flash mode was used and synchronized with an automatic camera.

![Figure 17](image)

**Figure 17** Effect of ply yarn twist on Singles yarn twist above the convergence point in the Sirospun process [19]
Their main results, figure 17, show that as the ply twist increases, the singles yarn twist above the convergence point also increases. However, the singles to ply twist ratio decreases considerably when the ply twist increases. It was also shown that as the spinning tension increases, the singles yarn twist above the convergence point increases.

From the standpoint of this thesis, the understanding of the sirospun process was very important and has a strong relevance to the understanding of the effect of major process variables in the ATP process as will be discussed in Chapter 8.

2.3 Commercial Alternate Twist Ply Processes

2.3.1 Repco ATP Process

The Repco ATP process has been around since the 1970’s. While the system never gained wide acceptance, it developed a niche market in Europe for the production of high-bulk acrylic yarns. [20] There were several in-house modifications applied over the years. These evolutionary concepts all have been combined into one unit marketed by the England-based Macart Spinning Systems as the Platt Self Twist Spinner 888 shown in figure 18. [21] The ATP yarn is formed by continuously advancing the singles yarns and inserting alternating 'S' and 'Z' twists in the singles yarns emerging from the drafting system. Twist insertion is done by passing the singles yarns between rollers which reciprocate along their axes as they rotate to deliver the yarns. The singles yarns are then brought together and allowed to self ply around each other to form a two ply yarn construction. The Repco process intermittently stops for reversing the singles yarn twist after each cycle. A complete cycle of 'S' and 'Z' twists occurs every 22 cm, providing a very short twist reversal length, which greatly affects the yarn appearance.
At the singles yarn twist reversal, the singles yarns are fastened together only by inter-filament friction. Due to this insufficient bonding method, long zero twist regions between twist reversals are practiced. Loss of singles and ply twist and lack of twist uniformity especially near the twist reversal region are serious quality problems. For these quality reasons, the ATP yarn produced by the Platt Self Twist Spinner 888 has found limited applications and is mainly used in the knitting industry.

### 2.3.2 Gilbos Air Twist Process

The Belgium-based Gilbos NV’s Air Twist system operates on a similar self plying principle as the Repco ATP process. The alternating twist is applied by means of detorque jets shown in figure 19 manufactured especially for Gilbos by Heberlein Fiber Technology Inc., Switzerland.

The zero twist region is reinforced by an air intermingling process. The main
features of this process include a computer-controlled timing of the various functions and processing parameters. The Gilbos process also offers the flexibility of independently setting the twist process parameters for each spindle, allowing a different product on each spindle. The Gilbos process is mainly applied to combining filament yarns to resemble a multifold twisted yarn. Due to quality issues similar to those of the Repco ATP yarn, this system has only found limited use in the area of loop pile carpet yarns, and other areas of application are still being pursued. [22]

2.3.3 Belmont Roto-Twist Process

The US-based Belmont Roto-Twist machine shown in figure 20 is considered the most successful machine in the market for producing ATP yarns currently. It has a relatively large world wide market for producing loop pile carpet yarns.
Alternate twist is inserted in the singles yarn using air jets called “Roto-Jets”. These Roto-Jets shown in figure 21 include an orifice extending through it for permitting the passage of a moving yarn. An air channel extends through and communicates with the orifice. [23]
This air channel communicates with the orifice at a tangentially-offset angle to the path of the yarn through the orifice to create a cyclonic air circulation pattern in the orifice to insert a predetermined direction of twist into the yarn as the yarn passes through the orifice. [23] The twisted singles yarns are then bonded together by an air tack before they are allowed to self ply, as shown in figure 22.

![Air Tack Bond on the Belmont Roto-Twist Machine](image)

Figure 22 Air Tack Bond on the Belmont Roto-Twist Machine

This air tack is inserted using a moving air bonder that allows the Roto-Twist machine to be a continuous non stop process that can run at very high speeds reaching 600 yd/min. One of the main features of this process is the delayed self plying zone, where the bonded singles yarns are not allowed to self ply except after they are taken up by a constant velocity roll. The ATP yarns are then wound on a mast accumulator which ensures a continuous yarn supply to subsequent processes in the production line. The Belmont Roto-twist process produces ATP yarns with long twist reversal lengths of about three feet. The Roto-Twist machine also has the flexibility of producing up to six plies in the yarn structure. Despite this very high productivity and the large flexibility that the Belmont Roto-twist process offers, these ATP yarns can not be used as cut pile carpet yarns. This is mainly attributed to the relatively long zero twist regions that exist between the twist
reversals reaching 1-2 inches in length, as shown in figure 23, and the low twist efficiency levels of the produced ATP yarns of 65% on average.

![Figure 23 Long Zero Twist Region in the Bemont Roto-Twist ATP Yarn](image)

2.3.4 DuPont ATP Process

The DuPont ATP process, [24-34] shown in figure 24, was first introduced by E.I. Du Pont de Nemours and Company in the 1970’s. This technology was later patented by E.I. Du Pont de Nemours and Company in 1989. A series of eleven patents then followed, each with different process or product claims. A table including these patent numbers, the dates filed and the main claims in each patent is shown in Appendix A. This process produces ATP yarns through the steps of advancing the singles yarns adjacent to each other, twisting the singles in the same direction with an air torque jet system as they advance, allowing the twisted yarns to self ply together, stopping the forward motion of the yarns, bonding the ply-twisted yarns with an ultrasonic bonder, stopping the twisting of the yarns, then repeating the previous steps while twisting the singles yarns in the opposite direction.

Twist insertion in the singles yarns is done using torque jets, named “main jets”, shown in figure 25. The cross-section of the main torque jet is shown in figure 26. The main torque jet has two parallel yarn passages each of which is intercepted by two air passages.
and located tangentially to the yarn passages but at different locations along the axis. As compressed air is admitted alternately to the air passages the yarns are twisted first in one direction and then the opposite.

![Figure 24 Machine Schematic of the DuPont ATP Process [24]](image)

An important feature of this process is use of an ultrasonic bonder, shown in figure 25. The ultrasonic bonder provides a method of achieving short, stable bonds and a very short zero twist region of about 0.2”. The main component of the bonder is an ultrasonic horn that is associated with an anvil, which moves vertically. There is a slot in the surface of the anvil which is opposed to the energizing surface of the horn. When a bond is to be fixed, the anvil rises and engages the ply twisted yarn which fits compactly into the anvil slot. The tension applied to the yarns during bonding aids in inserting the plied strands in the anvil slot while maintaining the plied angled orientation of the strands.
which is essentially maintained during bonding and assists in consolidating the filaments after bonding. During bonding, the anvil moves upward and presses the plied yarn against the tip of the horn which is continuously energized, heating the plied yarns and forming a thermal bond between them. Titanium and aluminum are two suitable materials for the horn. The portion of the anvil contacting the yarn is made of a material having low heat thermal conductivity, good wear resistance and anti-stick properties. Suitable materials are polyimide resins and certain ceramics. [24-34] The ultrasonic transducer can be either magneto-strictive or piezoelectric, although a piezoelectric transducer is preferred because of its high electrical to vibrational conversion efficiency, which is particularly important because of its continuous operation.

A helper torque jet, shown in figure 25, is placed after the ultrasonic bonder and works identically as the main torque jet and its function is to twist the plied yarns in the same direction as the main torque jet to assist in the self ply.

![Figure 25 Torque Jets and Ultrasonic Bonder on the DuPont ATP process [24-34]](image-url)
Unlike the previous ATP processes, the DuPont process is able of producing ATP yarns with adequately uniform twist and bulk, with long twist reversal lengths. The bonding method is unique, in that the bond is formed by the ultrasonic bonder after the twisted singles are allowed to ply together, and before the singles twist is reversed. The uniqueness of this process also lies in the fact that it is the only process that uses a helper torque jet, placed after the main torque jet, to assist in yarn plying. The DuPont ATP process also has the flexibility of producing up to six ply yarn constructions. It can also be run with velocity profiles of both axial and rotational speeds.
Table 3 shows a comparison of the main features of the DuPont ATP process with the Belmont Roto-twist process. Of these main features, is the bonding method where a fixed ultrasonic bonder is used on the DuPont process producing very short bonds as compared to the long ones produced by the moving air bonder on the Belmont Roto-twist. However, the moving air bonder gives the Belmont process a major advantage over the DuPont process is being a continuous non-stop process.

Although the DuPont process was never really commercialized in the market, its unique features offer it a very large potential of being used for cut pile carpet yarn production. This DuPont process was recently donated to Drexel University to allow for continued scientific research that is needed to optimize the process in order to reach its commercialization goal. This process is now known as the Drexel ATP process.

<table>
<thead>
<tr>
<th></th>
<th>DuPont</th>
<th>Belmont</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bond</strong></td>
<td>Ultrasonics</td>
<td>Moving Air Jet</td>
</tr>
<tr>
<td><strong>Self Ply</strong></td>
<td>Immediately after Torque Jets</td>
<td>Delayed Plying after Velocity Rolls</td>
</tr>
<tr>
<td><strong>Helper Jet</strong></td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>Velocity</strong></td>
<td>Profiled</td>
<td>Constant</td>
</tr>
<tr>
<td><strong>Bond Length</strong></td>
<td>~0.1”</td>
<td>~1.5”</td>
</tr>
<tr>
<td><strong>Carpets Application</strong></td>
<td>Loop and Cut Pile</td>
<td>Loop Pile</td>
</tr>
</tbody>
</table>

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CHAPTER 3: OBJECTIVES

One of the largest applications of ply yarn is in the carpet industry. The cabling process is currently the primary process used to supply ply yarns to the carpet industry. However, its major drawbacks in speed limitation and product flexibility, urge the need for the development of an alternate process for ply yarn production. Current researches in conventional ply twisting processes have been aimed to increase their production speeds, but to date, none of these developments have been successful to achieve significant improvements compatible with today’s dynamic market strategies. The ATP yarn technology has been recognized for its ability to produce ply yarns at ultimate production speeds. Few currently available commercial ATP processes, reviewed in Chapter 2, have been able produce ATP yarns for use in loop pile carpets. However, efforts to produce ATP yarns for use in cut pile carpets have not been yet fruitful. The yarn prerequisites for such a use are the uniformity of the twist profile along the ATP yarn length and high yarn twist efficiency. The Drexel ATP process, (based on the DuPont ATP), has been identified as a promising process for production of ATP yarns with the required high quality levels at very competitive production speeds.

Since alternate twist plying with ultrasonic bonding and profiled velocity offer the possibility of high speed high quality yarn production, it is envisioned that optimizing the ATP yarn twist profile and yarn twist efficiency on the Drexel ATP would enable its use for cut pile carpet yarn production. Successful demonstration of this pilot-scale process should lead to demonstration on a commercial machine.
The objectives of this thesis are:

3.1 Production of ATP yarn on the Drexel ATP process

This section presents an investigation into the feasibility of producing ATP yarns with reproducible characteristics on the Drexel ATP process. Bulk Continuous filament (BCF) nylon yarns were mostly used as being the most common material used in cut pile carpet yarns.

3.2 Characterization of the ATP yarn

This section establishes the characterization procedures used for the quantitative evaluation of the ATP yarn twist profile and twist efficiency.

3.3 Process Optimization and Prediction of the Yarn Twist Profile

The main objective of this section is to improve the yarn twist profile of the Drexel ATP process to achieve a square wave twist profile shown in figure 27. The main features of a square wave twist profile is a constant twist level along the twist reversal length with a sharp transition from “S” to “Z” twist at twist direction alternation. A square wave twist profile should have a very short zero twist region including the bond of approximately 0.2 inch. This objective is approached by providing an understanding of how the twist is inserted in the yarn along its path through the different zones of the ATP process and thus controlling the yarn twist profile.
Process modeling of the yarn twist across the different process zones was done through establishing the equations of state for the different zones using a set of differential equations. Prediction of the yarn twist profile was based on the solution of the differential equations using a stiff integrator and a computer simulation of time dependant velocity and rotation profiles. Experimental verification of the computational model results was provided through on line measurements of the yarn twist profile on the Drexel ATP process. This computational model was used to determine the optimum process profiles and variables required to achieve a square wave twist profile.
3.4 Process Optimization and Prediction of the Yarn Twist Efficiency

A major objective of this thesis is to improve the yarn twist efficiency on the Drexel ATP process. This problem is tackled through conducting a detailed analysis to determine the effect of the process variables on the yarn twist efficiency and introducing several theoretical and experimental techniques to identify the pathway for achieving maximum yarn twist efficiency.

3.4.1 Effect of Process Variables on the Yarn Twist Efficiency

An experimental investigation of the effect of the Drexel ATP process variables on the yarn twist efficiency was carried out. The main process variables are the main jet pressure, helper jet pressure, singles yarn tension and yarn temperature. The experiments were conducted by changing one variable at a time to establish a clear understanding of its effect.

3.4.2 Empirical Modeling of the Yarn Twist Efficiency

This section presents an analysis based on Response Surface Methodology (RSM) to predict and determine the optimum process parameters required to obtain maximum possible yarn twist efficiency on the Drexel ATP process. RSM was carried out to provide a systematic means for the optimization of the process parameters. An empirically determined response function was obtained by a linear regression analysis using observed responses (yarn twist efficiency) and coded variables (main jet pressure, helper jet pressure, singles yarn tension and yarn temperature). The relationship between the response and variables is visualized by a response surface or contour plot. From the graphical representations as contour plots, the operating conditions necessary to generate ATP yarns with maximum twist efficiency can be predicted.
3.4.3 Equilibrium Analysis and Static Modeling of the ATP Process at the Convergence Point

This section of the thesis presents a method of gaining a better understanding of the underlying mechanics of alternate twist plying at the self ply point. The motivation behind that was to examine the possibility of further improving the yarn twist efficiency beyond that obtained and predicted by the RSM. A mechanistic analysis of the tension and torques, acting on the yarn at the self ply point at equilibrium, taking into account the geometry of self plying, was developed. This equilibrium analysis revealed the primary key points to further improving the twist efficiency. Experimental verification of the equilibrium analysis results was provided through a series of experiments done on a static tester designed and built specifically to simulate the self ply point In the ATP process. Further on, the Drexel ATP process was redesigned to allow for the confirmation the static tester results.

3.4.4 Mathematical Modeling of the ATP yarn Twist Efficiency

This section provides the development of a mathematical model to derive the relationships between the twist in singles yarns, the ply yarn twist and the equilibrium tension and torques acting on the ATP yarn structure. This section thus establishes a physical expression of the yarn twist efficiency in terms of the process variables. The computed twist efficiency values were experimentally verified by the static tester results.
CHAPTER 4: MATERIAL AND METHODS

4.1 Introduction

The objectives of this thesis were applied to the Drexel ATP Process which is based on the DuPont ATP described in Section 2.3.4. This process was donated from DuPont to Drexel University. In order to be able obtain reliable and reproducible data, several upgrades were required. The following section describes the main machine components of the Drexel ATP process and includes a description of the upgrading of several features in it. The remaining sections, of this chapter, include descriptions of the materials and methods employed in attaining the thesis objectives. The experimental parts of this thesis can be subdivided according to the objectives into the following sections: 1) Production of ATP yarn on the Drexel ATP process 2) Characterization of the ATP yarns 3) Process optimization of the yarn twist profile and yarn twist efficiency.

4.2 Upgrading of the Drexel ATP Process

The Drexel ATP process, donated from DuPont, is shown in figure28. The Drexel ATP process in its initial status was composed of a two yarn holder wooden creel, a stainless steel plate, with the main jets, the ultrasonic bonder and the helper jet mounted on it, in a horizontal plane and a profiled velocity roll. The main jets, ultrasonic bonder and helper jets, shown in figure29, represent the key elements characterizing the Drexel ATP process. Several process and machinery upgrades including the addition of new machine components were required in order to enable continuous production of ATP yarns on the Drexel ATP process. This equipment upgrade was also crucial because of the need to ensure that the ATP yarn features resulting from the different experimental trials, conducted to achieve the thesis objectives, are reliable and reproducible.
Figure 28 ATP process donated from DuPont to Drexel University

Figure 29 Key machine elements of the Drexel ATP process
A schematic of the yarn path along the current Drexel ATP process illustrating the main machine components is shown in figure 30. The singles untwisted yarns, supplied from stationery yarn packages mounted on a creel, are first passed through yarn tensioners. The main torque jets insert twist in each singles yarn. Once the singles yarns emerge from the main jets they spontaneously self ply. The self ply yarn then passes over the anvil of the ultrasonic bonder. After each half cycle of the ATP process, before the twist inserted by the main jets alternates its direction, the ultrasonic anvil moves vertically upward and presses the self ply yarn against the energized ultrasonic horn to form a thermal bond. The full stroke of the ultrasonic anvil is 0.191 inch. The clearance between the ultrasonic horn and anvil was set to 0.08 inch and allow for compression of the yarn under the horn to ensure the formation a good strong bond.

The ply yarn then passes through the helper jet whose function is to insert ply torque in the same direction of the main jets torque. The helper jet is placed 2 inch apart
from the main jets. The yarn is then passed through a profiled velocity roll that controls the yarn velocity profile along the machine. A Leesona yarn winder, working on a constant tension principle, was also added to wind the ATP yarn onto packages to prevent yarn entanglement. The operating manual for the Drexel ATP process is included in Appendix B.

The main upgrades incorporated to the Drexel ATP process are

1. **Yarn Tension Control**

Tension control on the ATP process is a very important parameter that has a major effect on the ATP yarn twist profile and twist efficiency. IRO yarn accumulators were installed after the yarn package creel holder to ensure that the singles yarns are fed at a constant tension unaffected by the variable unwinding tensions. Singles yarns tensioners were also installed after the IRO yarn accumulators to be able to apply a certain level to tension on each singles yarn. A Mechanical Hand-Held Tension Meter (Model ZD2), shown in figure 31, was used to calibrate the tension applied by the yarn tensioners and to maintain equal tension on both of the singles yarn while the machine is running.

![Figure 31 Mechanical Hand-Held Tension Meter (Model ZD2)](image)

2. Improve Machine Alignment

Due to the requirements of the ATP process, the Drexel ATP is a fairly long machine approximately 10ft. long and is separated into four main separate units; the yarn creel, the yarn tensioners, the jets and bonder unit and the profiled velocity roll. This machine setup makes the vertical and horizontal alignment of the yarns paths along the machine length extremely difficult. Any misalignment along the yarns paths would result in a tension variation problem thus affecting the ATP yarn twist profile and twist efficiency. To overcome this problem, complete framing of the ATP machine, shown in figure 32 was designed. Frames accommodating the separate units were all designed to the same height to allow the vertical alignment of the yarns paths. A base frame integrating all the separate units together using an IPS extruded aluminum frame, rigid IPS fasteners and joining plates was designed to ensure perfect horizontal alignment of the yarns paths along the machine lengths.

Figure 32 Framing of the Drexel ATP to improve the machine alignment
3. Air Pressure Control

Controlling the air pressure supplied to the main torque jets and the helper jet affects the amount of twist inserted in the yarn. The main torque jets insert twist in the singles yarn while the helper jet inserts twist in the plied ATP yarn structure. Independent control of the air pressure supplied to each of the main torque jet and the helper jet was needed to allow us to study the effect of each of them on the ATP yarn twist efficiency separately. This was enabled by assigning a separate pressure regulator to each of the main jet and helper jet.

4. Continuous Output Yarn Flow

A J-Box for yarn accumulation, shown in figure32, placed between the profiled velocity roll and the yarn winder, was also designed to ensure a continuous flow of yarn to the yarn winder and minimize yarn entanglement.

5. Operator Interface / Control Software Upgrade

A software upgrade was also done to be able to operate the Drexel ATP process at a profiled yarn velocity with sequenced torque jets, ultrasonic bonder, helper jet, and variable speed roll. The computer software, written in Microsoft Visual BASIC.Net and in commands for the Delta Tau PMAC controller, was provided by Onexia Inc. (Appendix C). The software facilitates changing the various machine parameters based upon a common timeline cycle. The Operator Interface shown in figure33 is graphical with time represented horizontally, and the various control parameters are represented vertically. The profiles of the yarn velocity, main jet, helper jet, energizing the ultrasonic horn and activation of the ultrasonic anvil are all controlled through data input of points along the horizontal time line in a data entry sheet shown in figure34. These data entry points become commands relative to time to PMAC.
controller. On the operator interface, the cycle time is given in milliseconds, the yarn velocity in yd/min. The average yarn velocity in yd/min and twist reversal length in feet are also provided on the upper right corner of the operator interface control panel.

![Figure 33 Operator Interface Control panel of the Drexel ATP process](image1)

![Figure 34 Data Entry sheets on the Operator Interface of the Drexel ATP process](image2)
Figure 35 shows an overall view of the upgraded Drexel ATP process currently present in Hess lab of Drexel University.

4.3 Production of ATP yarn

Bulk Continuous Filament (BCF) 1245 denier nylon yarns, 65 filaments in cross-section, were used for all of the experiments, directed to improve the ATP yarn twist profile and twist efficiency on the Drexel ATP process. These yarns were manufactured by DuPont. The choice of these yarns provides a good representation of the yarns actually used commercially in cut pile carpets.

1670 denier Kevlar®, 1300 denier Spectra® 1000 and 3600 denier S-Glass yarns were also used for a limited number of scouting experiments to explore new potential non-carpet applications. In these scouting experiments, one of the singles yarns is 1245 denier
nylon yarn and the second is either Kevlar®, Spectra® or S-Glass yarn. The reason for this was to make use of the nylon’s thermoplastic properties during bonding at the twist reversals.

4.4 Characterization Methods

This section describes the characterization methods used to provide quantitative measurements of the yarn twist profile and twist efficiency.

4.4.1 Twist Profile Measurement

The measurement of the twist profile of the ATP yarn samples produced on the Drexel ATP was done by the examination of a length of at least 25 ft. of each yarn sample. The twist profile was determined by measuring the wavelength of one turn of twist corresponding to its position along the yarn length. The twist level in turns per inch is then determined by calculating the reciprocal of the wavelength of one turn of twist.

In order to establish a quick and accurate method of measurement, a cork board, with pins inserted to form 13 subsequent rows each of 59 cm in width and equally separated at 4 cm apart, was used. The ATP yarn sample to be measured is then wound around the pins, as shown in figure 36, with the machine direction identified on the yarn. The head of the yarn sample taken from the ATP machine corresponds to position “zero” along the yarn length and is tied to the pin in the top left corner. The rows are then numbered in an ascending order starting from the top row.
A digital photo of the cork board is then digitally analyzed using “Turbo Cad” software which enables zooming into the photo for measurements while preserving the correct measurement scale. The first step in the analysis of the digital photo is to mark the regions of twist reversals along the yarn sample. The wavelength of each turn of twist for successive ten turns of twist is digitally measured from each side of the twist reversal. For the rest of the twist reversal length the wavelength of one turn of twist is measured every three turns of twist apart.
The position along the yarn length, corresponding to each measured wavelength of twist, was determined using the following equations

\[ S = L_P + L_C \]  \hspace{1cm} (4.1)

\[ L_P = (R-1)(W+\Delta y) \]  \hspace{1cm} (4.2)

\[ L_C = \begin{cases} X, & \text{for } R \text{ is an odd integer} \\ W - X, & \text{for } R \text{ is an even integer} \end{cases} \]  \hspace{1cm} (4.3)

Where \( S \) is the position along the yarn length in (inch), \( L_P \) is the yarn length (inch) in the previous rows to the one where twist measurement is done, \( L_s \) is the yarn length (inch) in the current row to the point where twist measurement is done, \( R \) is the current row number where twist measurement is done, \( W \) is the row width (inch), \( \Delta y \) is the spacing between the rows (inch) and \( X \) is the position of point where twist measurement is done in the current row, i.e. the distance from the left start point of the row to the point of measurement (inch).

The twist profile along the yarn length is then obtained by plotting the twist measurements in turns per inch versus the position along the yarn in inches.

4.4.2 Twist Efficiency Measurement

The twist efficiency of the ATP yarns produced on the Drexel ATP process is determined by measuring the ply yarn twist and singles yarn twist in the produced yarns using an ITC-5 hand operated Twist Tester, shown in figure37.
A sample length of 40cm between two successive bonds in the ATP yarn is placed between the two jaws of the twist tester. A tension of 5g weight is applied to the test sample at the spring loaded left jaw. The counter dial is then set to zero and the crank handle is turned manually to unwind the ply twist. The counter reading is then recorded. This reading is the ply twist in turns per 40cm. With the un-winded ply yarn still held between the two jaws, one of the singles yarns is cut and removed. The counter dial is then set to zero again and the crank handle is now turned in the opposite direction to unwind the twist in the remaining singles yarn. The twist in the singles yarn is measured using the Untwist-Rewist Method according to ASTM standard D1422-99. In this method, the singles yarn is first untwisted and then twist is reinserted until the tension loaded left jaw returns to its initial position. The counter reading is then recorded and divided by 2 to give the singles twist in turns per 40cm. The yarn twist efficiency is calculated by the following equation

\[
\text{Yarn Twist Efficiency} = \frac{\text{Ply yarn Twist}}{\text{Singles yarn Twist}} \quad (4.4)
\]
The yarn twist efficiency of the ATP yarn is determined by calculating the average twist efficiency of five samples.

4.5 Process Optimization of the Yarn Twist Profile

A series of experiments were conducted on the Drexel ATP process to study the effect of the yarn velocity and rotational profiles on the resulting yarn twist profile. These experiments were all done using 1245 denier BCF nylon yarns under a constant singles yarn tension of 34g. The different time functions of the yarn velocity and rotational profiles, and their time-function coordination with the ultrasonic bonder activation, were fed to the data entry sheets on the machine control panel as was shown in figure 34.

4.6 Process Optimization of the Yarn Twist Efficiency

4.6.1 Effect of Process Variables on the Yarn Twist Efficiency

The main process variables on the Drexel ATP process are the main jet pressure (PSI), the helper jet pressure (PSI) and the singles yarn tension (g). In this section of the thesis, the effect of each process variable on the yarn twist efficiency was studied by varying the values of the process variable being studied while keep the rest of the variables constant.

In order to improve the performance of the helper jet and enhance its effect on yarn twist efficiency, it was proposed to apply hot air to the ATP yarns after they are bonded by the ultrasonic bonder and before they pass through the helper jet. To enable hot air application, the Drexel ATP process was modified to allow for more spacing between the ultrasonic bonder and the helper jet. This was done by moving the helper jet further down
along the yarn path and a hot air gun was placed before the helper jet as shown in figure 38. A Weldy Plus hot air gun, with a digital variable temperature control, an LCD display and a digitally controlled air flow adjustment, was used.

![Modified machine schematic by adding hot air gun and relocating helper jet.](image)

The effect of yarn temperature on the yarn twist efficiency was studied by controlling the hot air temperature on the gun and the resulting yarn temperature was determined using an Infrared thermometer.

### 4.6.2 Empirical Modeling of the Yarn Twist Efficiency

In order to obtain a more systematic understanding of the effect of the process variables and to establish a quantitative basis for the relationship between the process variables and the yarn twist efficiency, response surface methodology was employed. A factorial experiment was designed to investigate and identify the relative significance of the process variables on the yarn twist efficiency (Table 4).
### Table 4 Factorial Design of Experiment

<table>
<thead>
<tr>
<th>Factor</th>
<th>Unit</th>
<th>Factor Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Jet pressure</td>
<td>PSI</td>
<td>30, 52.5, 75</td>
</tr>
<tr>
<td>Helper Jet pressure</td>
<td>PSI</td>
<td>0, 37.5, 75</td>
</tr>
<tr>
<td>Singles Yarn Tension</td>
<td>G</td>
<td>30, 42.5, 55</td>
</tr>
<tr>
<td>Yarn Temperature</td>
<td>Deg. °C</td>
<td>24, 49.5, 75</td>
</tr>
</tbody>
</table>

#### 4.6.3 Design and Construction of the Static Tester to Model the ATP Process at the Point of Self Ply

The Drexel ATP process is a very dynamic process where even at very low laboratory operating speeds of 35 yd/min, a complete cycle time could be about 800 milliseconds. This very short cycle time does not enable us to clearly observe the geometrical and mechanistic details of the self plying process which is considered the “Heart” of the ATP process and primarily affects the yarn twist efficiency. Thus, in order to obtain a complete understanding of the processing mechanics of the ATP process, a static tester simulating the ATP process at the point of self ply was designed. This section gives a description of the design, construction and operating procedure of the static tester. A schematic design of the static tester is shown in figure 39.
In order to simulate the action of the main jets, two motors were used to insert twist in the singles yarn above the convergence point. The two motors were connected to a control box shown in figure 40, for rotation direction and speed control. The singles tension on the Drexel ATP process was simulated on the static tester by hanging weights on the ply yarn as shown in figure. In order to simulate the effect of the helper jet i.e. adding ply torque, a clever design was required to be able to apply tension and torque on the ply yarn.
This was achieved through the use of a calibrated elastic rubber yarn as the torque transducer, shown in figure 41. The rubber yarn is an extruded silicone rubber cord, round cross section of 1/32 inch in diameter, custom made by Simolex Rubber Corp., MI, USA. A loop of this rubber yarn was passed through the bottom tip of the ply yarn and through a copper 5 inch long clip. The tension weights were hanged on the copper clip. A horizontal bar is then passed through the copper clip and fixed from both ends to two vertical bars. These vertical bars are connected to a wooden base that is allowed to rotate, shown in figure. The functions of this bar system is to allow for the free vertical movement of the ply yarn during self plying and free rotation while at the same time applying ply torque. Rotation of the base allows us to insert turns of twist in the loop of rubber yarn which in turns acts as ply torque, thus simulating the effect of the helper jet.
In order to determine the amount of ply torque to be added, an evaluation of the ply torque produced by the helper jet on the Drexel ATP process was done. (Appendix D) The amount of ply torque applied by the torque transducer is varied by changing the length and configuration (i.e. number of strands) of the rubber yarn loop. Calibration of the ply torque applied by the rubber yarn torque transducer is provided in Appendix E.

Experiments on static tester were done using 1/32 inch rubbers yarns and 1245 denier BCF nylon yarns. The following procedure was used in conducting the experiments on the static tester:

1. A test length of 24inch yarn is cut. In case of using nylon yarn, it is then knotted to a black sewing thread tracer yarn of the same length. As for the rubber yarn, a black marker is used to draw a straight black line along its side.
2. The test yarn is passed through the torque transducer calibrated rubber loop.
3. The test yarn is then threaded from both ends to the twist motors.

4. The desired weights are then hanged on the copper clip creating a “V” shape of the test yarn.

5. The two twisting motors are turned on to rotate counter clockwise and a contact tachometer, Model DT-105A with an LCD display and accuracy of ±0.06 rpm, is used to check that the motors are running at the same speed of 12 rpm.

6. Twist is inserted in the same direction in both strands of the “V” of the test yarn.

7. When a certain level of twist per inch length of the test yarn is reached, the two strands start to self ply spontaneously creating a “Y” shape in the test yarn.

8. The twist motors are turned off and two turns of twist are inserted in the torque transducer by rotating the wooden base in counter clockwise direction.

9. The twist motors are turned on again and the yarn is allowed to self ply further.

10. After each turn of self ply twist created in the ply, the twist motors are stopped, a digital photo of the “Y” shaped configuration of the test yarn is taken, twist is reinserted in the torque transducer then the twist motors are turned on again and the yarn is allowed to self ply further. In the case where the test is to be run under the effect of ply tension only without applying any ply torque, the weights are hanged on the copper clip connecting it to the ply yarn and are left free to rotate in space without connecting it to the wooden base through the vertical and horizontal bar system. In this case, after several turns of self ply twist created in the ply, the twist motors are stopped, a digital photo of the “Y” shaped configuration of the test yarn is taken, then the twist motors are turned on again and the yarn is allowed to self ply further.
11. Step no. 10 is repeated until the maximum convergence angle at the point of self-ply is reached where the yarn can not self-PLY any further.

12. The digital photos are then analyzed, where the reciprocal of the turns per inch in the single yarns (1/TPIS) and the ply yarn (1/TPIp), and the half convergence angle (Θ) are measured digitally, as shown in figure 42.

13. The values of the measured turns per inch in the single yarns and the ply yarn are then multiplied by the scale of 1in. length of a ruler included in the digital photo.

14. The twist efficiency corresponding to each convergence angle is obtained by the ratio of the scaled values of the turns per inch of the ply to that of the singles at that instant of convergence angle.

Figure 42 Digital Photo of the “Y” shaped configuration of the test yarn on the static tester
CHAPTER 5: PROCESS OPTIMIZATION AND PREDICTION OF THE YARN TWIST PROFILE

5.1 Background and Significance

ATP yarns produced by the current commercial ATP technologies (Repco, Gilbos and Belmont) lack a uniform square wave twist profile along the yarn length and have a long zero twist region at the twist reversal. As attempts are made to increase the processing speeds, reaching 600yd/min in the Belmont ATP process, this requires twisting the yarns more forcefully to be able to twist them more rapidly. However, this forceful twisting also results in a higher yarn compact, so that they have inadequate bulk when tufted into a carpet. Such compaction becomes more pronounced and can vary extremely along the yarn length in the presence of non-uniformly twisted sections thus affecting the carpet appearance to a great extent. Non-uniformity in the twist will create sections of substandard twist. These sections tend to separate and mat together and appear as defects in the carpet. Furthermore, the twist reversal length also affects the carpet appearance to a great degree. In ATP yarns with a short twist reversal length, as in the case of the Repco ATP process, the zero twist region at the reversals would occupy a substantial percentage of the total yarn length and appear at the surface of a cut pile carpet more frequently. In addition to that, tufts which are cut at a bond are more compact than those which are cut between bonds, and the more frequently they occur, the less uniform is the carpet appearance. Therefore, it is desirable to make the distances between bonds as great as possible to minimize their visibility. Furthermore after the bonds are fixed, they must have sufficient strength to resist separating under tension and abrasion encountered in the subsequent handling and tufting into carpet. If just one bond fails to hold, the plies untwist for a remarkable distance and form separated sections which mat together in the carpet and
appear as streaks or defects. Therefore, a means of producing ATP yarn at increased speed with a uniform square wave twist profile, long twist reversal lengths and bonds of adequate strength would be greatly desired.

The main feature of a square wave yarn twist profile is a sharp transition from “S” to “Z” twists at the twist reversal and vice versa. This means that the level of twist in the ATP yarn just before the bond should be maintained the same just after the bond but in the opposite direction as shown in figure43. The bond region is also a very short one of approximately 0.2 inch.

The objective of this section is to determine the process parameters affecting the yarn twist profile. The goal is to achieve a square wave twist profile on the Drexel ATP process.
5.2 Materials and Methods

Considering the amount of twist inserted in singles yarn, the Drexel ATP process can be divided into three main zones as shown in figure 44. Zone 1 of length $L_1$ is the distance between the yarn tensioners and the main torque jets. Zone 2 of length $L_2$ is the distance between the main torque jets and the point of self ply on the ATP yarn. Zone 3 of length $L_3$ is the distance between the point of self ply and the profiled velocity roll.

The main process parameters affecting the yarn twist profile were determined through a mathematical model of the amount of twist accumulating in the yarn while it passes across the different zones of the Drexel ATP process. “MatLAB” programming software was later used to provide the solution to the mathematical model and to simulate the yarn twist profile resulting for different yarn velocity and rotational profiles.
This mathematical simulation was experimentally verified on the Drexel ATP process. Experimental measurements of the yarn twist profile were done according to the procedure described in section 4.4.1.

5.3 Mathematical Modeling and Simulation of the Yarn Twist Profile

This section provides a mathematical model of the amount of twist accumulating in the singles yarn in Zone1 and Zone2 up to the point of self ply. The main hypothesis of this model was that if a constant and equal level of twist is inserted in each of the singles yarn before they are allowed to self ply, then the resulting ATP yarn will maintain a uniform square wave twist profile along its length. The twist continuity principle was adopted in this model; stating that the amount of turns of twist accumulating in the yarn in any specific machine zone is the difference between the turns of twist flowing into the yarn in that zone and the turns of twist flowing out of the yarn from that zone in addition to the number of turns added. The basic model assumptions are; 1) There is no stretch in the yarn, 2) The length of the different machine zones is constant and 3) The input feed yarns have zero twist.

Consider the yarn path of one singles yarn across Zone 1 and Zone 2 on the Drexel ATP machine as shown in figure45.

![Figure45 Yarn path of one singles yarn across Zone1 and Zone2 on the Drexel ATP](image)
Applying the following twist continuity equation to Zone 1 for an amount of time $\Delta t$,

$$\text{Turns flowing In} - \text{Turns flowing Out} + \text{Added Turns} = \text{Rate of Turns Accumulating} \quad (5.1)$$

Since it is assumed that the input feed yarns have zero twist, there are no turns of yarn twist flowing into zone 1. The turns of yarn twist flowing out of zone 1 in time $\Delta t$ are those previously provided by the rotating action of the main jets where the twist propagates upstream into zone 1 in one direction and downstream into zone 2 in the opposite direction. The added turns are those resulting while the singles yarns pass through the main jets and depends on the rate of rotation of the main torque jet $w(t)$. Thus, substituting the value of these terms in the twist continuity equation (5.1) we obtain

$$0 - T_1 V(t) \Delta t + \omega(t) \Delta t = \left[ \frac{dT_1 L_1}{dt} \right] \Delta t \quad (5.2)$$

Where $T_1$ is the turns per unit length in Zone 1, $V(t)$ is the average yarn velocity as a function of processing time $t$, $w(t)$ is the rate of rotation of the main torque jet in turns per unit time $t$ and $L_1$ is the length of Zone 1. Thus the differential equation describing the twist generated in Zone 1 can be written as

$$L_1 \frac{dT_1}{dt} + V(t) T_1 = w(t) \quad (5.3)$$
The differential equation describing the twist generated in Zone2 can be similarly obtained by applying the twist continuity equation (5.1) to Zone 2. In this case, the turns of yarn twist flowing into Zone2 are the turns of yarn twist generated in Zone1 in time $\Delta t$, $[T_1 V(t) \Delta t]$. In Zone2, the turns added by the rotation of the main torque jet are of negative values because they are in the opposite direction of twist to those inserted in Zone1. Thus the twist continuity equation of Zone2 is expressed as

$$(T_1 - T_2) V(t) \Delta t - \omega(t) \Delta t = [d(T_2 L_2) / dt ] \Delta t$$ \hspace{1cm} (5.4)$$

Where $T_2$ is the turns per unit length in Zone2 and $L_2$ is the length of Zone2. Thus for Zone 2, the differential equation describing the twist generated is

$$L_2 \frac{dT_2}{dt} + V(t)T_2 = -\omega(t) + V(t)T_1$$ \hspace{1cm} (5.5)$$

Equations (5.3) and (5.5) establish the equations of state for Zone1 and Zone2. The solution of these differential equations would yield the yarn twist profile as a function of processing time $t$. In order, to obtain the solution of the twist profile as a function of its position along the yarn length, a third equation (5.6) was introduced to determine the position along the yarn length as a function of processing time $t$.

$$\frac{dS}{dt} = V(t)$$ \hspace{1cm} (5.6)$$

Where $S$ is the position along the yarn length.
For reasons of simplification, equations (5.3), (5.5) and (5.6) were reduced to a dimensionless form by introducing the dimensionless variable $\tau$ shown in equations (5.7).

$$\tau = \frac{L_R}{V_M} \quad (5.7)$$

Where $V_M$ is the maximum yarn speed, $L_R$ is the twist reversal length. The physical meaning of $\tau$ is the time taken for one half cycle to be completed or the time taken for one twist reversal length (i.e. distance between two successive bonds) to pass through at maximum yarn speed. Equations (5.8) through (5.11) illustrate the dimensionless form of the different process parameters.

$$\hat{L} = \frac{L}{L_R} \quad (5.8)$$

$$\hat{T} = T L_R \quad (5.9)$$

$$\hat{t} = \frac{t}{\tau} \quad (5.10)$$

$$\hat{\omega} = \omega \tau \quad (5.11)$$
Substituting into equations (5.3), (5.5) and (5.6), the reduced dimensionless equations are shown below

\[
\frac{d\hat{T}_1}{d\hat{t}} = \frac{\hat{\phi}(\tau)}{\hat{L}_1} - \frac{\hat{\nu}(\tau)\hat{T}_1}{\hat{L}_1} \tag{5.12}
\]

\[
\frac{d\hat{T}_2}{d\hat{t}} = -\frac{\hat{\nu}(\tau)\hat{T}_2}{\hat{L}_2} + \frac{\hat{\phi}(\tau)}{\hat{L}_2} + \frac{\hat{\nu}(\tau)\hat{T}_1}{\hat{L}_1} \tag{5.13}
\]

\[
\frac{d\hat{S}}{d\hat{t}} = \hat{\nu}(\tau) \tag{5.14}
\]

Equations (5.12), (5.13) and (5.14) represent the main differential equations required to predict the yarn twist profile. These equations also determine the main process parameters that affect the yarn twist profile. The yarn twist profile is greatly affected by the yarn velocity profile and the rotational profile of the main torque jet. This mathematical model also reveals a very surprising result that the yarn twist profile is also affected by the zone lengths of the ATP process \((L_1\text{ and } L_2)\).

A computational model was used to provide the solution to equations (5.12), (5.13) and (5.14) through the use of a stiff integrator. “MatLab” programming software was used to develop the computational model. The initial conditions were identified as \(T_1(0)=0\) and \(T_2(0)=0\), where at time \(t=0\), the turns per unit length in zone1 and zone2 are equal to zero. A simulation of the yarn velocity profile and the rotational profile of the main torque jet as functions of the cycle time were done and used as inputs to the
computational model. The dimensionless zone lengths $\hat{L}_1$ and $\hat{L}_2$ were also inputs to the computational model. The command functions of the computational model are shown in Appendix F.

Several runs of the computational model using different yarn velocity profiles and zonal lengths were done in order to determine the optimum process conditions needed to obtain a square wave twist profile in the ATP yarn.

5.4 Experimental Verification and Results

Experimental trials on the Drexel ATP process were conducted to substantiate the mathematical model. The yarns used in these experiments were 1245 denier BCF nylon singles yarn. A singles yarn tension of 34g was used for all these experiments. The same yarn velocity profile and rotational profile of the torque jet used as the inputs to the computational model were fed to the operator interface control panel of the Drexel ATP process.

5.4.1 Effect of Velocity Profile on Twist Profile

In order to determine the optimum yarn velocity profile required to obtain a square wave twist profile, several profiles were constructed and the computational model was used to predict the yarn twist profile. The predicted yarn twist profiles were examined, and the features of the yarn velocity profile required to achieve the square wave twist profile were then determined. The dimensionless zone lengths values used in these model runs were calculated from the actual lengths of zone1 and zone2 on the Drexel ATP process, such that $\hat{L}_1 = 3.55$ and $\hat{L}_2 = 0.03$. 
The rotational profile for the main torque jet, shown in figure 46, was kept the same for all computational model runs. The main torque jet is operated so as to insert one direction of twist for one half of the cycle time then stop for bonding then insert twist in the opposite direction for the second half of the cycle time.

![Rotational Profile of main torque jet used for the computational model](image)

Experimental verification was done by feeding the same velocity profile to both the computational model and the operator interface control panel of the Drexel ATP. Figure 47 shows an example of a yarn velocity profile used as an input to the computational model and figure 48 shows the corresponding control panel on the Drexel ATP with the same yarn velocity profile and all the various time functions coordinated with the yarn velocity profile, including the rotational profiles for the main torque jets and the helper jet, the profile for energizing the ultrasonic horn and the activation profile of the ultrasonic anvil.
Figure 47: Example of poor yarn velocity profile input to the computational model.

Figure 48: Operator Interface control panel corresponding to the poor velocity profile used for the computational model.
The corresponding yarn twist profile, predicted by the computational model, is shown in figure 49. Figure 50 shows a sample of the ATP yarn produced on the Drexel process corresponding to the yarn velocity profile shown in figure 48. Experimental measurements of the yarn twist profile along the ATP yarn sample, in order to obtain an accurate objective evaluation, were done according to the procedure previously described in section 4.4.1. The experiments measurements of the ATP yarn sample in figure 50, corresponding the velocity profile in figure 48, are shown in figure 51.

Figure 49 Example of poor yarn twist Profile predicted by the Computational Model

Figure 50 ATP yarn sample produced using poor yarn velocity profile shown in figure 48
Comparison of figures 49 and 51 shows that the prediction of the computational model is in good agreement with the experimental measurements, which validates the mathematical model of the yarn twist profile.

The resulting yarn twist profile shows that using a yarn velocity profile with a gradual increase in yarn speed till it reaches the maximum followed by a gradual decrease in yarn speed till the process stops for bonding, figure 47, yields a non uniform yarn twist profile, obtained both computationally and experimentally, figures 49 and 51.

Several runs were done using different profiles of the yarn velocity in order to determine the optimum yarn velocity profile. These trials were done using the computational model followed by experimental measurements of the twist profile of the ATP yarn sample, to confirm the results.

The optimum yarn velocity profile, yielding approximately a square wave twist profile in the ATP yarn, is shown in figure 52 and the various time functions fed to the
Drexel ATP to produce this yarn is shown in figure 53. The main features of this yarn velocity profile include an abrupt increase in speed to reach maximum speed in the few milliseconds of the half cycle time, the yarn velocity stays constant for most of the half cycle time and then is followed by an abrupt decrease in speed till the yarn stops bonding at the twist reversal. The data entry points fed to the operator interface control panel to obtain this velocity profile and the other time functions is shown in Appendix G.

Figure 52 Optimum yarn velocity profile yielding approximately a square wave twist profile in the ATP yarn

Figure 54 shows the predicted twist profile, illustrating a near to a square wave twist profile with only a very slight decrease in twist just before the bond. The ATP yarn sample produced, using the velocity profile shown in figure 53, and experimental measurements of the yarn twist profile are shown in figures 55 and 56 respectively. The predicted and experimental results are in very good agreement, where the yarn twist profile achieved has an approximately equal level of twist along the yarn length and an abrupt change from one direction of twist to another.
Figure 53 Operator Interface Control Panel corresponding to the optimum yarn velocity profile

Figure 54 A near to square wave yarn twist profile predicted by the computational model using the optimum yarn velocity profile, shown in figure 52
These results show that any change in the yarn velocity during the cycle time directly affects the yarn twist profile. Decreasing the yarn velocity, increases the twist insertion time, resulting in an obvious increase in the twist level along the yarn length and vice versa. Thus, in order to achieve a square wave twist profile, the yarn velocity must meet two conditions: 1) for the majority of the cycle time, the yarn velocity should be almost constant with a very slight decrease to avoid a noticeable decrease in the twist level along the yarn length. 2) In the region near the twist reversal bond where the yarn has to
stop for bonding the yarn velocity must decrease and then increase very abruptly in the minimum cycle time possible.

### 5.4.2 Effect of Machine Zone Lengths on Twist Profile

The computational model was also used to study the effect of the machine zone lengths. The model results have shown that by using the optimum yarn velocity profile shown in figure 52 and increasing the dimensionless length of zone\(_1\), \(\hat{L}_1 = 6\), and decreasing the dimensionless length of zone\(_2\), \(\hat{L}_2 = 0.002\), a perfect square wave twist profile could be obtained, as shown in figure 57. Experimental confirmation of this result was not possible because of the limited lab space where it was not possible to physically increase the length of zone\(_1\). However, this could be done by redesigning the Drexel ATP process to allow vertical in-feed of the singles yarns.

![Perfect Square Wave Twist Profile](image.png)

**Figure 57** Perfect Square Wave Twist Profile predicted by the computational model
These results could be attributed to that increasing the length of zone 1 with respect to the twist reversal length would allow a more uniform propagation of twist upstream through the singles yarn before they are allowed to self ply. However, the length of zone 2 with respect to the twist reversal length should be as short as possible to force the twist inserted by the main jets to propagate downstream along the yarn and generate sufficient detwisting torques in the singles yarn causing them to spontaneously self ply.

5.4.3 Coordination of the Velocity, Rotation and Bonding Profiles on the Drexel ATP Process

Coordination of the jets rotational profiles and the ultrasonic horn and anvil profiles together with the yarn velocity profile also has a great effect on the yarn twist profile. This coordination is very crucial especially during bonding at the twist reversal. To obtain a good strong bond at the twist reversal, it is recommended that both the main torque jets and the helper jet stop during bonding and the yarn too has to completely stop during the bonding time. If that is not the case, then during bonding, the yarns pushed by the ultrasonic anvil against the horn will not be in a self ply structure, as shown in figure 58. This will in turn result in the presence of a long zero twist region between the twist reversals, as shown in figure 59. The optimum case is shown in figure 60, where the yarns are in a self ply structure during bonding and thus resulting in a very short bond and zero twist region, as shown in figure 61. The bonding time on the Drexel ATP process is about 40-100 milliseconds. During bonding the ultrasonic anvil ascends upward to press the yarns against the ultrasonic horn, however, the ultrasonic horn is energized for only half of the bonding time. This is done so as to allow the yarns to cool down in the remaining half of the bonding time to ensure that the yarns do not unbond after that.
Figure 58: The singles yarns are not in a Self Plied structure during Bonding

Figure 59: Long Zero Twist Region at the Twist Reversal

Figure 60: The singles yarns are Self Plied during Bonding

Figure 61: Very Short Zero Twist Region at the Twist Reversal
5.4 Discussion

A mathematical model to predict the ATP yarn twist profile was done. The model was based on studying the rate of turns of twist accumulating in the singles yarns across the different ATP process zones before they self ply. This mathematical model has defined the yarn velocity profile and the process zone lengths as the key process parameters affecting the yarn twist profile. A computational model used to solve the mathematical model together with a computer simulation of the yarn velocity and main jet rotational profiles. The results of the computational model were experimentally verified on the Drexel ATP process and are in very good agreement. [35]

The computational model has determined the optimum yarn velocity profile and the process zone lengths needed to obtain a square wave twist profile. This yarn velocity profile must have a minimal change in velocity while twist is being inserted in the yarn by the main torque jet. Before bonding at the twist reversal, there should be an abrupt decrease in speed to stop for bonding, followed by an abrupt increase to the maximum after bonding. This yarn velocity profile should also be coordinated with the jets rotational profiles and the ultrasonic horn and anvil bonding profiles to ensure short zero twist regions at the twist reversals and strong bonds. In order to assist in a uniform distribution of twist in the singles yarn, before the twist is trapped in the self ply structure, the length of zone1; distance between the yarn tensioners and the main torque jets, should be at least six times the twist reversal length. The length of zone2; distance between the main torque jets, with respect to the twist reversal length should be very small ~ 0.003, to force the spontaneous self plying process.
CHAPTER 6: PROCESS OPTIMIZATION OF THE YARN TWIST EFFICIENCY

6.1 Background and Significance

The objective of the previous chapter was to achieve a square wave twist profile in the ATP yarn produced on the Drexel ATP process. The second major objective of this thesis is to improve the yarn twist efficiency of the ATP yarn. Twist efficiency is determined by the ratio of the ply yarn twist to the singles yarn twist. The ATP yarn twist efficiency is a very complex feature of the ATP yarn. The physical meaning of twist efficiency is how much of the torque energy saved in the singles yarn structure is released into the ply yarn structure through the self plying process. A 100% twist efficiency yarn is one that has no residual torque in the singles yarn inside the ATP yarn structure. 100% twist efficiency yarns can only be produced by the cabling process. This is basically because no twist is actually being inserted in the singles yarns during cabling. The action, of the yarns wrapping around each other, dissolves all the false twist in the balloon yarn.

The maximum twist efficiency of the ATP yarns produced on the current commercial ATP processes is 65%. This presents the major limitation of the current ATP processes that holds them from being used as cut pile carpet yarns. The reason for that is that higher yarn twist efficiency is needed to be able to provide two important features: 1) Cut Tip Stability and 2) Greater Yarn Coverage Area. Yarns with higher twist efficiency will in turn have a lower residual singles torque; this is greatly desirable for cut pile carpet yarns to decrease the tendency for the individual singles yarns to split at the tuft tips after they are being cut. The tuft tips should be completely balanced and stable structures capable of preserving their ply twisted structure after they are cut, as shown in figure62.
Yarns with higher twist efficiency, i.e. lower residual singles torque, will have a more open bulkier structure which increases the fullness of the plied tufts. This effect has a tremendous impact on the economics of the carpet industry. Higher yarn bulk will provide more coverage of carpet square footage for the same weight of material. This means a huge material saving for larger surface floor cover constructions. An evaluation of how much twist efficiency is actually needed to produce enough bulk in the carpet yarns has not been reported anywhere in literature. Appendix H provides an experimental procedure that was designed to produce several ply yarn samples with different twist efficiency levels and determine their effect on bulk. The bulk in these experiments was determined by calculating the specific fiber to yarn volume ratios from the measured values of the ply yarn diameter and length after being exposed to boiling water. The boiling water is used to simulate the steaming process to which the ply yarns are exposed to before they are cut into tufts. The result of this preliminary experiment suggests that optimum yarn bulk is obtained in ply yarns with 80% yarn twist efficiency. Although this result provides a good approximation of the minimum yarn twist efficiency needed to be able to use ATP yarns in cut pile carpet, but a wider range of experiments including yarns with different types and deniers are needed to confirm this result.
Improving the ATP yarn twist efficiency is thus a very challenging task and accomplishing this task would indeed revolutionize the whole carpet industry. The rest of this thesis focuses mainly on solving this problem. This chapter and the following chapters provide different methods of tackling this problem and novel approaches to improve the twist efficiency of the ATP yarn. None or very little work, available in literature, has studied the effect of the different process parameters on the ATP yarn twist efficiency. In this chapter, the main process parameters affecting the yarn twist efficiency are determined, on the Drexel ATP process. This provides the starting point and the basis of the detailed studies that will be conducted in the subsequent chapters to determine how is it possible to improve the yarn twist efficiency.

6.2 Materials and Machine Setup

1245 denier BCF nylon yarns were used in the following experiments conducted on the Drexel ATP process. The yarn velocity profile used in these experiments is the optimum profile, determined in Chapter 5, to produce a square wave yarn twist profile. This profile and the corresponding main jets and helper jet rotational profiles and the ultrasonic horn and anvil bonding profiles are shown figure 53. The yarn twist efficiency of the produced ATP yarn samples was determined using the twist tester according to the procedure described in section 4.4.2.
6.3 Results
6.3.1 Effect of Main Jet Pressure on Twist Efficiency

The function of the main torque jets on the Drexel ATP process is to apply equal and same direction torque on each of the singles yarns. This applied singles torque is the main driving force for the self plying process. The applied singles torque generates twist in the singles yarns before they are allowed to converge for self ply. The magnitude of the singles torque, applied by the main torque jets on the Drexel ATP, is controlled by the pressure of the compressed air supplied to the main jets. This compressed air pressure is controlled using a pressure gauge. The direction of the applied singles torque is also controlled using an electronic pressure regulator.

In order to determine the effect of the applied singles torque on the yarn twist efficiency, the main torque jets pressure was varied from 30 PSI to 80 PSI which is the maximum capacity of the air pressure line supplied to the Drexel ATP process. In this experiment, the helper jet was turned off so as to allow us to understand the effect of the main torque jets clearly and independently. Figures 63 and 64 illustrate the effect of the main jet pressure on the singles yarn twist and the twist efficiency respectively, for two different singles yarn tension.

The results show that as the main jet pressure increases, the twist in the singles yarn increases. This is attributed to the increase in the torque applied to the singles yarns as the jet pressure increases. The increase in the singles torque generates a higher level of twist in the singles yarn. Figure63 also shows that for different singles yarn tension, the rate of increase in the singles yarn twist as the jet pressure increases is not the same. This suggests that there is an interaction between the different process variables.
Figure 64 shows that as the main jet pressure increases there is a slight increase in the yarn twist efficiency. An average of about 8% increase in the yarn twist efficiency is obtained at a main jet pressure of 80 PSI. This result may be due that the as the jet pressure...
increases the driving force for the self plying process increases which allows them to self ply more efficiently. However, this improvement has yielded a maximum yarn twist efficiency of only 65%, which is insufficient for the desired end use of the ATP yarns as cut pile carpet yarns.

6.3.2 Effect of Yarn Tension on Twist Efficiency

The singles yarn tension applied by the yarn tensioners on the Drexel ATP process is one of the main process variables. Experiments to study the effect of singles yarn tension on the singles yarns twist, the ply yarn twist and on the twist efficiency accordingly were done. The main torque jets pressure was held constant in these experiments at 60 PSI, while the helper jet was turned off to minimize any interaction between the different process variables. The results of these experiments are shown in figure65 and 66.

Figure65 Effect of singles yarn tension on singles and ply yarn twist
The results in figure 65 show that as the singles yarn tension is increased both the singles yarn twist and ply yarn twist decrease. This could be attributed to the increase in the torsional rigidity of the singles yarns as the yarn tension increases thus resulting in stiffer singles yarns structures with a lower level of twist generated for the same applied singles torque. As the singles twist decreases, the resulting ply twist, produced from the self plying process, will accordingly decrease. Figure 66 also shows that as the singles yarn tension increases the twist efficiency varies very slightly.

![Figure 66 Effect of singles yarn tension on the ATP yarn twist efficiency](image)

Although the amount of change in twist efficiency due to tension is quite low, this relation suggests the presence of an optimum yarn tension at which maximum yarn twist efficiency should be achieved. This may be explained as follows: At very low singles yarn twist levels, the driving force of the self plying process may not be sufficient to produce a ply yarn with adequate twist efficiency, while at very high singles yarns twist levels the
twist will be locked in the highly rigid yarn structure and is unable to self ply efficiently. Thus, an optimum yarn tension producing a singles yarns twist lying between these two extremes should be used to obtain maximum yarn twist efficiency.

6.3.3 Effect of Helper Jet Direction and Pressure on Twist Efficiency

The helper torque jet is a very unique feature of the Drexel ATP process. None of the current commercial ATP technologies (Repco, Gilbos and Belmont) include a helper jet in their process. The inclusion of the helper torque jet in the Drexel ATP process was first patented by DuPont in 1989. [24] The hypothesis for adding the helper jet at the time, was that if the self plying process is unable to produce ATP yarns with 100% twist efficiency on its own, addition of a helper torque jet would apply a ply torque on the already self plied yarn and force the ply yarn to turn more thus increasing the ply yarn twist and the yarn twist efficiency accordingly.

However, an evaluation of the performance of the helper torque jet and its effect on the twist efficiency was not reported anywhere in literature. Thus a detailed study in order to fully understand the helper jet effect needs to be done. In order to confirm the basic function of the helper torque in applying ply torque, preliminary experiments were done where the operating direction of the ply torque applied by the helper torque jet is varied with respect to that of the main torque jets and compared with the base case where the helper torque jet is turned off. As is the case with the main torque jets, the magnitude of the ply torque, applied by the helper torque jet is controlled by the pressure of the compressed air supplied to the helper jet, controlled using a separate pressure gauge. The direction of the applied ply torque is controlled using a separate electronic pressure regulator. In these preliminary experiments, the main torque jets pressure was held...
constant at 60 PSI while helper jet pressure was set at 80 PSI and the singles yarns tension applied was 35g.

Figure 67 Effect of the operating direction of the ply torque applied by the helper jet on the singles yarn and ply yarn twist

Figure 67 illustrates the results of these preliminary experiments. As is shown, when the operating direction of the ply torque applied by the helper jet is opposite to the singles torque applied by the main torque jets, the ply twist decreases as compared to the base case where the helper jet is turned off. This is due to the fact that in this case, the ply torque applied is actually unplying the twist in the ply yarns and cancelling the effect of the singles torque. On the other hand, when the operating direction of the ply torque is the same as the singles torque applied by the main torque jets, the ply twist increases slightly.
as compared to the base case where the helper jet is turned off. This in itself confirms the function of the helper torque jet in applying ply torque to the self plied yarn to increase the ply twist.

However, an unexpected result was also noticed in figure 67, where the ply torque applied by the helper torque jet does not only change the ply yarn twist but it also affects the singles yarn twist. Figure 67 shows that as the ply yarn twist increases due to the effect of ply torque operating in the same direction of the singles yarns torque, the singles yarn twist also increases. This important finding has a large effect on the yarn twist efficiency. This means that the helper torque jet indeed increases the ply yarn twist due to the action of the ply torque but does not certainly increase the yarn twist efficiency because of the increase in the singles yarn twist.

Figure 68 Effect of the operating direction of the ply torque applied by the helper jet on the ATP yarn twist efficiency
This result is illustrated in figure68, where applying the ply torque in the same direction of the singles yarns torque produced by the main jets, does not offer much improvement in the yarn twist efficiency as compared to the base case when the helper jet is turned off i.e. no ply torque applied.

The effect of the magnitude of ply torque applied to the ATP yarn was also studied. This was done by varying the pressure of the compressed air supplied to the helper torque jet through the use of the pressure gauge. The air pressure of the helper jet was varied from 40 PSI to 80 PSI in these experiments, the main torque jets pressure was held constant at 60 PSI and the singles yarns tension applied was 35g.
The results, shown in figures 69 and 70, do not show any clear effect of the helper torque jet pressure on either the singles yarn twist, ply yarn or the yarn twist efficiency. These results were quite unexpected because based on the understanding of the helper torque jet effect obtained from figure 67, it was expected that as the helper jet pressure increases thus increasing the magnitude of the applied ply torque, both the singles yarn and ply yarn twist would increase accordingly.

These results of this section has emphasized the need for an in depth analysis of the effect of helper torque jet on the ATP yarn structure and its twist efficiency, which will be later discussed in Chapter 8 of this thesis.
6.3.4 Effect of Heat on Twist Efficiency

An additional process variable that was expected to have a positive effect on the yarn twist efficiency is the application of heat to the ATP yarns after they are self plied. The reasoning for this was attributed to the expectation that application of heat should soften the singles yarn and result in a decrease in the singles yarn modulus of rigidity allowing it to relieve the stresses and release all the residual singles torque into the plied yarn structure and thus increasing the ply twist and in turn the yarn twist efficiency. [33]

According to this expectation, the Drexel ATP process was redesigned to allow the positioning of a hot air gun between the ultrasonic bonder and the helper torque jet along the yarn path, as was described in section 4.6.1 and shown in figure 71.

![Figure 71](Weldy Hot air gun positioned between the ultrasonic bonder and the helper torque jet)

To determine the effect of heat on the ATP yarn twist efficiency, the self plied yarn was exposed to hot air, provided by the gun, after they are bonded and before they are passed through the helper torque jet. The digital temperature control on the gun was used to control the hot air temperature and the resulting yarn temperature was measured...
using an Infrared thermometer. In order to achieve a certain yarn temperature, the hot air
temperature on the heat gun had to be set to a much higher temperature. The maximum
yarn temperature that could be obtained was 85°C and the corresponding hot air
temperature was set to 350°F on the hot air gun. Any further increase in the hot air
temperature, to obtain a higher yarn temperature, results in the melting and breaking of the
nylon ATP yarn. Although the melting point of nylon is higher than 85°C, this is most
probably due to the presence of localized portions of the nylon yarn acquiring the higher
temperature of the surrounding hot air and thus approaching the melting point of nylon. In
these experiments, the main torque jets pressure was set at 60 PSI while helper jet pressure
was set at 80 PSI and the singles yarns tension applied was 35g.

Figure 72 Effect of the yarn temperature, due to hot air exposure, on the singles yarn and ply yarn
twist
The experimental results, shown in figure 72, did not illustrate any significant effect of increasing the yarn temperature on the either the singles yarn or the ply yarn twists. In addition to that, figure 73, did not show any improvement in the yarn twist efficiency as a result of increasing the yarn temperature, but on the contrary, increasing the yarn temperature up to 85°C, resulted in a slight decrease in the yarn twist efficiency. These unsatisfactory results may be attributed to several reasons. One possibility could be that subjecting the nylon yarns to these high temperatures might result in the overdrying of the yarns. Sudduth [36] has shown that the sensitivity of nylons to hydrolysis increases with the decrease of their moisture content, and that nylon 6 /6 can increase in brittleness and viscosity to an unacceptable level after drying below a critical moisture content. Thus
the decrease in the yarn twist efficiency might be attributed to the increased brittleness of
the yarn structure due to over drying. Another possibility could be that the method of
applying heat to the ATP yarns using the hot air gun was not very efficient especially with
the high yarn speeds of the process and that another method of heat application should be
designed.

6.4 Discussion

The main objective of this chapter was to determine and study the main process
variables on the Drexel ATP process that affect the ATP yarn twist efficiency. Each
process variable was studied independently keeping all other parameters constant in order
to gain a good understanding of its effect on the singles yarns twist, the ply yarn twist and
the twist efficiency.

The main torque jets control the twist in the singles yarns, where increasing the
main jet pressure increases the magnitude of the applied singles torque which in turn
generates a higher twist in the singles yarn. Increasing the main torque jet pressure was
also found to slightly increase the yarn twist efficiency to about 65%. However the main
jet pressure needed to produce maximum twist efficiency still needs to be determined.

The singles yarns tension has also been found to affect both the singles yarn and
ply yarn twist. In the range of singles yarn tensions used, an increase in the singles yarn
tension resulted in a decrease in the resulting singles yarn and ply yarn twists and a slight
increase in the yarn twist efficiency to about 64%.

The above results show that the maximum ATP yarn twist efficiency that can be
obtained from the self plying process on its own through the use of the main torque jets
and applied singles tension is 65%. This twist efficiency level is in agreement with
literature [30], which shows that for two 1050 denier plied strands of BCF nylon, only about 60% to 70% of the twist in the singles yarn is converted to ply twist during spontaneous self plying with no external assistance or restraint to the plying. This was attributed to the presence of frictional forces resisting the plying forces and thus not all of the twist applied to the singles yarns is converted to ply twist.

The use of a helper torque jet to improve the yarn twist efficiency was also studied. The experimental results show that the ply torque applied by the helper jet on the self plied yarn does not only affect the ply twist but also the singles yarn twist. Thus, the helper torque jet does not have a direct effect on the yarn twist efficiency and more research needs to be done to establish a clear understanding of the helper jet performance.

The experimental results have also shown the effect of increasing the yarn temperature, through the use of a hot air gun, on the yarn twist efficiency. The results were not successful in improving the twist efficiency, most possibly due to the overdrying of the nylon yarns while being exposed to the hot air.

This chapter has provided an overview of the effect of the different process variables on the yarn twist efficiency, however a more systematic approach is needed to establish a good solid understanding of the effect of these variables, study the interaction between these different process variables and determine the optimum process parameters required to achieve the maximum possible twist efficiency in the yarns produced on the Drexel ATP process.
CHAPTER 7: EMPIRICAL MODELING OF THE YARN TWIST EFFICIENCY USING RESPONSE SURFACE METHODOLOGY

7.1 Background and Significance

In the preceding chapter, the important processing parameters that affect the yarn twist efficiency of ATP yarns were identified. It was also empirically determined that approximately 8% increase in the yarn twist efficiency could be obtained by increasing main torque jet pressure, without the application of ply torque through the helper jet.

The purpose of this chapter is to investigate the interaction of these variables and to identify the optimum combination of main torque jet pressure, singles yarn tension, helper torque jet pressure and yarn temperature in order to produce ATP yarns on the Drexel process with the highest possible twist efficiency.

In order to obtain a more systematic understanding of these process conditions and to establish a quantitative basis for the relationships between the ATP process parameters and the yarn twist efficiency, Response Surface Methodology (RSM) [37] was employed in this study. The objective is to develop an empirical model to guide the forthcoming research on how to further improve the ATP yarn twist efficiency and to determine the optimum values of these parameters to be used in the future commercial application of the Drexel ATP process.

RSM has been used successfully for material and process optimization [38] in numerous studies including various textile processing applications. This approach has the advantage of taking into account the combined effects of several parameters and it uses statistical methods to fit an empirical model to the experimental data.

The use of a model to describe the effects of the processing parameters permits the representation of the influencing parameter in a simple and systematic way and prediction
of the results of the experiments with different parameter combinations. Thus RSM not only gives an overview of the processing parameters but also their influence on each other. Furthermore, it helps to obtain the surface contours of these parameters using experimental and predicted values. These contour plots outline the processing window and point out the direction to attain the optimum condition in the form of an Eigen value [37, 38]. A brief introduction is provided herein.

7.1.1 Response Surface Methodology (RSM)

RSM is used in situations where several variables influence a feature (called the response) of the system. The steps in the procedure are described briefly as follows [37]:

1. Identification of variables $\zeta_1, \zeta_2, \zeta_3 \ldots \ldots$ for response $\eta$

2. Calculation of corresponding coded variables $(x_1, x_2, x_3\ldots)$ by using the following equation.

$$x_i = \frac{\zeta_i - \left(\zeta_{Ai} + \zeta_{Bi}\right)/2}{\left[\zeta_{Ai} - \zeta_{Bi}\right]/2}$$  \hspace{1cm} (7.1)

Where, $\zeta_{Ai}$ and $\zeta_{Bi}$ refer to the high and low levels of the variables $\zeta_i$, respectively.

3. Determination of the empirical model by multiple regression analysis to generate the theoretical response ($\hat{y}$). The second-order model is widely used in RSM. The general equation for response $\eta$ of the second-order model is given by:

$$\eta = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_i x_i^2 + \sum_{i=1}^{k} \sum_{j=i+1}^{k} \beta_{ij} x_i x_j$$  \hspace{1cm} (7.2)

Where $k$ is the number of factors, $x_i$ are the coded variables and $\beta$ are the coefficients.
4. Calculation of the coefficients $\beta$ to fit the experimental data as closely as possible.

The relationship between the response and the variables is visualized by a response surface or contour plot to see the relative influence of the parameters, to find an optimum parameter combination, and to predict experimental results for other parameter combinations. The RSM procedure use to optimize the ATP process parameters for achieving maximum yarn twist efficiency is shown in figure 74.
7.2 Materials and Methods

7.2.1 Materials and Machine Setup

1245 Denier BCF nylon yarns were used in the following experiments. The profiles used for the yarn velocity, main and helper torque jets and ultrasonic horn and anvil are shown in figure 75. The setup of the Drexel ATP process to allow for the use of a hot air gun is as described in section 6.3.4. The yarn twist efficiency measurements for the ATP yarn samples were done according to the procedure described in section 4.4.2.

Figure 75 Profiles used for the yarn velocity, main and helper torque jets and ultrasonic horn and anvil for experiments used in the Response Surface analysis.
7.2.2 Experimental Design

The experimental design used in this study is the central composite design (CCD), shown in figure 76. It is the most popular RSM design used for most industrial applications. CCD is designed to estimate the coefficients of a quadratic model. A CCD has three groups of design points: (a) two-level factorial design points (b) axial points ("star" points) (c) center points.

The two-level factorial design points consist of all possible combinations of the high and low levels of the factors. The star points have all of the factors set to 0, the midpoint, except one factor, which has the value (+/- $\alpha$). The value for ($\alpha$) is calculated in each design for the rotatability of its blocks. The value of $\alpha$ determines the location of the star points in a central composite design. ($\alpha$) is usually somewhat larger than 1. The center points, as implied by the name, are points with all factors set to the coded level (0) i.e. the midpoint of each factor range. The center points are usually repeated 4-6 times to get a
good estimate of experimental error (pure error). In summary, central composite designs require 5 levels of each factor: $-\alpha, -1, 0, 1, +\alpha$ in coded factor values. [39]

Table 5 shows the four process factors used in the construction of the CCD; main torque jet pressure, singles yarn tension, helper torque jet pressure and yarn temperature, the actual values of each factor level and the corresponding coded values.

<table>
<thead>
<tr>
<th>Process Variables</th>
<th>Units</th>
<th>Actual Values</th>
<th>Coded Values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>- $\alpha$</td>
<td>Low</td>
</tr>
<tr>
<td>Main Jet pressure</td>
<td>PSI</td>
<td>8</td>
<td>30</td>
</tr>
<tr>
<td>Helper Jet pressure</td>
<td>PSI</td>
<td>-37.5</td>
<td>0</td>
</tr>
<tr>
<td>Singles Yarn Tension</td>
<td>g</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>Yarn Temperature</td>
<td>Deg. °C</td>
<td>24</td>
<td>24</td>
</tr>
</tbody>
</table>

The low and high level values for each of the process factors were determined according to the maximum permissible working range on the Drexel ATP process. Several investigatory experiments were initially run on the ATP process to determine this permissible working range. This explains why there is not a very wide range between the high and low level values of the process factors. In addition to that, the values of +/- $\alpha$
shown in red in Table 5 are modified values, because the initially calculated values were beyond the workability extremes of the ATP process.

7.3 Results

7.3.1 Response function

In this study, a quadratic polynomial function was used. The response function was obtained using multiple regression analysis using “Design-Expert” software. An initial model is first built using the method of least squares in a hierarchical fashion to compute the coefficients, building from a base that contains the intercept. Initially, all the terms, including all the main factors and the two-factor interactions are selected. The effect of each term is then calculated in the following order: 1) main effects, adjusted for other main effects 2) two-factor interactions, adjusted for main effects and other two-factor interactions [39].

Secondly, the significant factors effects must be identified and separated from the insignificant effects. Selection of terms having significant effect is done by the probability value, (Prob > F), i.e. Probability of seeing the observed F value if the null hypothesis is true (there is no factor effect). If the Prob>F value is very small (less than 0.05) then the individual terms in the model have a significant effect on the response. However, if a two factor interaction is a significant term, then the model should also include the main effects of this interaction, even if the main effects do not appear to be statistically significant on their own. A well-formulated model should include the factors and interactions that are significant, plus any terms that are needed to maintain hierarchy.

After the significant terms have been selected for the model, The term effects are recalculated in the following order: 1) all terms selected for the model, adjusted for other
terms in the model 2) main effects, adjusted for other main effects, 3) two-factor interactions, adjusted for main effects and other two-factor interactions. [39] Table 6 shows the significant terms selected for the model. Although, D-yarn temperature factor was not a significant term it was included in the model to be able to study its effect.

Table 6 Significant factors and interaction terms selected for the response surface model

<table>
<thead>
<tr>
<th>Term</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td></td>
</tr>
<tr>
<td>A-Main jet pressure</td>
<td>4.16 + 8.5x10^{-3}A + 0.059B - 0.026C - 4.9x10^{-3}D - 0.028AB + 0.012AC + 0.019A^2</td>
</tr>
<tr>
<td>B-Helper jet pressure</td>
<td></td>
</tr>
<tr>
<td>C-tension</td>
<td></td>
</tr>
<tr>
<td>D-yarn temperature</td>
<td></td>
</tr>
<tr>
<td>AB</td>
<td></td>
</tr>
<tr>
<td>AC</td>
<td></td>
</tr>
<tr>
<td>A^2</td>
<td></td>
</tr>
</tbody>
</table>

The fitted second-order equation for the natural logarithmic yarn twist efficiency is given by:

\[ \text{Ln(Yarn Twist efficiency)} = 4.16 + 8.5 \times 10^{-3}A + 0.059B - 0.026C - 4.9 \times 10^{-3}D - 0.028AB + 0.012AC + 0.019A^2 \] (7.3)

Where A, B, C and D are the coded values of the main factors; main torque jet pressure, helper torque jet pressure, singles yarn tension and yarn temperature respectively.
The values of these coefficients in terms of the actual values of the main factors is shown in Table 7.

<table>
<thead>
<tr>
<th>Term</th>
<th>Coefficient Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>+4.31</td>
</tr>
<tr>
<td>Main jet pressure</td>
<td>-4.11E-003</td>
</tr>
<tr>
<td>Helper jet pressure</td>
<td>+3.3E-003</td>
</tr>
<tr>
<td>Single Yarn tension</td>
<td>-4.4E-003</td>
</tr>
<tr>
<td>Yarn temperature</td>
<td>-1.9E-004</td>
</tr>
<tr>
<td>Main jet pressure * Helper jet pressure</td>
<td>-3.3E-005</td>
</tr>
<tr>
<td>Main jet pressure * Singles tension</td>
<td>+4.4E-005</td>
</tr>
<tr>
<td>Main jet pressure²</td>
<td>+3.67E-005</td>
</tr>
</tbody>
</table>

The regression model has a P-value (a measure of the statistical significance) of 0.0001, less than the significance level of 0.05, which validates the adequacy of the model. The "Lack of Fit F-value" for the model is 3.24 which implies that the Lack of Fit is not significant relative to the pure error. Non-significant lack of fit is desired so that model fits. An $R^2$ value (a measure of the percent of the response being represented by the variables) of 0.8223 was obtained for the multiple regression model. The "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. The regression model
has a ratio of 13.155 which indicates an adequate signal and that the model can be used to navigate the design space.

7.3.2 Response Surfaces of Yarn Twist Efficiency as a function of the Main Process Factors

7.3.2.1 Effect of Main Torque Jet and Singles Yarn Tension on Twist Efficiency

Figure 77 shows the response surface of the yarn twist efficiency as a function of the main torque jet pressure and the singles yarn tension. The helper torque jet pressure was set to zero for this response. The response indicates that changes in yarn twist efficiency are more responsive to the singles yarn tension at the low main torque jet pressures. In general, increasing the singles yarn tension tends to decrease the yarn twist efficiency.

Low main torque jet pressure gives lower yarn twist efficiency. A main torque jet pressure of 30 PSI gives twist efficiencies ranging from 59-61% while a main torque jet pressure of 75 PSI gives a yarn twist efficiency of 64%. The increase in the yarn twist efficiency with the increase of the main jet pressure in the absence of the helper jet is in good agreement with the experimental results previously shown in figure 64. The interaction effect of the singles yarn tension can also be observed.
7.3.2.2 Effect of Helper Jet on Twist Efficiency

Figure 77 shows the response surface of the yarn twist efficiency as a function of the main torque jet pressure and the singles yarn tension when the helper jet pressure is 42 PSI. Comparing figures 77 and 78 together, it is noticed that the yarn twist efficiency values are shifted to a higher level in the presence of the helper jet. It could also be pointed out that the increase in the yarn twist efficiency is more responsive to the helper jet pressure at low main torque jet pressure. This is also much more pronounced in figure 79 where the helper jet pressure is increased to an even higher level of 75 PSI.
Figure 78 Response Surface of the yarn twist efficiency as a function of the main torque jet pressure and the singles yarn tension, with the helper jet pressure of 42PSI in the absence of heat (room temperature).

Figure 79 Response Surface of the yarn twist efficiency as a function of the main torque jet pressure and the singles yarn tension, with the helper jet pressure of 75PSI in the absence of heat (room temperature).
Taking a closer look at figure 79, a very important trend can be deducted; when a ply torque is applied to the ATP yarns through the action of the helper torque jet, higher levels of yarn twist efficiency could be obtained using low main jet pressure, i.e. low singles torque, and low singles yarn tension. Figure 79 shows that, at a main jet pressure of 30 PSI, a singles yarn tension of 34g and a helper jet pressure of 75 PSI, a yarn twist efficiency of 73% is obtained. It must be noted that this was not the case in the absence of the helper jet in figure 77, where higher twist efficiency was obtained by increasing the main jet pressure. Figure 80 also shows the interaction between the main and helper jets pressures at a singles yarn tension of 34g, which confirms the same trend described above. Figure 80 also explains why the helper jet did not show a significant effect on the yarn twist efficiency when it was initially studied in section 6.3.3, where the main torque jet pressure used in those experiments was 60 PSI.

Figure 80 Response Surface of the yarn twist efficiency as a function of the main torque jet pressure and the helper torque jet pressure, with the singles yarn tension 34g, in the absence of heat (RT).
7.3.2.3 Effect of Heat on Twist Efficiency

The application of heat to the ply yarns through the use of the hot air gun did not show any effect on the yarn twist efficiency. For three different levels of the yarn temperatures used ranging from 24°C to 85°C, the yarn twist efficiency stayed more or less the same. The yarn temperature main factor as well as its interaction with other main factors all showed insignificant effects in the regression model, where their Prob>F values were greater than 0.05. This result is also illustrated in figure 81 showing that for different yarn temperature values, the yarn twist efficiency was 64%.

Figure 81: Effect of yarn temperature on yarn twist efficiency resulting from the RSM model
7.3.2.4 Optimum Processing Window for High Twist Efficiency ATP yarns

The use of RSM has enabled us to study the effect of the main process factors and their interactions over the whole range of possible processing conditions. This has allowed us to point out the optimum processing window on the Drexel ATP process to produce yarns with an improved twist efficiency level, higher than the previously obtained average of 65%. As can be concluded from the results of the response surfaces demonstrated in the previous section, the use of low main torque jet pressure of 30 PSI, low singles yarn tension of 34g, high helper torque jet pressure of 75PSI and processing at room temperature with no heat application constructs the main window frame that produces ATP yarns with a 73% yarn twist efficiency. This result has also been confirmed experimentally with a number of repeated trials.

7.4 Discussion

In this chapter, RSM was introduced to the Drexel ATP process for the first time. RSM has proved to be a very useful tool providing us of a complete vision of the effect of all the possible interactions between the different process factors across the complete workability range of the Drexel ATP process. RSM has employed Multiple Regression analysis to correlate the yarn twist efficiency to the main process factors by using a quadratic polynomial function. Regression analysis has allowed us to determine the main factors and interactions with a significant effect on the yarn twist efficiency and exclude them from the insignificant ones. This has provided an extremely useful guide which will greatly influence the further work of this thesis on how to further improve the yarn twist efficiency as will be discussed in Chapter 8.

Response surfaces for the yarn twist efficiency were generated based on the multiple regression model. The response surfaces have shown that the use of minimum
singles yarn tension just enough to satisfy the requirements of the self plying process is recommended to obtain higher values of yarn twist efficiency. The response surface has also illustrated the presence of an interaction between the main torque jet pressure and the singles yarn tension which influences the twist efficiency. It has also been shown that increasing the yarn temperature insignificantly affects the yarn twist efficiency. This could be due to the same reasons of over drying the nylon yarns previously discussed in section 6.3.4.

Response surfaces relating the yarn twist efficiency to the main torque jet pressure and singles yarn tension for different levels of helper jet pressure have shed the light on a very important result that was not possibly obtained in Chapter 6. The response surfaces have shown that in the absence of a helper torque jet in the ATP process, the yarn twist efficiency increases with the increase of the main torque jet pressure, and the maximum possible yarn twist efficiency is about 65%, which is the base case for most current commercial ATP processes. When a helper torque jet is used, the unique feature of the Drexel ATP process, the interaction between the main torque jet and the helper torque jet strongly influences the yarn twist efficiency. This interaction allows us to achieve yarns with improved yarn twist efficiency of 73%. This is achieved through the use of low main jet pressure and a high helper jet pressure. [40] This result has emphasized the need for a scientific physical explanation for the interaction between the two torque jets which would be the point of focus in Chapter 8.

Thus RSM has identified the main torque jet pressure, singles yarn tension, helper torque jet pressure as the main process variables affecting the ATP yarn twist efficiency. The use of the optimum processing window determined by the response surface allows us to achieve an 8% increase in the twist efficiency, than the initial base case, reaching 73%.
8.1 Background and Significance

The results of the previous chapter have enabled us to achieve an improvement in the twist efficiency of the ATP yarns produced on the Drexel ATP process. However, this improvement is not still sufficient to fulfill the requirements of bulk and tuft stability demanded for use as cut pile carpet yarns. Nevertheless, these results have paved the pathway to further improve the twist efficiency. It has been empirically shown that the means for increasing the yarn twist efficiency is through applying a small singles yarn torque through the action of the main torque jet, a low singles yarn tension, and a high ply torque through the action of the helper torque jet. Although this empirical solution has been confirmed, reasoning for it remains yet unavailable. Thus in order to step up with the yarn twist efficiency to a higher level, a physical understanding of the processing mechanics involved in the ATP process including a role effect analysis of the singles yarn torque and tension and the applied ply yarn torque must first be provided.

The self plying zone in the ATP process is considered the “heart” of this process, basically because it is in this zone that twist is transferred from the singles yarns structure to the ply yarn structure. It is thus the efficiency of this transfer that results in the yarn twist efficiency value. Thus the key to understanding the underlying effects of the main factors controlling the ATP process is through the establishing of a mechanistic analysis of the self ply zone. A very few researchers in literature [7-11, 14], previously mentioned in section 2.2.4.2, have actually already studied and modeled the self plying process. However, all of these models were based on the analysis of the self plying process of two parallel strands, which is not the actual case in any running ATP process. In all
commercially available ATP processes and in the Drexel ATP process, the two singles yarn are not in a parallel configuration when they converge at the point of self ply, instead they converge together at an angle defined as the “yarn convergence angle” as shown in figure82. This geometrical consideration of the yarns configuration at the self ply point will have a major effect on the forces and torques acting in this zone.

![Diagram of Yarn Convergence Angle at the point of self ply on the Drexel ATP process](image)

**Figure82** Yarn Convergence Angle at the point of self ply on the Drexel ATP process

In addition to that, none of these studies have modeled the effect of an applied ply torque which has been shown to have a positive effect on the yarn twist efficiency. These limitations of previous models, in turn, call for the need of an overall analysis of the self plying process taking into consideration these critical issues, which will be the focus of this chapter.

The Drexel ATP process is a very dynamic process, where a complete cycle time
including two twist reversal lengths could take only 1000 milliseconds or even less. Thus actually observing and investigating the yarns configuration and structure at the self plying point is practically impossible. To allow the feasibility of investigating the self plying zone, a static tester was designed to exactly simulate the self plying conditions on the Drexel ATP process. The static tester has also allowed us to experimentally study the effect of varying the yarn convergence angle ($2\theta$) at the point of self ply on the resulting yarn twist efficiency. These experiments could not be possibly done on the Drexel ATP process, because, as shown in figure 82, the yarn convergence angle is restricted to a maximum value of $35^\circ$ due to the design of the singles main torque jets.

The objective of this chapter is to provide an understanding of the underlying mechanics governing the self plying process through the development of an equilibrium analysis of all the tensions and torques acting on the yarns at the point of self ply. This analysis in conjunction with the static tester will be used to determine the method for achieving a further improvement of the yarn twist efficiency.

**8.2 Materials and Methods**

Experiments were conducted on the static tester to study the effect of the yarn convergence angle and the main process factors, namely; the singles yarn torque, the singles yarn tension and the ply yarn torque on the resulting singles and ply yarns twists and accordingly the yarn twist efficiency specifically at the point of self ply. The design of the static tester, previously shown in figure 40, and the experimental procedure were previously described in section 4.6.3. Two sets of experiments were conducted on the static tester. In the first set of experiments, extruded silicone rubber yarns of round cross section and 1/32 inch in diameter, custom made by Simolex Rubber Corp., MI, USA, were
used. The purpose of using the rubber monofilament yarn is to examine the performance of an ideal material and to be able to compare the base case of these experimental results with the previous results available in literature, namely “Tayebi Monofilament Rubber Model” [9-11], discussed in section 2.2.4.2 and thus validate the static tester results. The second set of experiments is done using 1245 BCF nylon multifilament yarns to simulate the process conditions on the Drexel ATP process.

8.3 Equilibrium Analysis of the ATP Process at the Point of Self Ply

Figure 83 Analysis of the tensions and torques acting on an ATP rubber model at the point of self ply and the resulting singles and ply twist directions
A stable balanced ATP yarn is one that will maintain its structure after the forces and torques exerted on it are removed. In order to produce this stable ATP yarn structure, an equilibrium condition must be maintained during the self plying process. This section analyzes the tension and torques acting in the self ply zone at equilibrium, illustrated in figure 83 for a monofilament rubber yarn. During self plying, the tensions in the singles yarns above the convergence point \( T_S \), applied by the yarn tensioners, must be balanced by the tension in the ply yarns \( T_P \) below the yarn convergence point. This results in the following equation relating the tensions in the self ply zone to fulfill equilibrium conditions:

\[
T_P = 2 T_S \cos \theta \quad (8.1)
\]

Where \( T_S \) and \( T_P \) are the tensions in the singles and ply yarn respectively and \( \theta \) is the half angle of convergence at the point of self ply.

At equilibrium, the torques produced in the singles yarns structure \( \tau_S \), due to the action of the main torque jets, and the torque produced in the ply yarn structure \( \tau_P \), due to the action of the helper torque jet, are counterbalanced by the unplying torque produced due to the singles tension components acting on the singles yarns cross-section with a moment arm equal to the singles yarns radius. This results in the following equation relating the different torques at equilibrium. This equation neglects the bending moment contribution to yarn torque for reasons of model simplicity.

\[
\tau_P + 2 \tau_S \cos \theta - 2 T_S D_S \sin \theta = 0 \quad (8.2)
\]
Where $\tau_s$ and $\tau_p$ are the singles yarn and ply yarn torques respectively and $D_s$ is the singles yarn diameter.

Equations (8.1) and (8.2) present the two main equations that are needed to fulfill the equilibrium conditions required for producing a stable ATP yarn structure. These two equations in themselves also illustrate the importance of taking into account the existence of the yarn convergence angle at the point of self ply which results in appearance of the component terms effects of the tensions and torques in these equations. The effect of the yarn convergence angle will further be emphasized section 8.3.1.

A special case for equation (8.2) is in the absence of the helper torque jet, which is the case for most current commercial ATP processes. In this case, the ply torque term in equation (8.2) diminishes and the unplying torque produced due to the singles tension components would be balanced by the components of the singles yarn torque only, as shown in equation (8.3).

$$2\tau_s \cos \theta - 2T_s D_s \sin \theta = 0 \quad (8.3)$$

In order to establish a quantitative relationship describing the effect of the ply torque in the Drexel ATP process, the equilibrium equations (8.1) and (8.2) were used. Substituting equation (8.1) into equation (8.2) and solving for the singles yarn torque we obtain the following equation

$$\tau_s = \frac{\left( \frac{D_s}{2} T_p \tan \theta \right) - \tau_p}{2 \cos \theta} \quad (8.4)$$
Converting equation (8.4) into a dimensionless form for simplification reasons is done through normalization by $(DSTP)$ to obtain the following equation

$$\hat{\tau}_s = \frac{\tan \theta - \hat{\tau}_p}{2 \cos \theta}$$

(8.5)

Figure 84 shows a plot of the dimensionless singles yarn torque ($\hat{\tau}_s$) versus the dimensionless applied ply yarn torque ($\hat{\tau}_p$) for different values of yarn half convergence angle ($\Theta$).
Figure 84 shows that when a ply yarn torque is applied through the action of the helper torque jet, the singles yarns torque decreases and reaches a negative value. A negative value of the singles yarns torque means that the applied ply torque produces a singles yarn torque opposite in direction to what is required for the self plying process. This result is extremely undesirable and implies that the helper torque jet affects the ATP process negatively.

In order to fully understand what is happening when a ply torque is applied, we will assume a special case that the main torque jets are turned off and that only the helper torque jet is operating on the same “Y” yarn configuration, shown in figure 83, in an equilibrium condition. The main purpose behind this assumption is to study the effect produced by the helper torque jet, on its own, on the singles and ply yarns. In this case, no self plying will take place because the driving force for the self plying process, the singles yarns torque, will now be absent. However, a ply yarn (not an ATP yarn) will still be produced, below the convergence point, due to the action of the ply torque. As twist is being inserted in the ply yarn for example Z twist, the singles yarn inside the ply yarn structure, below the convergence point, will in turn acquire twist in the opposite direction, S twist. In order to achieve equilibrium, twist will also be generated in singles yarns, above the yarn convergence point, equal but opposite in direction to that in the singles yarn below the convergence point. Thus, Z twist is generated in the singles yarns, above the yarn convergence point. Figure 85 shows a schematic illustrating this case, where in summary, under the action of an applied ply torque by the helper torque jet and in the absence of an applied singles torque by the main torque jets, the twist generated in the singles yarns above the yarn convergence point will have the same twist direction of the ply yarn twist.
Comparing figures 83 and 84, a very important result can be concluded; during the self plying process produced by the action of the singles yarn torque applied by the main torque jets, the twist in the singles yarn above the yarn convergence point is opposite to the ply yarn twist direction, figure 83, however, when a ply torque is applied by the helper torque jet, the twist generated in the singles yarns above the yarn convergence point will have the same twist direction of the ply yarn twist, figure 85. This is of extreme importance because this means that the helper torque jet has an opposite effect on the twist in the singles yarns above the convergence point to that of the main torque jets. This means that the action of the helper torque jet is basically cancelling at least some of the twist previously inserted by main torque jets and thus decreasing the singles yarn torque which is the main driving force for the self plying process. This thus provides an explanation for
the trend observed in figure 84.

In addition to that, in the Drexel ATP process, when a helper torque jet is used to apply a ply torque, while serving to increase the ply yarn twist, but it also increases the twist in the singles yarns inside the ply yarn structure, i.e. increase the singles residual twist, which explains why the singles twist levels increased together with the ply twist level when the helper torque was turned on in figure 67. This also explains why the helper torque jet did not offer much improvement in the yarn twist efficiency in figures 68 and 70, because the ratio of ply to singles yarn twist stayed more or less the same.

A very interesting point that was also noted by taking a closer look on the action of the helper torque jet in the absence of the main torque jets, in figure 84, is that it completely resembles the Sirospun process previously described in section 2.2.5. Thus the equilibrium equations (8.1) and (8.2) also apply to the Sirospun process, except that the singles yarn torque, in this case, will be the torque generated due to the twist produced in the singles above the yarn convergence point as a result of the ply yarn torque. This complete resemblance has been made use of in determining how much singles yarn twist is inserted in the singles yarn above the yarn convergence point due to the action of the helper torque jet. The results of the experiments done on a steady-state Sirospun spinning system, obtained by Miaoj et al [19], previously discussed in section 2.2.5, were shown in figure 17. Figure 86 also illustrates that as the ply yarn twist level is increased, the ratio of the singles yarn twist above the yarn convergence point to the ply yarn twist is decreased dramatically. This means that the higher the ply torque applied, the higher will be the increase in the ply twist level and the lower will be the amount of singles twist generated above the yarn convergence point as a ratio of the ply twist.
This means that the main criteria for using a helper torque jet on the Drexel ATP process, to achieve some improvement in the yarn twist efficiency if any, is through the use of a very high helper torque jet pressure i.e. high applied ply torque. The is because through the use of a high ply torque, yes that will still result in a decrease in the singles yarn torque but the amount of ply twist added will still be higher than the amount of undesired residual singles twist added and thus the overall yarn twist efficiency will thus be improved to some extent. This conclusion also now explains clearly why the response surfaces of the RSM, in section 7.3.2.2, showed that the maximum yarn twist efficiency of 73% that could be obtained on the Drexel ATP process is through the use of a maximum helper torque jet pressure of 75PSI.
8.3.1 Effect of Yarn Convergence Angle on Singles Yarn Torque

Going back to the equilibrium analysis plot, shown in figure 84, another extremely important feature can be realized. Figure 84 shows that increasing the half yarn convergence angle ($\Theta$), results in a smaller decrease in the singles yarn torque for the same applied ply yarn torque. Figure 87, further illustrates this trend, where plotting the dimensionless singles yarn torque versus the half yarn convergence angle shows that as the half convergence angle increases the singles yarn torque increases for different values of applied ply yarn torque.

Figure 87 Effect of yarn convergence angle on the dimensionless singles yarn torque for different applied ply yarn torques
This means that if the singles yarns are forced to converge at a high convergence angle, this would remarkably reduce the undesired effect of the applied ply yarn torque, in reducing the singles yarn torque, and at the same time increase the ply yarn twist and thus produce a tremendous increase in the yarn twist efficiency on the Drexel ATP process. In order to confirm this proposed method for further improving the yarn twist efficiency, through the use of the combined effect of applied high ply yarn torque and high yarn convergence angle at the point of self ply on the Drexel ATP process, a series of experiments demonstrating this effect were required.

Since the two main torque jets on the Drexel ATP process are confined in space together inside a stainless steel box, as shown in figure 82, varying the yarn convergence angle on this process was not feasible at the time because it required redesigning the jets configuration which is a time consuming and expensive process. For this reason and for purposes of acquiring a detailed analysis of the change in the levels of the singles and ply yarns twist with the change of the applied ply yarn torque and yarn convergence angle at the self ply point, the static tester previously described in section 4.6.3 and shown in figure 40 was used in the following experiments.

8.4 Results of Static Modeling using Rubber Monofilament Yarn

In this set of experiments, 1/32” rubber monofilament yarn was used to study the effect of ply yarn torque and the yarn convergence angle on the resulting singles and ply yarn twists at the self ply point. These rubber yarns were used in order to study these effects with the use of a perfectly elastic ideal material as a base case thus eliminating any friction or interfilament interaction effects in nylon multifilament yarns. The procedure used in these experiments is as previously mentioned in section 4.6.3. The ply tension used
in this set of experiments was 34g. Experiments using higher ply tensions were also done but the results were not reported because a great degree of stretching of the rubber yarn occurred during the self pllying process due to the higher applied tension. For this reason, studying the effect of the ply yarn tension on the yarn twist efficiency was not possible in this set of experiments using rubber yarns and will be studied in the second set of experiments using BCF nylon yarns.

8.4.1 Validation of Static Tester Results with Previous ATP Models

In order to validate the results of the static tester, an initial experiment was done with no ply torque applied to the ply yarns and the self pllying process was examined under the effect of applied ply tension only. These results are compared to the experimental and theoretical results previously obtained by Tayebi et al [9-11] using a rubber monofilament model to simulate the self pllying process of two parallel yarns under the effect of tension only.

Figure 88 shows a plot of the ply twist helix angle versus the singles twist helix angle. The helix angle \( \Phi \) expressed in radians is a measure of the twist in the yarn structure and is related to the twist \( t \) expressed in turns per inch through the following equation derived by Treloar [41]

\[
t = \frac{1}{2\pi} \frac{d\phi}{ds}
\]

(8.6)

Where \( \frac{d\phi}{ds} \) is the angle of twist in radians per inch. Figure 88 shows that that the static tester results are in good agreement with results of the “Tayebi” monofilament...
rubber model [9] which validates the static tester results. The reason that the static tester results may be a little bit higher than the experimental results obtained by Tayebi could be attributed to the bigger diameter of the rubber yarn, 0.05 inch, used in Tayebi’s experiments. [9]
This was also shown in 2004, by Aikawa et al [42], where a series of experiments to determine the relation between the singles yarn twist and the ply yarn twist when a twist filament yarn is folded in two at the median point and allowed to self ply, were done. Their results have shown that as the yarn diameter increases the ratio of the ply yarn twist to the singles yarn twist decreases.

Figure 88 also illustrates that as the twist in the singles yarns increases the resulting ply twist increases. However, as the singles twist increases, the deviation from the dotted 45° diagonal line representing the 100% twist efficiency line, also increases. This indicates that the higher the singles yarn twist level the lower is the yarn twist efficiency.

### 8.4.2 Effect of Ply Torque on Twist Efficiency

The ply yarn torque is applied in these experiments by inserting two turns of twist in the elastic rubber torque transducer, which is equivalent to a ply yarn torque of 25 μN.m as shown in Appendix E. The ply yarn tension used is 34g.

Figure 89 shows that applying a ply yarn torque to the self ply yarn results in some increase in the ply yarn twist for the same singles twist as compared to when no ply torque is applied. This increase in the ply yarn twist will thus improve the yarn twist efficiency. The maximum increase in the ply yarn twist due to the ply yarn torque effect is seen for medium levels of twist in the singles yarns ranging from 4 to 6 turns per inch and ply yarns with 100% yarn twist efficiency could be obtained. For high levels of singles yarns twist, the effect of applying ply yarn torque on the ply yarn twist nearly diminishes.
8.4.3 Effect of Yarn Convergence Angle on Twist Efficiency

Figure 90 illustrates the effect of the yarn convergence angle on the yarn twist efficiency under a ply yarn tension of 34g, with and without applying a ply yarn torque of 25μN.m. It can be seen that increasing the half yarn convergence angle from 25° to 35°, a large increase in the yarn twist efficiency could be obtained. Beyond this angle of convergence, the yarn twist efficiency decreases greatly. This result suggests the presence of an optimum yarn convergence angle that would provide maximum twist efficiency.
The same trend for the change of yarn twist efficiency with the yarn convergence angle was obtained both with and without applying a ply yarn torque. A half yarn convergence angle of 35° yielded the highest values of yarn twist efficiency in both cases. However, it can be realized that, in figure90, when the singles yarns converge at a half yarn convergence angle of 35° at the self ply point, applying a ply yarn torque produces a very large effect in increasing the yarn twist efficiency, about 14% increase, much larger than that previously shown in figure89. Thus it could be concluded that it is the combined
effect of allowing the singles yarn to converge at an optimum convergence angle together with applying a ply yarn torque that could achieve a large improvement in the yarn twist efficiency.

It should be noted the half yarn convergence angle on the Drexel ATP process is approximately 15°. It was not possible to study the effect of the yarn convergence angle on the yarn twist efficiency in this range on the static tester because the yarns would start to self ply spontaneously at a larger half yarn convergence angle of about 25° on average.

It is also worth noting, that the yarn convergence angle was a not a completely controllable independent variable on the static tester, where it’s a factor of the other process variables to some extent. This result can also be shown from equation (8.2) of the equilibrium analysis, shown in section 8.3.

![Figure 9.1 Effect of the dimensionless ply yarn tension and the applied ply yarn torque on the half yarn convergence angle at equilibrium](image-url)
Figure 91 shows that in order to maintain equilibrium conditions the half yarn convergence angle is decreased as the dimensionless ply yarn tension increased and that the applied yarn torque increases the half yarn convergence angle.

In order to study the nature of the relation between the half yarn convergence angle and the ply yarn twist, the half yarn convergence angle was plotted against the ply helix angle in figure92. Figure92 illustrates the presence of a linear relationship between the ply yarn helix angle and the half yarn convergence angle obtained at this ply twist. The slope of the linear regression line is equal to 1.3. This result will be later used in Chapter9 in attempt to develop a mathematical expression relating the yarn twist efficiency to the singles and ply yarn twists, the ply yarn torque and the yarn convergence angle.

![Figure92 Relation between the ply yarn helix angle and the half yarn convergence angle under ply yarn tension of 34g and without applied ply yarn torque](image-url)
8.5 Results of Static Modeling using Nylon Multifilament Yarn

1245 denier BCF nylon yarn were used in this set of experiments to examine if the applied ply yarn torque and the yarn convergence angle will have the same effects on the yarn twist efficiency as that observed using the rubber monofilament yarn. The use of the nylon yarns, with limited stretch, has also allowed us to study the effect of the ply yarn tension on twist efficiency and its interaction with the process variables. The experimental procedure is the same as used in the previous section and described in section 4.6.3.

8.5.1 Validation of Static Tester Results with Drexel ATP Process Results

In order to validate the design of the elastic yarn torque transducer for applying ply yarn torque on the static tester, results from the static tester, showing the effect of singles yarn twist on the resulting ply yarn twist with and without an applied ply torque, were compared with results of experiments done on the Drexel ATP process using 1245 denier BCF nylon yarn with and without the effect of the helper torque jet. These results are shown in figure93 which shows that the effect of applying ply yarn torque on the ply yarn twist on the static tester is in very good agreement with the effect of the helper torque jet on the ply yarn twist and that in both cases the applying a ply torque produces about 8% improvement in the yarn twist efficiency from the base case; without applying ply yarn torque. The overall results of the static tester are, however, somewhat higher than the Drexel online process results, which may be due to the nature of the dynamic conditions on the Drexel ATP process.

The results of figure93 also show that for both cases, higher twist efficiency levels could be obtained at lower levels of singles yarn twist and as the singles yarn twist is increased the deviation from the 100% twist efficiency line is increased.
Figure 93 Effect of the singles yarn twist on the ply yarn twist with and without applying a ply yarn torque on the static tester and on the Drexel ATP process.
8.5.2 Effect of Yarn Tension on Twist Efficiency

Four different levels of ply yarn tensions were used to study the effect of ply yarn tension on the yarn twist efficiency. A ply yarn torque of $25\mu N.m$ was used for these experiments. As can be seen in figure 94, the at low ply yarn tension very high twist efficiency levels can be achieved and the higher the ply yarn tension the lower is the yarn twist efficiency. However, the use of very low ply yarn tension does not offer the practical solution for increasing the yarn twist efficiency on the Drexel ATP process. This is because the practical lower limit of ply yarn tension that could be used on the Drexel ATP process is 55g, where decreasing the ply yarn tension below this limit causes the singles yarn to entwine over each other before the torque jets due to the twist propagating upstream in Zone1, which in turn causes yarn entanglement and harms the self plying process.

![Graph showing the effect of ply yarn tension on yarn twist efficiency](image)

Figure 94: Effect of ply yarn tension on yarn twist efficiency with an applied ply yarn torque of $25\mu N.m$
8.5.3 Effect of Ply Torque on Twist Efficiency

Figure 95 presents a close up of the results of applying a ply yarn torque on the static tester previously shown in figure 93. These results emphasize the fact that applying a ply yarn torque could achieve a limited improvement in the twist efficiency which is in agreement with the equilibrium analysis results discussed in section 8.3.

Figure 95 Effect of applying ply yarn torque on the yarn twist efficiency on the static tester
8.5.4 Effect of Yarn Convergence Angle on Twist Efficiency

In order to clearly study the effect of the yarn convergence angle on the yarn twist efficiency, several experiments were done to examine its effect with and without applying a ply yarn torque, for different tension levels and for different applied ply torque levels. For each experiment, the corresponding change in the singles yarn twist level with the yarn convergence angle was also studied.

Figures 96 and 97 show the effect of varying the half yarn convergence angle on the yarn twist efficiency and the singles yarn twist, respectively, without any applied ply yarn torque. The results show that when the half yarn convergence angle is increased beyond $35^\circ$, the yarn twist efficiency tends to decrease and the corresponding singles yarn twist increases. Higher values of yarn twist efficiencies were obtained for lower ply yarn tensions. The minimum half yarn convergence angle, i.e. the point where self plying starts on its own, that could be obtained in these experiments was $30^\circ$, thus it was not possible to determine the yarn twist efficiency at lower convergence angles. These results, although they do not show clearly the presence of an optimum yarn convergence angle, but they suggest that the highest yarn twist efficiency value of about 85% was obtained at a half yarn convergence angle of $35^\circ$ which is the same value of the optimum half convergence angle yielded by the static tester results using rubber monofilament yarns.
Figure 96 Effect of the half yarn convergence angle on the yarn twist efficiency without any applied ply yarn torque for different ply yarn tensions.

Figure 97 Effect of the half yarn convergence angle on the singles yarns twist without any applied ply yarn torque for different ply yarn tensions.
Figures 98 and 99 show the effect of varying the half yarn convergence angle on the yarn twist efficiency and the singles yarn twist, respectively, under the effect of an applied ply yarn torque of 98μN.m. Comparing figures 96 and 99, suggests that applying a ply yarn torque emphasizes the presence of an optimum yarn convergence angle for obtaining maximum twist efficiency. Figure 99 also shows that as the half yarn convergence angle increases together with the application of the ply yarn torque, the singles yarns twist is also increasing which confirms the role of the yarn convergence angle in increasing the singles yarns torque. As was shown previously in figure 96 increasing the ply yarn tension affects the yarn twist efficiency negatively. Figure 98 shows the yarn twist efficiency increases with the increase of the yarn convergence angle till an optimum convergence angle is reached, and beyond this angle, any further increase in the half yarn convergence angle results in the decrease of the yarn twist efficiency. This trend is the same trend previously noticed in the static tester results using rubber monofilament yarn.
Figure 98 Effect of the half yarn convergence angle on the yarn twist efficiency with applied ply yarn torque 98 μN.m for different ply yarn tensions

Figure 99 Effect of the half yarn convergence angle on the singles yarns twist with applied ply yarn torque 98 μN.m for different ply yarn tensions
Figures 100 and 101 show the effect of the yarn convergence angle on the yarn twist efficiency and the corresponding singles yarns twist, respectively, for different applied ply yarn torques. The ply yarn tension used in these experiments is 83g, which is in the range of the ply yarn tensions used on the Drexel ATP process. Figure 101 shows that as the yarn convergence angle increases the singles yarn twist is also in generally increasing. The results of figure 100 show that under the effect of a ply yarn torque applied, there exits an optimum half yarn convergence angle, at which maximum twist efficiency is obtained. Figure 100 shows that a half yarn convergence angle of 47° yields a maximum yarn twist efficiency value of 90% for an applied ply yarn torque of 25μN.m. It is also shown that increasing the applied ply yarn torque to 98μN.m, 100% yarn twist efficiency can be obtained for the same convergence angle. Although this applied ply yarn torque, of 98μN.m, is higher than the ply yarn torque applied by the action of the helper torque jets on the Drexel ATP, the results suggest that the use of this optimum half yarn convergence angle together with a high ply yarn torque is the pathway to achieve a major improvement in the yarn twist efficiency. These critically important results confirm the understanding previously provided by the analysis of the equilibrium conditions at the point of self ply, in section 8.3, and have led to the filing of a provisional patent. [43] Another future suggestion based on these results is also to study the possibilities of increasing the ply yarn torque applied through the action of the helper torque jet on the Drexel ATP process.
Figure 100: Effect of the half yarn convergence angle on the yarn twist efficiency for different applied ply yarn torques.

Figure 101: Effect of the half yarn convergence angle on the singles yarns twist for different applied ply yarn torques.
8.6 Effect of Yarn Convergence Angle on Twist Efficiency on the Drexel ATP Process

The very promising results of the previous section have motivated us to redesign the main torque jets on the Drexel ATP process to allow for the use of a high yarn convergence angle at the self ply point. Many thanks to Paul Yngve for his great assistance in redesigning these jets and to Belmont Textile Machinery Inc, NC for their generosity in manufacturing the jets for us, at their own expense, in a very short time.

8.6.1 Redesign of the Singles Jets on the Drexel ATP Machine

Figure 102 shows the redesigned main torque jets on the Drexel ATP process. The main torque jets for the two singles yarns were separated from each other and designed in such a way that they are free to move in a 180° circular slot so that the desired angle of convergence between them can be adjusted and then the jets are fixed to that position.
In order to allow the singles yarns to pass through the centerlines of the main torque jets as they are drawn from the yarn tensioners, a bar and low friction roller system as shown in figure 103, was used for each jet and position in alignment with the jets such that the angle between the two bars is the same as that between the jets.

![Figure 103 Design of a bar and low friction roller system so the singles yarns are passed around the roller then through the centerline of the main torque jets](image)

During operation, when a high yarn convergence angle was set between the main torque jets, the singles yarns emerging from the main jets did not immediately self ply and converged later in the yarn path. In order to overcome this problem, and to ensure that the singles yarns would self ply at the desired angle of convergence and that they are in a self plied structure as they pass through the ultrasonic bonder, a yarn guide, shown in figure104, was inserted between the main torque jets and the ultrasonic bonder to force the yarns to converge.
8.6.2 Material and Machine Setup

1245 BCF nylon yarns were used in these experiments. The different process variables were set according to the optimum processing window previously identified using RSM in section 7.3.2.4 where a main torque jet pressure of 30 PSI, singles yarn tension of 34g and helper torque jet pressure of 75PSI were used. The profile of the yarn velocity, rotational profiles of the main and helper torque jets and profiles of the ultrasonic horn and anvil are shown in figure75.
8.6.3 Experimental Results on the Drexel ATP Process

The effect of the yarn convergence angle on the yarn twist efficiency with and without an applied ply yarn torque i.e helper torque jet on/off is shown in figure 105. The results show that in the absence of a ply yarn torque, as the yarn convergence angle is increased the yarn twist efficiency is decreased which is in good agreement with the results of the static tester shown in figure 96. However, in the case of applying a ply yarn torque through the action of the helper torque jet, increasing the half yarn convergence angle increases the yarn twist efficiency till an optimum is reached and then the yarn twist efficiency decreases with further increase in the yarn convergence angle.

![Figure 105 Effect of the half yarn convergence angle on the resulting yarn twist efficiency with and without an applied ply yarn torque](image-url)
The optimum half yarn convergence angle obtained in these results is 45° which is in close agreement with the static tester results shown in figure 100. The maximum twist efficiency obtained at this half convergence angle is an average 78%. This presents a 13% increase in the yarn twist efficiency from the base case of 65%. The reason this twist efficiency value is a little lower than the static tester results may be attributed to that a higher ply yarn torque value was used on the static tester.

The results of this section provide an experimental confirmation and support the hypothesis from the mathematics and basic static experiments that “TWIST EFFICIENCY CAN BE IMPROVED BY USING BOTH A HELPER TORQUE JET AND A RELATIVELY HIGH CONVERGENCE ANGLE”.

8.7 Discussion

In this chapter, an equilibrium analysis of the ATP process at the self ply was presented. This analysis has taken into account the effect of applying a ply yarn torque and using a high yarn convergence angle at the self ply point was has never been studied in any previous work done on self plying. This equilibrium analysis has unveiled the unobserved effects on the helper torque jet on the Drexel ATP process and provided us of a good interpretation of the previous experimental results and RSM modeling results obtained in chapters 6 and 7. The results have shown that the helper torque jet while serving to increase the ply yarn twist also has a very critical hidden effect in decreasing the singles yarns torque above the yarn convergence point. The second very important result that was revealed by this equilibrium analysis is that the use of high yarn convergence angle at the point of self ply would overcome the undesired effect of the helper torque jet in decreasing the singles yarn torque and thus achieve an overall improvement in the yarn twist
efficiency.

The results of the equilibrium analysis were further confirmed in this chapter through a series of experiments on the static tester. The static tester has enabled us to study the effect of the yarn convergence angle on the yarn twist efficiency which was not possible to be done on the Drexel ATP process at the time. The static tester results were first validated with the previous experimental and theoretical results in literature and showed close agreement. The effect of applying a ply yarn torque using an elastic yarn torque transducer were also validated through comparing them with the experimental results of the Drexel ATP process. The results of the static tester have shown that the yarn convergence angle does not show much effect on the yarn twist efficiency in the absence of a ply torque. In the presence of an applied yarn torque, the yarn twist efficiency increases as the yarn convergence angle is increased until an optimum angle is reached. The optimum half yarn convergence angle obtained in case of using rubber monofilament yarns was 35° while that in case of using BCF nylon yarns was 47°. The use of a ply yarn torque of 98μN.m at this optimum half yarn convergence angle and a ply yarn tension of 83g has yielded a 100% yarn twist efficiency using the BCF nylon yarns.

This chapter has also included redesigning the main torque jets on the Drexel ATP process to allow for a high yarn convergence angle at the self ply point, based on the previous results. Experiments done on the Drexel ATP process using the redesigned jets have shown a 13% percent increase in the yarn twist efficiency using a half yarn convergence angle of 45° which is very close to that determined by the static tester results.
CHAPTER 9: MATHEMATICAL MODELING OF THE YARN TWIST EFFICIENCY

9.1 Background and Significance

The results of the previous chapter have enabled us to improve the yarn twist efficiency greatly on the Drexel ATP process and achieve 100% yarn twist efficiency on the static tester. The reason for this improvement was attributed to the use of a high ply yarn torque and an optimum yarn convergence angle at the point of self ply. The hypothesis for the use of a high ply yarn torque and increasing the yarn convergence angle was established from the analysis of the equilibrium forces, torques and singles yarns geometry at the point of self ply. The value of the optimum yarn convergence angle required for obtaining maximum twist efficiency was determined empirically from the experimental results. Although the results of this approach were very promising, there still remains the need of developing a mathematical expression relating the yarn twist efficiency to the ply yarn torque, singles yarn torque and the yarn convergence angle.

The mathematical expression previously developed by RSM modeling, in Chapter 7, relating the yarn twist efficiency to the main process variables; main and helper torque jets pressures, the singles yarn tension and yarn temperature serves as an excellent guide to determine the optimum processing window for operation on the Drexel ATP process. However, this empirical expression does not express the yarn twist efficiency in terms of the applied singles and ply yarn torques to allow us to gain a better mechanistic understanding and it does not take into account the effect of the yarn convergence angle because the possibility of increasing the yarn convergence angle on the Drexel ATP process was not feasible at the time.
The objective of this chapter is to develop a mathematical mechanistic model able to predict the yarn twist efficiency from the main process input variables. This mathematical model must satisfy the equilibrium conditions at the self ply point, which are the essence of all the resulting improvement in the yarn twist efficiency. In order to further relate the resulting yarn twist efficiency to the underlying mechanics of the ATP yarn system, equations expressing the strain energy of the singles yarns and the strain energy of the self ply yarn were also derived. The predicted yarn twist efficiency values of the mathematical model are also compared against the experimental results.

9.2 Materials and Methods

Experiments were done on the static tester using rubber yarns to verify the results of the mathematical model. The experimental procedure used is as previously described in section 4.6.3.

9.3 Monofilament Rubber Model of the Yarn Twist Efficiency

This section provides the development of a mathematical model to predict the yarn twist efficiency, the singles strain energy and the ply strain energy for two monofilament rubber yarns at the self ply point.

A model for multifilament yarns was not developed due to its increased complexity while its prediction of the yarn twist efficiency will not offer much difference in the understanding and analysis of the results as compared to the rubber monofilament model. The increased complexity of a multifilament model lies in the complex differential geometry of the plied multifilament yarns due to their double helical structure, presence of friction and filament to filament interaction during bending in the ply structure, local
filament torsion and curvature change with the yarn bending inside the ply in a complex manner and change of the single yarn cross sectional shape in the ply yarn structure. [11, 41, 44, 45]

The main assumptions of this model are 1) there is no stretching in the rubber yarns i.e. No change in the length of the rubber yarns occurs after twisting 2) The yarns circular cross-section remains perpendicular to the yarn axis after twist is inserted 3) No deformation of the yarn circular cross-section inside the ply yarn structure.

The list of symbols and their definition used in this section is provided in Appendix I.

9.3.1 Singles Yarn Torque

The torque generated in the singles yarn above the yarn convergence point is in major due to twist inserted in the yarns that is the main driving force of the self plying process. Since the tensions accompanying the self plying process are small, the singles torque generated due to tension is assumed negligible. Thus the singles yarns torque in the direction of the yarns axis [46] is equal

\[ \tau_s = GL_p \phi_s \]  \hspace{1cm} (9.1)

Where a good approximation of the shear modulus [45] is taken to be

\[ G \sim \frac{E}{3} \]  \hspace{1cm} (9.2)

And relating singles yarn helix angle (Φs) to the singles yarn twist (ts) through the following equation derived by Treloar [41]

\[ \phi_s = 2 \pi t_s \]  \hspace{1cm} (9.3)
And the polar moment of inertia \((I_D)\)

\[
I_D = \frac{\pi d^4}{32}
\]  
(9.4)

Thus substituting equations (9.2), (9.3) and (9.4) into equation (9.1), the singles yarns torque \((\tau_S)\) can be expressed in terms of the singles yarn twist \((t_S)\) as

\[
\tau_s = \frac{\pi^2}{48} Ed_s^4 t_s
\]  
(9.5)

For reasons of simplification, all the derived equations are converted into a dimensionless form. A list of the dimensionless variables and their definitions is provided in Appendix J. Equation (9.6) shows the expression for the dimensionless singles yarn torque.

\[
\hat{\tau}_s = \frac{\pi^2 \hat{E}}{48} \left( \hat{t}_s \right)
\]  
(9.6)

**9.3.2 Equations of Equilibrium at the Self Ply Point**

The equilibrium equations at the point of self ply (8.1) and (8.2) are expressed in terms of the singles yarn tension \((T_S)\) and singles yarns torque \((\tau_S)\), and converted into a dimensionless form to yield

\[
\hat{T}_s = \frac{1}{2 \cos \theta}
\]  
(9.7)

\[
\hat{\tau}_s = \frac{\hat{T}_s \sin \theta - \hat{\tau}_p}{2 \cos \theta}
\]  
(9.8)
Solving equations (9.6), (9.7) and (9.8) simultaneously for input values of dimensionless singles yarns twist and dimensionless ply yarn torque, the resulting half yarn convergence angle at the point of self ply ($\Theta$) is obtained. In order to be able to relate the half yarn convergence angle ($\Theta$) to the resulting ply twist ($t_p$) and yarn twist efficiency, the empirical relationship between the half yarn convergence angle ($\Theta$) and the ply twist helix ($q$) previously shown in figure 92 is used, where

$$\theta = 1.3 q$$  \hspace{1cm} (9.9)

Where the ply twist helix angle ($q$) is related to the ply yarn twist ($t_p$) from the geometry of the helical path of twisted singles yarn in the ply yarn structure [47] shown in figure

Figure106 Geometry of the helical path of twisted singles yarn in the ply yarn structure

$$\tan q = \pi d_s t_p = \pi \hat{t}_p$$  \hspace{1cm} (9.10)

### 9.3.3 Strain Energy of the Singles Yarns

The strain energy of the singles yarn above the convergence point is a sum of the tensile strain energy and the shear strain energy generated due the applied tension and twist. For a perfectly elastic isotropic material, the tensile strain energy per unit length ($T.S.E$) [46] is equal
\begin{equation}
T.S.E_S = \frac{1}{2} EA\varepsilon^2
\end{equation} 

(9.11)

And expressing the values of the singles yarn tensile strain ($\varepsilon$) and singles yarn cross sectional area ($A$) in the following equations (9.12) and (9.13) respectively

\begin{equation}
\varepsilon = \frac{T_s}{EA}
\end{equation} 

(9.12)

\begin{equation}
A = \frac{\pi}{4} d_s^2
\end{equation} 

(9.13)

Substituting equations (9.12) and (9.13) into (9.11), the tensile strain energy per unit length per single yarn ($T.S.E_S$) is

\begin{equation}
T . S . E_S = \frac{2T_s^2}{\pi d_s^2 E}
\end{equation} 

(9.14)

Thus the expression of the tensile strain energy per unit length for two singles yarn ($T.S.E_{2S}$) is

\begin{equation}
T . S . E_{2S} = \frac{4T_s^2}{\pi d_s^2 E}
\end{equation} 

(9.15)

And in dimensionless form

\begin{equation}
T . \hat{S} . E_S = \frac{4}{\pi \hat{E}} \left( \hat{T}_s^2 \right)
\end{equation} 

(9.16)

Similarly, the shear strain energy per unit length ($S.S.E_S$) for a twisted rod [46] is

\begin{equation}
S.S.E_S = \frac{1}{2} \frac{\tau_s^2}{Gl_p}
\end{equation} 

(9.17)
Substituting equations (9.2) and (9.4) for the shear modulus \((G)\) and the polar moment of inertia \((I_p)\) respectively in equation (9.17), we obtain the following expression for the shear strain energy per unit length for two singles yarns

\[
S \cdot S \cdot E_S = \frac{96 \tau_s^2}{\pi d_s^4 E}
\]  
(9.18)

Converting equation (9.18) into dimensionless form, we obtain

\[
S \cdot \hat{S} \cdot \hat{E}_S = \frac{96}{\hat{E}} \left(\hat{\tau}_s^2 \right)
\]  
(9.19)

Thus the total singles strain energy per unit length for the two singles yarns \((U_S)\) above the yarn convergence point expressed as the sum of the tensile and shear strain energies in a dimensionless form, shown in equations (9.16) and (9.19), is given as

\[
\hat{U}_S = \frac{4}{\pi \hat{E}} \left(\hat{T}_s^2 + 24 \hat{\tau}_s^2 \right)
\]  
(9.20)

Substituting for the values of the dimensionless singles tension and torque obtained from solving equations (9.6), (9.7) and (9.8) simultaneously, the strain energy of the singles yarns above the yarn convergence point is determined.

**9.3.4 Strain Energy of the Ply Yarn**

The strain energy in the self ply yarn below the convergence point is a sum of the tensile strain energy due to the applied ply yarn tension, shear strain energy due to the ply
yarn twist and the bending strain energy due to the curvature of the singles yarns inside the ply yarn structure upon twisting.

From equations (9.11) and (9.12), the tensile strain energy of a singles yarn per unit length of the singles yarn as it lies inside the ply yarn can be expressed as

$$T.S.E_s = \frac{1}{2} \frac{T_s^2}{EA}$$  \hspace{1cm} (9.21)

And since the self ply yarn consists of two singles yarn, then the tensile strain energy of a self ply yarn per unit length of the singles yarn is

$$T.S.E_p = \frac{T_s^2}{EA}$$  \hspace{1cm} (9.22)

Thus the tensile strain energy of a self ply yarn per unit length of the ply (T.S.E_p) could be expressed as

$$T.S.E_p = \frac{T_s^2}{EA} \xi$$  \hspace{1cm} (9.23)

Where \(\xi\) presents the decrease in the resulting ply yarn length with respect to the length of the singles yarns used to produce the ply yarn and can be expressed as

$$\xi = \frac{\delta S_p}{\delta S_s}$$  \hspace{1cm} (9.24)

Since the length of the resulting ply yarn is smaller than length of the singles yarns used to produce it, owing to the fact that the singles yarns follow a straight path above the
yarn convergence point and after self plying they follow a helical path inside the ply yarn structure due to the ply yarn twist. Thus from the geometry of ply yarn twist shown in figure 107, ($\xi$) can be expressed as

$$\xi = \frac{\delta S_p}{\delta S_s} = \cos q$$  \hspace{1cm} (9.25)

![Figure107 Geometry of the helical path followed by the singles yarns in the ply yarn](image)

And the resulting tensile strain energy of a self ply yarn per unit length of the ply is given by

$$T . S . E_p = \frac{T_s^2}{E A} \cos q$$ \hspace{1cm} (9.26)

Substituting for the cross-sectional area ($A$), given in equation (9.13), in equation (9.26) and converting the equation into a dimensionless form, the dimensionless tensile strain energy of a self ply yarn is obtained in the following equation
The bending strain energy per unit length stored in a bent beam [46] is given by

\[ T \hat{S} E_p = \frac{4}{\pi E} \left( \hat{T}_s^2 \cos q \right) \]  

(9.27)

The bending strain energy per unit length stored in a bent beam [46] is given by

\[ \frac{1}{2} \frac{M_B^2}{EI} \]  

(9.28)

Where \( EI \) is the bending rigidity of the beam and \( M_B \) is the bending moment and is given by

\[ M_B = \frac{EI}{\rho} \]  

(9.29)

Where \( \rho \) is the radius of curvature [46] and is given by

\[ \rho = \frac{d_s}{2 \sin^2 q} \]  

(9.30)

Thus the bending strain energy for the two singles yarns as lie inside the ply yarn structure \( (B.S.E.P) \) can be expressed as

\[ B.S.E_p = \frac{EI}{d_s^4} \sin^4 q \]  

(9.31)

Substituting for the value of the moment of inertia \( (I) \)

\[ I = \frac{\pi d_s^4}{64} \]  

(9.32)

The dimensionless bending strain energy of the ply yarn is given by

\[ B \hat{S} E_p = \frac{\pi \hat{E}}{16} \left( \sin^4 q \right) \]  

(9.33)
Similarly, the shear strain energy per unit length for a twisted shaft [46] is given by

\[
\frac{1}{2} \frac{M_T^2}{GI_p}
\]  

(9.34)  

Where the torsional moment \(M_T\) is equal

\[
M_T = GI_p \varphi_{\text{eff}}
\]  

(9.35)  

Where \((\varphi_{\text{eff}})\) is the effective angle of twist per unit length in the self ply yarn structure and was previously derived by Tayebi and Backer [9] to give the following expression

\[
\varphi_{\text{eff}} = 2\pi t_s \cos q - \frac{2 \sin q \cos q}{d_s}
\]  

(9.36)  

Substituting equations (9.2), (9.4), (9.35) and (9.36) in equation (9.34), the shear strain energy of the two singles yarns in the ply yarn structure \((S.S.E_p)\) can be expressed as

\[
S.S.E_p = \frac{\pi E d_s^4}{24} \left( \pi t_s \cos q - \frac{\sin q \cos q}{d_s} \right)^2
\]  

(9.37)  

And in dimensionless form

\[
S.\hat{S}.E_p = \frac{\pi \hat{E}}{24} \left( \pi \hat{t}_s \cos q - \sin q \cos q \right)^2
\]  

(9.38)
Thus the dimensionless total strain energy of the ply yarn can be expressed as the sum of equations (9.27), (9.33) and (9.38), where it is expressed as

$$\hat{U}_p = B.\hat{S}.E_p + S.\hat{S}.E_p + T.\hat{S}.E_p$$  \hspace{1cm} (9.39)

9.4 Experimental Verification and Results

The equations derived in section 9.3 are used to determine, from the model inputs, the resulting ply yarn twist and thus the yarn twist efficiency, the strain energy of the singles yarns above the convergence point and the strain energy of the ply yarn. The model inputs are the singles yarn diameter, singles yarn modulus, ply yarn tension, singles yarn twist and applied yarn torque. The values used for the singles yarn diameter (0.05 in) and the singles yarn modulus (300 lbf/in²) are the actual values for the rubber yarn used in the experiments done on the static tester to verify the model results. An input ply yarn tension of 60g and applied ply yarn torque of 100μN.m were used.

9.4.1 Model Verification with Previous ATP Model and Static Tester Data

The model prediction for the ply yarn twists resulting for different values of input singles yarn twists in the case where no ply yarn is applied ($\tau_p=0$) is shown in figure 108. The model results are also compared with the theoretical and experimental results of previous models that did not account for a ply yarn torque namely, Tayebi Model [10]. The experimental results of the static tester using rubber yarns are also plotted on the same graph. Figure 108 also includes the experimental results of the Drexel ATP process using 1245 denier nylon BCF yarn, in the case where the helper jet is off, to examine how close
Figure108 Model verification with Tayebi Model [10], static tester experimental results and nylon experimental results on the Drexel ATP process without applying ply yarn torque.

Figure108 shows that the model results are in excellent agreement with the experimental results of the static tester. The model results shows the same slope of the increase in the ply yarn twist as the singles yarn twist increases as that provided by the Tayebi model [10] with shows that the results are good agreement. However, the higher
values of ply yarn twist obtained from model results as compared to those of the Tayebi model [10] may attributed to the difference in the model inputs used including the rubber yarn diameter and modulus and the ply yarn tension. The experimental results of the Drexel ATP process were also very close to the model results, which show that model provides a good approximation of these results.

Figures 109 and 110 also shows the effect of the singles yarn twist on the ply yarn twist, without and with applying a ply yarn torque respectively. The model results were compared with the results of the experimental rubber results on the static tester.

![Figure 109](image-url)  
Figure109 Effect of Singles yarn twist on the ply yarn twist values predicted by the model and experimentally on the static tester without applying a ply yarn torque.

Both figures show that model results are in good agreement with the static tester results at medium values of singles yarn twist, however, as higher values of singles yarns twist the experimental results tend to give higher values for the resulting ply yarn twist.
The same trend was also observed in the results of previous models [9-11] and was attributed to the nature of the stress-strain behavior of the rubber yarns used, where if the strain in the rubber exceeds the linearity region on the stress-strain curve, the actual tensile strain energy developed in the singles rubber yarn would be less than the theoretical value, thus result in the continuation of the self plying process to a higher ply twist angle.

![Graph showing the effect of singles yarn twist on ply yarn twist](image)

**Figure 110** Effect of Singles yarn twist on the ply yarn twist values predicted by the model and experimentally on the static tester with applying a ply yarn torque.

### 9.4.2 Effect of Applying a Ply Yarn Torque on Ply Yarn Twist

Figure 111 illustrates the results of the model in predicting the effect of applying a ply yarn torque on the resulting ply yarn. The results show that applying a ply yarn torque increases the ply yarn twist for the same value of singles yarns twist, which turn increases the yarn twist efficiency. Thus the model results are in good agreement with the
experimental results of the static tester shown in section 8.4. The negative region for the plot of the ply yarn twist versus the singles yarn twist in the case of applying a ply yarn torque resembles the case where the helper torque jet is operating on its own with the absence of the action of the main torque jets i.e Sirospun process, previously discussed in section 8.3, where that singles yarn twist developed would be opposite in direction to that desired for the self plying process.

Figure 111 Effect of singles yarn twist on the ply yarn twist with and without applying a ply yarn torque as a predicted by the model
9.4.3 Effect of Singles Yarn Twist on the Singles Yarn Strain Energy

The change in the strain energies in the singles yarn as the singles twist increases allows us to attribute these changes to the corresponding changes in the singles tension, ply yarn twist, yarn twist efficiency and the yarn convergence angle. Figure112 shows that the tensile and shear strain energies of the singles yarns increase as the singles yarn twist increases and that the shear strain energy is the dominant strain energy in the singles yarn system.

![Figure112 Effect of singles yarn twist on the singles strain energy and its components.](image-url)
9.4.4 Effect of Ply Helix Angle on the ATP Yarn Strain Energy

Figure 113 shows that as the ply helix angle i.e. the ply yarn twist increases the ply strain energy of the ATP yarn system shows a small increase until a ply helix angle of about 30° is reached where the ply strain energy increases greatly. Looking at the components of the ply strain energy it could also be seen that at low ply yarn twists the tensile strain energy seems to be dominant. However, at a ply helix angle of about 35°, the bending and shear strain energies start to increase above the tensile strain energy and at higher ply twist helix angles the shear strain energy becomes the dominant. This change in the dominancy of the components of the ply strain energy relative to each other could be used to explain the presence of an optimum yarn convergence angle, as obtained by the static tester results in section 8.4, and will be discussed later.
9.4.5 Effect of Singles Yarn Twist on Yarn Tension

The model results shown figure 114 illustrate that as the singles yarn twist increases the tension on the singles yarns also increases which is attributed to the tension generated due to twisting. Applying a ply yarn torque is also shown to increase the singles yarn tension further for the same singles yarn twist. This could be attributed to that applying ply yarn torque produces an increase in the ply yarn twist. This increased ply twist would be accompanied by an increase in the ply yarn tension due to twisting which would in turn affect the singles yarn tension at equilibrium.

Figure 114 Effect of singles yarn twist on the singles yarn tension with and without applying a ply yarn torque as a predicted by the model
9.4.6 Effect of Singles Yarn Twist on Twist Efficiency

Figure 115 shows that as the singles yarn twist increases, the yarn twist efficiency decreases which confirms the previous results shown experimentally on the Drexel ATP process and the static tester and concluded by the RSM modeling. This could be attributed to the increase in the singles strain energy as the single twist increases, as shown in figure 112, and as the strain energy increases this makes it more difficult for the singles yarn system to be able to release all this energy into the ply yarn system. The figure also shows that applying a ply yarn torque produces higher yarn twist efficiency but this effect tends to decrease at the higher levels of singles twist which is in good agreement with the static tester results previously shown in figure 89.

Figure 115 Effect of the singles yarn twist on the resulting yarn twist efficiency with and without applying ply yarn torque
9.4.7 Effect of Yarn Convergence Angle on Twist Efficiency

Figure 116 shows the effect of increasing the half yarn convergence angle together with increasing the applied ply yarn torque on the resulting yarn twist efficiency. The results confirm the previous experimental results of the static tester, shown in section 8.4, that the combined effect of using a high yarn convergence together with increasing the applied ply yarn torque produces a large improvement in the yarn twist efficiency. However, the model results did not show an optimum half yarn convergence angle after which the yarn twist efficiency decreases. This is probably because of the numerical limits of the model, where the maximum ply yarn helix angle that can be reached is about 35° after which the model fails numerically. According to equation (9.9), which relates the half yarn convergence angle to the ply helix angle, a ply helix angle of 35° would yield a half yarn convergence angle of 46° which is about the same optimum half convergence angle obtained from the experimental results of both the static tester and the Drexel ATP process in Chapter 8. This could explain why, using the model, the twist efficiency continued to increase with increasing the convergence angle till this half yarn convergence angle limit was reached.
Effect of the combined effect of increasing the half yarn convergence angle and the ply yarn torque on the resulting yarn twist efficiency
9.5 Discussion

This chapter has developed a model able to predict the ATP ply yarn twist and twist efficiency from given values of singles yarn diameter and modulus, singles yarn twist, ply yarn tension and applied ply yarn torque. The results of this model have shown excellent agreement with the experimental results of the static tester and in close agreement in its base case; no ply yarn torque applied, with previous models in literature. The model has shown also to provide a close approximation of the experimental results of the Drexel ATP process.

The model has also established mathematical expressions for the singles and ply strain energies and their components which have enabled us to study the change in the energy of the singles and ply yarns as the singles yarn twist; the main driving force, is increased.

The developed model has also been able to demonstrate the effect of the ply yarn torque in increasing the yarn twist efficiency together with increasing the yarn convergence angle which confirms the previous experimental results in chapter 8.
CHAPTER 10: CONCLUSIONS

- Alternate twist plying with ultrasonic bonding at the twist reversals and the use of a profiled velocity profile offers the possibility of a high speed process for producing high quality cut pile carpet yarns.

- A complete review of all the commercially available ATP processes, their aspects of design, their applications and comparing them to the conventional ply twisting processes and the cabling process has been provided.

- The Drexel ATP process has been upgraded to offer accurate and reproducible test results. This upgrade has included the installation of IRO weft accumulators, yarn tensioners, J-box and a yarn winder. Complete framing of the machine has been designed and installed to achieve perfect two-dimensional alignment. Upgrading the Drexel ATP process has resulted in a pilot-scale machine ready for transformation into a commercial machine.

- Demonstration of the capability of the Drexel ATP process in processing a wide variety of materials, including Nylon, Kevlar, Spectra 1000 and glass fibers has been done.

- Measurement procedures to obtain an objective accurate evaluation of the ATP yarn twist profile and yarn twist efficiency have been established.

- A static tester capable of simulating all the process variables of on the Drexel ATP was designed and built for the first time. This innovative design has allowed us to apply a ply yarn torque on the order of micro newton. meters while fulfilling the process the process requirements of tension and freedom of movement.
• A square wave twist profile was achieved on the Drexel ATP Machine using process and computational modeling and simulation.
  - The key process parameters affecting the yarn twist profile were determined through process modeling. The equations of state describing the amount of twist accumulating in the singles yarns across zone1 and zone2 of the Drexel ATP process where established using a set of differential equations. The yarn velocity profile, the rotation profile of the main torque jets and the machine zone lengths were identified as the key process parameters.
  - The computational model was used to provide the solution for these differential equations in the dimensionless form using a stiff integrator. Computer simulation of the yarn velocity profile, the main torque jet rotation profile and the resulting yarn twist profile was done.
  - The effects of the yarn velocity and rotational profile and the machine zone lengths were studied through the computational model predictions of the yarn twist profile. Experimental verification of the computational model was done by experimental measurements of the yarn twist profile of ATP yarn samples produced on the Drexel ATP process. The experimental results showed very good agreement with the model.
  - The computational model and computer simulation were able to determine the optimum process parameters required to achieve a square wave yarn twist profile.
  - The optimum yarn profile required to achieve a square wave twist profile is characterized by an abrupt increase in speed to reach the maximum at the start.
of the twist reversal cycle followed by a nearly constant yarn velocity across the
cycle to prevent the twist from decreasing along the yarn length. At the twist
reversal where the yarn must stop for bonding the yarn velocity must then
decrease abruptly to a stop.

- The optimum length of zone1; distance between the yarn tensioners and the
  main torque jets, was found to be at least six times the twist reversal length to
  assure a uniform distribution of twist in the singles yarn, before the twist is
  trapped in the self ply structure. The optimum length of zone2; distance between
  the main torque jets and the self ply point, with respect to the twist reversal
  length was found to be very small ~ 0.003, to force the spontaneous self plying
  process.

- Coordination between the different profiles of the different functions on the
  Drexel ATP process which is also very crucial to produce a uniform twist profile
  with a very short bond and a short zero twist region at the twist reversal has also
  been done.

- The yarn twist efficiency has been significantly improved on the Drexel ATP process.

- The main process variables of the Drexel ATP process affecting the singles and
  ply yarns twists and thus the yarn twist efficiency were determined.
  - The main torque jets control the twist in the singles yarns, where
    increasing the main jet pressure increases the magnitude of the applied
    singles torque.
  - The singles yarns tension has also been found to affect both the singles
    yarn and ply yarn twist. Increasing in the singles yarn tension results in
    a decrease in the resulting singles and ply yarn twists.
- The helper torque jet was also found to affect both the singles and ply yarns twists through applying a ply yarn torque.
- The effect of increasing the yarn temperature, through the use of a hot air gun, on the yarn twist efficiency was also studied.
- The maximum ATP yarn twist efficiency that could be obtained on the Drexel ATP through the use of the main torque jets and applied singles tension, as the base case, is 65%.
- RSM analysis was applied to the experimental results to develop a processing window which will produce ATP yarns with maximum yarn twist efficiency.
  - Response surfaces relating the yarn twist efficiency to the main torque jets pressure and the singles yarns tensions were generated for different helper torque jet pressures of 0 PSI (off), 42 PSI and 75 PSI.
  - The RSM model has shown that a low main torque jet pressure of 30 PSI, low singles yarn tension of 34g, high helper torque jet pressure of 75PSI and processing at room temperature with no heat application were found to be the optimum conditions for achieving maximum yarn twist efficiency of 73%.
  - This result has also been confirmed experimentally with a number of repeated trials.
- The equilibrium analysis has provided the key findings of how to improve the twist efficiency
  - An analysis of the forces and torques acting on the yarns at the self ply point was done taking into account the effects of applying a ply yarn torque and the geometry of the yarn convergence angle at the self ply
point.

- The results have shown that applying a ply yarn torque decreases the singles yarns torque above the yarn convergence point while increasing the ply yarn twist.

- The action of the helper torque jet has also been found to resemble the sirospun process and from thus it was concluded that a limited improvement in the twist efficiency could only be achieved through applying a high ply yarn torque.

- The equilibrium analysis has also shown that increasing the yarn convergence angle at the point of self ply increases the singles yarn torque under the effect of ply yarn torque and thus achieves an overall improvement in the yarn twist efficiency.

- It was also found that increasing the ply torque for the same tension a higher convergence angle can be obtained.

  - The yarn twist Efficiency was largely improved on the Static Tester through the use of high ply torque and an optimum yarn convergence angle.
    - The static tester has enabled us to study the effect of the yarn convergence angle on the yarn twist efficiency.
    - The static tester results showed close agreement with the previous experimental and theoretical results in literature.
    - The static tester also approximates the experimental results of the Drexel ATP process with 1.8% increase in twist.
    - The results have shown that higher twist efficiency is obtained for lower yarn tensions and at lower twist levels.
Applying a ply yarn torque without increasing the yarn convergence angle showed little effect in improving the twist efficiency.

The use of a ply yarn torque of 98μN.m at the optimum half yarn convergence of angle, 47°, and a ply yarn tension of 83g has yielded a 100% yarn twist efficiency using the BCF nylon yarns.

- Results of the experiments done on the Drexel ATP process using the redesigned jets have shown a 13% percent increase in the yarn twist efficiency to reach 78%, on average, using a half yarn convergence angle of 45° and maximum helper jet pressure.

- A mathematical model able to predict the yarn twist efficiency and the singles and ply strain energies of the ATP yarn system has also been developed and has been verified against the results of previous models and with the experimental result of the static tester. The results of the model have confirmed the effect of increasing the ply yarn torque and the half yarn convergence angle in increasing the twist efficiency.

### 10.1 Future Work and Recommendations

- Achieving a square wave twist profile and high twist efficiency together on the wide convergence angle setup on the Drexel ATP process.

- Methods of enhancing the helper jet performance through increasing its applied ply yarn torque to better improve the twist efficiency on the Drexel ATP process.

- Evaluation of the feasibility of a providing constant velocity process on the Drexel ATP process.

- Develop methods of combining the best features of both types of ATP processes:
High convergence angle of convergence yarn process; Drexel ATP, and Constant speed of parallel yarn process; Belmont Roto-twist.

- Produce a range of ply yarns, including four and six plies of ATP yarn, to demonstrate process versatility.
- Estimate process limits relative to fiber (type, size, form) and feed yarns (type and denier variation).
- Explore the possibilities of using ATP yarns in other non-carpet applications such as high performance industrial applications or composites.
- Explore the possibilities of producing ATP yarn structures with core insertion of a different material of finer denier as shown in figure117 and its use in biomedical applications, where silk yarns could be used with a core insertion of nano-fiber yarns.

![Figure 117 Modified Drexel ATP process schematic for core insertion](image-url)
LIST OF REFERENCES

1. Carpet, Rug Sales set top $20 Billion, Int. fiber journal, 21, 3, 2006
4. http://www.ucl.ac.uk/
12. Coleman, Swigon, Theory of supercoiled elastic rings with self contact and its application to DNA plasmids, J. Elasticity, 60, 173-221, 2000


21. http://www.platt.co.uk/


23. US Patent, 6, 345,491, 2002


27. US Patent, 5,179,827, 1993

28. US Patent, 5,228,282, 1993


36. Sudduth, Hydrolysis Effects on the Molecular Weight Degradation of Condensation Polymers as Estimated From Their Prior Drying Condition, Polymer engineering and science, Vol. 36, No.16, 1996


41. Treloar, The geometry of multi-ply yarns, J. Text. Inst, 47, T348-68, 1956


Table A1: List of Patents describing the DuPont ATP process and their important claims

<table>
<thead>
<tr>
<th>Patent Number</th>
<th>Date Issued</th>
<th>Claims</th>
</tr>
</thead>
<tbody>
<tr>
<td>4,873,821</td>
<td>10/17/1989</td>
<td>(15) Process claims- profiling – heat setting (3) apparatus claims (1) Method claim</td>
</tr>
<tr>
<td>5,003,763</td>
<td>4/2/1991</td>
<td>(4) Method Claims for making the twisted yarns and ultrasonic bond</td>
</tr>
<tr>
<td>5,179,827</td>
<td>1/19/1993</td>
<td>(2) claims - describes the bond characteristics- Reveals continuous bonding and other node fixing</td>
</tr>
<tr>
<td>5,228,282</td>
<td>7/20/1993</td>
<td>(2) claims on “core” jet</td>
</tr>
<tr>
<td>5,465,566</td>
<td>11/14/1995</td>
<td>(6) claims on ultrasonic bond for increased bond strength</td>
</tr>
<tr>
<td>5,557,915</td>
<td>9/24/1996</td>
<td>(4) claims for carpets (5) claims for improved bond</td>
</tr>
<tr>
<td>5,577,376</td>
<td>11/26/1996</td>
<td>(2) claims - Add yarn snub w/ &amp; w/o booster jets (6) claims w/ types and locations of snub - Improved twist uniformity by delaying ply twist development</td>
</tr>
<tr>
<td>5,598,694</td>
<td>2/4/1997</td>
<td>(4) claims - Improved ultrasonic bonding w/ new geometries (6) claims - describes ultrasonic equipment geometries- Improved bonding strength and reliability</td>
</tr>
<tr>
<td>5,644,909</td>
<td>7/8/1997</td>
<td>(2) Claims - overall apparatus used - primarily heating &amp; overtwisting (11) Claims - process conditions - Low residual twist yarns - Yarns w/ high bulk and good ply integrity in cut pile</td>
</tr>
<tr>
<td>5,829,241</td>
<td>11/3/1998</td>
<td>(1) claim - APT yarn with low defects</td>
</tr>
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APPENDIX B: EQUIPMENT MANUAL AND OPERATIONAL PROCEDURE FOR THE DREXEL ALTERNATE TWIST PLY MACHINE

The main components of the machine are (figure B1):

- feeding system including yarn creel, IRO yarn accumulators and yarn tensioners;
- Torque Jets /ultrasonic welding system; connected to a pneumatic system
- Generator; sends ultrasonic electrical energy to the welder
- Profile velocity Roll, J-box and Yarn winder;
- Control panel and Operator Interface; governs the pneumatic piston of the welder, the air jet yarn twister, and the winder
- Pneumatic System
- Electrical Connections

Figure B1: Scheme of the Drexel ATP
1. Feeding System

The feeding system is composed of a six yarn package yarn holder creel (figure B2), then the yarns are passed through IRO weft yarn accumulators (figure B3) to maintain constant feed, and then through yarn tensioners, to apply tension to each yarn (figure B4).

![Figure B2 Six yarn package yarn holder creel](image)

Figure B2 Six yarn package yarn holder creel

![Figure B3 IRO Weft yarn accumulators](image)

Figure B3 IRO Weft yarn accumulators
2. **Air Torque Jets /Ultrasonic Welding System**

The air torque jets /ultrasonic welding system (figures B5 and B6) is composed of:

- Main Torque jets and Helper Torque jet;
- Ultrasonic bonder horn and anvil.
The main torque jets insert twist into a moving yarn. The apparatus includes a first body with two orifices to permit the passage of the moving primary yarns. Two air channels extend therethrough and communicate with each orifice. The air channels communicate with the orifices at a tangentially-offset angle to the path of the yarns through each orifice, to create a cyclonic air circulation pattern in the orifices, to insert a
same predetermined direction of twist into each primary yarn, as the yarns pass through the orifices. This twisting action allows the primary yarns to spontaneously ply together.

The helper torque jet is a second body with one orifice to permit the passage of the moving plied yarn. An air channel extends therethrough and communicates with the orifice. The air channel communicates with the orifice at a tangentially-offset angle to the path of the yarn through the orifice, to create a cyclonic air circulation pattern in the orifice, to insert a predetermined direction of twist into the plied yarn, as the yarn passes through the orifice.

The first and the second body, governed by the pneumatic system, intermittently insert opposite directions of twist in the primary yarns and in the plied yarn.

The ultrasonic welder (Dukane) is used to bond the plied yarn, in the twist reversal places, in order to prevent torsional movement of one primary yarn in relation to the other primary yarn. The ultrasonic welder is composed of a stack, and of a pneumatic actuator. The stack is composed of a piezoelectric crystal, a transducer, a booster and a horn (figure B7). The electric connection of the piezoelectric crystal to a high frequency electric current generator, creates the ultrasonic vibrations which heat up the horn. The pneumatic actuator presses the yarns onto the horn, creating a welded bond.
3. Generator

The Dukane 351 *generator* converts normal line voltage electrical energy to high frequency ultrasonic electrical energy, which is sent to the piezoelectric crystal in the stack of the ultrasonic welder by an ultrasound cable.
The generator controls and indicators (figure B8) are:

**Power ON/OFF Switch**

The power ON/OFF switch switches the electrical power to the generator. It is also a circuit breaker for overload protection.

**OPERATE/STOP/TEST Selector**

This selector provides a means of turning on and off the generator’s ability to produce ultrasounds.

OPERATE Position – This is an on position. With the selector in this position, the generator will send ultrasounds.

STOP Position – This is an off position. The generator cannot generate ultrasounds when this selector is in this position.

TEST Position – Use this position only to evaluate the vibrational characteristics of the stack, using the appropriate procedure (machine’s manual, procedure V.E.).

**Front Panel Meter**

The front panel meter indicates the percentage of power drawn from the generator when the ultrasound is on. The power draw varies with each application. The meter scale is from 0 to 10, in increments of 1. If the meter reading is in the red portion of the scale (beyond 100%), too much power is being drawn and the system operation should be discontinued. During an overload condition the red OVERLOAD light will be on.

**Red OVERLOAD Light**

The red OVERLOAD light illuminates to indicate a mismatch between the ultrasound signal and the vibrational characteristics of the stack. It also lights when too much power is drawn from the generator and the meter reading is in the red portion. Either conditions may damage the generator. When the OVERLOAD light glows or flickers, stop the operation.

**Power**

This control adjusts the amplitude of the vibration of the stack. To achieve optimum efficiency from this generator, set this control to a setting, as high as possible. Use this control only for fine adjustment.
The power characteristics of the generator are shown in Table B1.

Table 1 Power characteristics of the generator

<table>
<thead>
<tr>
<th>Power input</th>
<th>120 VAC, single phase, 50-60 Hz, 3.5 amp ground service</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power output</td>
<td>350 watts</td>
</tr>
<tr>
<td>Output frequency</td>
<td>40 kHz</td>
</tr>
</tbody>
</table>

For an efficient operation of the welding system, the ultrasound signal from the generator must match the vibrational frequency and phase characteristics of the stack that the signal is driving. The Dukane AUTO-TRAC feature automatically adjusts the ultrasound signal to match the vibrational characteristic of the stack. However, damaged, worn, improperly assembled equipment, or non-Dukane horns can result in vibrational characteristics outside the range of the AUTO-TRAC.

4. Profile velocity Roll, J-box and Yarn winder

The profiled velocity roll (figure B9 and B10) continuously pulls the plied yarn, during the operation of the machine.

Figure B9 Profiled velocity roll
Two conducting wheels, moved by an electric motor, pull the plied yarn from the twisting/welding system, and drive it into the vacuum-exhaust pneumatic valve, which pulls out the yarn from the winder.

![Diagram of profiled velocity roll](image1)

Figure B10 Scheme of Profiled velocity roll

The J-Box (figure B11) serves to store the ATP yarn such as to provide a continuous supply of yarn to the yarn winder and prevent the yarn entanglement.
A Leesona Yarn winder (Figure B12) is used to wind the ply yarn onto cardboard packages. It operates on a constant tension principle and has a yarn sensor that stops the winder in case the yarn cuts.
5. Control Panel and operator Interface
The control panel (figure B13 and B14) contains the programmed logic of the machine, and is equipped with a USB plug. It is also supplied with an emergency stop button to cut off the electrical connection to the all the machine units, including the IRO weft accumulator and the yarn winder. The operator interface (figure B15) controls the profiles of the various functions. This software facilitates changing the various parameters for thread transport and twist, all based upon a common timeline cycle. The Operator Interface is graphical with time represented horizontally, and the various control parameters represented vertically. For the cycle of the servo motor, for instance, the operator will enter in points along the horizontal time line that will become velocity commands relative to time to the servo motor. Below that, the operator can indicate ON and OFF times for the various I/O, synchronous with the servo motor timeline and the timelines of all other I/O.
Once the timelines have been entered for each parameter, they will be able to be saved in a file for later retrieval. Previous files will be able to be edited and saved as new files. The software provides the operator with the means to start and stop the machine. The software is written in Microsoft Visual BASIC.Net, and in commands for the Delta Tau PMAC controller.

Figure B13 Control Panel.

Figure B14 START and STOP buttons on the control panel.
Figure B15 Operator Interface
6. Pneumatic System

The pneumatic system (figure B16) requires 80-100 psi of clean, dry, unlubricated air.

Figure B16 Scheme of the pneumatic system
7. **Electrical Interconnections**

There can be identified two main electrical systems:

1. Power Supply – Generator – Stack
2. Power Supply – Control Panel – [Motor (Profiled roll)/electrovalve (bonder’s actuator)/electrovalve (air torque jet)]

The electrical interconnections are represented in the scheme of figure B17.

![Figure B17 Scheme of the electrical interconnections within the machine.](image-url)
8. Operational Procedure

The following is a recommended procedure for starting the equipment at the beginning of a day of operation. Following this procedure will result in a safer operation for the operator and the equipment.

1. **Check control cables** - Are all cable plugs are properly connected to their respective receptacles. Specifically check the ultrasound cable.

2. **Check the ground strap** – Verify that there is a good ground connection to the generator and the control panel.

3. **Check the stack** – Is the stack properly assembled and installed with the cover bolted and closed

4. **Check horn** – Visually check horn for cracks, misalignment, etc.

5. **Load the creel with the yarn packages**

6. **Insert the yarns into the IRO, yarn tensioner, torque jets, and through the winder**

7. **Turn generator ON/OFF switch to ON** – The lamp in the switch should light.

8. **Turn air power on.**

9. **If you have disassembled the stack or changed any stack component since you last performed the Operational Test of Stack** (procedure V.E.2. in the Operation Manual of the Ultrasonic Welder), perform this test again.

10. **Set the generator’s OPERATE/STOP/TEST selector on OPERATE.**
11. Adjust the POWER control of the generator to the proper value for the current application (carpet yarn: 500).
   If this value is unknown, start with a relatively low value for the POWER, run the machine, and check if the welded joints meet your quality standards. If the welding is of a poor quality, raise this value, run the machine, and check again. Repeat this until you reach the optimum value.

12. Begin Operation – Press the START button on the operator interface after selecting the required profiles for the different machine functions.

13. Monitor the generator meter and the OVERLOAD light during operation.
   If an overload condition occurs, immediately stop the operation, and reset the stack (procedure V.E.2. in the Operation Manual of the Ultrasonic Welder).

14. End the Operation – Press the STOP button on the control panel.

15. Turn generator ON/OFF switch to OFF.

16. Turn air power off.

17. Inspect the machine for any visible damage or irregularities.

18. Wipe the mating surface with a clean cloth – ATTENTION: the horn is hot after operation. Allow it to cool down before touching it.
9. Safety Recommendations

For Operator

- Certain plastic materials, when processed, may emit hazardous fumes. Proper ventilation of the work station should be provided when such materials are processed.
- Do not put head, hands, or body near the horn during operation.
- Do not operate the equipment unless it is properly grounded.
- The operator’s head should be kept at least 6 inches away from the ultrasonic welder during operation, to reduce ear annoyance and discomfort.
- The horn gets hot during operation. Allow the horn to cool down before touching it.
- Safety Glasses should be put on before turning on the machine.
- Ear protection devices should be put on in case the noise increases with higher speeds.

No loose jewelry, rings, watches or lockers should be worn during operation.

For Equipment

- Never activate the ultrasound generator, unless the generator is connected with the transducer.
- Do not continue the operation if the generator OVERLOAD light glows or if the meter needle rises into the red zone.
- The main air pressure valve should be opened gradually before turning on the machine and should be closed after turning it off.
APPENDIX C: VISUAL BASIC PROGRAM FOR COMPUTER CONTROL OF THE DREXEL ALTERNATE TWIST PLY MACHINE

Imports System.Runtime.InteropServices
Imports System.Text
Imports System.Threading
Imports System.ComponentModel
Imports System.IO

#Region "RS232"
Public Class Rs232 : Implements IDisposable
'===============================================
' Module    : Rs232
' Description : Class for handling RS232 communication with VB.Net
' Created    : 10/08/2001 - 8:45:25
' Author : Corrado Cavalli (corrado@mvps.org)
' WebSite : www.codeworks.it/net/index.htm
' Notes :
'===============================================

* Revisions *
02/12/2000 First internal alpha version built on framework beta1
1st Public release Beta2 (10/08/2001)
Rev.1 (28.02.2002)
1. Added ResetDev, SetBreak and ClearBreak to the EscapeCommFunction constants
2. Added the overloaded Open routine.
3. Added the modem status routines, properties and enum.
4. If a read times out, it now returns a EndOfStreamException (instead of a simple Exception).
5. Compiled with VS.Net final

Rev.2 (01.03.2002)
Added Async support

Rev.3 (07.04.2002)
Minor bugs fixed

Rev.3 (05/05/2002)
Fixed BuildCommDCB problem
Rev.4 (24/05/2002)
Fixed problem with ASCII Encoding truncating 8th bit

Rev.5 (27/05/2002)
Added IDisposable / Finalize implementation

Rev.6 (14/03/2003)
Fixed problem on DCB fields Initialization

Rev.7 (26/03/2003)
Added XON/XOFF support

Rev.8 (12/07/2003)
Added support to COM port number greater than 4

Rev.9 (15/07/2003)
Added CommEvent to detect incoming chars/events
Updated both Tx/Rx method from Non-Ovelapped to Overlapped mode
Removed unused Async methods and other stuff.

Rev.10 (21/07/2003)
Fixed incorrect character handling when using EnableEvents()

Rev.11 (12/08/2003)
Fixed some bugs signaled by users

Rev.12 (01/09/2003)
Removed AutoReset of internal buffers and added PurgeBuffer() method

Rev.13 (02/09/2003)
Removed GetLastErrorUse in favour of Win32Exception()

Rev.14 (14/09/2003)
Added IsPortAvailable() function
Revised some API declaration
Fixed problem with Win98/Me OS

Rev.15 (24/09/2003)
Fixed bug introduced on Rev.14

Rev.16 (12/10/2003)
Added SetBreak/ClearBreak() methods

Rev.17 (02/11/2003)
Fixed field on COMMCONFIG

Rev.18 (03/03/2004)
Fixed bug: Testing mhRS for <>0 is not correct

Rev.19 (08/04/2004)
Fixed bug: Fixed bug on DTR property

Rev.20 (12/07/2004)
CommEvent is no more raised on a secondary thread
pEventsWatcher now uses a background thread

Rev.21 (24/10/2004)
EscapeCommFunction declaration fixed
Pariti enum fixed to Parity

Rev. 22 (05/03/2005)
Fixed memory leak problem causing program closing
without any message on some systems.
Thanks to Ralf Gedrat for testing this scenario

Rev.23 (05/04/2005)
Fixed bug DisableEvents not working bug

Rev.24 (20/04/2005)
Fixed memory leak on Read method
Added InBufferCount property
IsPortAvailable method is now shared
Thanks to Jean-Pierre ZANIER for the feedback

=================================================================
// Class Members
Private mhRS As IntPtr = New IntPtr(0)  '// Handle to
Com Port
Private miPort As Integer = 1  '// Default is COM1
Private miTimeout As Int32 = 70  '// Timeout in ms
Private miBaudRate As Int32 = 9600
Private meParity As DataParity = 0
Private meStopBit As DataStopBit = 0
Private miDataBit As Int32 = 8
Private miBufferSize As Int32 = 512 ('// Buffers size default to 512 bytes
Private mabtRxBuf As Byte()  '// Receive buffer
Private meMode As Mode  '// Class working mode
Private moThreadTx As Thread
Private moThreadRx As Thread
Private moEvents As Thread
Private miTmpBytes2Read As Int32
Private meMask As EventMasks
Private mbDisposed As Boolean
Private mbUseXonXoff As Boolean
Private mbEnableEvents As Boolean
Private miBufThreshold As Int32 = 1
Private muOvlE As OVERLAPPED
Private muOvlW As OVERLAPPED
Private muOvlR As OVERLAPPED
Private mHE As GCHandle
Private mHR As GCHandle
Private mHW As GCHandle
'================================================================
#Region "Enums"

'// Parity Data
Public Enum DataParity
    Parity_None = 0
    Parity_Odd
    Parity_Even
    Parity_Mark
End Enum

'// StopBit Data
Public Enum DataStopBit
    StopBit_1 = 1
    StopBit_2
End Enum

<Flags()> Public Enum PurgeBuffers
    RXAbort = &H2
    RXClear = &H8
    TxAbort = &H1
    TxClear = &H4
End Enum

Private Enum Lines
    SetRts = 3
    ClearRts = 4
    SetDtr = 5
    ClearDtr = 6
    ResetDev = 7      ' // Reset device if possible
    SetBreak = 8      ' // Set the device break line.
    ClearBreak = 9    ' // Clear the device break line.
End Enum

'// Modem Status
<Flags()> Public Enum ModemStatusBits
    ClearToSendOn = &H10
    DataSetReadyOn = &H20
    RingIndicatorOn = &H40
    CarrierDetect = &H80
End Enum

'// Working mode
Public Enum Mode
    NonOverlapped
    Overlapped
End Enum

'// Comm Masks
<Flags()> Public Enum EventMasks
    RxChar = &H1
    RXFlag = &H2
    TxBufferEmpty = &H4
    ClearToSend = &H8
    DataSetReady = &H10
    CarrierDetect = &H20
    Break = &H40
StatusError = &H80
Ring = &H100
End Enum

#End Region
#Region "Structures"
<StructLayout(LayoutKind.Sequential, Pack:=1)> Private
Structure DCB
Public DCBlength As Int32
Public BaudRate As Int32
Public Bits1 As Int32
Public wReserved As Int16
Public XonLim As Int16
Public XoffLim As Int16
Public ByteSize As Int16
Public Parity As Byte
Public StopBits As Byte
Public XonChar As Char
Public XoffChar As Char
Public ErrorChar As Char
Public EofChar As Char
Public EvtChar As Char
Public wReserved2 As Int16
End Structure
<StructLayout(LayoutKind.Sequential, Pack:=1)> Private
Structure COMMTIMEOUTS
Public ReadIntervalTimeout As Int32
Public ReadTotalTimeoutMultiplier As Int32
Public ReadTotalTimeoutConstant As Int32
Public WriteTotalTimeoutMultiplier As Int32
Public WriteTotalTimeoutConstant As Int32
End Structure
<StructLayout(LayoutKind.Sequential, Pack:=8)> Private
Structure COMMCONFIG
Public dwSize As Int32
Public wVersion As Int16
Public wReserved As Int16
Public dcbx As DCB
Public dwProviderSubType As Int32
Public dwProviderOffset As Int32
Public dwProviderSize As Int32
Public wcProviderData As Int16
End Structure
<StructLayout(LayoutKind.Sequential, Pack:=1)> Public
Structure OVERLAPPED
Public Internal As Int32
Public InternalHigh As Int32
Public Offset As Int32
Public OffsetHigh As Int32
Public hEvent As IntPtr
End Structure
<StructLayout(LayoutKind.Sequential, Pack:=1)> Private
Structure COMSTAT
Dim fBitFields As Int32
Dim cbInQue As Int32
Dim cbOutQue As Int32
End Structure

#Region "Constants"
Private Const PURGE_RXABORT As Integer = &H2
Private Const PURGE_RXCLEAR As Integer = &H8
Private Const PURGE_TXABORT As Integer = &H1
Private Const PURGE_TXCLEAR As Integer = &H4
Private Const GENERIC_READ As Integer = &H80000000
Private Const GENERIC_WRITE As Integer = &H40000000
Private Const OPEN_EXISTING As Integer = 3
Private Const INVALID_HANDLE_VALUE As Integer = -1
Private Const IO_BUFFER_SIZE As Integer = 1024
Private Const FILE_FLAG_OVERLAPPED As Int32 = &H40000000
Private Const ERROR_IO_PENDING As Int32 = 997
Private Const WAIT_OBJECT_0 As Int32 = 0
Private Const ERROR_IO_INCOMPLETE As Int32 = 996
Private Const WAIT_TIMEOUT As Int32 = &H102&
Private Const INFINITE As Int32 = &HFFFFFFFF
#End Region

#Region "Win32API"
'// Win32 API
<DllImport("kernel32.dll", SetlastError:=True)> Private Shared Function SetCommState(ByVal hCommDev As IntPtr, ByRef lpDCB As DCB) As Int32
End Function

<DllImport("kernel32.dll", SetlastError:=True)> Private Shared Function GetCommState(ByVal hCommDev As IntPtr, ByRef lpDCB As DCB) As Int32
End Function

<DllImport("kernel32.dll", SetlastError:=True, CharSet:=CharSet.Auto)> Private Shared Function BuildCommDCB(ByVal lpDef As String, ByRef lpDCB As DCB) As Int32
End Function

<DllImport("kernel32.dll", SetlastError:=True)> Private Shared Function SetupComm(ByVal hFile As IntPtr, ByVal dwInQueue As Int32, ByVal dwOutQueue As Int32) As Int32
End Function

<DllImport("kernel32.dll", SetlastError:=True)> Private Shared Function SetCommTimeouts(ByVal hFile As IntPtr, ByRef lpCommTimeouts As COMMTIMEOUTS) As Int32
End Function

<DllImport("kernel32.dll", SetlastError:=True)> Private Shared Function GetCommTimeouts(ByVal hFile As IntPtr, ByRef lpCommTimeouts As COMMTIMEOUTS) As Int32
End Function

<DllImport("kernel32.dll", SetlastError:=True)> Private Shared Function ClearCommError(ByVal hFile As IntPtr, ByRef lpErrors As Int32, ByRef lpComStat As COMSTAT) As Int32
End Function
"
<DllImport("kernel32.dll", SetLastError:=True)> Private Shared Function PurgeComm(ByVal hFile As IntPtr, ByVal dwFlags As Int32) As Int32
End Function

<DllImport("kernel32.dll", SetLastError:=True)> Private Shared Function EscapeCommFunction(ByVal hFile As IntPtr, ByVal ifunc As Int32) As Boolean
End Function

<DllImport("kernel32.dll", SetLastError:=True)> Private Shared Function WaitCommEvent(ByVal hFile As IntPtr, ByRef Mask As Int32, ByRef lpOverlap As OVERLAPPED) As Int32
End Function

<DllImport("kernel32.dll", SetLastError:=True)> Private Shared Function WriteFile(ByVal hFile As IntPtr, ByVal Buffer As Byte(), ByVal nNumberOfBytesToWrite As Integer, ByRef lpNumberOfBytesWritten As Integer, ByVal lpOverlapped As OVERLAPPED) As Integer
End Function

<DllImport("kernel32.dll", SetLastError:=True)> Private Shared Function ReadFile(ByVal hFile As IntPtr, ByVal Buffer As Byte(), ByVal nNumberOfBytesToRead As Integer, ByRef lpNumberOfBytesRead As Integer, ByVal lpOverlapped As OVERLAPPED) As Integer
End Function

<DllImport("kernel32.dll", SetLastError:=True, CharSet:=CharSet.Auto)> Private Shared Function CreateFile(ByVal lpFileName As String, ByVal dwDesiredAccess As Integer, ByVal dwShareMode As Integer, ByVal lpSecurityAttributes As IntPtr, ByVal dwCreationDisposition As Integer, ByVal dwFlagsAndAttributes As Integer, ByVal hTemplateFile As IntPtr) As IntPtr
End Function

<DllImport("kernel32.dll", SetLastError:=True)> Private Shared Function CloseHandle(ByVal hObject As IntPtr) As Boolean
End Function

<DllImport("kernel32.dll", SetLastError:=True)> Public Shared Function GetCommModemStatus(ByVal hFile As IntPtr, ByRef lpModemStatus As Int32) As Boolean
End Function

<DllImport("kernel32.dll", SetLastError:=True)> Private Shared Function SetEvent(ByVal hEvent As IntPtr) As Boolean
End Function

<DllImport("kernel32.dll", SetLastError:=True, CharSet:=CharSet.Auto)> Private Shared Function CreateEvent(ByVal lpEventAttributes As IntPtr, ByVal bManualReset As Integer, ByVal bInitialState As Integer, ByVal lpName As String) As IntPtr
End Function

<DllImport("kernel32.dll", SetLastError:=True)> Private Shared Function WaitForSingleObject(ByVal hHandle As IntPtr, ByVal dwMilliseconds As Integer) As Int32
End Function

<DllImport("kernel32.dll", SetLastError:=True)> Private Shared Function GetOverlappedResult(ByVal hFile As IntPtr, ByRef lpOverlapped As OVERLAPPED, ByRef lpNumberOfBytesTransferred As Integer, ByVal bWait As Integer) As Integer

End Function

<DllImport("kernel32.dll", SetLastError:=True)> Private Shared Function SetCommMask(ByVal hFile As IntPtr, ByVal lpEvtMask As Int32) As Int32
End Function

<DllImport("kernel32.dll", CharSet:=CharSet.Auto)> Private Shared Function GetDefaultCommConfig(ByVal lpszName As String, ByRef lpCC As COMMCONFIG, ByRef lpdwSize As Integer) As Boolean
End Function

<DllImport("kernel32.dll", SetLastError:=True)> Private Shared Function SetCommBreak(ByVal hFile As IntPtr) As Boolean
End Function

<DllImport("kernel32.dll", SetLastError:=True)> Private Shared Function ClearCommBreak(ByVal hFile As IntPtr) As Boolean
End Function

#Region "Events"
Public Event CommEvent As CommEventHandler
#End Region

#Region "Delegates"
Public Delegate Sub CommEventHandler(ByVal source As Rs232, ByVal Mask As EventMasks)
#End Region

Public Property Port() As Integer
'===================================================
'| Description : Comunication Port
'| Created :
| 21/09/2001 - 11:25:49
',
' *Parameters Info*
',
' Notes :
'===================================================
Get
Return miPort
End Get
Set(ByVal Value As Integer)
    miPort = Value
End Set
End Property

Public Sub PurgeBuffer(ByVal Mode As PurgeBuffers)
'===================================================
| ©2003 ALSTOM FIR S.p.A All rights reserved
',
| Description : Purge Communication Buffer
| Created : 01/09/03
10:37:39
Public Overridable Property Timeout() As Integer
'===================================================
'  Description:  Comunication timeout in seconds
'  Created   :
'  21/09/2001 - 11:26:50
'  
'  *Parameters Info*
'  Notes    :
'===================================================
Get
Return miTimeout
End Get
Set(ByVal Value As Integer)
miTimeout = CInt(IIf(Value = 0, 500, Value))
'// If Port is open updates it on the fly
pSetTimeout()
End Set
End Property
Public Property Parity() As DataParity
'===================================================
'  Description :  Comunication parity
'  Created   :
'  21/09/2001 - 11:27:15
'  
'  *Parameters Info*
'  Notes    :
'===================================================
Get
Return meParity
End Get
Set(ByVal Value As DataParity)
meParity = Value
End Set
End Property
Public Property StopBit() As DataStopBit
Public Property StopBit() As Integer
'==============================================================================
'                Description:      Comunication
'                Created:          21/09/2001 - 11:27:37
'
'                *Parameters Info*
'
'                Notes           :
'==============================================================================
Get
    Return meStopBit
End Get
Set(ByVal Value As DataStopBit)
    meStopBit = Value
End Set
End Property

Public Property BaudRate() As Integer
'==============================================================================
'                Description:      Comunication
'                Created:          21/09/2001 - 11:28:00
'
'                *Parameters Info*
'
'                Notes           :
'==============================================================================
Get
    Return miBaudRate
End Get
Set(ByVal Value As Integer)
    miBaudRate = Value
End Set
End Property

Public Property DataBit() As Integer
'==============================================================================
'                Description:      Comunication
'                Created:          21/09/2001 - 11:28:20
'
'                *Parameters Info*
'
'                Notes           :
'==============================================================================
Get
    Return miDataBit
End Get
Set(ByVal Value As Integer)
    miDataBit = Value
End Set
End Property

Public Property BufferSize() As Integer
    '===================================================
    ' Description : Receive Buffer size
    ' Created : 21/09/2001 - 11:33:05
    ' *Parameters Info*
    ' Notes :
    '===================================================
    Get
        Return miBufferSize
    End Get
    Set(ByVal Value As Integer)
        miBufferSize = Value
    End Set
End Property

Public Overloads Sub Open()
    '===================================================
    ' Description : Initializes and Opens comunication port
    ' Created : 21/09/2001 - 11:33:40
    ' *Parameters Info*
    ' Notes :
    '===================================================
    '// Get Dcb block, Update with current data
    Dim uDcb As DCB, iRc As Int32
    '// Set working mode
    meMode = Mode.Overlapped
    Dim iMode As Int32 = Convert.ToInt32(IIf(meMode = Mode.Overlapped, FILE_FLAG_OVERLAPPED, 0))
    '// Initializes Com Port
    If miPort > 0 Then
        Try
            '// Creates a COM Port stream handle
            mhRS = CreateFile("\\.\COM") & miPort.ToString, GENERIC_READ Or GENERIC_WRITE, 0, 0, OPEN_EXISTING, iMode, 0)
            If (mhRS.ToInt32 > 0) Then
                '// Clear all comunication errors
                Dim lpErrCode As Int32
            End If
        Catch ex As Exception
            // Error handling
        End Try
    End If
End Sub
iRc = ClearCommError(mhRS, lpErrCode, New COMSTAT)
   ' // Clears I/O buffers
iRc = PurgeComm(mhRS, PurgeBuffers.RXClear Or PurgeBuffers.TxClear)
   ' // Gets COM Settings
iRc = GetCommState(mhRS, uDcb)
   ' // Updates COM Settings
sParity = sParity.Substring(meParity, 1)
   ' // Set DCB State
Dim sDCBState As String = String.Format("baud={0} parity={1} data={2} stop={3} ", miBaudRate, sParity, miDataBit, CInt(meStopBit))
iRc = BuildCommDCB(sDCBState, uDcb)
uDcb.Parity = CByte(meParity)
   ' // Set Xon/Xoff State
If mbUseXonXoff Then
   uDcb.Bits1 = 768
Else
   uDcb.Bits1 = 0
End If
iRc = SetCommState(mhRS, uDcb)
If iRc = 0 Then
   Dim sErrTxt As String = New Win32Exception().Message
   Throw New CIOChannelException("Unable to set COM state " & sErrTxt)
End If
   ' // Setup Buffers (Rx,Tx)
iRc = SetupComm(mhRS, miBufferSize, miBufferSize)
   ' // Set Timeouts
pSetTimeout()
   ' // Enables events if required
If mbEnableEvents Then
   Me.EnableEvents()
Else
   ' // Raise Initialization problems
   Dim sErrTxt As String = New Win32Exception().Message
   Throw New CIOChannelException("Unable to open COM" + miPort.ToString + ControlChars.CrLf + sErrTxt)
End If
Catch Ex As Exception
   ' // Generic error
   Throw New CIOChannelException(Ex.Message, Ex)
End Try
Else
   ' // Port not defined, cannot open
   Throw New ApplicationException("COM Port not
defined, use Port property to set it before invoking InitPort")
    End If
  End Sub
  Public Overloads Sub Open(ByVal Port As Integer, ByVal BaudRate As Integer, ByVal DataBit As Integer, ByVal Parity As DataParity, ByVal StopBit As DataStopBit, ByVal BufferSize As Integer)
    '===================================================
    ' Description: Opens communication port (Overloaded method)
    ' Created : 21/09/2001 - 11:33:40
    ' *Parameters Info*
    ' Notes :
    '===================================================
    Me.Port = Port
    Me.BaudRate = BaudRate
    Me.DataBit = DataBit
    Me.Parity = Parity
    Me.StopBit = StopBit
    Me.BufferSize = BufferSize
    Open()
  End Sub
  Public Sub Close()
    '===================================================
    ' Description: Close communication channel
    ' Created : 21/09/2001 - 11:38:00
    ' *Parameters Info*
    ' Notes :
    '===================================================
    If mhRS.ToInt32 > 0 Then
      If mbEnableEvents = True Then
        Me.DisableEvents()
      End If
      Dim ret As Boolean = CloseHandle(mhRS)
      If Not ret Then Throw New Win32Exception
      mhRS = New IntPtr(0)
    End If
  End Sub
  ReadOnly Property IsOpen() As Boolean
    '===================================================
    ' Description: Returns Port Status
    ' Returns: Boolean
    ' Status:
    '===================================================

Public Overloads Sub Write(ByVal Buffer As Byte())

'===================================================
' Description: Transmit a stream
' Created: 21/09/2001 - 11:39:51
' Notes:
'===================================================
Dim iRc, iBytesWritten As Integer, hOvl As GCHandle
'muOvlW = New Overlapped
If mhRS.ToInt32 <= 0 Then
   Throw New ApplicationException("Please initialize and open port before using this method")
Else
    '/ Creates Event
    Try
       hOvl = GCHandle.Alloc(muOvlW, GCHandleType.Pinned)
       muOvlW.hEvent = CreateEvent(Nothing, 1, 0, Nothing)
       If muOvlW.hEvent.ToInt32 = 0 Then Throw New ApplicationException("Error creating event for overlapped writing")
    '/ Clears IO buffers and sends data
    iRc = WriteFile(mhRS, Buffer, Buffer.Length, 0, muOvlW)
    If iRc = 0 Then
       If Marshal.GetLastWin32Error <> ERROR_IO_PENDING Then
          Throw New ApplicationException("Write command error")
       Else
          '/ Check Tx results
          If GetOverlappedResult(mhRS, muOvlW, iBytesWritten, 1) = 0 Then
             Throw New ApplicationException("Write command error")
       End If
    End If
End Try
'muOvlW.Free
End Sub
ApplicationException("Write pending error")
Else
  '// All bytes sent?
  If iBytesWritten <> Buffer.Length Then Throw New ApplicationException("Write Error - Bytes Written " & iBytesWritten.ToString & " of " & Buffer.Length.ToString)
End If
End If
Finally
  '//Closes handle
  CloseHandle(muOvlW.hEvent)
  If (hOvl.IsAllocated = True) Then hOvl.Free()
End Try
End If
End Sub
Public Overloads Sub Write(ByVal Buffer As String)
  '===================================================
  ' Description : Writes a string to RS232
  ' Created   : 04/02/2002 - 8:46:42
  '  *Parameters Info*
  '  Notes    : 24/05/2002 Fixed problem with ASCII Encoding
  '===================================================
  Dim oEncoder As New System.Text.ASCIIEncoding
  Dim oEnc As Encoding = oEncoder.GetEncoding(1252)
  '-----------------------------------------------------
  Dim aByte() As Byte = oEnc.GetBytes(Buffer)
  Me.Write(aByte)
End Sub
Public Function Read(ByVal Bytes2Read As Integer) As Integer
  '===================================================
  ' Description: Read Bytes from Port
  ' Created   : 21/09/2001 - 11:41:17
  '  *Parameters Info*
  '  Bytes2Read : Bytes to read from port
  '  Returns     : Number of readed chars
  '  Notes
  '===================================================
  Dim iReadChars, iRc As Integer, bReading As Boolean,
hOvl As GCHandle
'
-----------------------------
-------
'// If Bytes2Read not specified uses Buffersize
If Bytes2Read = 0 Then Bytes2Read = InBufferCount
'miBufferSize
muOvlR = New Overlapped
If mhRS.ToInt32 <= 0 Then
    Throw New ApplicationException("Please initialize and
open port before using this method")
Else
    '// Get bytes from port
    Try
        hOvl = GCHandle.Alloc(muOvlR, GCHandleType.Pinned)
        muOvlR.hEvent = CreateEvent(Nothing, 1, 0, Nothing)
            If muOvlR.hEvent.ToInt32 = 0 Then Throw New
ApplicationException("Error creating event for overlapped
reading")
        '// Clears IO buffers and reads data
        ReDim mabtRxBuf(Bytes2Read - 1)
        iRc = ReadFile(mhRS, mabtRxBuf, Bytes2Read,
iReadChars, muOvlR)
            If iRc = 0 Then
                If Marshal.GetLastWin32Error() <> ERROR_IO_PENDING Then
                    Throw New ApplicationException("Read
pending error")
                Else
                    '// Wait for characters
                    iRc = WaitForSingleObject(muOvlR.hEvent,
miTimeout)
                        Select Case iRc
                        Case WAIT_OBJECT_0
                            '// Some data received...
                            If GetOverlappedResult(mhRS,
muOvlR, iReadChars, 0) = 0 Then
                                Throw New ApplicationException("Read
pending error.")
                            Else
                                Return iReadChars
                        Case WAIT_TIMEOUT
                            Throw New IOTimeoutException("Read
Timeout.")
                        Case Else
                            Throw New ApplicationException("General read error.")
                        End Select
                    End If
                    Case mhRS
                        Throw New ApplicationException("Error opening
port")
                End If
            End If
Finally
'//Closes handle
CloseHandle(muOvlR.hEvent)
If (hOvl.IsAllocated) Then hOvl.Free()
End Try
End If
End Function

Overridable ReadOnly Property InputStream() As Byte()
    '=================================================================
    ' Description: Returns received data as Byte()
    ' Created   : 21/09/2001 - 11:45:06
    ' *Parameters Info*
    ' Notes
    '=================================================================
    Get
    Return mabtRxBuf
End Get
End Property

Overridable ReadOnly Property InputStreamString() As String
    '=================================================================
    ' Description: Return a string containing received data
    ' Created   : 04/02/2002 - 8:49:55
    ' *Parameters Info*
    ' Notes
    '=================================================================
    Get
    Dim oEncoder As New System.Text.ASCIIEncoding
    Dim oEnc As Encoding = oEncoder.GetEncoding(1252)
    '-----------------------------------------------
    If Not Me.InputStream Is Nothing Then Return oEnc.GetString(Me.InputStream)
    '-----------------------------------------------
End Property

Public Sub ClearInputBuffer()
    '=================================================================
    ' Description: Clears Input buffer
    ' Created   : 21/09/2001 - 11:45:34
    ' *Parameters Info*
    '=================================================================

Notes: Gets all character until end of buffer

If mhRS.ToInt32 > 0 Then
    PurgeComm(mhRS, PURGE_RXCLEAR)
End If
End Sub

Public WriteOnly Property Rts() As Boolean

Description: Set/Resets RTS

Line

Created: 21/09/2001 - 11:45:34

*Parameters Info*

Notes:

Set(ByVal Value As Boolean)
    If mhRS.ToInt32 > 0 Then
        If Value Then
            EscapeCommFunction(mhRS, Lines.SetRts)
        Else
            EscapeCommFunction(mhRS, Lines.ClearRts)
        End If
    End If
End Set

End Property

Public WriteOnly Property Dtr() As Boolean

Description: Set/Resets DTR

Line

Created: 21/09/2001 - 11:45:34

*Parameters Info*

Notes:

Set(ByVal Value As Boolean)
    If mhRS.ToInt32 > 0 Then
        If Value Then
            EscapeCommFunction(mhRS, Lines.SetDtr)
        Else
            EscapeCommFunction(mhRS, Lines.ClearDtr)
End If
End If
End Set
End Property
Public ReadOnly Property ModemStatus() As ModemStatusBits
    '===================================================
    ' Description : Gets Modem status
    ' Created : 28/02/2002 - 8:58:04
    '
    ' *Parameters Info*
    ' Notes :
    '===================================================
    Get
    If mhRS.ToInt32 <= 0 Then
        Throw New ApplicationException("Please initialize and open port before using this method")
    Else
        '// Retrieve modem status
        Dim lpModemStatus As Int32
        If Not GetCommModemStatus(mhRS, lpModemStatus) Then
            Throw New ApplicationException("Unable to get modem status")
        Else
            Return CType(lpModemStatus, ModemStatusBits)
        End If
    End If
End Property
Public Function CheckLineStatus(ByVal Line As ModemStatusBits) As Boolean
    '===================================================
    ' Description : Check status of a Modem Line
    ' Created : 28/02/2002 - 10:25:17
    '
    ' *Parameters Info*
    ' Notes :
    '===================================================
    Return Convert.ToBoolean(ModemStatus And Line)
End Function
Public Property UseXonXoff() As Boolean
    '===================================================
    ' Description : Set XON/XOFF mode
    ' Created : 26/05/2003 - 21:16:18
    '
    '
' *Parameters Info*
'
' Notes : ----------------------------------------
Get
Return mbUseXonXoff
End Get
Set(ByVal Value As Boolean)
  mbUseXonXoff = Value
End Set
End Property

Public Sub EnableEvents()
  '===================================================
  '
  ' Description : Enables monitoring of incoming events
  ' Created : 15/07/2003 - 12:00:56
  '
  ' Notes :
  '===================================================
  If mhRS.ToInt32 <= 0 Then
    Throw New ApplicationException("Please initialize and open port before using this method")
  Else
    If moEvents Is Nothing Then
      mbEnableEvents = True
      moEvents = New Thread(AddressOf pEventsWatcher)
      moEvents.IsBackground = True
      moEvents.Start()
    End If
  End If
End Sub

Public Sub DisableEvents()
  '===================================================
  '
  ' Description : Disables monitoring of incoming events
  ' Created : 15/07/2003 - 12:00:56
  '
  ' Notes :
  '===================================================
  If mbEnableEvents = True Then
    SyncLock Me
    mbEnableEvents = False
    ' // This should kill the thread
    End SyncLock
    ' // Let WaitCommEvent exit...
If muOvlE.hEvent.ToInt32 <> 0 Then
    SetEvent(muOvlE.hEvent)
    moEvents = Nothing
End If
End Sub

Public Property RxBufferThreshold() As Int32
    '=================================================================
    '©2003 www.codeworks.it All rights reserved
    ' Description : Numer of characters into input buffer
    ' Created   : 16/07/03 - 9:00:57
    ' Author   : Corrado Cavalli
    ' *Parameters Info*
    ' Notes    :
    '=================================================================
    Get
        Return miBufThreshold
    End Get
    Set(ByVal Value As Int32)
        miBufThreshold = Value
    End Set
End Property

Public Shared Function IsPortAvailable(ByVal portNumber As Int32) As Boolean
    '=================================================================
    '©2003 www.codeworks.it All rights reserved
    ' Description : Returns true if a specific port number is supported by the system
    ' Created   : 14/09/03 - 17:00:57
    ' Author   : Corrado Cavalli
    ' *Parameters Info*
    ' portNumber : port number to check
    ' Notes    :
    '=================================================================
    If portNumber <= 0 Then
        Return False
    Else
        Dim cfg As COMMCONFIG
        Dim cfgsize As Int32 = Marshal.SizeOf(cfg)
        cfg.dwSize = cfgsize
        Dim ret As Boolean = GetDefaultCommConfig("COM" + portNumber.ToString, cfg, cfgsize)
        Return ret
    End If
End Function

Public Sub SetBreak()
Public Sub SetBreak()
' ==============================================================
' ©2003 www.codeworks.it All rights reserved
' Description : Set COM in break modem
' Created : 12/10/03 - 10:00:57
' Author : Corrado Cavalli
' *Parameters Info*
'
' Notes :
' ==============================================================
If mhRS.ToInt32 > 0 Then
    If SetCommBreak(mhRS) = False Then Throw New Win32Exception
End If
End Sub
Public Sub ClearBreak()
' ==============================================================
' ©2003 www.codeworks.it All rights reserved
' Description : Clear COM break mode
' Created : 12/10/03 - 10:02:57
' Author : Corrado Cavalli
' *Parameters Info*
'
' Notes :
' ==============================================================
If mhRS.ToInt32 > 0 Then
    If ClearCommBreak(mhRS) = False Then Throw New Win32Exception
End If
End Sub
Public ReadOnly Property InBufferCount() As Int32
' ==============================================================
' ©2003 www.codeworks.it All rights reserved
' Description : Returns the number of bytes inside Rx buffer
' Created : 20/04/05 - 10:02:57
' Author : Corrado Cavalli/Jean-Pierre ZANIER
'
' Get
Dim comStat As COMSTAT
Dim lpErrCode As Int32
Get
Dim comStat As COMSTAT
Dim lpErrCode As Int32
Dim iRc As Int32
comStat.cbInQue = 0
If mhRS.ToInt32 > 0 Then
    iRc = ClearCommError(mhRS, lpErrCode, comStat)
    Return comStat.cbInQue
End If
Return 0
End Get
End Property

#Region "Finalize"
Protected Overrides Sub Finalize()
    '===================================================
    ' Description : Closes COM port if object is garbage collected and still owns COM port resoures
    ' Created   : 27/05/2002 - 19:05:56
    ' *Parameters Info*
    ' Notes    :
    '===================================================
    Try
        If Not mbDisposed Then
            If mbEnableEvents Then Me.DisableEvents()
            Close()
        End If
    End Try
Finally
    MyBase.Finalize()
End Try
End Sub
#End Region

#Region "Private Routines"
Private Sub pSetTimeout()
    '===================================================
    ' Description: Set communication timeouts
    ' Created   : 21/09/2001 - 11:46:40
    ' *Parameters Info*
    ' Notes    :
    '===================================================
    Dim uCtm As COMMTIMEOUTS
    '// Set ComTimeout
    If mhRS.ToInt32 <= 0 Then
        Exit Sub
    End If
End Sub
Else
   '// Changes setup on the fly
   With uCtm
      .ReadIntervalTimeout = 0
      .ReadTotalTimeoutMultiplier = 0
      .ReadTotalTimeoutConstant = miTimeout
      .WriteTotalTimeoutMultiplier = 10
      .WriteTotalTimeoutConstant = 100
   End With
   SetCommTimeouts(mhRS, uCtm)
End If
End Sub

Private Sub pDispose() Implements IDisposable.Dispose
   '===================================================
   ' Description : Handles correct class disposing
   Write
   ' Created : 27/05/2002 - 19:03:06
   ' *Parameters Info*
   ' Notes :
   '===================================================
   If (Not mbDisposed AndAlso (mhRS.ToInt32 > 0)) Then
      '// Closes Com Port releasing resources
      Try
         Me.Close()
      Finally
         mbDisposed = True
         '// Suppress unnecessary Finalize overhead
         GC.SuppressFinalize(Me)
      End Try
   End If
End Sub

Private Sub pEventsWatcher()
   '===================================================
   ' describe : Watches for all events raising
   ' Created : 15/07/03 - 11:45:13
   ' Author : Corrado Cavalli
   ' *Parameters Info*
   ' Notes :
   '===================================================
   '// Events to watch
Dim lRetMask As EventMasks, iBytesRead, iTotBytes, iErrMask As Int32, iRc As Int32, aBuf As New ArrayList
Dim uComStat As COMSTAT

'-----------------------------------
'// Creates Event
muOvlE = New Overlapped
Dim hOvlE As GCHandle = GCHandle.Alloc(muOvlE, GCHandleType.Pinned)
muOvlE.hEvent = CreateEvent(Nothing, 1, 0, Nothing)
If muOvlE.hEvent.ToInt32 = 0 Then Throw New ApplicationException("Error creating event for overlapped reading")

'// Set mask
SetCommMask(mhRS, lMask)

'// Looks for RxChar
While mbEnableEvents = True
WaitCommEvent(mhRS, lMask, muOvlE)
Select Case WaitForSingleObject(muOvlE.hEvent, INFINITE)
Case WAIT_OBJECT_0
'// Event (or abort) detected
If mbEnableEvents = False Then Exit While
If (lMask And EventMasks.RxChar) > 0 Then
'// Read incoming data
ClearCommError(mhRS, iErrMask, uComStat)
If iErrMask = 0 Then
Dim ovl As New Overlapped
Dim hOvl As GCHandle = GCHandle.Alloc(ovl, GCHandleType.Pinned)
ReDim mabtRxBuf(uComStat.cbInQue - 1)
If ReadFile(mhRS, mabtRxBuf, uComStat.cbInQue, iBytesRead, hOvl) > 0 Then
If iBytesRead > 0 Then
'// Some bytes read, fills temporary buffer
If iTotBytes < miBufThreshold Then
aBuf.AddRange(mabtRxBuf)
iTotBytes += iBytesRead
End If
'// Threshold reached?, raises event
If iTotBytes >= miBufThreshold Then
'//Copies temp buffer into Rx buffer
ReDim mabtRxBuf(iTotBytes - 1)
aBuf.CopyTo(mabtRxBuf)
'// Raises event
Try

EventMasks.RxChar Or EventMasks.RXFlag Or _
EventMasks.StatusError
Me.OnCommEventReceived(Me, lMask)

Finally
    iTotBytes = 0
    aBuf.Clear()
End Try
End If
End If
End If
End If
End If
Else
    '// Simply raises OnCommEventHandler event
    Me.OnCommEventReceived(Me, lMask)
End If
Case Else
    Dim sErr As String = New Win32Exception().Message
    Throw New ApplicationException(sErr)
End Select
End While
'// Release Event Handle
CloseHandle(muOvlE.hEvent)
muOvlE.hEvent = IntPtr.Zero
If (hOvlE.IsAllocated) Then hOvlE.Free()
muOvlE = Nothing
End Sub

#End Region

#Region "Protected Routines"
Protected Sub OnCommEventReceived(ByVal source As Rs232, ByVal
    mask As EventMasks)
    '===================================================
    '©2003 www.codeworks.it All rights reserved
    ',
    ',
    ',
    ',
    ',
    ',
    ',
    ',
    ',
    ',
    ',
    ',
    ',
    ',
    ',
    ',
    ',
    ',
    ',
    ',
    ',
    ',
    ',
    ',
    '
    Dim del As CommEventHandler = Me.CommEventEvent
    If (Not del Is Nothing) Then
        Dim SafeInvoker As ISynchronizeInvoke
        Try
            SafeInvoker = DirectCast(del.Target,
                ISynchronizeInvoke)
        Catch
            Throw New ApplicationException(sErr)
        End Try
If (Not SafeInvoker Is Nothing) Then
    SafeInvoker.Invoke(del, New Object() {source, mask})
Else
    del.Invoke(source, mask)
End If
End If

#End Region

End Class

#End Region

#Region "Exceptions"

Public Class CIOChannelException : Inherits ApplicationException
    '===================================================
    ' Module    : CChannelException
    ' Description: Customized Channel Exception
    ' Created   : 17/10/2001 - 10:32:37
    ' Notes     : This exception is raised when NACK error found
    '===================================================
    Sub New(ByVal Message As String)
        MyBase.New(Message)
    End Sub
    Sub New(ByVal Message As String, ByVal InnerException As Exception)
        MyBase.New(Message, InnerException)
    End Sub
End Class

Public Class IOTimeoutException : Inherits CIOChannelException
    '===================================================
    ' Description : Timeout customized exception
    ' Created     : 28/02/2002 - 10:43:43
    ' Notes
    '===================================================
    Sub New(ByVal Message As String)
        MyBase.New(Message)
    End Sub
    Sub New(ByVal Message As String, ByVal InnerException As Exception)
        MyBase.New(Message, InnerException)
    End Sub
End Class

#End Region
APPENDIX D: MEASUREMENT OF THE YARN TORSIONAL RIGIDITY AND THE HELPER JET TORQUE

Evaluation of the Torque applied on the yarn by the Helper Jet

\[ \tau = K \theta \]

\( \tau \) = Torque applied in N.m
\( K \) = Yarn Torsional Rigidity in N.m/rad
\( \theta \) = Angle in radians

Evaluation of the Helper Jet Effect (\( \theta \)) on the ATP machine
- Helper Jet turned Off
- Produce ATP yarn
- Yarn is clamped at 20cm away from helper torque jet
- Digital Photo of the ATP yarn
- Turns per inch of the ATP yarn is measured digitally
- Helper Jet turned On
- Digital Photo of the same ATP yarn
- Turns per inch of the ATP yarn is measured digitally
- The difference in the measured turns per inch is determined

\( \theta \sim 0.5 \) TPI

Ply Yarn Torsional Rigidity
- Torsional Pendulum Technique

\[ K = \frac{1}{8} Md^2 \left( \frac{n}{2\pi} \right)^2 \text{ N.m / rad} \]

\( M \) = Weight (g)
\( d \) = Rod Diameter (cm)
\( n \) = No. of Revolutions / sec

\( K = 5.5 \times 10^{-8} \) N.m / rad

Ply Torque Applied by the Helper Jet \( \sim 0.02 \) \( \mu \)N.m
APPENDIX E: CALIBRATION OF THE ELASTIC YARN TORQUE TRANSUDER

The elastic yarns used as the torque transducer on the static tester were calibrated using a force arm balance technique, as shown in figure E1, where a certain number of turns of twist were inserted the yarn loop and the corresponding weight needed to hold a very light weight arm, placed at the midpoint of the loop length at equilibrium is determined. The results are shown for a two strand and a four strand elastic yarn loop in figure E2.
Figure E2 Calibration of the elastic yarn torque transducer
APPENDIX F: MATHEMATICAL SIMULATION OF YARN TWIST PROFILE

(Mat-Lab Programming Software)

function yprime=AltTwistEq(t,y)
%dimensionless equations
%equations for alternate twisting with arbitrary functions for V and w

global Parameters;
L1=Parameters(1);
L2=Parameters(2);

uu=altlinesegments(t)/L1-linesegments(t)*y(1)/L1;
vv=linesegments(t)*(-y(2)/L2+y(1)/L2)-altlinesegments(t)/L2;
ww=linesegments(t);
yprime=[uu vv ww]';

function yy=linesegments(xx)
%creates a continuous function from discrete points (straight line segments)

global Pv; %points of 1st cycle describing straight line segments
P=Pv;
Mp=max(P(:,1)); %max x = half cycle time
x=mod(xx,Mp)+1e-10;
i=min(find(P(:,1)>=x))-1; %gets the index of xx at the start of any range
m=(P(i+1,2)-P(i,2))/(P(i+1,1)-P(i,1)); %slope of i-th segment
b=-m*P(i,1)+P(i,2); %y intercept of i-th segment
yy=(m*x+b);
function yy=altlinesegments(xx)
% creates a continuous function from discrete points (straight line segments)

global Pw; % points of 1st cycle describing straight line segments
P=Pw;

Mp=max(P(:,1)); % max x = half cycle time
x=mod(xx,Mp)+1e-10;

i=min(find(P(:,1)>=x))-1; % gets the index of xx at the start of any range
m=(P(i+1,2)-P(i,2))/(P(i+1,1)-P(i,1)); % slope of i-th segment
b=-m*P(i,1)+P(i,2); % y intercept of i-th segment

e=floor(xx/Mp);

ee=(-1)^e;

yy=ee*(m*x+b);

% floor(A) rounds the elements of A to the nearest integers less than or equal to A.

%% AltTwistEq Function for dimensionless equations for alternate twisting with arbitrary functions for Velocity and rotation
% linesegments Function FOR REPEATING CYCLE
% altlinesegments Function FOR +/- REPEATING CYCLE

% INPUTS
clear
global Pv; % velocity profile
global Pw; % rotation profile
global Parameters;

% INPUTS
L1=6; % L1/Lr
L2=.002; % L2/Lr
Parameters=[L1 L2];

% Vprofile
% INPUT VEL DISTR - dimensionless
Pv=[0 0;0 2;.5 1.73;.5 0;.54 0;.54 2;1.04 1.73;1.04 0;1.08 0];
xxx=[0:.01:5];
a=size(xxx);
nx=a(2);
for i=1:nx;
    V(i)=linesegments(xxx(i));
end

%RotationProfile
%INPUT ROTATION DISTR - dimensionless
Pw=[0 0;0 1;.5 1;.5 0;0.54 0];
xx=[0:.01:5];
a=size(xx);
nx=a(2);
for i=1:nx;
    w(i)=altlinesegments(xx(i));
%altlinesegments reverses the sign for each half cycle of inputs)
end

refresh

%COMPUTATION PARAMETERS
DeltaT=10;        %total time (d'mless time)
tspan=[0 DeltaT]; %range of calculation
y0=[0;0;0];     %initial conditions for differential equation

[t,y]=ode23s('AltTwistEq',tspan, y0);

%Stiff INTEGRATOR - Solution of differential equation

plot(y(:,3),y(:,2))
axis([0 10 -4 4]);
title('Yarn Twist Distribution - dimensionless');

figure;

plot(xx,w)
axis([-0.01 1.01 -2 2]);
title('Rotation Profile - dimensionless');

figure;

plot(xxx,V)
axis([-0.01 1.01 0 3]);
title('Velocity Profile - dimensionless');
Figure G1 Operator Interface on the Control Panel using Optimum Profiles to produce a Square Wave Twist Profile
Figure G2 Data Entry points for the Optimum Yarn Velocity Profile

<table>
<thead>
<tr>
<th>Time</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>55</td>
</tr>
<tr>
<td>2075</td>
<td>47.5</td>
</tr>
<tr>
<td>2075</td>
<td>0</td>
</tr>
<tr>
<td>2175</td>
<td>0</td>
</tr>
<tr>
<td>2185</td>
<td>55</td>
</tr>
<tr>
<td>4225</td>
<td>47.5</td>
</tr>
<tr>
<td>4250</td>
<td>0</td>
</tr>
<tr>
<td>4350</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure G3 Data Entry points for the Optimum Main Jet Rotational Profile

<table>
<thead>
<tr>
<th>Time</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2075</td>
<td>0</td>
</tr>
<tr>
<td>2175</td>
<td>-1</td>
</tr>
<tr>
<td>4250</td>
<td>0</td>
</tr>
<tr>
<td>4350</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure G4 Data Entry points for the Optimum Helper Jet Rotational Profile

<table>
<thead>
<tr>
<th>Time</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>2075</td>
<td>0</td>
</tr>
<tr>
<td>2175</td>
<td>-1</td>
</tr>
<tr>
<td>4250</td>
<td>0</td>
</tr>
<tr>
<td>4350</td>
<td>0</td>
</tr>
<tr>
<td>Time</td>
<td>Velocity</td>
</tr>
<tr>
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Figure G5 Data Entry points for the Optimum Ultrasonic Anvil Profile

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<tr>
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Figure G6 Data Entry points for the Optimum Ultrasonic Activation Profile
APPENDIX H: EFFECT OF ATP YARN TWIST EFFICIENCY ON BULK

Experimental Procedure:

1. BCF 1245 denier Single BCF Nylon yarns of different Twist levels were prepared.

2. Each Singles yarn is folded in two, without allowing to self ply and then plied to a fixed ply twist level. This produces ply yarn samples with different twist efficiencies.

3. The ply yarn length and diameter of each sample is measured digitally by taking photos along the yarn sample length. An average of reading is taken.

4. The ply yarns are then soaked in boiling water for 15 min to simulate the steaming process used for carpet yarns.

5. The ply yarns are allowed to dry at room temperature for 24 hrs.

6. The ply yarn length and diameter of each sample is measured again after boiling. An average of reading is taken.

7. The Specific Volume of each yarn is calculated from the average ply yarn length and diameter after boiling. The ratio of the specific yarn volume to the specific fiber volume is calculated.
Results:

![Graph showing the effect of yarn twist efficiency on bulk](image)

**Figure H1** Effect of Yarn Twist Efficiency on Bulk
APPENDIX I: LIST OF SYMBOLS

\[ d_s = \text{Singles Yarn Diameter (m)} \]
\[ \theta = \text{Half Yarn Convergence Angle (degrees)} \]
\[ a = \text{Ply helix angle (degrees)} \]
\[ \Phi_s = \text{Singles Yarn twist (rad/inch)} \]
\[ \Phi_p = \text{Ply Yarn twist (rad/inch)} \]
\[ t_s = \text{Singles Yarn twist (turns/m)} \]
\[ t_p = \text{Ply Yarn twist (turns/m)} \]
\[ E = \text{Singles Yarn Modulus of Elasticity (N/m}^2) \]
\[ G = \text{Singles Yarn Shear Modulus (N/m}^2) \]
\[ T_p = \text{Ply yarn Tension (Kgf)} \]
\[ T_s = \text{Singles yarn Tension (Kgf)} \]
\[ \tau_s = \text{Singles Yarn torque (N.m)} \]
\[ \tau_p = \text{Added Ply torque (N.m)} \]
\[ U_s = \text{Singles strain energy/ unit length of singles (N)} \]
\[ U_p = \text{Ply strain energy / unit length of ply (N)} \]
\[ \delta S_s = \text{Unit length of Singles Yarn (m)} \]
\[ \delta S_p = \text{Unit length of Ply Yarn (m)} \]
\[ I = \text{Moment of Inertia (m}^4) \]
\[ I_p = \text{Polar Moment of Inertia (m}^4) \]
\[ A = \text{Singles Yarn cross sectional area (m}^2) \]
\[ \epsilon = \text{Singles yarn tensile strain (\%)} \]
\[ \rho = \text{Radius of Curvature (m)} \]
APPENDIX J: LIST OF DIMENSIONLESS VARIABLES

- Dimensionless Ply Twist = \( \hat{t}_p = t_p d_s \)
- Dimensionless Singles Twist = \( \hat{t}_s = t_s d_s \)
- Dimensionless Modulus = \( \hat{E} = \frac{E d_s^2}{T_p} \)
- Dimensionless Singles Tension = \( \hat{T}_S = \frac{T_s}{T_P} \)
- Dimensionless Singles Torque = \( \hat{\tau}_s = \frac{\tau_s}{T_P d_s} \)
- Dimensionless Ply Torque = \( \hat{\tau}_p = \frac{\tau_p}{T_P d_s} \)
- Dimensionless Singles strain energy = \( \hat{U}_S = \frac{U_s}{T_P} \)
- Dimensionless Ply strain energy = \( \hat{U}_p = \frac{U_p}{T_P} \)
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• Training at SSM Company, Horgen, Switzerland, for manufacturing Yarn Winding Machines, (07/99-09/99)

Publications:
• Elkhamy, Popper, Yngve & Ko, Introduction to Pneumatic Alternate Twist Ply (ATP) Yarn Technology, The 35th Textile Research Symposium, Hangzhou, China, August 2006
• Elkhamy, Li, Ko, US Patent, Drexel Docket # 05-0625D, Regenerated Ultrafine wool fibers by Electrospinning, August, 22, 2005
• Elkhamy, Atchison, Ko, Concentrically Electrospun Hollow PAN and PEO Nanofibers, Seventh Annual Research Day, Drexel University, Philadelphia, PA, 2005
• Elkhamy, Seyam, Kim, Electro-Static Web Formation, 12th Annual NTC Forum, Hilton Head, SC, 2004
• Elkhamy, ELMeseiry, Int. Conf. of the Textile Institute, Cairo, Egypt, March 2003
• Elkhamy, ELGeheiny, Int. Conf. on Computers and Communications (ICCC’01), Omman, 2001

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