ANALYSIS OF YARN PARAMETERS INFLUENCING THE KNITTABILITY OF THERMOPLASTIC POLYURETHANE YARNS

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Abstract

Knittability specially in synthetic yarns such as polyester and nylon is an essential index of the performance in ensuring the proper conversion of yarn to a knitted fabric. This can be affected by various conditions of the yarn manufacturing, yarn storage, knitting machine, knitting pattern and the environment. In footwear knitting industry, Thermoplastic Polyurethane synthetic yarn is being used due to its higher heat resistance and colour fastness properties compared to normal melt spun yarns. One of the major concerns in the process of knitting is the continuous yarn burst, which occurred significantly in thermoplastic polyurethane yarn. Occurrence of this burst appeared to be random and emerged in every yarn knitted areas. This research aimed to identify the critical factors affecting the yarn burst. After identifying the most critical factors through literature review, temporary and permanent countermeasures were developed. Initially, Prisma approach was applied to extract the relevant information from literature. Then, parameters were categorized into three based on factors related to: yarn compound, storage environment, and machine and knitting pattern. Under each category the critical parameters relevant to each factor was identified after analyzing the significance of each quantitatively and qualitatively. In terms of yarn aging, previous literature explains three types of tests namely natural exposure, field aging and artificial acceleration. According to literature, the strength of Thermoplastic Polyurethane yarn deteriorates once it is subjected to extreme conditions. In this study, the relationship between the Thermoplastic Polyurethane polymer manufactured date, the yarn lot manufactured date and the yarn burst was experimentally tested. The correlation with knittability and the yarn manufacturing dates were found to be not significant. In terms of yarn compound related factors, yarn unevenness was identified as the most critical parameter. An experimental set up was developed to measure the unevenness of black and white colourway samples. These colourways were selected as the defect rate of white colour was the highest while the black colour was the lowest. Through the statistical analysis of "t" distribution, it was identified that the statistical variance of the data set was high between the two colourways. This proves that the factor of yarn unevenness is directly correlated with defect rates. Related to machine and method related factors, the programming structures were less researched in the literature. According to the relevant footwear application, initial all needle knit structure is changed to 1*1, 1*2, and 2*2 structures. All 1*1, 1*2 and 2*2 structures prove better knittability compared to initial all needle structure. Depending on the aesthetic factors, 1*1 structure is considered as the optimum one for the relevant application. This study was limited to few parameters and the dependence of other parameters such as temperature, time and moisture absorption has to be further investigated in future works. Further, the needle knit structure is also an interesting avenue for further research.

Keywords: Knittability, Thermoplastic Polyurethane

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1. Introduction

This chapter gives the basic overview on flat knit industry and describe the basic yarn types used for the knitting process. It covers the basic yarn types and the chapter narrows it down to Thermoplastic Polyurethane yarn which has been the raw material of the research problem in this thesis. This chapter further digs into the manufacturing process of this TPU yarn before it describes the research problem. Together with the problem, aim and objectives are listed.

1.1 Background

Sri Lankan garment industry took off immediately Once Sri Lanka liberalized its economy in 1977. With this liberalization, East Asian garment exporters started investments in Sri Lanka with the liberal trade supports and transferred their manufacturing facilities to Sri Lanka. Liberal trade regime supported the Sri Lankan entrepreneurs to start their own garment facilities with a guaranteed quota for the exports. Business startups were financially supported by Sri Lankan Government and liberal trade regime further giving incentives for the same. Sri Lankan apparel productions started to be considered as an alternative for India’s garment manufacturers whilst expanding the business from 1980 onwards. Open economy policy and the investment and trade supportive environment were the key reasons of this. Currently the apparel industry comprises with 15% of the country’s total workforce while earning 50% of country’s total export sales.

Thereafter, apparel sector took over a vital portion of exports among the country’s total exports. Under the following chapters, total value of exports in apparel sector accounted for US $ 4675Mn in the year 2016. In selected markets exist US $ Mn 61 amount of clothing and apparel accessories crocheted or knitted. Sri Lanka is given with the GSP+ facility to export covering 28 EU markets whilst USA and UK being the top markets. Current direct employments through the apparel industry in Sri Lanka ranges from 300,000 to 600,000 including considerable ration of women in the country.

The performance index of a yarn during the process of knitting can be defined as the knittability of the yarn. Knittability is a key parameter in producing knitted fabrics with good quality. The easiness of yarn being converted into a knitted fabric is increased with higher knittability. Literature proves that this can be caused due to many yarn properties including strength failure, elongation at breaking point, bending characteristics and frictional properties of yarn. Adhering to these, the ability of the yarn to cause less stress on knitting machine parts provides a better knittability.

The knitting operation is done in a two-bed flat knitting machine. The central programming unit acts as the brain of the machine. The supporting functions are the yarn feeding and transmission system, fabric take-down motion, needle-bed racking system and the supporting frame. According to the central programming given, the yarn feeding system feeds the yarns located on the bobbin board with a given tension. Yarn feeds to the needle bed and knit, miss, tuck and transfer operations happens according to the given knit structures, needle point tensions and fabric take-downs.

Generally, the knitting yarns can be categorized under the natural base and the synthetic base. Natural yarns are deprived with living organisms of plants and animals and the fiber size is comparatively short. As examples, cotton, wool, silk, linen can be considered. Synthetic yarns are produced by fibers which has been created using a chemical process. Nylon, polyester, and acrylic can be considered as examples

The internal appearance of the synthetic yarn is shown in Figure 1-1 with the cladding and the core.

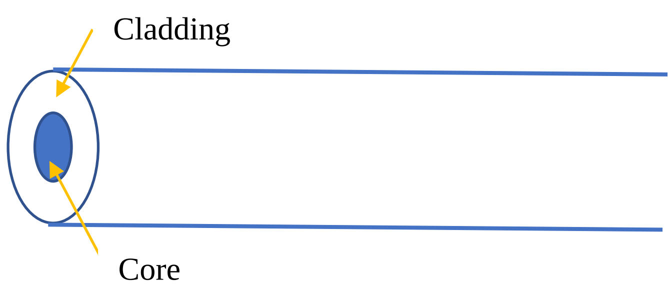


Figure 1-1: Synthetic yarn internal structure

The base for this research has been a continuous yarn burst in one of such synthetic yarns, called Thermoplastic Polyurethane yarn which has caused significant damage rate for the footwear knitting application which the research focuses on. As the initial step, background brings the breakdown for this yarn type and initial literature of the yarn.

Application of both natural and synthetic yarn types being subjected to loop formation process under the controlled tension is the manufacturing concept of a knitted fabric. Here in this specific situation, predominantly synthetic yarns being used to knit the fabric. Therefore, the background starts with the introduction of different synthetic yarns.

Synthetic yarn can basically be broken down to 4 categories.

1. Polyester
2. Nylon
3. Acrylic
4. Polypropylene

Polyesters are produced using a functional ester group including their prominent chain giving stretching, versatility, shrinking and toleration strength for a range of applications including producing lightweight conveyors, sailing clothes, mechanical rubber goods and general fabrics.

The core base of semi-aromatic polyamides is created combining several additives in achieving several property variations. Nylon 6 and Nylon 6.6 are mainly used in technical apparel industry applications. The base of almost all the Nylons are in semi-crystalline structure, which is developed to endure high temperature applications, chemical resistance applications and extreme strength applications. Rubber reinforcements and high-performance inflatables are mainly used.

The main source of acrylic yarns is acrylonitrile. Modacrylic is most applied which has a percentage of 35-40% acrylonitrile manufactured with other polymers. This is strong, highly flame retardant, and bult with higher dimensional stability. Main applications are protective clothing, screens, and shades.

Polypropylene is comprised with a propylene monomer which is a thermoplastic polymer. Like other synthetic fibres, the physical and chemical structure mainly contributes to its mechanical properties. Therefore, the selection of starting material and conditions related to fiber forming are significant parameters [1].

1.1.1 Polyester Yarns

The common bases of the polyester fibers are air, water, coal, and petroleum byproducts. Normally an acid and alcohol are combined and forming a chemical reaction. By combining two or more molecules, this reaction makes a large molecule whose structure repeats throughout its length. In this way, long polyester molecules being formed which are strong and stable [2].

Polyester yarns can be further broken down under different categories. Mono yarn, staple fiber, embroidery thread, high tenacity yarn, spun yarn, air covered yarn, POY – yarns with partial orientations, PSF – polyester with staple fiber, FDY – fully drawn polyester yarns, PSY – spun yarns with polyester, Technical Yarn are some of those [3].

The raw materials used to make polyester fibers are fabrics, pet bottles, etc. which are post-consumer products. This is comprised with polyester ethylene terephthalate (PET) which gives high elasticity, superior strength, and resilience. The commonly used geotechnical applications of PET are reinforcement in roadways, preventing cracks, reinforcing, and stabilizing riversides [4].

1.1.2 Applications of Synthetic Yarn in the Industry

Synthetic yarns are referred as main made fibers since the core fibers are polymers which is artificially treated. The main reason to use these are its features such as elasticity, lightweight, ability to wash, soft feel, cost-effectiveness. Rather than those basic properties, they have special features such as crease recovery, resistance to wrinkles and resistance to moisture. Referring to these features, the applications of such fibers vary from home furnishing, clothing, filtration, automotive industry, construction industry, toys net manufacturing and different types of ropes.

Synthetic yarn costing has been considered depending on factors such as production costs, and work costs. The investigation further expands relevant to factors like Supply chain, and sourcing methodology, producing costs.

The synthetic yarn market depends on several cost factors. This is majorly separated to production costs, working costs, the market fixing dates of crude materials, suppliers, and value streams. Evaluation is done for different factors such as downstream purchasing, supply chain, and sourcing methodology. Depending on the evaluation, the bottom to top market values identified.

As per the records in 2016, the market size synthetic fibers globally were valued around USD 51,213.0 million. The trendline at that point was calculated a revenue of USD 4.50 billion in the year 2019. The expanded trendline calculated to be USD 6.58 billion by the year 2027. The forecasted period compound annual growth (CAGR) is valued on 6.2% rate. This steady growth has continued over the last three-year period of time. The chemical, mechanical and physical properties are superior which ensures higher market growth within this forecasted period. [5].

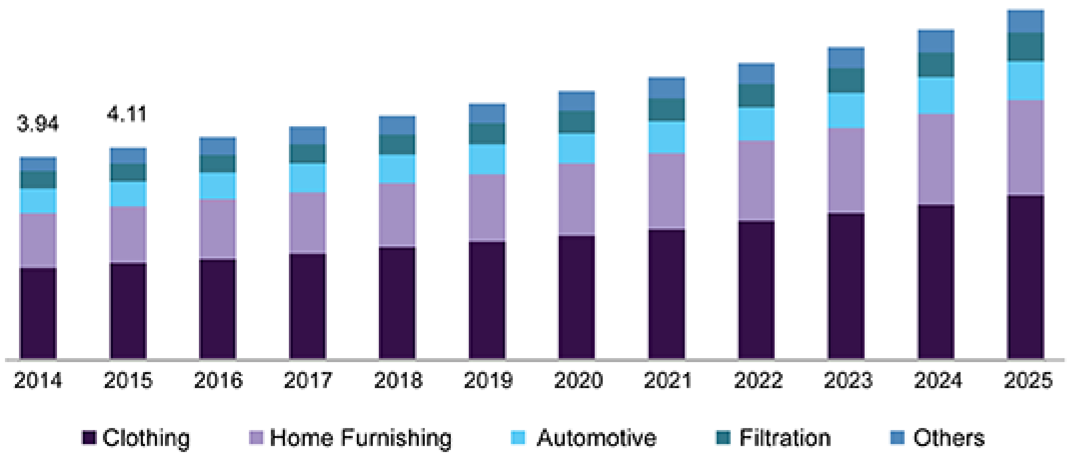


Figure 1-2: U.S. synthetic fibers market, by application, 2014 - 2015 (USD Billion)

Figure 1-2 illustrates the application of U.S synthetic yarn since 2014 to 2025 along with its market value. The Figure 1-3 shows that the Asia Pacific Region accounts for around 65 – 70% of the synthetic fiber market and Sri Lanka popular in catering a significant portion of the above market.

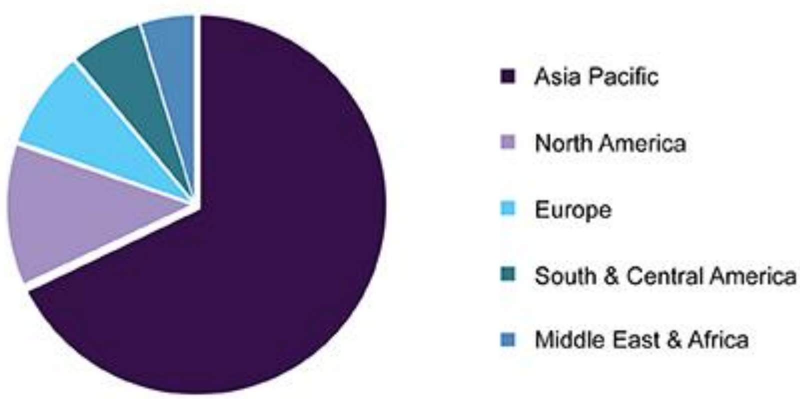


Figure 1-3: Global synthetic fibers market revenue, by region, 2016 %

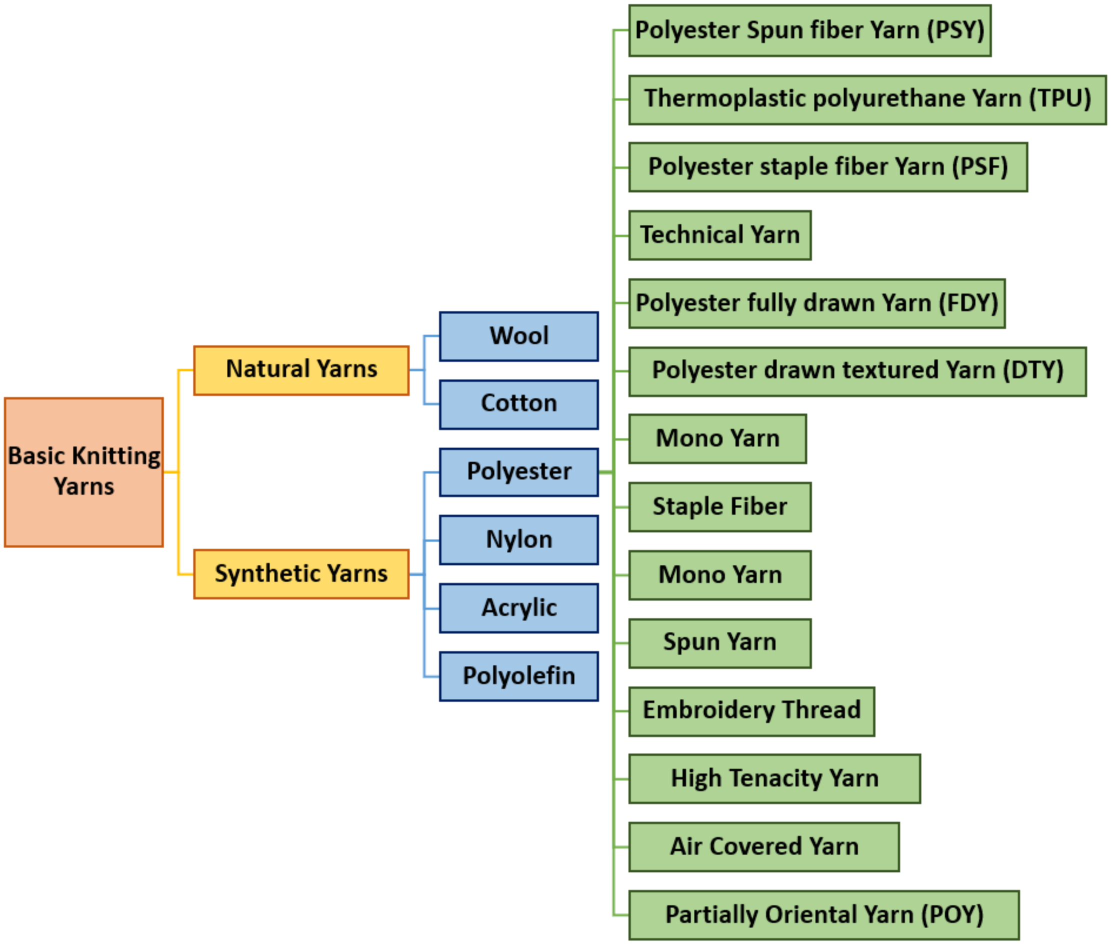


Figure 1-4: Commonly used yarn types breakdown

Figure 1-4 represents the commonly used types of yarns. Since our application is relevant to polyester yarns, the types of polyester yarns are further broken down.

In applications like creating durable fabrics, creating stretchable and elastic fabric, achieving required aesthetics and appearance, uplifting the strength of the fabric, increasing heat resistance, dimensional stability, the polyester fabrics play a vital role. Other than the functional features, polyester yarns can be developed at a lower cost. Current textile industry is running around 75% from the synthetic fibers which has evolved in a rapid phase. This replacement of synthetic yarns in textile industry is mainly due to comfortability in wearing and almost having the natural fibers feeling which have been achieved through special finishing processes like texturing.

The material which are spinnable is passed through the small openings of spinneret by pressing. The next stage of the filaments manufactured by reeling or combined for tow forming. Since this consumes a lot of energy, the pressure and temperature values should be monitored and controlled. While maintaining the process parameters, a pumping of the molted polymer is done through the holes of the spinneret. The temperature maintained between 250 to 300 Celsius in the formation of filaments and through quenching these will be cooled and solidified.

Common products of polyester yarns include home furnishings, clothing, industrial fabrics, and electrical insulations. One of the major advantages of using polyester over natural fibers like cotton is its ability to absorb oil. Although the moisture absorbency is very low, the oil absorbency makes the fabric very useful in water, soil, and fire-resistant applications. Natural resistance for stains is high in polyester yarns due to low moisture absorbance. Since the preshrinking has happened in the finishing process, further shrinking while in the usage is avoided ensuring the fabric remains with its original shape. The ability for dyeing is also high in these fibers. Also, with the nonallergenic insulation properties, textured polyester fibers are used in outerwear, comforting pillows, sleeping bags and quilting.

Characteristics of Polyester fiber

1. Higher strength
2. Less stretching and shrinking
3. Chemical Resistance
4. Faster drying
5. Resilient and crispy
6. Resistance to wrinkling
7. Resistance to Mildew
8. Resistance to abrasion
9. Retains heat
10. Easily washable

Thermoplastic polyurethane yarn, which is one type of polyester yarn, comes with a thermoplastic polyurethane coating applied onto the core fibers.

Applications of Polyurethane in industry

It is virtually impossible for anyone not to meet a variety of polyurethane types in several times a day. As a result of its unique characteristics, Polyurethanes have found in wide variety of applications such as automobile, furniture, construction, and apparel industries. Polyurethanes accounts for more than 20% of the forms in modern car. Typical components of that application are dash boards, bumping coverings, fending’s, and molds. In the furniture applications, flexible foams are used to make bedding sofas, cushions, carpet backs and car seats. In construction industry, rigid foams are used for insulation in freezers, refrigerators, building walls and roofs. Solid Polyurethanes are used to produce several elastomers coatings, medical items, and coatings. Most of the shoe soles are made up of tough elastomeric polyurethanes.

The composition of the copolymer used in polyurethane is a melting soft segment and a hard segment. The soft segment normally includes the connection of a diiocyanate and a low-molecular chain. The materials can be adopted for a broad range of physical properties since it is available in the forms of hard to soft or within that range. Once analyzing the microstructure in the polyurethane elastomer, it is significant it exists two phase separation created through the chemical incompatibility between the hard and soft elements. The segregation happens in the hard segments to be semi crystalline or glassy type. Further analysis reveals the hard section to be a physically applicable cross-linking compound or a reinforcement filter whilst the soft part to act as a matrix. This feature of two-phase microstructure separation accounts for outstanding mechanical and physical properties such as reversible deformation and high modulus.

Thermoplastic polyether polyurethane undergoes a melt spinning process to make elastic fibers. Here the polymers are disclosed and mixed with a non-polyether crosslinking agent to achieve long run times. polyester polyol reacted with a diisocyanate is used preferably as the crosslinking agent. Long melt spinning run times can be achieved in the spinneret without experiencing excessive pressure buildup.

Applications of Thermoplastic polyurethane

This yarn is developed for very specific applications since having properties such as high tensile strength, high tearing resistance, less flexibility to temperature, high endurance to fatigue and high adhesion properties [6].

1.2 Problem Formulation

The frequent yarn burst is observed in the following mentioned Thermoplastic polyether polyurethane yarn when the fabric part is knitting. Below images shows the appearance of the yarn breakage. Both the core fiber and thermoplastic cladding has been damaged randomly. This damage is visual at the point of the fabric coming out from the knitting machine. Production process is highly impacted since this is frequently appearing in most of the uppers.

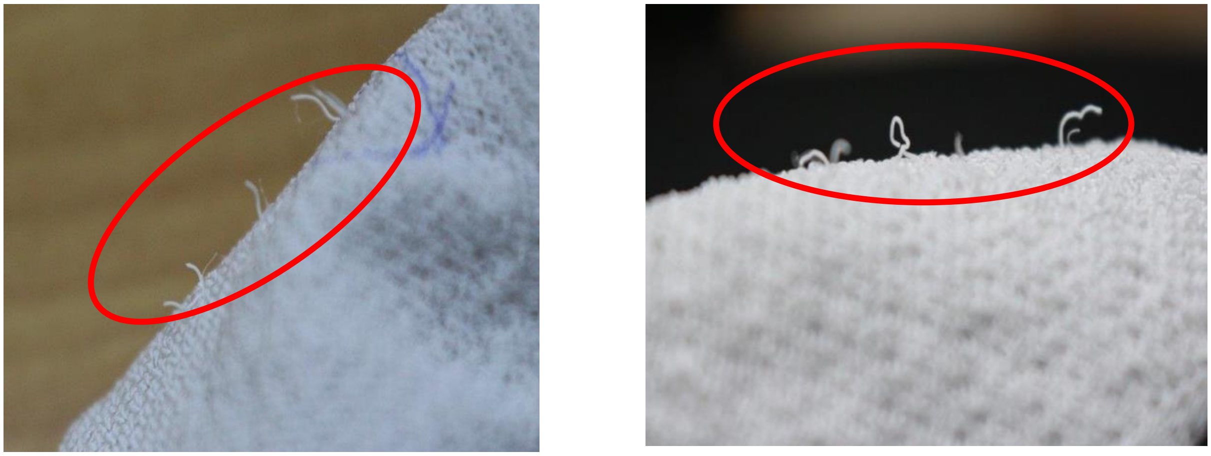


Figure 1-5: TPU yarn burst

Further, microscopic view is obtained in the surface of the same yarn samples to understand the irregularity.

Figure 1-6: Microscopic view of a thermoplastic polyurethane yarn

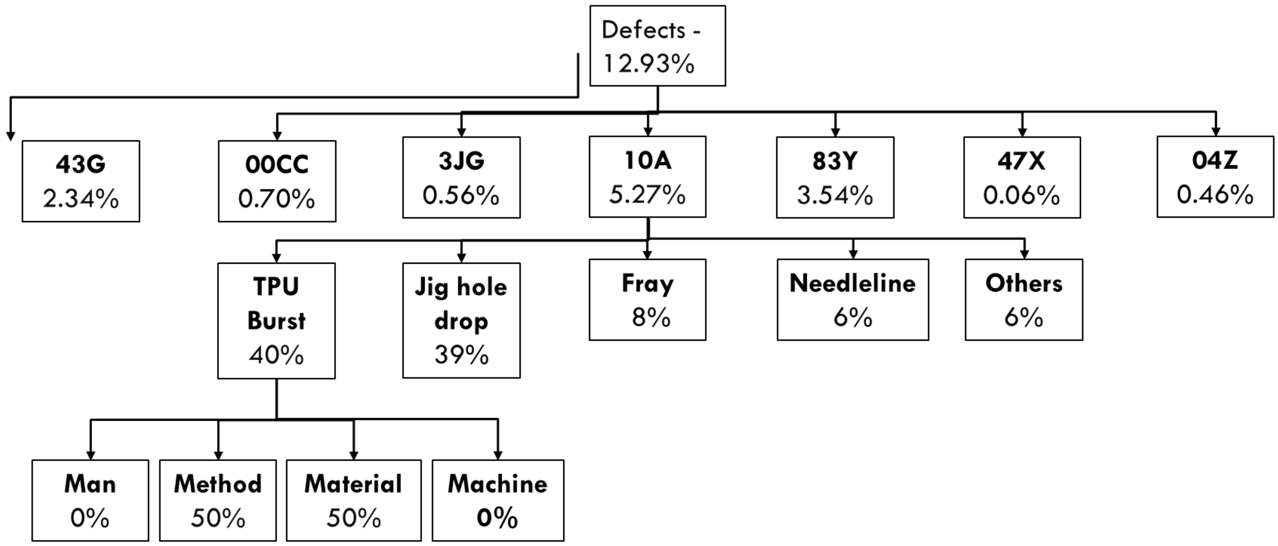


Figure 1-7: Defects Breakdown

Figure 1-5 shows how the TPU burst appeared on the fabric after knitting. Further this has been visualized through a microscope and the images received is as per the figure 1-6. This clearly shows the thick and thin places in the yarn. Figure 1-7 is how the problem is broken down to identify the TPU burst to be the major problem. The possible causes for the damage are categorized mainly under three sections namely yarn compound related factors, environmental and storage factors, and method related factors. Each affecting parameter is listed down under these three categories based on literature.

1.3 Aim

The aim is to analyze the parameters influencing the knittability of thermoplastic polyurethane yarns.

1.4 Objectives

- To understand the specifications and conditions of Thermoplastic Polyurethane yarn.
- To explore the basic parameters of Tensile strength, elongation, and denier count, to understand its significance to cause this damage.
- To map significant variables under the categories of Yarn compound related factors, Environmental and Storage factors, and Method related factors. Consider

the steps to understand the critical variables and how each of such variable independently influences the specific knit damage.

- To analyze the behavior influence of yarn unevenness and thick and thin places towards knittability
- To critically analyze knitting structures influence on knittability and discover the optimum knit structure
- To evaluate the findings on TPU and yarn lot parameters that influence the knittability

1.5 Summary

A basic overview on flat knit industry and the yarn types used for the knitting process were presented. Thermoplastic Polyurethane yarn is the focus of the research problem. Further, the manufacturing process of this TPU yarn was also presented. Afterwards, the problem formulation, aim and objectives were presented. Using the Prisma approach, the literature review was conducted and presented in the next chapter. The critical variables were plotted under the yarn compound related factors, environmental and storage factors and machine and method related factors. Afterwards the criticality is mapped as high, medium, and low. Experiment set up is developed for the critical variables of yarn unevenness, TPU and yarn lot manufacturing time and knitting structures. Final conclusions included in the discussion chapter together with the improvement points.

2. Methodology

The approach in achieving the objectives is explained through the methodology. The structure of the report first comprises of the methodology on each step taken to proceed with the report. The initial step is the identification of the problem. The damage quantity is broken down in colourway wise and damage wise and identified the significant colourway and the damage. Through microscopic and visual examinations, identify the point which this damage happens and due to which yarn it happens. As the second point, thermoplastic polyurethane yarn samples were taken using several colourways and identified at which colourways this damage is significant. Then the next step has been conducting a thorough literature review relevant to critical parameters which can cause the yarn burst. The parameters mapped under three sections namely Yarn compound related factors, Environmental and Storage factors and Machine and Method related factors.

2.1 Prisma approach for Literature Review

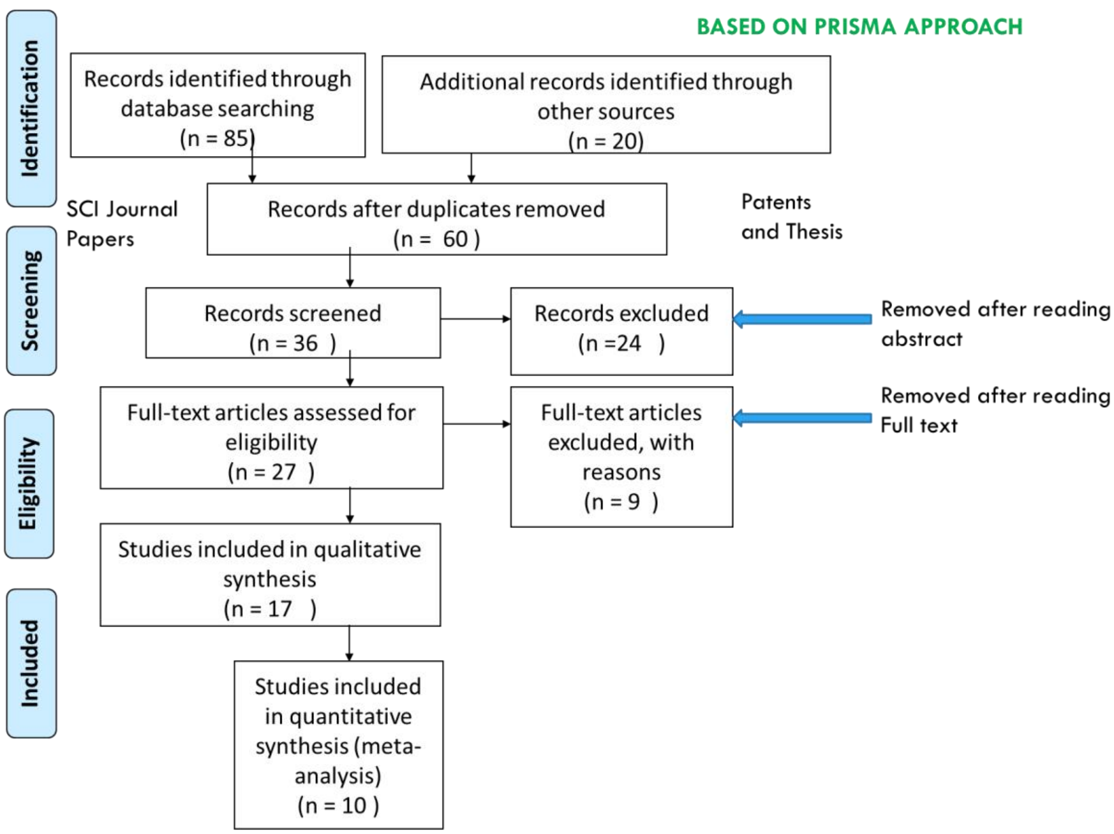


Figure 2-1: Prisma Approach

Figure 2-1 represents the breakdown through the reference of science journals, thesis, and patents. Identification stage represents extracting out the possible resources under previous databases. Screening is removing out the duplicate records. Under eligibility, remove out the non-applicable reference after reading both abstract and full text. Then the remaining studies is used to quantitative synthesis of literature.

Afterwards, the manufacturing process of the Thermoplastic Polyurethane Yarn is studied to understand the behavior and the aging characteristics. For this, previous research findings related to natural exposure test, artificial accelerated test and field aging test is considered.

The mechanism of selecting the most critical variables is to plot the relevant variables under yarn compound related factors, environmental and storage factor, machine, and method related factors and name each variable as criticality, high, medium, and low. Accordingly, yarn unevenness, manufacturing time of thermoplastic polyurethane and core yarn and knit program structures is considered to carry out the experiments.

2.2 Tensile strength, Elongation at Break and Denier Count testing

Elongation and Breaking Strength is two key quality parameters in any filament yarn. The processability is highly reliant with the elongation and tensile strength and the operational life is expanded once the values are high. Initial data collection has been done to identify the Tensile Strength, Elongation at Break and Denier Count for all the colourways. The values are checked against the customer defined specs.

The direct impact of the yarn exist for the fabric since the breaking strength of yarn proportionately influences the breaking strength of the fabric. The other factor in which the breaking strength of yarn depends on is its own construction and manufacturing process. The product and process are influenced with the elongation property of yarn. In garments certain areas are subjected to more stress such as the elbow, knee. In such areas the requirement of elongation property is high.

2.2.1 Tensile Strength and Elongation at Break Testing

ASTM D2256 is used to determine elongation and breaking strength of the threads which is the common standard for quantification. The principle is simple in which constant pulling force is applied until the thread breaks. The clamping happens such that, the access of machine loading tally with specimen axis. This alignment is commonly used as it is compatible reliant and repeatable. Specimen failures can cause from sharp edges which happens out of the gauge even below the actual values of strength in the yarn.

2.2.2 Denier Count Testing

Count defines the density of yarn since he correlation is with the fineness and coarseness of yarn. Depends on the type of yarn, the count is defined to be the mass per unit length or length to unit mass.

Two methods being used to calculate the count, these are:

1. Indirect System / Fixed weight system (length per unit mass)
2. Direct system / Fixed length system (mass per unit length)

The fixed weight system, which is commonly named as the indirect system, in which the count is calculated by measuring the length of one-gram weight. This value indicates the length per unit mass of the yarn. The finer the yarn the count is higher. The mass is kept fixed in this system whilst the length of the yarn changes. Specially on natural yarns such as cotton, this system is used to calculate the count.

In the direct system, this is the other way round where the length kept constant (usually 1 meter) and the mass is measured for this specific length. This system expresses for a unit length what the measure of weight the yarn becomes coarse if the count value is high. Here in indirect system the length is kept fixed and the weight varied depending on the yarn fineness. Synthetic yarn counts such as in polyester, nylon, acrylic is taken in this method

2.3 Understanding Critical Variables

The Table 2-1 is prepared with the past analysis to categorize each variable as High, Medium, and Low under yarn compound related factors, Environmental and Storage factors and Machine and Method related factors

Table 2-1: Identifying effectiveness of critical parameters of related factor categories

Yarn compound factors	**Effect**	**Cone storage conditions**	**Effect**	**Machine and method factors**	**Effect**
Static electricity of yarn	**Low**	Cone storage temperature	**High**	Machine speed	**High**
Yarn count	**Low**	Cone storage humidity	**High**	Types of needles	**Medium**
Oil content	**Medium**	TPU lot production time	**High**	Cam settings	**Medium**
Moisture regains	**Medium**	Yarn lot production time	**Medium**	Input tension	**Medium**
Tensile strength	**High**			Take down tension	**Medium**
Yarn friction	**Medium**			Oil level	**Medium**
Yarn elongation at break	**High**			Moisture level	**Medium**
Uniformity of yarn	**High**			Needle point tension	**Medium**
Yarn twist	**High**			Knit patterns	**High**
Fiber strength	**High**			Knit structures	**High**
Yarn crimp	**Low**				

As the Table 2-1 represents according to the study carried out for the considered factors, the strength of the yarn is the vital parameter in managing the defect. According to the relevant literature and experimental learning, the most critical factors affecting the yarn strength is plotted as below. Further analysis needs to be carried out to capture the relationship for those affecting parameters. The summary of the parameter breakdown is as follows

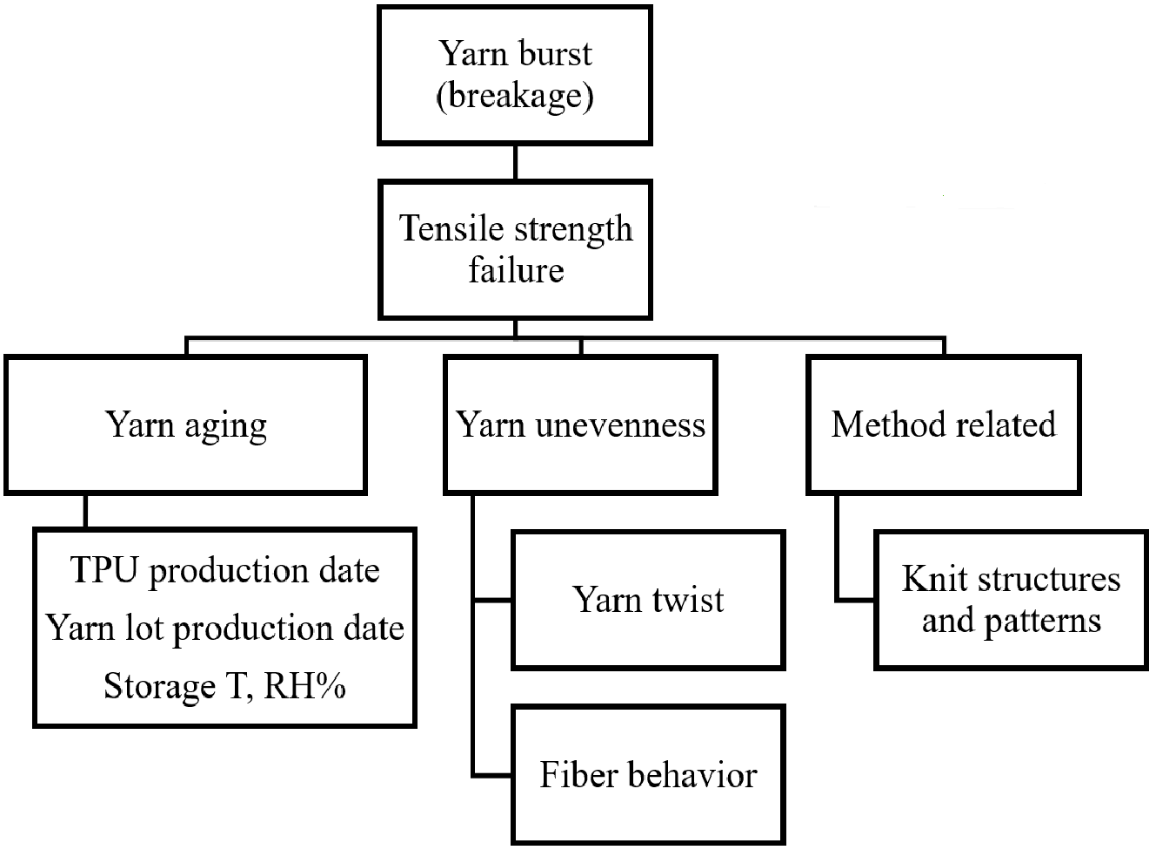


Figure 2-2: Summary of the parameter breakdown

As the critical variables being plotted according to figure 2-2, the next step is to experiment each to understand direct behavioral impact. All the experiments planned to vary the testing parameter under controlled environment where significant changes in the other variables is not allowed. Any minor variations in other influencing variables are assumed to be negligible with the controlling steps taken.

2.4 Yarn Unevenness Testing

First experiment is designed to understand the effect of yarn unevenness which is considered as the most critical factor related to yarn compound related factors. Initially selected two colourways of black colour and white colour. Black colour is having less defect rate and white is having high defect rate.

The initial purpose is to ensure that the unevenness is within the customer defined standards. The experiment was planned by using a customized unevenness tester. The unevenness data has been collected for two colourways of the same yarn where the black colour shows a low defect rate and the white colour shows a high defect date. The testing is designed as follows:

1. Place a spoon of yarn (cable) on top of shelf or table
2. Place the 5g clip weight at the end of the yarn
3. Align the top edge of the binder clip to the meter mark
4. Wait 10 seconds to settle the tension
5. Use a sharp scissor to cut yarn(thread) at the meter cutting point
6. Repeat step 2 to step 6 five times
7. Measure the weight of all 5 pieces yarn (cable) together using weight balance

$$Denier\ (\frac{g}{9000m}) = \frac{Weight \times 9000}{5}$$

Above equation is used to calculate the Denier using weight balance.

Figure 2-3: Customized setup to measure unevenness

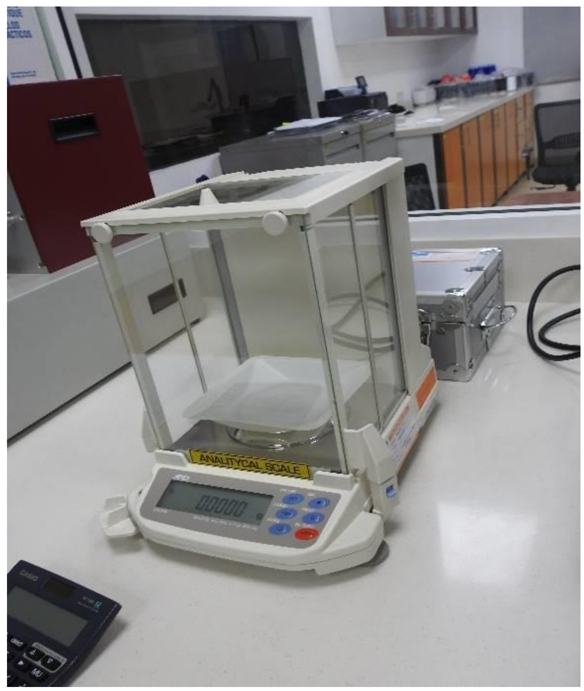


Figure 2-4: Yarn weight measuring instrument

According to the Figure 2-3, the experiment setup is prepared so that the yarn can be hold at the top and 5g weight is applied and cut 1 m pieces to check the weight variance. Figure 2-4 is the weight measuring setup used. The next stage was to vary the machine and knit the same yarn under same conditions to identify machine variability impact towards the problem

2.5 Discovering the Optimum Knit Structure from the available Knitting Techniques

First step is the identification of applicable knit structures. Trialing out varying the structure is done afterwards. Studies being carried out to select three points in the Stoll machine yarn path and measured the tension behavior of each. The points are the top tension in the machine, the side tension point and the yarn feeding point tension. According to tension behavior and defect rates, the optimum structure is selected.

2.6 Yarn Manufacturing Time Influence Testing

Second experiment is designed to identify the influence of TPU lot manufacturing time and Yarn lot manufacturing time influence towards knittability. The trial is carried out varying the yarn lot, machine, and the machine speed. The results were plotted on a graph with 40 different samples. The ultimate results have shown no significant relation with TPU and Yarn lot manufacturing time with knittability.

3. Literature Review

The possible causes for the damage are categorized mainly under three sections namely yarn compound related factors, environmental and storage factors, and method related factors. Each affecting parameter is listed down under these three categories based on literature.

Yarn compound related factors

- Static electricity of yarn [7]
- Yarn count [8]
- Oil content [9]
- Moisture regains [10]
- Tensile strength [11]
- Yarn friction (surface condition of the yarn, surface condition of the metal part) [12]
- Yarn elongation at break [13]
- Uniformity of the yarn [14]
- Yarn twist [15]
- Fiber length [16]
- Yarn crimp [17]
- Yarn moisture content [18]
- Fiber relaxation at that moment [19]

Environmental and storage factors

- Cone storage temperature [20]
- Cone storage humidity [21]
- TPU lot production time [22]
- Yarn lot production time [23]

Method related factors

- Machine running speed [24]
- Needle type [25]
- Machine settings including the cam [26]
- Tension value of input and tension value of takedown [27]

- Oil level [28]
- Moisture level [29]
- Needle point tension [30]
- Programming techniques [31]

3.1 Thermoplastic Polyurethane Yarn Manufacturing Process

Industrial using yarns or shoe upper using yarns are generally taken from as polyester, nylon, acryl resin types. The disadvantages of such common yarns are the low abrasion resistance, low durability, and bad adhesion forces. Specially in high functional durable shoes those common materials are not adequate. To avoid this matter, a coated yarn with the thermoplastic resin on surface is used. The purpose is to enhance the strength of the yarn. The coating process happens through pressing the thermoplastic resin.

Initial step is to inject compounded Nano silica mixed contents together with the TPU resin into a general type of twin extruder. The compounding can happen in the temperature scope of 170°C to 240°C. Afterwards the pellet compounds are produced and injected in a yarn processing general extruder. The extrusion of the material happens at the temperature range of 170°C to 230°C. Cooling water is used to cool the yarn to a temperature range of 25° C to 40° C once the TPU yarn is discharged from extruder dies. Averagely the cooling yarn is subjected to elongation maximum up to 7 times. The annealing of the elongated TPU yarn is done at a heating chamber which has a temperature range of 150° C to 160° C. The processed yarn is concluded in finishing the manufacturing process [32].

The raw wire is made from certain core fibers from spandex, nylon, and polyester fibers. In a separate process, thermoplastic coating is manufactured using Resins and adhesives. Previously generated compounded wire coating is allowed to be mixed in an extruder together with thermoplastic polyurethanes the coating layer adheres into the raw yarn surface [33]. The critical component production dates and the yarn manufacturing date time intervals are as shown in the Figure 3-1 below.

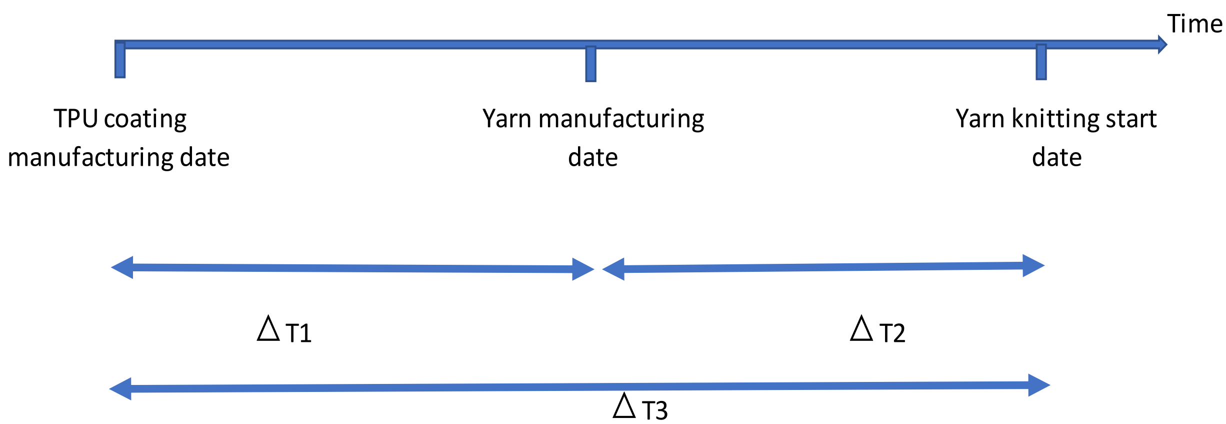


Figure 3-1: TPU yarn production time intervals

Figure 3-1 shows the time differences between TPU coating manufacturing date, yarn manufacturing date and yarn knitting start date as above mentioned.

Several investigations being done to reveal that solar UV radiation absorption is high in most of the polymers including thermoplastic polyurethane. This absorption acts as the energy media to start degradation reactions. These reactions are called as thermo-oxidative and photo oxidative reactions. Exposing to aggressive elements such as sunlight and UV and weather exposure can affect its durability of thermoplastic polyurethane (TPU) material once it is exposed into variety of conditions.

Extensive research scope is available to be exploited in the experimental characterization of the above area. Defined basically three methods available namely artificial acceleration properties, natural exposure testing, field aging testing which evaluates aging properties.

In previous literature experiments were done under normal weathering conditions and started to analyze this materials weather resisting property. The effectiveness of natural exposure testing is high, since the test condition is very close to natural environment, but such experiments are time consuming and having less repeatability. Therefore, the experiments were initiated with extreme aging conditions applied artificially. The artificially accelerated testing can reduce the test time and can easily model the behavior under various environments. Artificial light sources being used to model ultraviolet radiations received from sunshine. The prominent sources were carbon arc lamps, Xenon lamps, mercury vapor lamps and ultraviolet fluorescent lamps [34].

Polfus [35] experimented using natural exposing tests in which a PVC-coated polyester is used. With the experiment he concluded in natural environment a deterioration of material happens with industrial pollution. His study is based in industrial zones n west and east coasts of US. Eichert [35] carried out a natural exposure test for 10 years to reveal an aging in the membrane of thermoplastic polyurethane material with the influence of air pollution. Toyada et al. [35] came up with a different opinion as he conducted natural exposure test for seven years and identified a residual strength failure from 50% for the first three years. The next four years the properties stayed unchanged.

Significant deviations in the chemical structure and morphology is identified in the aged material by Scaffaro et al when focusing on the mechanical and structural responses given when the polymer is subjected to degrading factors such as thermal degradation and photo-oxidation. A consequent alteration of mechanical performance is visible over time and a morphology variation in chemical and physical structure. This results to show that the ultraviolet radiation and temperature has direct impact on the mechanical properties such as tensile strength, tear strength and elastic modulus of yarns [35].

According to the research findings it shows that subjecting thermoplastic polyurethane to thermal degradation and photo oxidation has significant effect on its properties. Below images shows the behavior of stress about strain under unaged, aged, and dried conditions. The curve breaks mainly for two regions: initially the linear region representing elastic modulus of the material. Next region represents viscos-elastoplastic behavior [36]. The summary of these curves proves steeper wear rate of aged and dried TPUs compared to unaged ones. This represents the significant impact of wear kinetics of aged and dried samples [37].

The above images explain how the performances indexes have varied in aged, dried, and unaged TPU yarns. Figure 3-2 shows how the tensile strength has behaved for each category. Figure 3-3 represents the wear rate with time of aged, dried, and unaged TPU. Last bar chart in figure 3-4 explains the stress at 200% strain, Y modulus comparison for aged, dried, and unaged TPU.

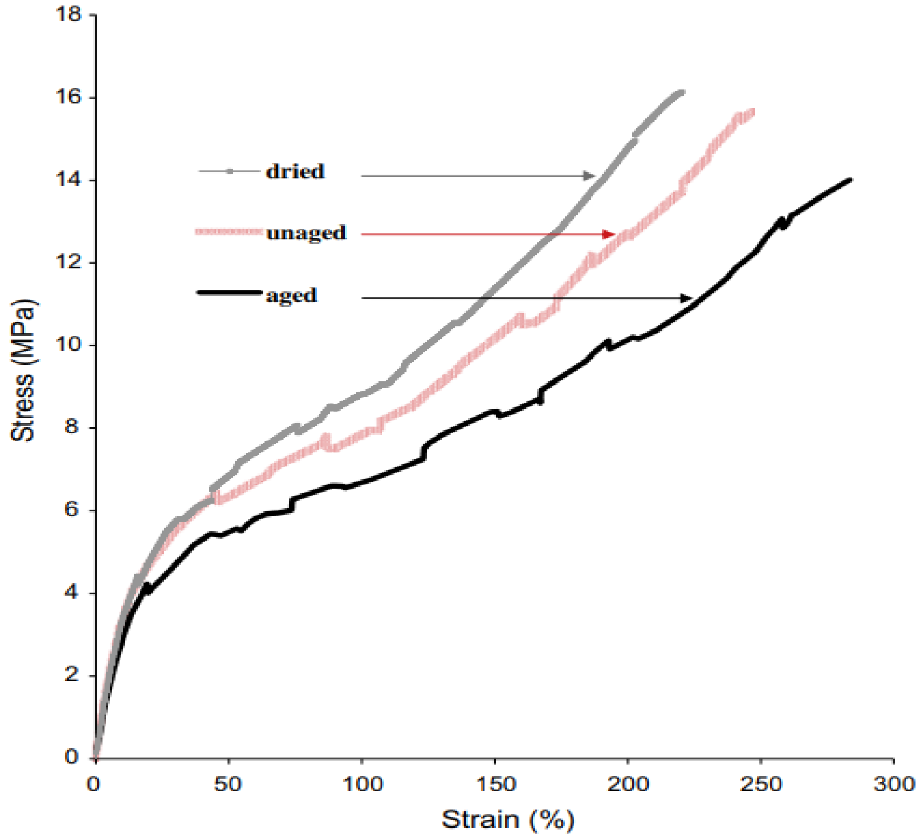


Figure 3-3: Tensile curves of aged, dried, and unaged TPU [37]

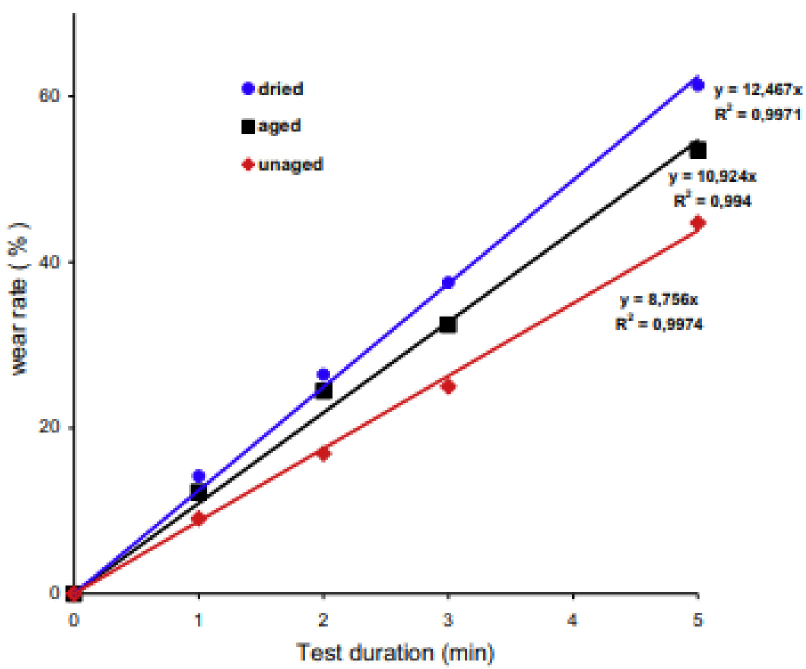


Figure 3-2: Wear rate with time of aged, dried, and unaged TPU [37]

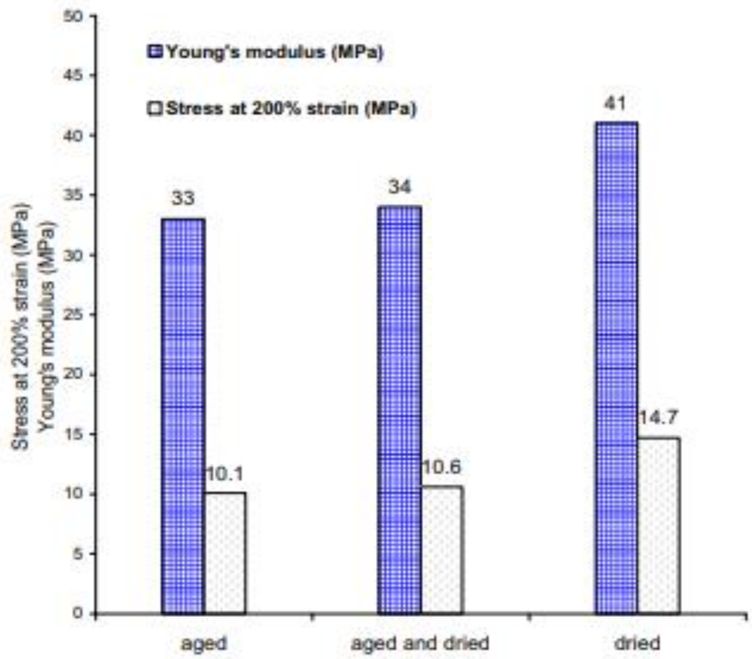


Figure 3-4: Stress at 200% strain, Y modulus comparison for dried, aged, unaged TPU [37]

The thermal environment causes degradation in the surface area of PVC-coating applied polymers. Afterwards, ultraviolet radiation was applied to the surface area which has not shown significant impact. The critical impact was identified with subjecting to thermal-humid and thermal environment which accounted in loosing majority of material properties such as tensile strength and elongation at break.

TPU undergoes significant changes on weather exposure. These changes lead to deterioration in its physical and mechanical properties. The particles are broken to smaller segments which has less influence on the mechanical properties. The resulting smaller fragments do not contribute effectively to the mechanical properties. Thus, the polymer becomes more vulnerable and brittle. The next studied scope is the influence of compact and precipitated polyurethane films to the weathering tests related to mechanical properties. The ultimate tensile strength, strain and modulus were found to decrease because of expanding weathering time.

This experiment has considered limited number of parameters but influence of certain variables such as temperature, time and moisture absorption must be further monitored in future works. Further, the influence on mechanical and physical factors under such variable conditions is open for investigations.

3.2 Investigation on Yarn Related Factors

The capability of the yarn to tolerate the stress while yarn to fabric transformation process happens, is a critical sphere. Literature expresses yarn fineness, yarn twist, yarn friction, yarn count, yarn unevenness, abrasion resistance, tensile strength, elongation, moisture regain, bending radius, static electricity to play key impacts on deciding the same. Breakdown on the defined parameters being mentioned to highlight the significance.

3.2.1 Fiber Fineness

The strength of the fine fibers is high comparatively with the coarse fibers which are having the same yarn count. The reason for this is finer fiber yarns having higher number of fibers and it increases internal friction between the surfaces. The further researches carried out emphasizes the knitting yarns which are having fine fibers, high in flexibility and loftiness with combination with low twist. However, with these features, appreciable losses in strength is not being identified [38].

The parameters such as porosity, material's surface area, filtration resistance is affected by Fiber fineness. These are major parameters which determines the applications and performance of the fiber. The diameter ranges from 100 -1000 nm in electro spun yarn and the pores are in the range of 2-465 μm. This is suitable in terms of air permeation. In melt electrospinning, the diameter decreases but only few materials can reach these types of ranges. The main reasons for this the complexity of the process and the requirement for prepare special devices. [39].

3.2.2 Yarn Count

To define the fineness or coarseness, yarn count has been expressed numerically either in terms of weight by length or length by weight [40].

Yarn count can be calculated through two systems

1. Direct system (weight/length)
2. Indirect system (length/weight)

3.2.3 Yarn Twist

For a single spun yarn, twist has an optimum level where the maximum level of strength is achieved. Once the twist increases or decreases this value, the strength will decrease. For a range of yarns, the optimum twist angle which gives the maximum strength, stays the same. The yarn breaking tenacity is increased through twist helical structure created with the twist level. The effect of twist helical structure is that it can vary the interaction among fibers by pressing them together [41].

Twist calculation

The spiral deposition is achieved of the components thread due to relative motion in the two ends. The measuring indicator of twist which is named as the deposition frequency is generally expressed as the amount of turns for unit length of yarn. A simple method is used to test this. The method is unwinding the yarn and counting the number of turns required in doing this. The used instrument has both one fixed jaw and a rotatable jaw in which the distance kept apart. A counter is used to calculate the number of turns.

Twist angle

The theoretical calculation is done for yarn having geometrical diameter ‘d’. In the twisting one total cycle is rotated with the helix angle θ in L units. The rotation is done parallel to the core axis. The three-dimensional structure is used to draw a right-angle triangle as shown in figure 3-5. Twist angle is calculated using this triangle and the equation is as below

$$T = \frac{\tan(\theta)}{\pi d} \qquad \text{...(1)}$$

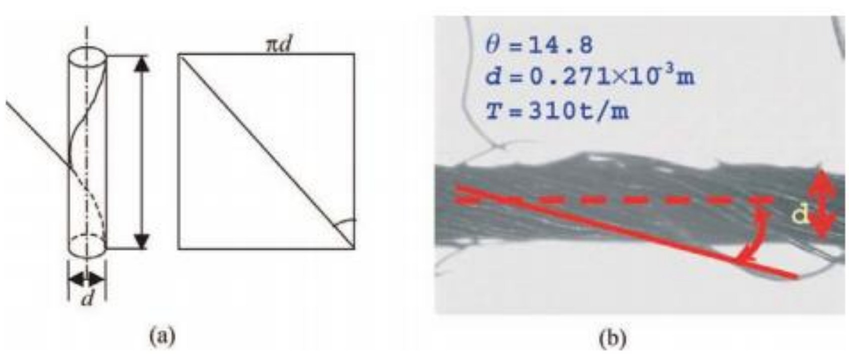


Figure 3-5:(a) How the twist relates to twist angle (b) yarn twist calculation

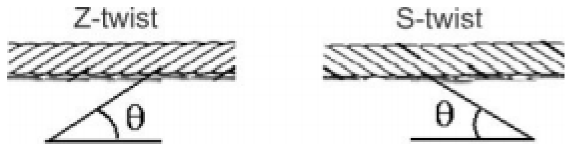


Figure 3-6: Twist directions

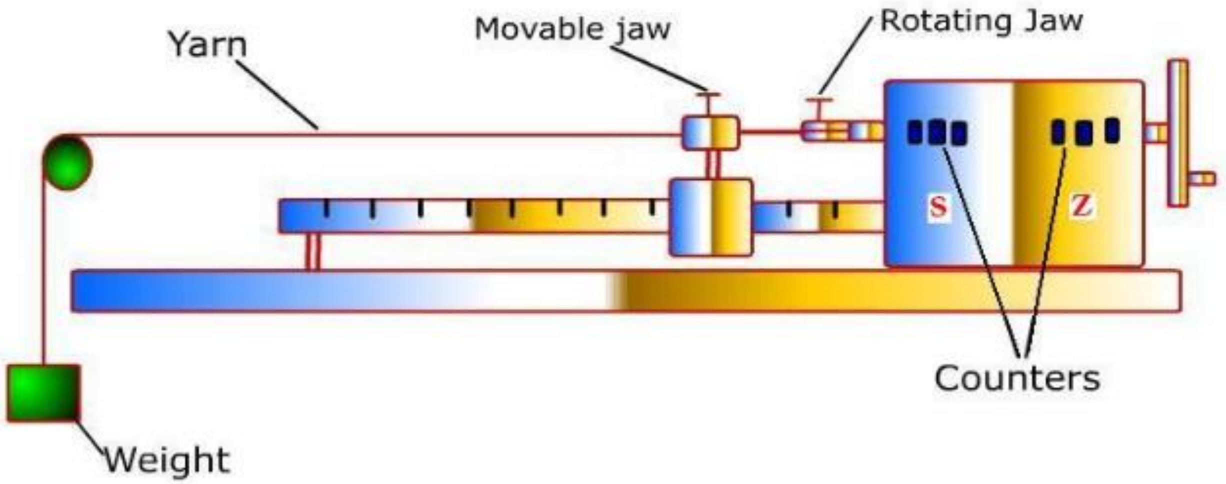


Figure 3-7: Simple twist tester

Figure 3-5 represents how the twist relates to the twist angle and yarn twist calculation equation. In figure 3-6 the s and z twist directions shown. Further in figure 3-7 is a simple setup of the twist tester.

3.2.4 Synthetic Yarn Unevenness

Unevenness in synthetic yarns is created by the variation of fineness in the yarn. This property is measured by the divergence in mass per one-meter length along the yarn. This can have the influence on many of the other properties. Yarn unevenness can be used as a comprehensive tool to reflect every process of polyester filament production under mechanical, technical, and operational conditions. Several investigations reveal the strong correlation between yarn unevenness and yarn strength. Uneven yarn will show reduction in strength whereas greater uniformity of yarn shows increases in strength [42].

Unevenness of synthetic yarns can be examined using two methods. Under visual examination, the yarn is laid on a black surface of a matt with turns equally spaced. The surface is then examined using uniform nondirectional light with higher luminosity. On the cut and weigh method, the weight variation of consecutive lengths is plotted on a graph for the calculation.

Yarn count, twist, and unevenness relationship

According to the investigations done by Hearle and Merchant (1963) relationships between specific volume, yarn count and twist of spun yarns were found out.

Further with the studies done by Sust and Barella (1964) the interrelations diameter, twist and unevenness are identified [43].

3.2.5 Yarn Friction

Yarn friction is mainly affected in the behavior it has after running. Further, yarn and fabric surface structure can be affected through this quantitatively and qualitatively varying the tactile characteristics of the fabric [44].

Definition of friction can be summarized into contacting functions such as rolling, flowing, or sliding onto the surface which it is contacted and create a relative motion.

The calculation of coefficient of friction is based on the tangential force applied to conserve the relative yet uniform motion. This relative motion among the two surfaces contacting against the perpendicular force which holds them with contact.

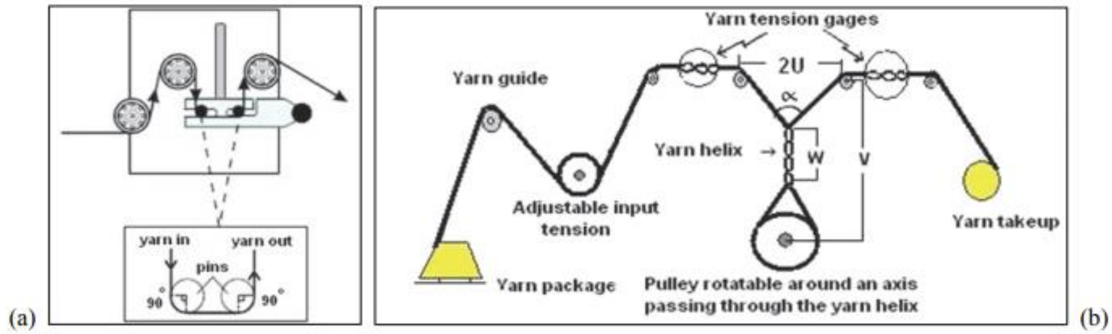


Figure 3-8: (a) friction test yarn to pin (b) friction test yarn to yarn

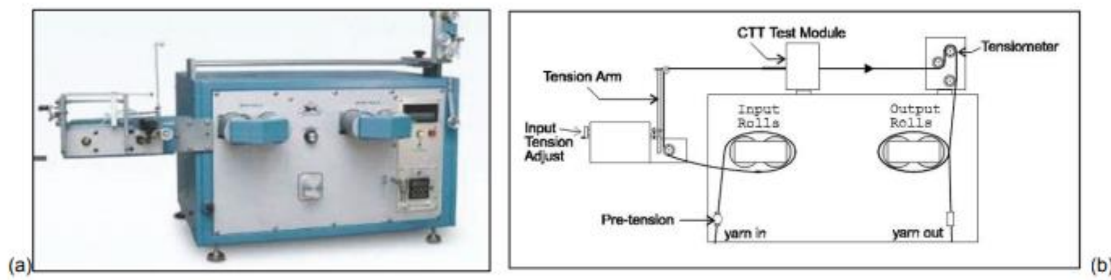


Figure 3-9: Friction Testing Machine

Figure 3-8 represents the friction creating points on the setup once it touches the surfaces. Figure 3-9 is the commonly used friction measuring set up with its components.

Literature exposes experiments done varying certain parameters to identify the impact on friction about them. The analysis was done under two frictional types namely environmental conditions and contact conditions. Under environmental conditions the focus is given on temperature and relative humidity. Under the contact conditions it is related to yarn tension and speed. In the first experiment a polyester yarn is made in a continuous flat filament base and rubbed with stainless steel surface. The purpose was to monitor the level of static generation and dissipation. Developed device is being used and operated under the desired tension in a room where environmental parameters can be varied. The potential charges being monitored in random locations.

Initial potentials being measured, and exponential plot is done with the distance to identify characteristic decaying time which is the measure of static dissipation. The results of this experiment show a significant effect of yarn tension, yarn speed, humidity and temperature towards static dissipation [45].

The countermeasure used to avoid the friction is lubricating the yarn and it can reduce the friction level averagely half of its original value. This that can lower the friction coefficient of different yarns to a low coefficient value which will increase knittability. Empirically tested several lubricants with different levels to identify the optimum for each yarn settings.

3.2.6 Abrasion Resistance

Fabric components tend to deteriorate through the rubbing of it in another surface. The level of such deterioration is called as abrasion. This will ultimately result in a loss of performance. Several parameters affect the abrasion resistance of textile materials such as fiber fineness, yarn count and yarn type [46]. The incorporation of longer fibers to the fabric proves higher resistance to abrasion than shorter fibers as the liberation process is easier comparatively from fabric structure. This result in filament yarn proving to be higher abrasion resistant than with staple fibers [47].

3.2.7 Strength & Elongation at Break

Literature emphasizes that tensile strength the prime influencing parameter in defining the suitability of yarn for any application. This has been proved in number of applications. In principle wise there are three basic methods to measure the strength at break. This applies to single yarns where the principles of constant rate of loading (CRL) and constant rate of extension (CRE) is used for calculations. These two methods show two different values due to the change in measuring system.

The application of testing is done by exposing the yarn to a constant rate of extension. The yarn is a combination of many threads and the simultaneous breaking point strength force is defined as the tensile strength. This is the maximum possible tensile strength a fabric can hold [48]. Fabric is subjected to elastic deformation until it arrives yield point. Yield point is the maximum strain which is recoverable. This averagely faults as the point where 0.2% withstand able variation achieved. [49].

The yarn is subjected stress while knitting and the strength of yarn is enough to endure this tensile stress. Standard tensile test is applied, and the yarn is enduring the high force continuously applied and breaks at one point. This point is identified as the maximum extension which is expressed as a percentage. Correlation is identified between the extension of yarn and its twist where the extension of yarn is inversely proportional to that specific yarn twist s[50].

ASTM D2256 is used to determine elongation and breaking strength of the threads which is the common standard for quantification. The principle is simple in which constant pulling force is applied until the thread breaks. The clamping happens such that, the access of machine loading tally with specimen axis. This alignment is commonly used as it is compatible reliant and repeatable. Specimen failures can cause from sharp edges which happens out of the gauge even below the actual values of strength in the yarn.

3.2.8 Static Electricity

Static electricity plays a significant role in the knittability of synthetic yarns. The phenomenon of generation is quantified with the level of electrical charge generation. Once a contact or rubbing happens between two surfaces, static electricity generation happens. An unbalance is generated in the molecule configuration of the two surfaces. This unbalance incurs static electricity in relatively nonconductive materials [51].

Static Electricity problems in knitting industry is significant in synthetic fibers and higher knitting speeds. Accumulation is easier among the electrostatic charges due to the hydrophobic nature. Several studies being carried out relevant to static dissipation and generation which will provide an understanding on the same in continuous surface of yarn. The parameters varied are the environmental conditions in relative humidity, temperature, tension of yarn and yarn. This parameter variance is higher in synthetic yarns specially. The results in literature experiments revealed significant influence in relative humidity, yarn tension, temperature and yarn speed which generates static electricity.

1. Environmental parameters, yarn speed and yarn tension influence towards generating and dissipating static electricity in continuous polyester filament yarn.
2. Changing the material attached to the continuous polyester filament yarn such as nylon, polyester, stainless steel, Teflon, Polypropylene to identify the generation and dissipation of static electricity.
3. Type of fiber used such as polyester, polypropylene and nylon in causing static generation/dissipation of finish free continuous filament yarns

4. Varying the type of fiber and filament count and test it with difference relative humidity, temperature, yarn speed and yarn tension to identify the static electricity generation and dissipation.

3.2.9 Moisture Regains

The definition of moisture content simply the percentage of moisture weight of the material and can be obtained by the difference in material weight and open dry weight. Moisture regain is the moisture percentage absorbed by the oven dry test. This is also expressed as a percentage of the total weight of the material. Literature shows that the factors like Temperature, Relative humidity and Time have significant correlation between moisture regains. Once the relative humidity is higher in the atmosphere, the ability of fabric achieving regain increases. Once the atmospheric conditions changed with a significant relative humidity variation, the material takes some time to come to its new equilibrium phase. This time depends on the physical form of the material and the ability of moisture to reach or escape from the considered fiber. But the temperature effect is proved to be very negligible on the amount of regain a yarn achieves.

In literature mainly the material related parameters are explored but, studies that consider all these parameters in an industrial knitting machine are not available in literature. There are several studies being conducted to investigate the needle movement real time on an industrial level circular knit machine to identify the effect with yarn type, yarn tension, machine running speed and fiber type including elastics. This was a novel approach and was done to find the impact and resistance applied on needles once these parameters are changed. This will be discussed deeply under the chapter on machine factors to knittability.

3.2.10 Bending Radius

Although bending radius is considered as a critical variable in defining yarn surface quality, still very less information is available in literature. The yarn creates resistance for bending which is generated by the combination of each fiber resistance force. Each fiber structure bends independently. Each has its own bending which implies non proportionality in bending resistance with the moment of inertia of the structure's cross section. The bending resistance in sum is proportional to the number of fibres in the cross section, which is again proportional to the square of the radius. Here the assumption is made that the fibres lie in simple helices within the yarn.

With this the analysis implies that the determination of the bending resistance of the fibres gives yarns bending resistance. Bending radius is understood by studying the fiber curve subjecting to a load at a certain point of the fiber length.

3.2.11 Yarn Conditioning

Once the yarn is received for the knitting area, a yarn conditioning operation is done to ensure the presence of exact amount of moisture in yarn packages. After conditioning, different properties of yarn like air permeability, tenacity, thermal conductivity, elongation at break, pilling resistance etc. get improved. The studies have identified that yarn conditioning provides better performances of yarn in the process of knitting.

3.3 Knitting Machine related Factors

Knitting machine related factors basically develops with the stresses developed among the knitting yarn and running needle hook. Stress incurring major points further can be broken down to the latch of the needle, stem, knock over process and at the withdrawal of the new loop. The major parameters looked at the previous researches includes knitting variables such as cam setting, machine speed, needle types and input and take down tension. The knitting patterns and structures developed through the program and as previously discussed, yarn properties being tested both theoretically and practically. Related to the previous researches, Wray and Burns conducted an experiment to measure the forces between the stitch, latch needle and guard cams. They developed a transducer system which calculates dynamic forces while a knitted loop is forming. Donmez and Marmarali focused on friction between yarn-yarn and yarn-needle. They have developed two equations to predict the values. A recode was done to count yarn breaks, number of machines stops, and holes for a rib one by one with a range of thirty different yarns. Another such experiment was done with purpose of weft knitting yarn breakages identification using a glass filament yarn. Hu and Zhu lead this by analyzing the effect of knitted structures, cam setting, and yarn parameters. According to the study carried out by Liu et certain yarn parameters being identified as critical on glass ply yarn knittability. He has found that a higher twist, fiber diameter with high fineness, optimized ply structure ensures higher strength and satisfactory durability Kowalski et plotted a probabilistic model to illustrate how the dynamic thread loads applied and their characteristics in this weft knitting machine knitting zone.

The concern point of occurrence is the loop formation condition. Various yarn parameters like the rigidness, diameter, friction coefficient, knit machine parameters like diameter, speed, cam shape, machine gauge, sinker and needle shape and knitting process parameters like input yarn tension, take down tension of fabric, cam settings etc. interact with each other to define the occurrence.

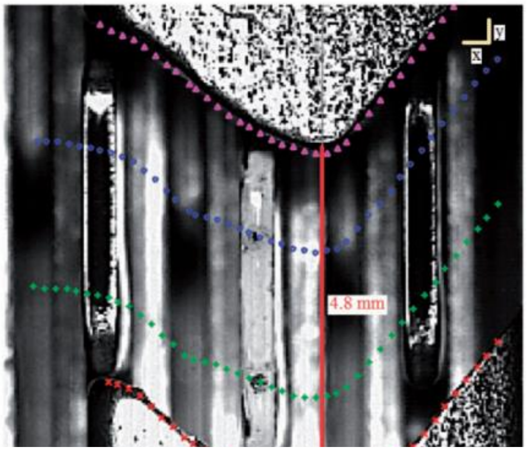


Figure 3-10: Needle movement Evaluation

3.3.1 Knitting Machine Friction

Stoll CMS 530 HP is the knitting machine used which is a multi-gauge knitting machine which can knit complex structures. Although the friction thread wheels ensure reduced and constant thread tension, the high abrasion of yarns in feed wheels can apply considerable machine friction. Stress incurring major points further can be broken down to the latch of the needle, stem, knock over process and at the withdrawal of the new loop. The major parameters looked at the previous researches includes knitting variables such as cam setting, machine speed, needle types and input and take down tension. The knitting patterns and structures developed through the program and as previously discussed, yarn properties being tested both theoretically and practically. [53].

Figure 3-11: Stoll HP 530 Flat knit machine

Figure 3-12: Feeding vector tension

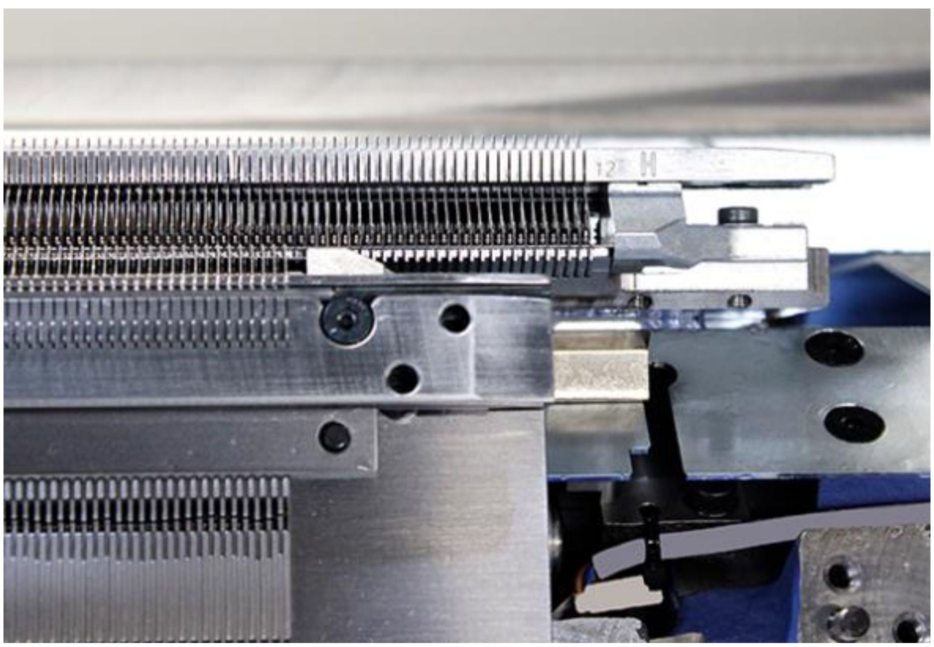


Figure 3-13: Needle point friction

Figure 3-14: Feeding Yarn to needle bed

Figure 3-11 is the flat knit machine named as Stoll HP 530 which is used in this application. Figure 3-12 indicates how the feeding vector tension is applied. Figure 3-13 is how the needle bed appears. Friction applies once the yarn rubs the needle and machine bed, which is seen in Figure 3-14.

3.3.2 Yarn Tension Effect on Knittability

The performance index of a yarn during the process of knitting can be defined as the knittability of the yarn. Knittability is a key parameter in producing knitted fabrics with good quality. The easiness of yarn being converted into a knitted fabric is increased with higher knittability. Literature proves that this can be caused due to many yarn properties including strength failure, elongation at breaking point, bending characteristics and frictional properties of yarn. Adhering to these, the ability of the yarn to cause less stress on knitting machine parts provides a better knittability.

Yarn tension is the value defines on the intensity of formation process while the knitting operation happens. Once the yarn tension is high the rate of yarn breaking increases and if the tension is less there is a chance of lapping the yarn under the needle [54]. The tension yarn achieves when going off the bobbin and additional tension arising by frictional forces between yarns and surfaces of guiding and working components. The problem is the difficulty to measure the tension at the exact point of loop formation, but the studies were done to determine tension within the threading areas in the loom from going off the bobbin to knitting area. Tension control maintenance and optimization is critical during the knitting process. Some adjustment parameters such as yarn guide position or yarn tension must be rigorously controlled with respect to tension control. Otherwise loop formation could be interrupted which can cause influence on some knitting parameters of fabric quality. However, all these studies are based on indirect methods to explain the knittability as they are being measured using indirect parameters such as number of thread breakage and number of holes in fabrics.

Although several experiments being done, optimal conditions for knitted fabric structure production is not yet being identified. Most of such experiments not being done on extreme conditions or actual production conditions and the productions were done under low stresses on needles or knitting yarns. This opens the requirement of researching the area to measure dynamic stresses under actual production conditions in terms of yarn, machine parameters and program. Here, variations in the machine and using disparate yarns specifications is required. Through this learning the second aim is to vary the knitted fabric structures and determining the optimal production settings for each [55].

However, all these studies are based on indirect methods to explain the knittability as they are being measured using indirect parameters such as number of thread breakage and number of holes in fabrics. Through these studies the presence of optimal settings depends on the application and not been thoroughly studied to realize the optimum points. [55].

3.4 General Factors

Other than the ones highlighted above, literature explains several other variables which can influence on knittability. After the initial spinning a chemical treatment is given to the yarn to achieve certain properties such as water repellency and such chemical addition or sizing can increase or decrease the strength. Further this can tender the base material which will reduce the strength of the yarn. Apart from that the fiber arrangement and the position of individual fibers can have influence on the tensile strength since the buildup of spun yarn is the resultant achieving from the combinations of twisting and drafting. The dynamic balance of the twist is influential towards the strength of the yarn since it ensures the stability of the yarn.

The objective is measuring the behavioral change in terms of fabric qualities, yarn breakages and measurements. Under the fabric quality, the hand feel, hairiness Strechability is investigated. Yarn breakages, fray yarns or yarn drops need to be zero. The knitted panel measurements should be within a defined measurement spec which is validated previously.

3.5 Literature Review Summary

Chapter has thoroughly researched previously classified yarn compound related factors, environmental and storage factors, and method related factors. Through Prisma Approach, the research database is narrowed and focused to the cause. The narrowed specific literature is further analyzed to map to understand the most critical variables and for those mentioned, experiments are defined from next stage onwards.

Further as the initial objective, drilling down of specifications and conditions of thermoplastic polyurethane yarn is described at the beginning of the chapter. The second objective is achieved of utilizing the literature review to identify the critical factors under Yarn compound related factors, Environmental and storage factors and Machine and method related factors.

4. Data Collection

The defining of the setup should be done to identify design alternatives, material evaluations, system tolerances and setting components. This will improve the robustness, reliability, and performance in knitting. Literature review is used to identify the most critical variables; therefore the experiments are designed such that they built correlations.

In the investigation done at MAS Fabrics Matrix, the available parameters for synthetic TPU yarns are studied. According to the yarn supplier specifications yarn lot number, TPU lot number and yarn code number is captured for the experimenting yarns. Yarn lot number is the core yarn production and TPU yarn coating date. TPU lot number is the TPU coating layer production date which is always earlier than yarn lot number. Yarn code number is provided by purchase order for all internal tracking.

In the laboratory, the captured parameters are denier count, tensile strength, and elongation at break. Those were considered as the major variables in the approval process of yarn in housing from the supplier.

4.1 Design for the Data Collection

Initially the main parameters which can be measured through the laboratory is captured. Yarn Tensile strength, Elongation, and Denier count is being listed under the following. Secondly, a set of experiments being planned to identify Yarn Manufacturing time influence towards the knittability. These experiments are done varying man, machine, method, and material factors. Under the critical parameters list, the next stage was to identify the Behavior of knit structure on knittability. Further research being carried out on the available knitting techniques and its feasibility to knitting Finally, Yarn unevenness testing is done on a separate experiment to identify the influence of surface thickness application towards knittability

4.1.1 Behavior of Knit Structure on Knittability

The application of knit types for advanced aesthetic has become the trend for recent developments. Current literature proves very less information regarding high-performance fibers such as high-grade synthetic yarns with the weft knitting process.

Knit Constructions

WRAP and WEFT is the two basic types of knit structures. All the knit panels are classified under these two types irrespective of it being tubular or flat knit. The knit constructions are defined within these two types.

Plain knitting structure uses single set of needles to produce the material. Stockinet, single jersey, cable knit, shaker stitch is named in industry for the same structure

Rib knitting structure uses both beds to knit two types of fabrics. This is further named as fleece knit, purl knit, interlock, sinker top etc. The flat knit machine used in the plant is having the capability to producing such complex knit structures.

Single Knits

- Single Jersey
- Lacoste

Double knits

- Rib Knit
- Purl Knit
- Interlock Knit
- Cable Fabric
- Bird's Eye
- Cardigans
- Milano Ribs
- Pointelle

Specialized Weft knits

- Intarsia
- Jacquard Jerseys
- Knitted Terry
- Knitted Velour
- Sliver Knit
- Fleece

Single knit fabric

Commonly referred as the T-shirt making fabric resulting being the highest use of fabric in the industry. This has light weight, one piled side and a jersey with single knit. This fabric is often stretchy.

Double knits

Defined as double knit because the surface is knitted double having two surfaces. Since the needle usage is twice the single knit, this has more yarn strands in the fabric. Finished fabric has two faces are combined with interlock.

4.2 Types of Data Collected

4.2.1 Yarn Tensile Strength, Elongation, and Denier Count Testing

Table 4-2: Denier count, Elongation and Tensile Strength testing

TPU yarn colours used	Yarn Testing	Knit Ability	Denier standard	Denier Actual	Tensile Standard	Tensile Actual	Elongation Standard	Elongation Actual
43G - Glacier Blue	Ok	Ok		747		1.09		15.3
43Z – Aluminum	Ok	Ok		733		0.98		12.8
83Y - Total Crimson	Ok	Ok		739		0.99		13.1
83Y - Total Crimson New	Ok	Ok		745		1.02		13.5
04Z - Pure Platinum	Ok	Ok	(690-750)	736	(0.9-1.2) %	1.02	(7-17) %	12.1
47X - Deep Royal Blue	Ok	Ok		745		1.01		16.7
10A – White	Ok	Not Ok		729		0.95		12.2
3JG – Sequoia	Ok	Ok		749		1.03		12.3
00A – Black	Ok	Ok		729		1		12.9

According to table 4-1, Initial testing was done for different colourways of TPU yarn to test tensile strength, elongation, and denier count. But the values were within the customer defined tolerance levels. The knittability is having major problems in 10A white colour yarn. Although the values of denier count, tensile standard and elongation standard is within the tolerance values defined in the resting spec, all these parameter values are at the minimum end in this colour compared to other yarn colours.

4.2.2 Yarn Unevenness Testing

Table 4-3: Measurement results of the experiment

	Black colour (g)	White colour (g)
1	0.0822	0.0783
2	0.0816	0.0775
3	0.0816	0.0785
4	0.0822	0.0782
5	0.0821	0.0781
6	0.0816	0.0779
7	0.0817	0.0780
8	0.0821	0.0776
9	0.0820	0.0777
10	0.0819	0.0782

Assumptions for the data set are as below:

- The sample size and data has been collected from a representative, randomly selected sample set
- The data has been evenly poised so that they can be plotted in a bell-shaped normal distribution

The standard for unevenness from customer was 0.075 to 0.085 range. Therefore, the test results are within the spec.

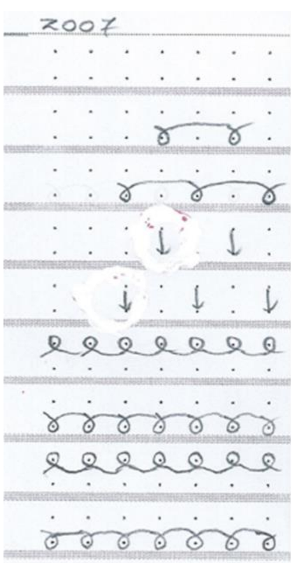
4.2.3 Research on the available Knitting Techniques and its Feasibility to Knitting

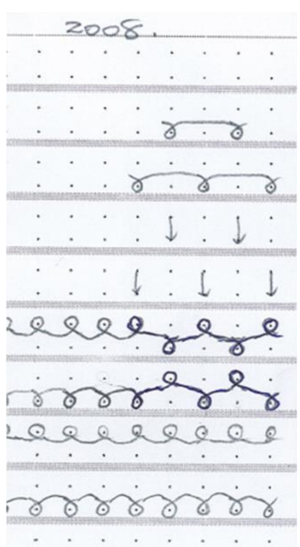
The knitting operation is done in a two-bed flat knitting machine. The central programming unit acts as the brain of the machine. The supporting functions are the yarn feeding and transmission system, fabric take-down motion, needle-bed racking system and the supporting frame. According to the central programming given, the yarn feeding system feeds the yarns located on the bobbin board with a given tension. Yarn feeds to the needle bed and knit, miss, tuck and transfer operations happens according to the given knit structures, needle point tensions and fabric take-downs.

The fabric has been manufactured on Stoll machines which are named as CMS 530 E6.2 and the program on M1 pattern station designed for this knitting machine. The system comprises of various techniques like flexible stitch technique, knit and tuck stitches with racking technique, knit and wear technique, multilayer/double (sandwich fabrics), and wedge technique (partial knitting) to improve the versatility and combination of having number of design features in the same fabrication [56].

Although several experiments being done, optimal conditions for knitted fabric structure production is not yet being identified. Most of such experiments not being done on extreme conditions or actual production conditions and the productions were done under low stresses on needles or knitting yarns. This opens the requirement of researching the area to measure dynamic stresses under actual production conditions in terms of yarn, machine parameters and program. Here, variations in the machine and using disparate yarns specifications is required. Through this learning the second aim is to vary the knitted fabric structures and determining the optimal production settings for each.

The knitting burst defect percentage was around 24.8% initially. Method improvement has been done through the knitting program to reduce the level of damages. The results are shown below:





	Defect Rate
Before method improvement	24.8%
After method improvement	11.0%
Improvement gap	13.8%

All knit structure One by one structure

Figure 4-1: All Knit structure to one by one structure

With the significant improvement of the knittability, trial has been done to develop programs with different knit structures. For that, all needle, double jersey, 1*1, 2*1, 2*2 structures being programmed, and results were verified on a theoretical basis. Figure 4-1 shows the difference of loop formation in all needle and one by one structures.

Knitting structure variation

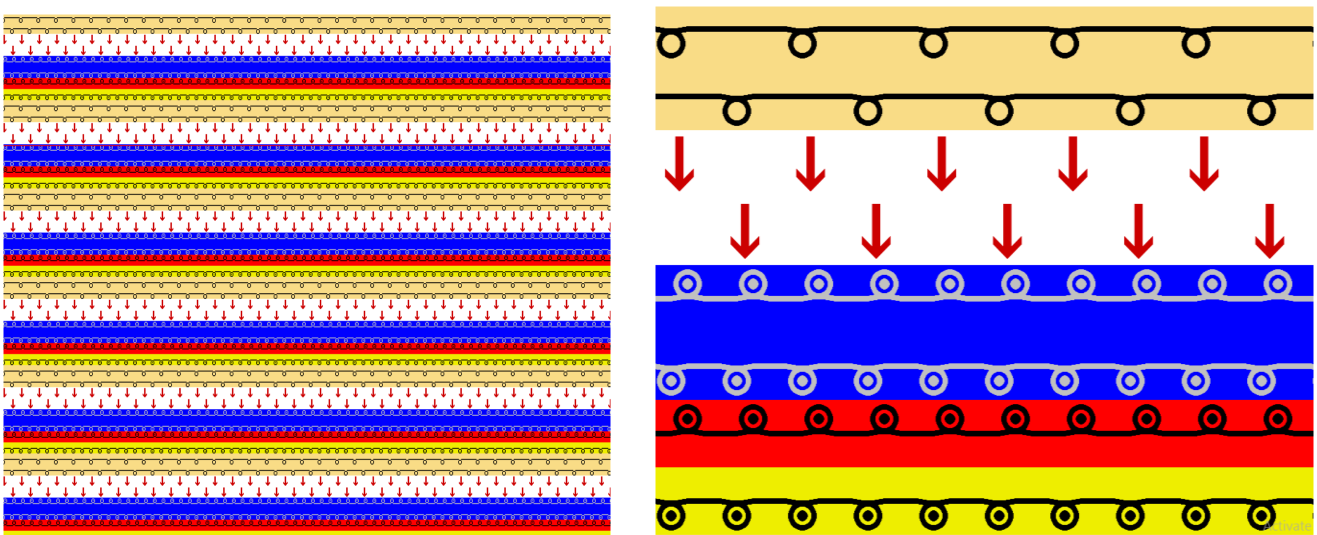


Figure 4-2: All Needle Structure from HP 530 Stoll machine

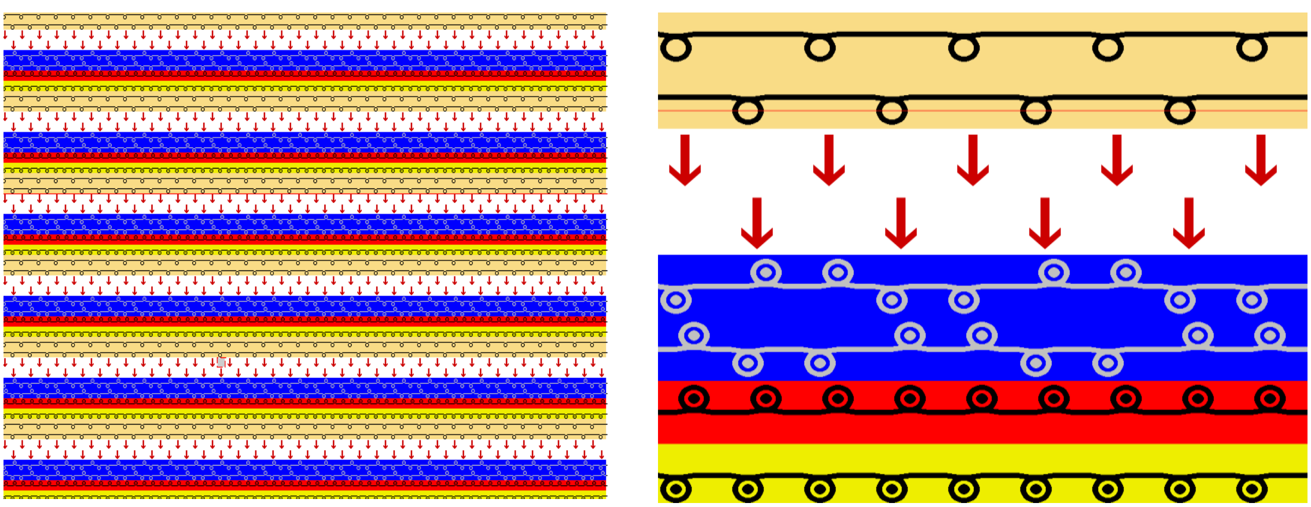


Figure 4-3 One by one structure from HP 530 Stoll machine

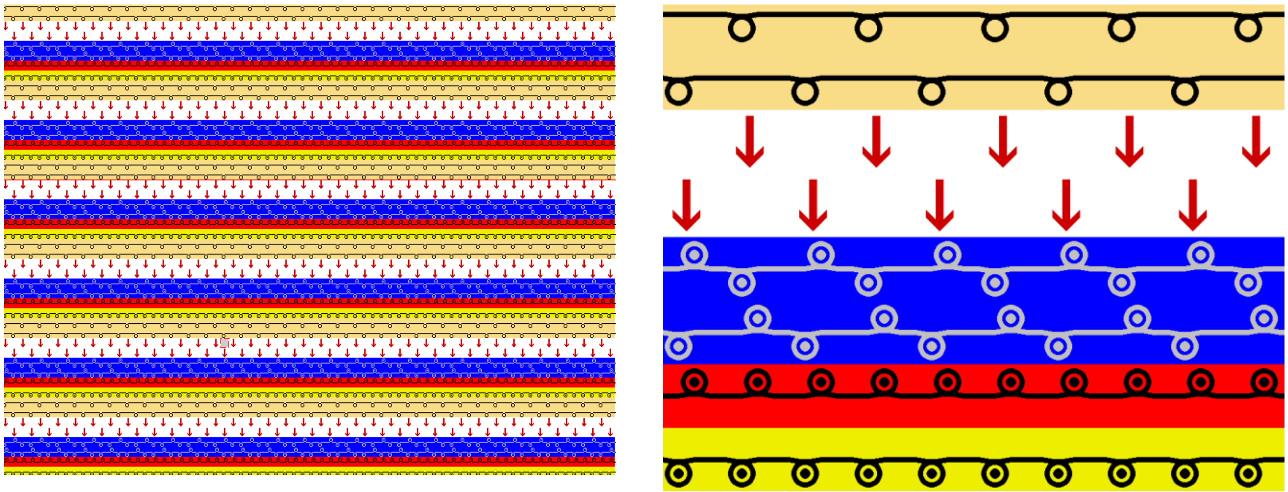


Figure 4-4: Two by Two Structure from HP 530 Stoll machine

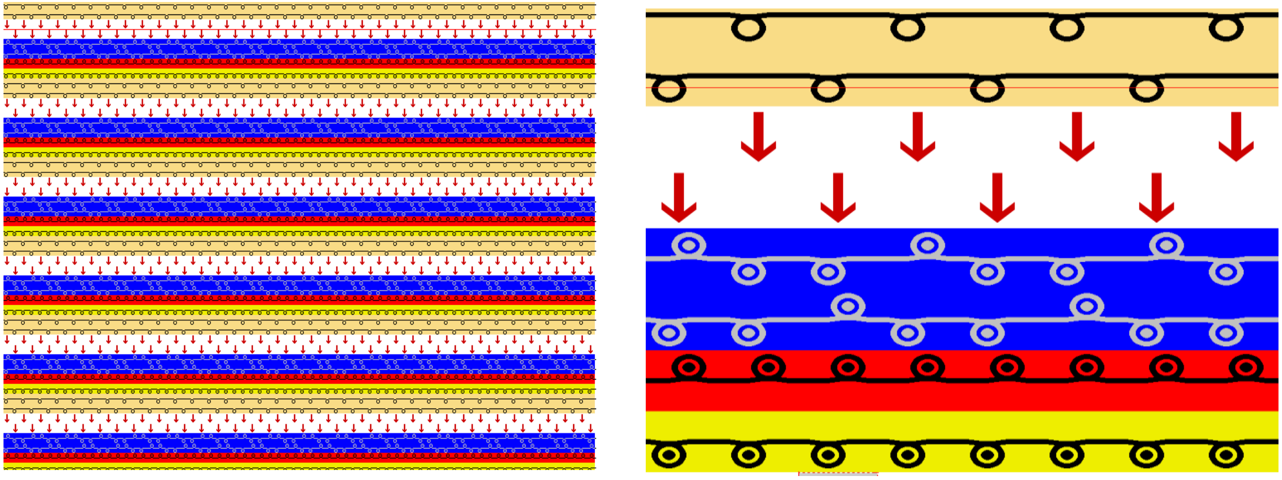


Figure 4-5: Two by One Structure from HP 530 Stoll machine

Figure 4-2 represents the all needle structure which is directly taken from the M1 plus program. Figure 4-3 is the one by one programming structure which knit and misses one loop sequentially. Figure 4-4 I the two by two structure and figure 4-5 represents the two by one structure.

4.2.4 Yarn Manufacturing Time Influence Testing

As previously classified, trials being carried out varying TPU Lot time and Yarn lot time and recorded the tensile strength, elongation and knittability. The results are shown as below.

Table 4-3: Trial 1-Model 1 yarn group 1 and 2

Model 1	TPU lot time	Yarn lot time	Tensile Strength	Elongation	Knit Ability	Defect rate
Yarn group 1	More than 6 months	Within 6 months	Within the spec	Within the spec	Fail	100%
Yarn group 2	Within 6 months	Within 6 months	Within the spec	Within the spec	Pass	0%

Table 4-4: Trial 2-Model 2 yarn set 1 and 2

Model 2	TPU lot time	Yarn lot time	Tensile Strength	Elongation	Knittability	Defect rate
Yarn Group 1	More than 6 months	Within 6 months	Within the spec	Within the spec	Fail	100%
Yarn Group 2	Within 6 months	Within 6 months	Within the spec	Within the spec	Pass	0%

Table 4-5: Trial 3-Model 1 Yarn set 2

	TPU lot time	Yarn lot time	Tensile Strength	Elongation	Knit Ability	Defect rate
Yarn Group 3	More than 6 months	More than 6 months	Within the spec	Within the spec	Pass	0% (due to TPU burst)
Yarn Group 4	More than 6 months	More than 6 months	Within the spec	Within the spec	Pass	0% (due to TPU burst)

Table 4-3 and 4-4 explains the knittability results achieved in two different models related to the variation with TPU lot time and yarn lot time. The ones with more than 6 months lead time have shown significant defect rates. Table 4-5 figures show the trial carried out reducing the knit speed of the machine, which has reduced the defect rate. This shows of a significant influence of machine speed towards the failure of the tensile strength at the loop formation point. But, reducing speed is not recommended commercially as it will increase the knit time influencing the cost of the product.

Table 4-6: Valid yarn with reduced machine speed

	TPU lot time	Yarn lot time	Tensile Strength	Elongation	Knit ability	Knitting speed	Defect rate
M/C 43	Within 6 months	Within 6 months	Within the spec	Within the spec	Pass	70	0%
M/C 44	Within 6 months	Within 6 months	Within the spec	Within the spec	Pass	70	0%

However, as per the below experiment result, the significance of the TPU lot number time does not show a correlation with defects rate.

The next experiment is carried out varying the knitting machine. The objective was to identify whether the yarn breakage issue is caused due to machine influence. But the below result shows there is no correlation between the variation of machines.

Table 4-7: Trial 5: Different yarn set with reduced speed

	TPU lot time	Yarn lot time	Tensile Strength	Elongation	Knittability	Knitting speed	Defect rate
M/C 43	Within 6 months	Within 6 months	Within the spec	Within the spec	Fail	70	100%
M/C 44	Within 6 months	Within 6 months	Within the spec	Within the spec	Fail	70	100%

The following yarn lot in table 4-7 is separately taken one which is conducted as a separate trial in the same machines which is within the defined time interval and supported through speed but still breaks. The experiments conducted by varying the machine, the material lot time intervals and then the machine speed. But all these does not show a significant relation between the yarn and TPU lot manufacturing times and knittability.

4.4 Summary

Data Collection chapter focuses on experimenting on defined variables in the previous chapters and collecting necessary data for analysis. Starting from Tensile Strength at Break, Elongation and Denier count testing, the chapter explains the experiments done on Yarn manufacturing Time influence, Behavior of Knit Structures, and available knitting techniques towards knittability, Yarn Unevenness testing and finally the mechanism of Yarn Storage. The Next Chapter focuses on analyzing the collected data to extract valid results which will lead to conclusions in the final chapter.

5. Analysis of Data

5.1 Yarn Unevenness Influence towards Knittability

Linking to the objective of this study is to understand the behavior influence of yarn unevenness and thick and thin places towards knittability. The standard for unevenness from customer was 0.075 to 0.085 range. Therefore, the test results are within the spec. Figure 5-1 and Figure 5-2 maps the black colour and white colour normal distribution of the data set. The normal distribution plot is created through Minitab software. The standard deviation values are used to map the "t" distribution.

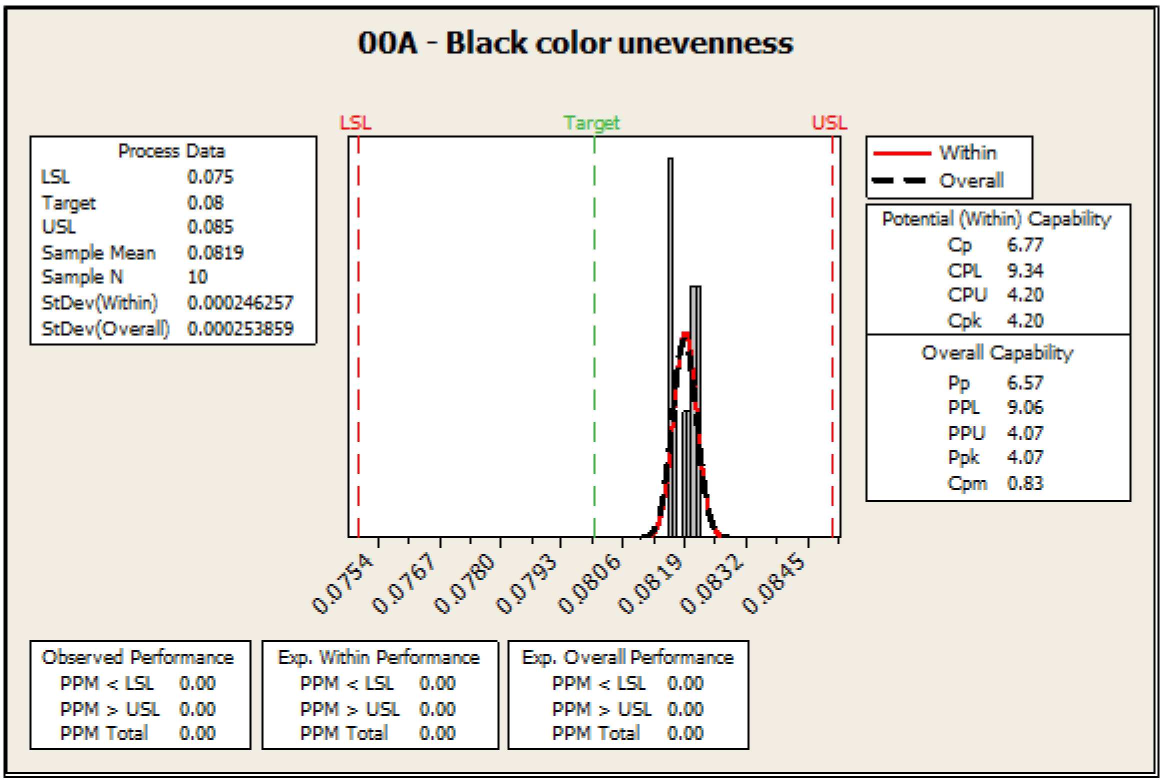


Figure 5-1: Black colour yarn unevenness

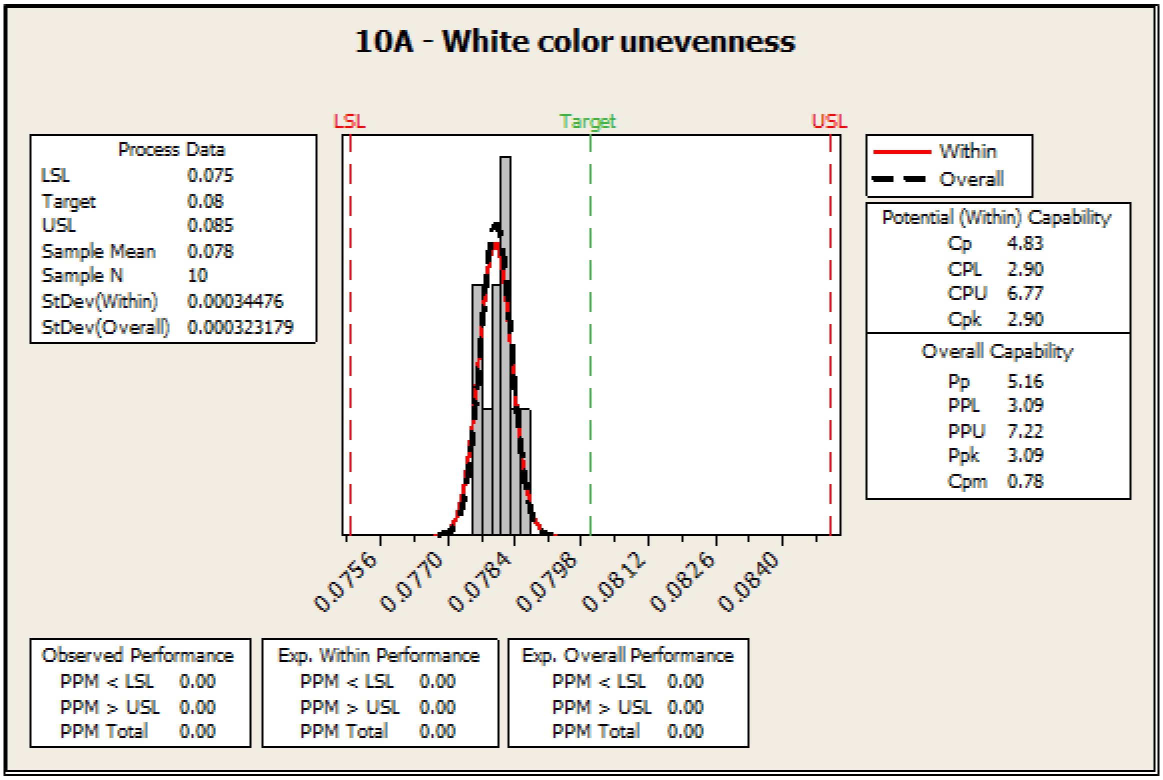


Figure 5-2: White colour yarn unevenness

Standard deviation value is a bit higher in white colour compared to black colour

	Black (A)	*White (B)*
Mean	*0.0819*	*0.078*
Standard deviation	*0.000254*	*0.000345*
Number	*10*	*10*

Significant level $\longrightarrow$ 0.001

No $\underbrace{\qquad\qquad}_{Assume}$ $= m_a = m_b$ $(null\ hypothesis)$

$Adversative\ hypothesis = 16a \ = \ M_{A \neq M_B}$

$$t = \frac{x^-_A - x^-_B}{\sqrt{\frac{S_{A^2}}{n_A} + \frac{S_{B^2}}{n_B}}} = \frac{0.0819 - 0.078}{\sqrt{\frac{0.000254^2}{10} + \frac{0.000345^2}{10}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$= \frac{3.9 \times 10^{-3}}{\lfloor 6.4516 \times 10^{-9+1.19025 \times 10^{-8}} \rfloor \, {}^{1}/_{2}}$$

$$= \frac{3.9 \times 10^{-3}}{(1.83541 \times 10^{-8}) \, {}^{1}/_{2}}$$

$$= \frac{3.9 \times 10^{-3}}{1.355 \times 10^{-1}} = \frac{39}{1.355}$$

$$= 28.78$$

The “t” value is significantly high means the groups are statistically different in terms of sample values. Since for this experiment all the other variables being kept the same expect for yarn, this variation implies of a correlation between the yarn unevenness and knittability.

5.2 Analysis on Optimum Knitting Structures and Techniques

Linking to the Objectives of this study is to critically analyze knitting structures influence on knittability and discover the optimum knit structure under machine and method related factors. Together with the different programs identified at the methodology, knittability trial has been done. The results for each program in 4 Yarn tensions are mapped machine top tension point, feeding to machine side tension point and knitting at the machine bed point and plotted to figure out how the tension simulates.

Table 5-4: Knit Structure vs Defect Rate

Structure	M/C No				Total Good Qty	Total Good Qty %	Total Damage Qty	Total Damage Qty %
	43	44	45	46				
All Knit	7/10	7/10	10/10	7/10	31	77.5%	9	22.5%
One By One	7/10	8/10	10/10	10/10	35	87.5%	5	12.5%
Two By One	9/10	10/10	10/10	9/10	38	95.0%	2	5.0%
Two By Two	8/10	10/10	10/10	10/10	38	95.0%	2	5.0%

According to Table 5-1 the structures are tested in four machines and defect rates are calculated. All needle structure had higher defect rates compared to the other structures.

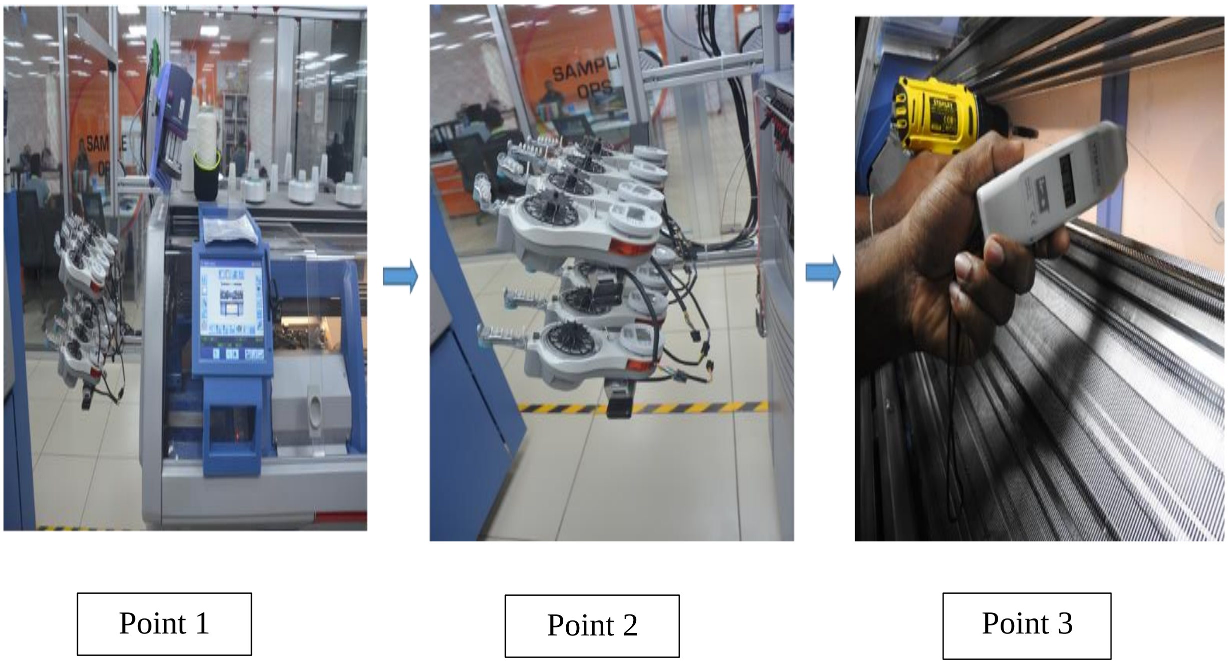


Figure 5-3: Tension reference points in the Stoll machine

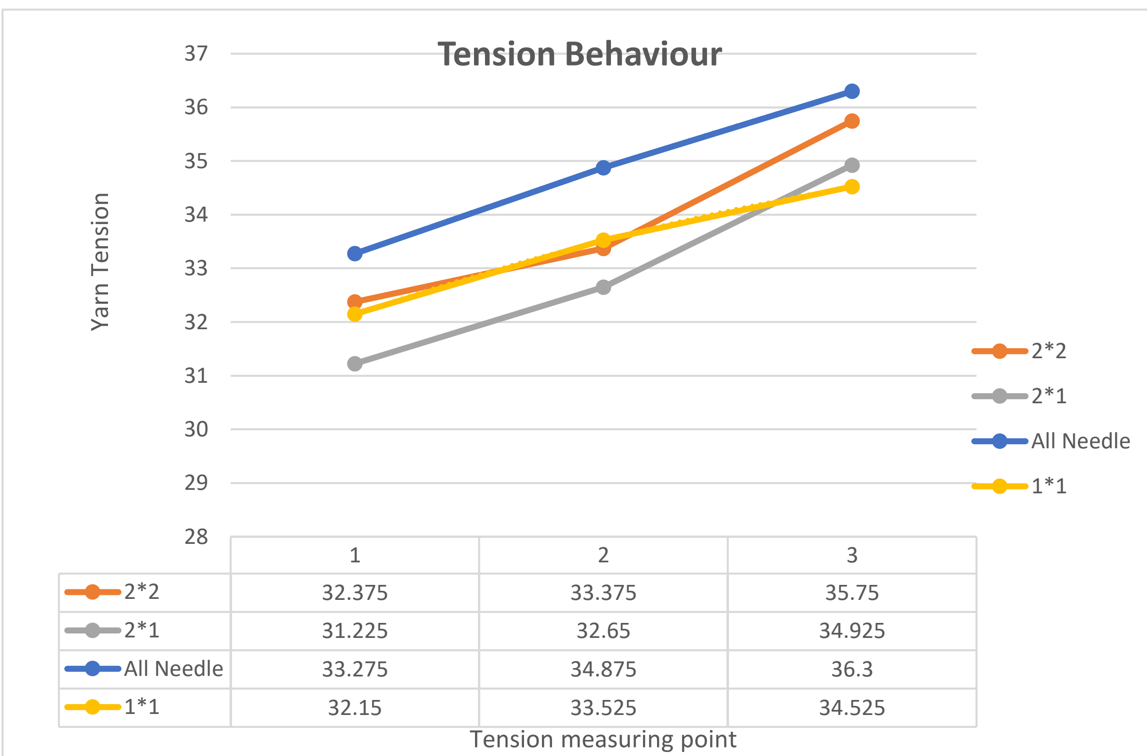


Figure 5-3 indicates the three tension measuring points of Top tension, Side tension and needle point tension. Figure 5-4 implies how the average tension values behaved considering a point of time in the process. Yarn tension is mapped according to different structures programmed as previously mentioned. Among these 1*1 structures is having the lowest of tensions at the feeding point. All needle structure is having significantly high-tension values while the other two behaves in between. According to the defect rates we have identified that two by one structure and two by two structure are having lowest defect rates. But considering the aesthetics one by one structure is having better similarity to original all needle structure. Therefore, although one by one structure is having a bit higher defect rate compared to the other two structures, it is selected with the customer requirement on the appearance. Further considering with the results since the tension values and the gradient is low, 1*1 structure is identified as the optimum. The reason for developing an empirical graph is developing a precise mathematical tension model is hard with time to time variation of tension values [57].

5.3 Analysis of Yarn Manufacturing Times for Knittability

Linking to the Objectives of the yarn manufacturing time influence study is to critically analyze TPU and yarn lot times influence towards knittability under environmental and storage factors. 20 yarn samples being used for each set in all the trials, but still delaying of TPU and yarn lot numbers more than 6 months does not show direct impact on knittability. As for the future research, the considered sample size should be validated to understand whether there is any correlation between knittability and manufacturing time once the sample size is high.

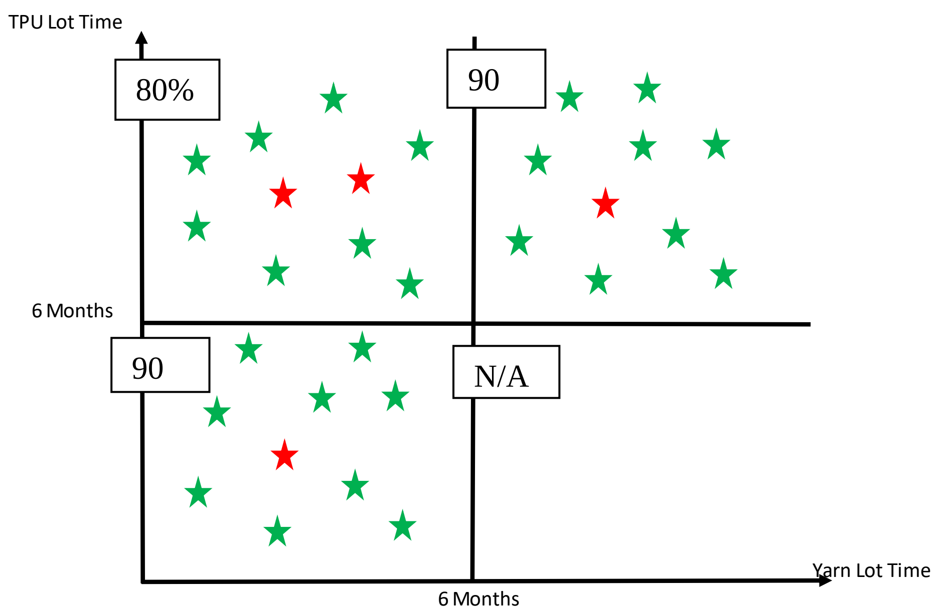


Figure 5-4: Trial results breakdown with yarn manufacturing times

5.4 Yarn storage conditions

It is necessary to know the general principals of care and storage of materials because they differ greatly in their resistance to various dangers such as moisture, temperature, relative humidity, absolute humidity etc.

Figure 5-5: Yarn Storage Racking

Yarn storage is done under the conditions of 25^0C to 29^0C temperature range and 60% to 70% relative humidity range. Following parameters being strictly controlled. Figure 5-6 visualizes how the racking system exists for the considered yarns.

5.5 Summary of Results and Analysis Chapter

Initially the results analysis carried out for yarn unevenness in two colourways. “t” distribution clearly states that there is a statistical variation between the two data sets. This opens the requirement in further research to find the exact correlation. Next the closest and most applicable knit structures were analyzed by keeping all the other variables the same. Here compared to the initial all needle structure, the one by one, one by two, two by two structures indicate less tension values and better knittability. Although two by one and two by two indicates the best knittability, the one by one structure is selected since it is the closest to the aesthetic appearance of all needle structure which ensures the customer requirement. But in a separate type of an application where this appearance differs, this finding will give even better results. Analysis of time influence is mapped onto a graph with axis of TPU lot time and Yarn lot time. With the tested data set, the correlation was not significant with manufacturing time and defect rate. But still research opportunity opens to ensure all the other parameters such as Relative Humidity, Absolute Humidity, Temperature to be monitored deeply and test this with a larger data set.

6. Results, Discussion and Conclusion

On the final note, the literature review has been done about a knitting concern on a specific polyester yarn namely Thermoplastic Polyurethane yarn. Background research has been done to understand the manufacturing process, specialties, and applications in a broader sense. Then the scope is narrowed down to the thermoplastic polyurethane yarn. The manufacturing process and aging behavior of it is investigated through the available literature. According to the research findings it shows that subjecting thermoplastic polyurethane to the combined effects of thermal degradation and photo-oxidation has significant effect on its properties. The dependence of certain aging parameters, namely time, temperature and moisture absorption and correlation of each is yet to explore out which will be one of the key focus areas in this research.

Through the literature all the affecting parameters of TPU yarn breakage is listed down under 4 categories namely yarn manufacturing conditions, yarn storage conditions, knitting machine conditions, knitting pattern conditions and environmental conditions. Depending on the severity each creates on the yarn burst concern, all the possible causes being listed under three categories namely yarn compound related factors, environmental and storage related factors, and method related factors. Under each section the critical parameters relevant to each factor being identified after analyzing the significance of each quantitatively and qualitatively. The root cause for the burst is being identified as the strength failure of yarn which can cause under yarn aging, yarn unevenness and method related factors. Under yarn aging, TPU lot production time, yarn lot production time, storage conditions, Yarn storage humidity and yarn storage temperature are being identified as the critical factors. Under yarn unevenness, yarn twist and fiber fineness have been identified as critical while knit structures and patterns being critical relevant to the method related factors. Introduction for each factor is presented through the literature.

The next step is to carry out experiments under each parameter to understand the significance each creates on the yarn burst. This can be one or combination of factors. Yarn testing, pattern variations yarn storage experiments are figured out for the next stage to conclude this by identifying the root cause and to provide permanent countermeasures for the problem.

6.1 Key Findings

- Experiments carried out for Denier count, Elongation and Tensile strength under the given protocol and the results were within the tolerances. But the colourway which had poor knittability, was having comparatively less tensile strength and elongation values. Although the values were within the customer given tolerances, the values being at the minimum ends signifies a drop in tensile strength and elongation of the yarn
- With the number of trials done, correlation with knittability was insignificant with yarn fiber and Thermoplastic Polyurethane polymer manufacturing times.
- Knittability increases once the knitting machine feeder system running speed reduces. This happens with the slow feeding of yarn to form the loop at the point where the highest tensile strength is required. But this is not commercially viable since the slow speed will cause the machine to run longer times which ultimately increases the power consumption to run the machine
- All needle, one by one, two by one and two by two knit structures being simulated to identify the tension map throughout the cycle. By the results, one by two, two by two and one by one structures had the lower tension values at the feeding point whereas all needle structure being the highest. Although the knittability is high in two by two and two by one structure, considering the aesthetics and initial appearance from all needle structure, the settings of knit structure need to be changed to one by one to improve knittability

6.2 Limitations

Although the testings are done for the given yarns under the parameters like tensile strength, elongation, denier count etc. the study wasn’t done at the manufacturing point of the yarn. The only possibility we had was to inspect the supplier sent yarns according to given testing spectrums. If we had the chance to inspect the process at the start of the yarn manufacturing point, much more critical variables might have incurred into the investigation.

Limitation existed in finding the proper yarn friction testing equipment and the method. This is cleared through the application of a lubricating oil, but it is recommended to test the friction with a proper equipment to identify yarn surface behavior.

In the investigation on TPU material behavior consideration limited number of parameters mentioned in the literature review. But dependence of certain parameters such as temperature, time and moisture absorption must be further monitored in future works. Further, the influence on mechanical and physical factors under such variable conditions is open for investigations.

6.3 Future work

In future work, it is recommended to go through the manufacturing process of the yarn material to identify the critical variables influencing while at the stage of yarn forming.

In the investigation on TPU material behavior consideration limited number of parameters mentioned in the literature review. But dependence of certain parameters such as temperature, time and moisture absorption must be further monitored in future works. Further, the influence on mechanical and physical factors under such variable conditions is open for investigations.

Further, the knit pattern variations, yarn storage experiments should have to be carried out deeply. These need to be figured out for the next stage to conclude this by identifying the root cause and to provide permanent countermeasures for the problem.

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