ANALYZING THE THERMAL SHRINKAGE BEHAVIOR OF POLYESTER/ ELASTOMERIC WEFT KNITTED FABRICS

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ABSTRACT

Thermoplastic polymer fabrics are normally heat set to make them dimensionally stable. These fabrics in garment panel form may again be exposed to heat during the processes such as rubber print curing and cause to change their dimensions. The key issue addressed in this study; the thermal shrinkage of heat-set polyester/elastomeric knitted fabrics during post-heat treatment processes which is a practical and a current problem in the garment industry.

The thermal shrinkage behavior of heat-set polyester knitted fabrics, under a wide range of conditions, mainly to simulate the post-heat treatment processes, using geometric and thermodynamic parameters were investigated. The findings present a statistically sound analysis of different thermal behavior patterns, while examining their causes based on both material properties and dimensions of the plain knitted fabrics.

The key findings reveal that heat-setting and heat-curing temperatures have a significant effect on thermal shrinkage behavior. Thermal shrinkage in course direction is highly related to the width-wise extension applied during heat-setting and the wale direction is highly correlated to the shrinkage behavior of the yarns in hank form. Noticeable changes in polyester thermal behavior occur at 160°C and thermal shrinkage is heavily influenced by thermal history of materials. Taut-end and slack-end conditions maintained while heat-setting and heat-curing significantly affected thermal shrinkage. The higher percentage of overfeed during heat-setting leads to lower thermal shrinkages in subsequent thermal activities.

Thermal shrinkage was evidence of a change in the structural parameters of knitted material. Structural changes are mainly due to the change of shape of the loop and/or thermal shrinkage of the stitch length. The introduction of elastomeric yarn to the polyester knitted structure led to make more thermally stable fabrics. In order to reduce thermal shrinkage during subsequent heat treatment, a high temperature heat-setting and a moderate percentage over feed should be retained during thermal setting.

The post heat treatment results revealed that the low temperatures during heat treatments though have no trend but causes comparatively low thermal shrinkage or expansion, it is safe and advisable to use low post heat setting temperatures where possible.

Key words: Polyester, Spandex, Plain knitted fabric, Thermal shrinkage, Post-heat treatments

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List of Abbreviations

Abbreviation	Description
ANOVA	ANalysis Of VAriance (ANOVA)
DSC	Differential Scanning Calorimetry
XDR	X-ray Diffraction
NMR	Nuclear Magnetic Resonance
FOY	Fully or High-speed spun Yarn
HMLS	High-Modulus and Low-Shrinkage
HOY	Highly-Oriented Yarn
LOY	Low-Oriented Yarn
MOY	Medium-Oriented Yarn
PBT	PolyButylene Terephthalate
PET	PolyEthylene Terephthalate
POY	Partially-Oriented Yarn
TTM	Taut Tie Molecules
WPI	Wales Per Inch
CPI	Courses Per Inch

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1 INTRODUCTION

1.1 Background of the Problem

Polyester, a thermoplastic polymer fibre, which has outstanding mechanical, physical, and enduring properties, is commonly used in manufacturing fabrics (Rudolf, Geršak, & Smole, 2011). Polyester is used in both knitted and woven fabrics as 100% polyester or blended with other fibres. Together with elastane, polyester is used to produce woven and knitted fabrics with excellent physical, mechanical and chemical properties. Knitted fabrics have the important advantage of being flexible and maintaining the ideal structural arrangement during use. However, both industry practitioners and researchers have found, maintaining the dimensional stability or resistance to stretch and shrink (Matlin & Nuessle, 1955), as a challenge in processing, manufacturing and use of polyester in knitted fabrics.

The most important advantage of knitted fabrics is the flexibility to deform the structure and maintain the ideal arrangement during use. Achieving ideal dimensional stability of knitted fabrics is yet to be a major concern of textile manufacturers, garment manufacturers and researchers. Knitted fabrics are susceptible to external influences due to the looped structure and can cause dimensional changes. Knitted fabrics made out of thermoplastic materials have an additional factor that causes dimensional instability. Manufacturing processes that involve heat causes dimensional changes in thermoplastic materials. Heat-related deformations are undesired in thermoplastic fibre textiles as they can easily form creases and wrinkles at moderately high temperatures and retain these creases and wrinkles at lower processing temperatures because of their thermoplastic character (Matlin & Nuessle, 1955). The most effective way to preserve dimensional stability in thermoplastic fibre fabrics has been identified as the heat-setting or heat treatment at elevated temperature with dimensional control (Matlin & Nuessle, 1955). Heat-setting requires the fabric to be subject to higher temperatures than those likely to be met in its subsequent use (Arghyros & Backer, 1982; Liu et al., 2016; Marvin, 1954).

Heat-setting of thermoplastic filaments provides dimensional stability and many other properties for subsequent processing conditions. The purpose of heat-setting is

to establish molecular configurations by supplying molecular chains with thermal energy to eliminate instability and relax the filament stresses incurred during earlier production phases (Venkatesh, Bose, Shah, & Dweltz, 1978). Heat-setting causes to relax the fibre stresses incurred during spinning, drawing and twisting in order to maintain twist, crimp, bulk, strength and dimensional stability in subsequent processes and to establish flat fabric geometry (Arghyros & Backer, 1982). With the advancements in technology and increased use of thermoplastic fibre materials in fabrics, new and/or existing processes such as panel printing, heat transfer printing, bonding are heavily utilized during the manufacturing process of the garments to impart quality, aesthetic and performance characteristics. Some of them are performed at high temperatures in specified conditions. Many of these embellishment processes are applied during the garment production and on fabrics in garment panel form.

Although it is expected to have high dimensional stability of the heat-set polyester plain knitted fabrics, further deformation is observed due to the heat applied during the above mentioned subsequent processes to heat-setting. Since these processes are applied on garment panel form, mechanisms to control dimensional stability are not possible/currently unavailable. The dimensional change cause by these post-heat treatments is a serious setback as it can cause product rejection or interruption of the manufacturing process leading to financial losses. Although many researchers have discussed thermal shrinkage of polyester fibres and yarns (Arghyros & Backer, 1982; Batra, 1976; Gupta, Majumdar, & Seth, 1974; Marvin, 1954), the thermal shrinkage behavior due to post-heat treatment processes polyester knitted fabrics were not covered in previous studies.

Thermal shrinkage of heat-set polyester knitted fabrics, in post-heat treatment processes are a practical and a current problem in the garment manufacturing industry. Under highly dynamic and time critical requirements of the textile and clothing market, failure to ensure dimensional stability of products can pose unacceptable financial risks. Therefore, it is essential to provide a solution to address the thermal shrinkage behavior of 100% polyester and polyester/elastane plain knitted fabrics.

1.2 Introduction to Thermal Shrinkage

Swelling, felting and fibre relaxation are well known to deform hydrophilic fibres such as cotton, wool and acetate as moisture and steam can easily alter hydrophilic fibres (Black, 1974; Heap et al., 1985; Onal & Candan, 2003; Van Amber, Niven, & Wilson, 2010). Moisture has less affect on thermoplastic synthetic fibre materials due to the hydrophobic nature of these synthetic fibres. Instead heat has effects over the thermoplastic synthetic fibre materials (Ghosh, 2006; Matlin & Nuessle, 1955; Rodriguez-Cabello, Santos, Merino, & Pastor, 1996; Stein & Misra, 1980). The thermal deformation either in thermal shrinkage or thermal expansion of semi-crystalline, oriented, thermoplastic fibres like nylons and polyesters is well known (Ribnick, Weigmann, & Rebenfeld, 1973). When these fibres are exposed to temperatures above the glass-rubber-transition but still well below the crystalline melting point, a substantial length decrease have been observed (Ribnick et al., 1973). Thermal exposure deformations are known causes for the dimensional distortion and instability of thermoplastic polymer materials (Arghyros & Backer, 1982; Batra, 1976, 2006; Haar, 2011; Marvin, 1954).

Previous findings described the thermal deformation of polyester using multiple mechanisms. Thermal distortion can be either a thermal shrinkage or a thermal expansion depending on the physical conditions maintained during thermal exposure (Rath, Chaki, Khastgir, 2011). Molecular disorganization and rearrangement (Matlin & Nuessle, 1955; Prevorsek et al., 1974; Ribnick et al., 1973), disorientation of oriented amorphous chains or extended interfibrillary tie molecules (Huisman & Heuvel, 1989; Nobbs et al., 1976; Peterlin, 1977; Prevorsek et al., 1974; Wilson, 1974; Wu, Yoshida, & Cuculo, 1998), crystallization (Ribnick, 1969), chain folding (Dismore & Statton, 1966; Dumbleton, 1970b; Dumbleton, Bell, & Murayama, 1968; Prevorsek & Sibilia, 2006; Statton, Koenig, & Hannon, 1970; M. P. W. Wilson, 1974) were identified as the main causes of thermal shrinkage. These investigations and related structural and other aspects led to the conclusion that the overall process of deformation depends on the temperature, time and forces applied during the heat-setting period.

1.3 Impact of Thermal Shrinkage Behavior of Heat-Set Polyester Knitted Fabrics on Sri Lankan Garment Industry

Sri Lanka is one of the leading garment manufacturers in the Asian region. Design, manufacture and export of textile and apparel are one of the largest industries in Sri Lanka and plays a key role in supporting the economy of the country. The production of sportswear, active wear, leisure wear and intimates apparel have become highly innovative fields that invest heavily on research and development. The use of synthetic fibre knitted fabrics has become the key raw material for many of the popular branded sportswear and active wear produced in Sri Lanka. The excellent mechanical, physical and chemical properties with excellent stretch and recovery properties possess by the synthetic knitted materials have become the best choice for the sportswear, active wear and intimates garments. The trends towards innovation and creativity have led the textile and apparel industry to intense use of new technologies. The sportswear and active wear with many localized print patterns in a single garment have led to the use of technologies like sublimation printing and rubber printing in garment cut panel form. Maintaining accepted dimensional stability when garment panels subjected to post-heat-treatments hence become critical for the Sri Lankan garment manufacturers due to the existing trend of garment industry towards more synthetic apparels with designer and innovative technologies.

The post-heat-treatment processes are often used in garment cut panel form in the garment industry. Printing in garment cut panels is such a process widely and intensively used in many categories of apparel industry such as sportswear, active wear and casual wear. The printing process has two distinct stages; print placement and print curing. Print curing is performed at elevated temperatures to facilitate proper adhesion and drying of printing paste on the material. Heat treatment during printing incurred as a curing or intermediate drying process in any graphical embellishment process. Along with print curing, thermal deformation of the fabric panels can also occur due to heat, if the material is thermoplastic. Since there is little awareness of controlling thermal shrinkage in knitted fabrics, additional allowances are added to the garment panels which are subject to graphic embellishments. This

additional fabric allowance incurred extra material costs and ultimately increases the cost of production. Despite these precautions, if the garment panel size becomes smaller than the specified dimensions due to heat, the panel has to be discarded. If the garment panel expands, then the alteration has to be done in order to get the required dimensions of the final product.

There are a number of processes to follow when preparing garment panels for application of embellishment that involve post-heat treatment. The ordering of fabrics, the making of markers, cutting and bundling are few major steps in the preparation of the garment panel. The entire process has to be repeated if the panels of the garment have been deformed during the application of embellishment and the panels of the garment has to be re-prepared. For this requirement, in the absence of the requested fabric in the garment factory or in the textile mill causes the required fabric to be reproduced. This is a long and time consuming process, as well as time and rework incurred by the value as well as the reputation of fabric and garment manufacturer.

Due to not having complete understanding on the thermal shrinkage behavior of polyester fabrics, the inconsistency of the thermal shrinkage between the fabric rollers in the same production batch is also inevitable. In such a situation it is necessary to observe critically the thermal shrinkage of each fabric roll. If large production batches are involved, this monitoring process becomes complicated. Further, in order to equalize the thermal shrinkage defect, the highest value of thermal shrinkage must be added to the garment panels for production.

1.4 Research Problem Statement

It is evidence that the key issue addressed in this study - thermal shrinkage of heat-set polyester knitted fabrics during post-heat treatment processes is a practical and a current problem in the garment manufacturing industry.

- Main research question

  To anticipate the thermal shrinkage of polyester plain knitted fabrics subjected to heat treatment processes at elevated temperatures subsequent to heat-setting?

- Partial research questions

  The extent of dimensional change in single jersey plain knitted polyester fabrics when subject to heat treatment processes succeeding to heat-setting

  What correlations describe shrinkage to yarn, knitting, structural and thermal parameters of a single jersey plan knitted polyester fabric subjected to heat treatment processes?

  What are the key recommendations to minimize shrinkage of single jersey plan knitted polyester fabric during the heat treatment processes subsequent to heat-setting?

Considering the research problems the following main research aim was decided.

- This research aims at analyzing the thermal shrinkage behavior of polyester plain knitted fabrics due to post-heat treatment processes subsequent to heat-setting process and to provide recommendations to minimize thermal shrinkage.

1.5 Research Objectives

1. To investigate the thermal shrinkage behavior of commercially used polyester/elastomeric plain knitted fabrics subjected to heat treatment processes subsequent to heat-setting.
2. To develop a testing method to measure thermal shrinkage of knitted fabrics
3. To investigate thermal shrinkage behavior of single jersey plain knitted polyester/elastomeric fabrics of different tightness factors.
4. To identify empirical relationships to predict the thermal shrinkage of polyester/elastomeric plain knitted fabrics
5. To provide recommendations to minimize thermal shrinkage upon heat treatment subsequent to heat-setting process

1.6 Significance of the Study

Heat-setting processes are known to be the most effective ways to reduce or eliminate thermal distortion of thermoplastic materials (Caihong et al., 2014;

Cullerton, Ellison, & Aspland, 1990; Dennis & Buchanan, 1987; Karmakar, 1999b; Khandaker et al., 2014; Wang & Hu, 1997a). Therefore, heat-setting has been the standard practice in the industry to stabilize thermoplastic fibre fabrics. However, after cutting the heat-set fabrics into garment panels, some of them may have to undergo through processes that involve heating of the garment panels. This behavior is not an accepted standard in the garment as well as textile industry since one of the main quality parameters; the dimensional stability is mainly affected.

The thermal shrinkage of spun, drawn and textured fibres or yarns has been discussed at length by varying production parameters and thermal process parameters by many researchers (Fischer & Fakirov, 1976; Phillips et al., 2003; M. P. W. Wilson, 1974). Many systems and mechanisms are in place in the industry to minimize these distortions in textiles and in clothing (Heap et al., 1985; Karmakar, 1999b; Quaynor, Nakajima, & Takahashi, 1999; Rath, Chaki, & Khastgir, 2008). Due to the structural complexity of knitted fabrics, the thermal shrinking behavior of heat-set thermoplastic knitted material is still not well understood. However, researches have been carried out to understand thermo mechanical behavior of polyester fibres and yarns. The thermal treatments may lead to yarn shrinkage or distortion of the loop or both to the gross fabric distortion. It would therefore be crucial to analyze the thermal shrinkage behavior of knitted thermoplastic fabrics, as the use of such products in the garment industry is enormous.

The finding of this study will contribute to the benefits of the garment manufacturer; fabric manufacturer and researchers considering that achieving the required dimensional stability play an important role in textile industry. The key issue addressed in this study; the thermal shrinkage of heat-set polyester knitted fabrics during post-heat treatment processes which is a practical and a current problem in the garment industry.

In this study the thermal shrinkage behavior of heat-set polyester knitted fabrics, under a wide range of conditions, mainly to simulate the post-heat treatment processes, using geometric and thermodynamic parameters were investigated. The findings of this study present a statistically sound analysis of different thermal

behavior patterns, while examining their causes based on both material properties and geometry of the plain knitted fabrics.

As issues related to thermal shrinkage are among on-going critical issues in textile industry, the industry related problem addressed in the study will interest a wide readership of both industry practitioners and researchers.

1.7 Scope and Limitations

In this study the heat-setting process and post-heat treatment processes were performed under wide range of conditions. The fabric geometry, material properties and thermodynamic parameters of heat-set and post-heat treated fabrics were theoretically and statistically analyzed. The main heat-setting parameters which were taken into study were heat-setting temperature and the overfeed percentage. Four main post-heat treatments were selected for the initial study and heat-curing process was selected as the post-heat treatment process for further study.

1.7.1 The following main areas were discussed in this study

- Significance of thermal shrinkages due to post-heat treatment processes
- Effects of panel parameters and heat-setting temperature on thermal shrinkage
- Thermal behavior of heat treated polyester plain knitted fabrics
- Comparative study on the thermal shrinkage behavior of polyester yarn and its plain knitted fabrics
- The influence of over feed during heat-setting on the thermal shrinkage behavior
- Thermal shrinkage behavior of polyester/elastomeric plain knitted fabrics

The effect of heat-setting time duration was not studied under this research and recommended for further studies. The various fabric panel shapes were not included and can be performed as a further study.

2 LITERATURE REVIEW

2.1 Use of Polyester in the Textile and Apparel Industry

Polyester is one of the most popular fibres used in the textile and apparel industry. Terylene® was first synthesized by W.H Carothers. During 1930s and 1940s, Polyester fibre was developed by DuPont Corporation for mass consumption. It is difficult to find consumer garments that does not containing at least a certain percentage of polyester fibre.

The major manufacturers of polyester are China, Taiwan, Korea, India, Japan and United State of America (USA). Once polyester fibres are produced in China and other Asian countries, they are mainly used in Asia for the production of polyester consumables. China accounts for 69% of all polyester fibre production globally, while India and Southeast Asia add up to 86% of global production.

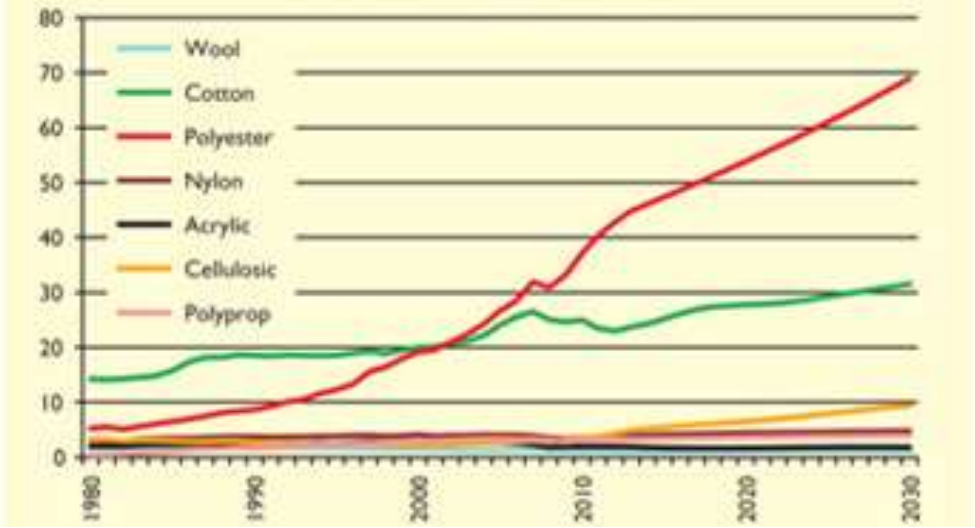


Figure 2.1 : The demand of polyester from 1980 to 2030 (Carmichael, 2015)

Figure 2.1 presents the history and forecast of fibre demand in millions of tonnes, showing the dominant role of polyester in the growth of fibre demand. The diagram also shows the continuing dominance of polyester, as calculated by PCI Fibers based in England in its forecast for 2030. Polyester demand increased cotton production in 2002 to a much faster rate than all other fibre types. As per the forecast results the demand for polyester was only 5.2 million tons worldwide in 1980, and reached 19.2 million tons in 2000. Demand is set at 46.1 million tons in 2014. From 1980 to

2014, total demand for fibre increased by 55.7 million tons, of which 73.4 percent was occupied by polyester. Demand was stated as 55.42 million tons in 2019.

2.2 Polyester

2.2.1 What is polyester?

Polyester is the type of polymers with functional ester group in the main chain. While several polyester forms exist, the term polyester primarily applies to poly(ethylene terephthalate) (PET) and poly(butylene terephthalate) (PBT) in industries (Gschel, 1996). Due to its high melting point, good mechanical properties and chemical resistance, polyester is one of the most multifunctional thermoplastic polymers in plastics, films and fibres (Liu et al., 2016). The high glass transition temperature (T_g) and slow crystallization rate of PET provides many methods to control its morphology in order to obtain desired properties (Liu et al., 2016). The desirable properties such as clear, lightweight, high strength, high stiffness, favourable creep characteristics, high chemical resistance, barrier properties and low price make polyester of choice for using as containers, fibres and films.

2.2.2 Chemical structure of polyester

The first process of industrial production of polyester is the condensation polymerization. Condensation polymerization occurs at high temperatures as terephthalic acid and ethylene glycol alcohol react (Han, Sarathchandran, & Thomas, 2012). After polymerization, the material is extruded in the form of a ribbon to a casting trough. After cooling, the ribbon hardens and is cut into chips for further processing.

Polyester can be classified as thermoplastic or thermosetting polymer depending on the chemical structures (Gschel, 1996). Aromatic–aliphatic polyesters are generally high melting semi-crystalline (150°C -270°C) materials that find applications as engineering thermoplastics, films, or fibres (Brown, 1999). Figure 2.2 presents the reaction between acid and alcohol condensation polymerization to produce polyester.

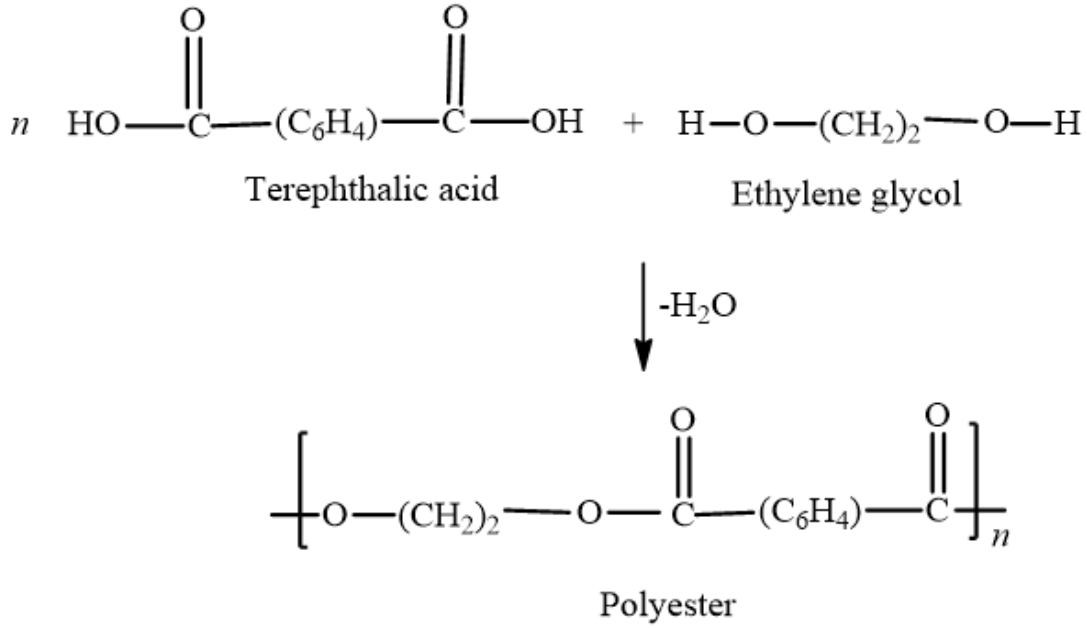


Figure 2.2 : Condensation polymerization of terephthalic acid and ethylene glycol (Oxtoby, Gillis, & Campion, 2011)

2.2.3 Different forms of polyester

PET is a crystallizable polymer due to its regularity in chemical and geometric structure. ' Crystalline ' means that the polymer chains are parallel and ' amorphous ' means that the polymer chains are distorted (Kajiwara & Ohta, 2009). The majority of polymers are composed of crystalline and amorphous regions as complex structures. Crystallinity is usually caused by heating above the glass transition temperature (T_g) of thermoplastic polymer and is often accompanied by molecular orientation. Glass transition temperature (T_g) can be defined as the temperatures at which the segmental chain mobility starts and the polymer shows a physical shift by becoming a hard, glassy state to a soft, rubbery state (Anton, 1968; Bosley & Du, 1967; Gulrajani & Saxena, 1979; Miller & Murayama, 1984; Venkatesh et al., 1978).

It is difficult to achieve 100% crystallinity in thermoplastic polymers with the lowest free energy of molecules since the polymers do not usually have uniform molecular weight (Kajiwara & Ohta, 2009). Instead, polymers can only react to partially crystalline structures, and they are known as "semi-crystalline" structures. Therefore, in general polyester is available in semi-crystalline or amorphous forms. The glass transition temperature of amorphous PET is about 67°C, and about 81°C

for semi-crystalline PET (Kajiwara & Ohta, 2009; Misra & Stein, 1979). Figure 2.3 presents the commercial methods of producing semi-crystalline and amorphous polyester.

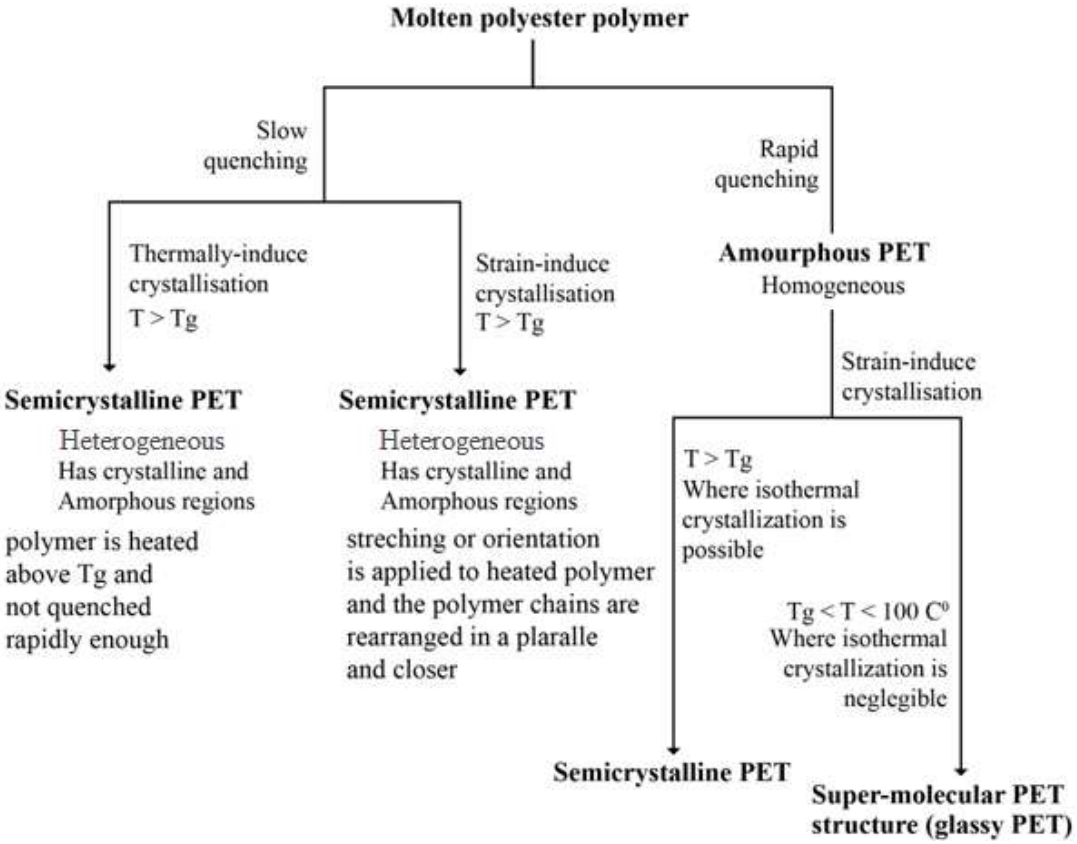
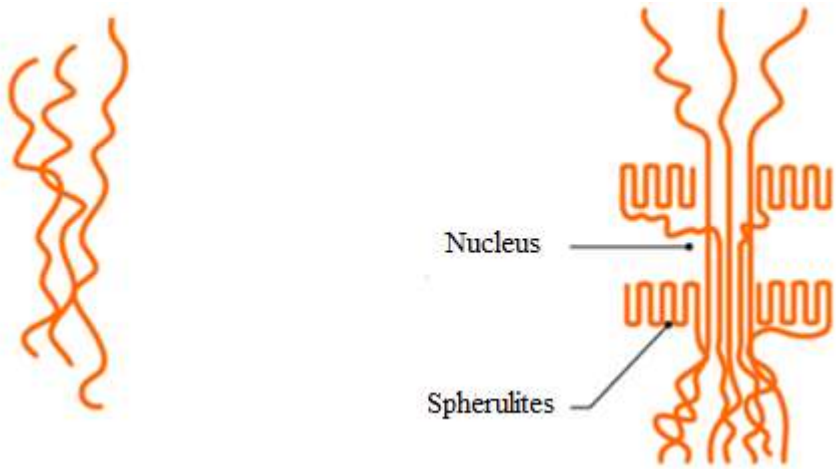


Figure 2.3 : Methods of producing semi-crystalline and amorphous polyester (Gschel, 1996; Trznadel & Kryszewski, 1988; Vries, 1980)

Thermal crystallization and/or stress or strain-induced crystallization usually induces crystallization in PET (Fischer & Fakirov, 1976; Vries, 1980). The quick quenching of the molten polymer leads to a completely amorphous PET. Thermally induced crystallization takes place when the PET polymer is heated above T_g and not quenched quickly enough. Stretching or orientation is applied to the heated polymer in stress-induced crystallization. During strain/stress- induce crystallization polymer chains are rearranged in parallel form and closely packed due to the external stretching force (Fischer & Fakirov, 1976; Vries, 1980). The process of crystallization consists of nucleation (the initial process that occurs in the formation of a crystal from a solution, a liquid, or a vapor, in which small number of ions,

atoms, or molecules become arranged in a pattern characteristic) and spherultic crystallization (presented in Figure 2.4), which can occur at temperatures above glass transition temperature (T_g) and below melting temperature (T_m). Figure 2.4 presents the basic structural representations of amorphous and semi-crystalline polyester.



(a) amorphous structure (b) semi-crystalline structure

Figure 2.4 : Structures presenting amorphous and semi-crystalline polyester (Kajiwara & Ohta, 2009)

Due to amorphous interspersed regions within crystalline structure, semi-crystalline polymers have a heterogeneous structure, while amorphous polymers have a homogeneous structure in all their forms (melts, rubbers, glasses, etc.) (Kajiwara & Ohta, 2009; Misra & Stein, 1979; Rodriguez-Cabello et al., 1996). Amorphous polymer has randomly coiled, folded and entangled molecular structure.

The level of crystallinity in a polymer is determined by inherent and extrinsic factors. Narrow molecular weight range, linear structure of the polymer chain and high molecular weight are very important preconditions for achieving high crystalline structures (Kajiwara & Ohta, 2009). Extrinsic factors such as stretch ratio, extension mode and crystallization temperature in polymer film production are also affected the level of crystallinity.

Koening and colleagues studied the structure developed in the amorphous and crystalline regions by drawing amorphous PET films and fibres at different temperatures (hot drawing). They concluded that the uncoiling of amorphous chains

occurs by converting the distorted *gauche* into the extended *trans* isomer and demonstrated that this conversion leads to a slight increase in crystallinity. When the temperature exceeds T_g during drawing, the randomly coiled polymer chains in the amorphous region begin to disengage, unfold, and straighten, while some molecular chains even slide over their neighbouring chains (Hegde, Kamath, & Dahiya, 2010). But drawing crystalline PET film results in a minimal increase in crystallinity, but in crystalline regions a higher degree of alignment.

2.2.4 Forms of polyester in commercial application

Glassy polyester and polyester fibres are two forms of polyesters commonly used in commercial applications. Sections 2.2.4.1 and 2.2.4.2 described in detail the glassy polyester and melt spun polyester fibres.

2.2.4.1 Glassy polyester

Glassy polyester is widely used in fibreglass, roofing membranes, polyester composites reinforced with glass fibre, etc. The glassy polyesters are produced by strain-induce crystallization of amorphous polyester below or above glass transition temperature where isothermal crystallization is negligible. Stretching is caused to form oriented amorphous polymers if the amorphous polymer is subjected to stretching below T_g where crystallization is negligible (Gschel, 1996; Misra & Stein, 1979; Trznadel & Kryszewski, 1988; Vries, 1980; Zhao et al., 2001). The stretching of amorphous PET strips below T_g caused to form stress-induce neck formation at a strain of 5%, and sample may break with a total strain of approximately 270% (Misra & Stein, 1979). The analysis on super-molecular structure produced during strain-induced crystallization of PET has been carried out in many studies. The super-molecular structure formed under stress (or strain) is considerably different from that in amorphous PET (Misra & Stein, 1979).

The effects on orientation and crystallinity resulting from drawing amorphous PET varying drawing ratio, temperature, and strain rate were well studied and reported (Ajji, Cole, Dumoulin, & Brisson, 1995; Dumbleton, 1970b; Pereira & Porter, 1983; Pinnock & Ward, 1966; Sharma & Misra, 1987; Smith & Steward, 1974; Trznadel & Kryszewski, 1988). The super-molecular structure will acquire an increasingly fluid

character at higher temperatures in the glass-rubber transition range and in the rubbery region. Researchers have also studied the effect of stretching conditions on stress-induced crystallization of amorphous PET film (Fischer & Fakirov, 1976; Heuvel & Huisman, 1981; Hsiue, Yeh, & Chang, 1989; Huisman & Heuvel, 1989; Maruhashi & Tadahro, 1996; Misra & Stein, 1979; Vries, 1980). The results of these studies revealed that the super-molecular structure formed by stretched amorphous samples is perpendicular to the direction of stretching (Gschel, 1996; Trznadel & Kryszewski, 1988; Vries, 1980). As the stretching rate increases, the orientation of amorphous segment increases and relaxing effect after orientation was lowered. Increasing birefringence values show an overall improvement in the orientation of glassy polyester.

2.2.4.2 Polyester fibre

Among many thermoplastic polymeric fibres, Polyethylene terephthalate (PET) finds wide commercial application in the form of fibres due to their excellent mechanical, physical and durable properties and characteristics (Rudolf et al., 2011). Polyester has also known for many years as a textile fibre forming material. Industrial production of polyester fibre involves three main steps; condensation polymerization, melt-spinning of molten polymer and hot drawing to produce polyester fibre (Han et al., 2012).

As the first step of condensation polymerization, fully dried polyester chips are melted at approximately 285°C and polymer molten is spun and extruded into the atmosphere by small troughs and refreshed by blowing air. The extruded filaments wind up on a bobbin a few meters below the point of extrusion when they reached room temperature (Drobny, 2003; Dumbleton, 1970a; Han et al., 2012; Marvin, 1954).

The extruded spun filaments are either drawn hot to produce partially crystalline filaments with high molecular orientation or heated in air at high temperatures to produce partially crystalline filaments with no preferred molecular orientation (Katayama, Nakamura, & Amano, 1968). Figure 2.5 presents the main production steps of polyester fibres.

Vries (1980) stated that the deformation of man-made fibres such as polyester and nylon during melt-spinning and winding are like rubber. In this form, the yarn is unoriented and lacks any textile qualities; however, the spun fibres are developed through a process of drawing that orients the fibre molecules resulting a high strength fibre which can be used for the fabric production (Marvin, 1954).

As a polymer is extruded from the melt during fibre production, a fraction of the polymer chains (0.5 nm diameter) crystallizes into *lamellae* (discuss in section 2.3.1.3) or small crystallites (10 nm in size), and another fraction remains amorphous as it freezes in its molten state. During the drawing process, in fibres, these *lamellae* are organized into *fibrils* (100 nm in length), which in turn form filaments (5 μm diameter) that are then made into fibres (0.5 mm diameter).

The crystalline structures formed during the melt-spinning process have been reported (Merino and Pastor, 1996). Using the kinetic theory of rubber elasticity, Dumbleton (1969) showed that spun polyester cannot be amorphous polymer. This is due to there is substantial evidence for the presence of order and disordered regions (Dumbleton, 1970b). Because of these two distinctive phases, polyester polymer structures are known as two-phase models and can be called semi-crystalline polymer materials (Murthy, 2004).

Different spinning and drawing conditions are used to produce polyester fibres with different molecular structures (Han et al., 2012; Matlin & Nuessle, 1955). The orientation of the spun yarn depends on the speed at which it is forwarded or spun into continuous filament yarn during the fibre production (Rodriguez-Cabello et al., 1996).

Based on the orientation, PET fibres can be categorized as low-oriented yarn (LOY), medium-oriented yarn (MOY), partially-oriented yarn (POY), highly-oriented yarn (HOY) and full or high-speed spun yarns (FOY). LOY, MOY, POY, HOY and FOY can be produced in speed ranges 500-1500, 1500-2500, 2500-4000, 4000-6000 and above 6000 m/min respectively (Rodriguez-Cabello et al., 1996). The differences in molecular orientation, crystallinity, structures and shrinkage behavior of the above fibres are presented in Table 2.1.

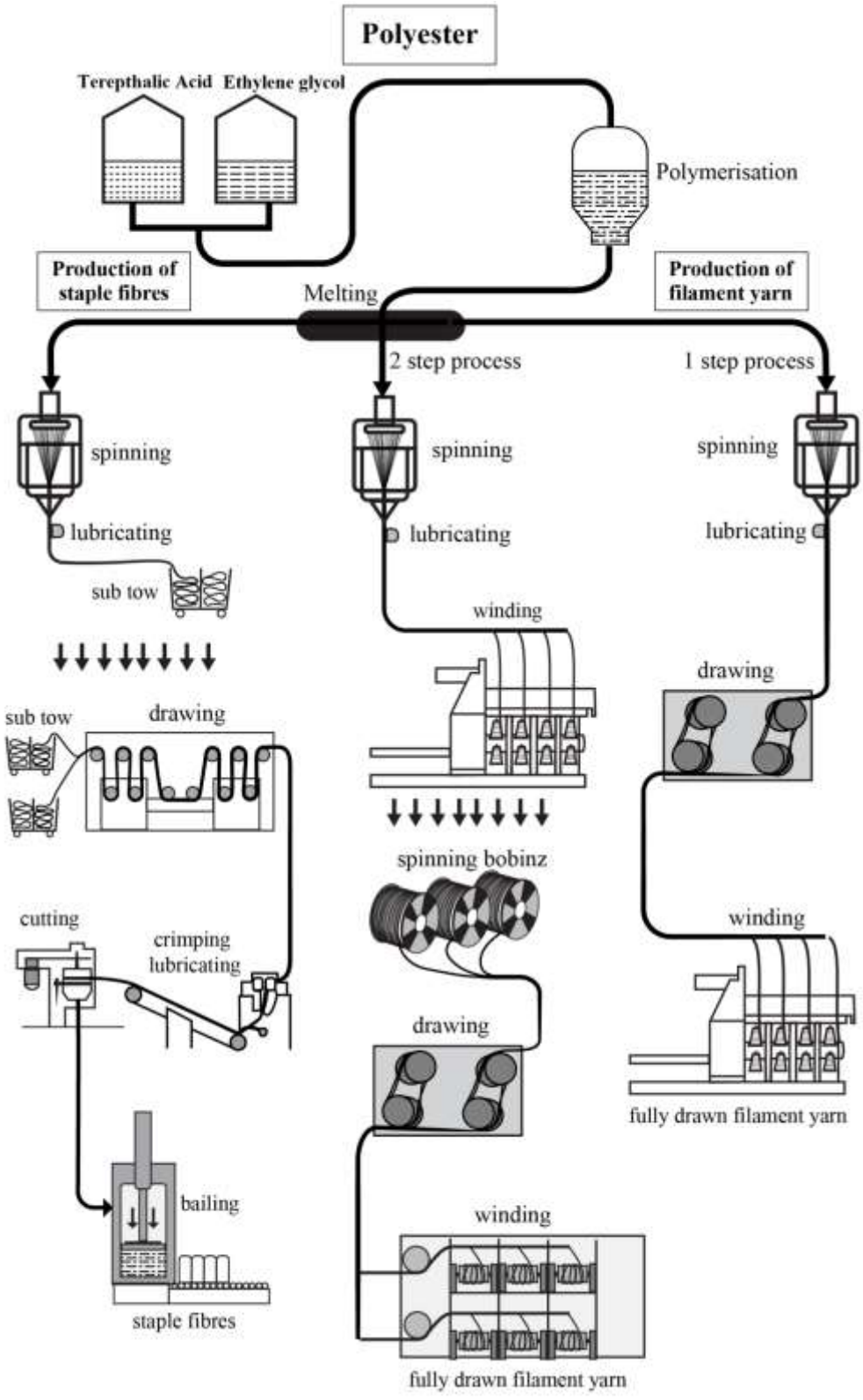


Figure 2.5 : Main production steps of polyester fibres (“Polyester”, n.d.)

Table 2.1: Different spinning and drawing conditions to produce polyester with different molecular structures (Rodriguez-Cabello et al., 1996)

Sample	Manufacturing	Crystallinity	Orientation	Stucture & Shrinkages
LOY	Spinning 500-1500 m/min	None	Very Poor	Amorphous Poor Shrinkage
MOY	Spinning 1500-2500 m/min	None	Poor	Amorphous High Shrinkage
POY	Spinning 2500-4000 m/min	None	Partial	Amorphous Very High Shrinkage Partially Crystilline
HOY	Spinning 4000-6000 m/min	Partial	High	Medium Shrinkage Particular Microfibrils
FOY	Spinning >6000 m/min	High	Very High	Skin-Core heterogeneity Poor Shrinkage
Spun-Drawn	Low speed Spinning + Drawing	None or Low	Very High	Mainly Amorphous High Shrinkage
LSPF	Low speed Spinning + Drawing + Heat Setting	High	Very High	Fibrillar Structure Transverse Homogeneity Poor Shrinkagez

Wasiak and Ziabicki studied the molecular structure of PET spun fibres at winding speeds from 350 to 850 m/min and found that the spun PET fibres produced by these speeds were amorphous. Heuvel and Huisman (1978) proposed molecular arrangement for spun yarns by varying the spun yarn winding speed. The findings revealed that spun yarn with various physical structures resulted due to winding speeds ranging from 2000 to 6000 m/min. Heuvel and Huisman (1978) findings reveal that yarns wound at relatively low speeds are amorphous, whereas yarns wound at high-speed have well developed molecular crystals. The findings also revealed that distinct crystalline structures were developed at the winding speeds above 4000 m/min (Heuvel & Huisman, 1978).

Studies carried out by Sharma and Misra (1987) revealed that crystalline orientation and amorphous orientation values were found to increase with the increase in stretching rates (drawing). There studies also revealed that low stretching rates resulting in lower orientation and low strength and high stretching rates resulting in high orientation and high strength in drawn fibres (Sharma & Misra, 1987).

The effect of spinning speed on the dynamic mechanical properties of polyester spun

yarns was studied by Miller and Murayama (1984). The findings revealed that the dynamic module of spun yarn in the temperature range from 25°C-160°C is increased as the spinning speed increases (3000-6000 m/min). These increases were suggested as a result of a combined effect of increased amorphous orientation and crystallinity since the segmental motion is greatly influenced by its environment. High glass transition peaks at around 98°C in DSC thermograms were observed for partially oriented yarns (POY) spun at 3000 and 3800 yards/min, while low glass transition peaks at around 125°C were observed for the partially oriented yarn which was spun at 5600 and 6200 yards/min. The low glass transition temperature of POY revealed that the fibre has low amorphous orientation with low crystallinity and the high spinning speeds has resulted high amorphous orientation with 35% crystallinity (Miller & Murayama, 1984).

Miller, Southern and Ballman (1983) examined the structure and characteristics of partially oriented polyester yarn (POY) and its false twist textured yarns (PTY) as a function of spinning and texturing processes. As the spinning speed increases from low to high, both amorphous and crystalline orientation, crystallinity, crystallite size and dye uptake increase in partially oriented yarn (POY). As per the results they revealed that the texturing rate increases the orientation of crystallinity in crystallite, mean volume of crystallite and amorphous volume per crystallite. The results also revealed the absorption of dye increases as orientation in amorphous region decreases (Miller, Southern, & Ballman, 1983).

2.3 Behavior of Polyester Fibre

The earlier research findings reveal that crystallinity and morphology levels affect the properties of the polymers significantly (Fischer & Fakirov, 1976; Groeninckx & Reynaers, 1980; Gupta, Ramesh, & Gupta, 1984; Stein & Misra, 1980). Different models for arranging individual molecular segments within crystallites have been proposed by previous authors. The following section 2.3.1 described the models that are used to describe the semi-crystalline polyester fibres.

2.3.1 Models

2.3.1.1 Two-phase model

During fibre production, polymeric fibres are formed into molecular structures with highly oriented fibre-directed chains. This is achieved by a series of thermo-mechanical processes. A high crystalline content is also achieved by the fibre. Rath, Chaki and Khastgir (2008) stated that while polymeric fibres are highly oriented and crystallized, amorphous regions still exist in the yarns. Fibre structure in conventional drawn polymers was usually discussed with the periodic structure of the crystalline and amorphous phases arranged approximately in series with fibre direction (Gupta, 1995). The periodic crystalline and amorphous structure is presented in Figure 2.6.

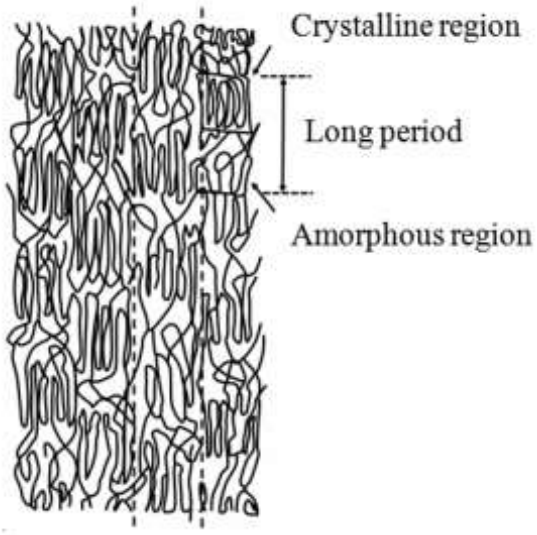


Figure 2.6 : Two-phase model of molecular arrangement of PET fibre (Park & Seo, 2011)

The periodic structure which contains crystalline (ordered and oriented in the direction of the fibre) and amorphous (disordered and polymer chains are less oriented) is called the two-phase model (Batra, 1976; Bhatt & Bell, 1976; Bosley & Du, 1967; Dumbleton et al., 1968; Fischer & Fakirov, 1976; Gupta & Kumar, 1976; Gupta et al., 1974, 1984; Katayama et al., 1968; Miller & Murayama, 1984; Misra & Stein, 1979; Nobbs et al., 1976; Prevorsek et al., 1974; Samuels, 1972; Statton et al., 1970; Vries, 1980; Warwicker, 1972; M. P. W. Wilson, 1974).

2.3.1.2 Fringed-micelle model

In Fringed-micelle model, the microfibril consists of a crystalline region and an amorphous region, and a single polymer chain penetrates the two regions. *Fibrils* are structural units in which coherence is predominantly found in the longitudinal direction of amorphous and crystalline domains. As described by Vries (1980) each long molecule is considered to thread its way through several adjacent crystalline and non-crystalline (fringed) regions (Vries, 1980). The model presented by Hess and Kiessing was used to schematically explain the structure of synthetic fibre *micro-fibrils* (Vries, 1980). Fringed-micelle model and the high order structure model of a synthetic fibre is presented in Figure 2.7 and Figure 2.8 respectively.

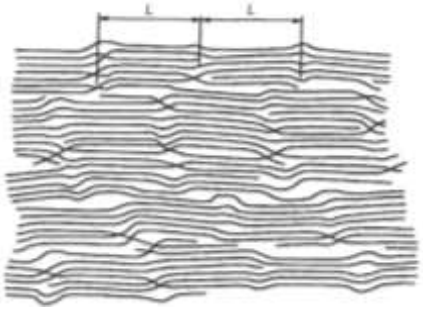


Figure 2.7 : Schematic diagram of Fringed-micelle model (Kajiwara & Ohta, 2009)

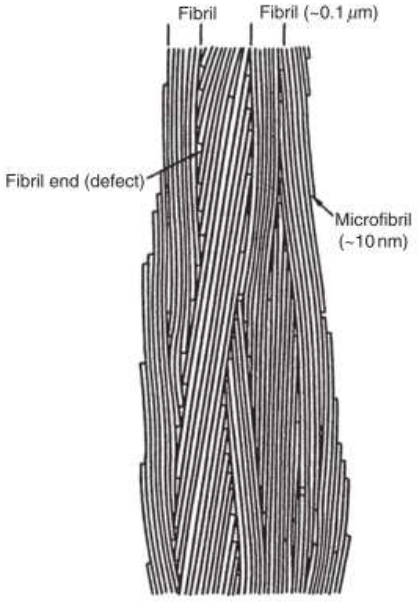


Figure 2.8 : Schematic diagram of high-order structure model of a synthetic fibre (Kajiwara & Ohta, 2009)

2.3.1.3 Lamellae model

As defined in the lamellae model, polymer chains fold in length in a single crystal. (chain-folding). The folded crystal structure is now considered the basic structure of a crystalline polymer rather than the fringed-micelle. The polymer condensed phase consists of folded chains as shown in Figure 2.9. In lamellae model, in which individual molecules are considered to fold back on themselves with regularity and form lamellae.

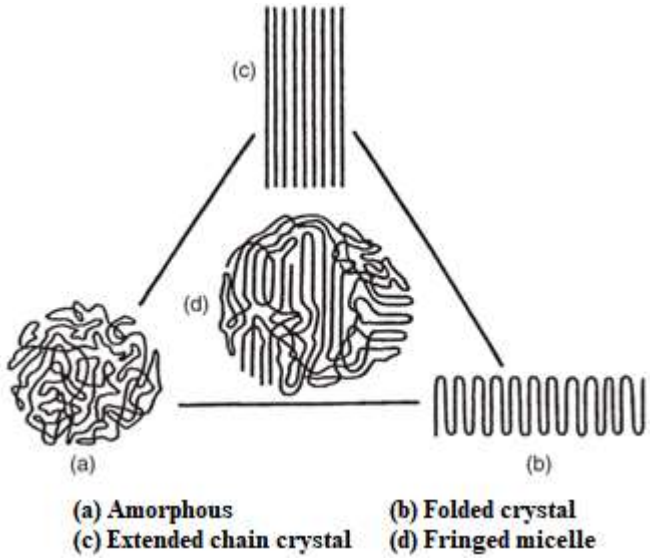


Figure 2.9 : Schematic diagram of various phases of polymer chains (Kajiwara & Ohta, 2009)

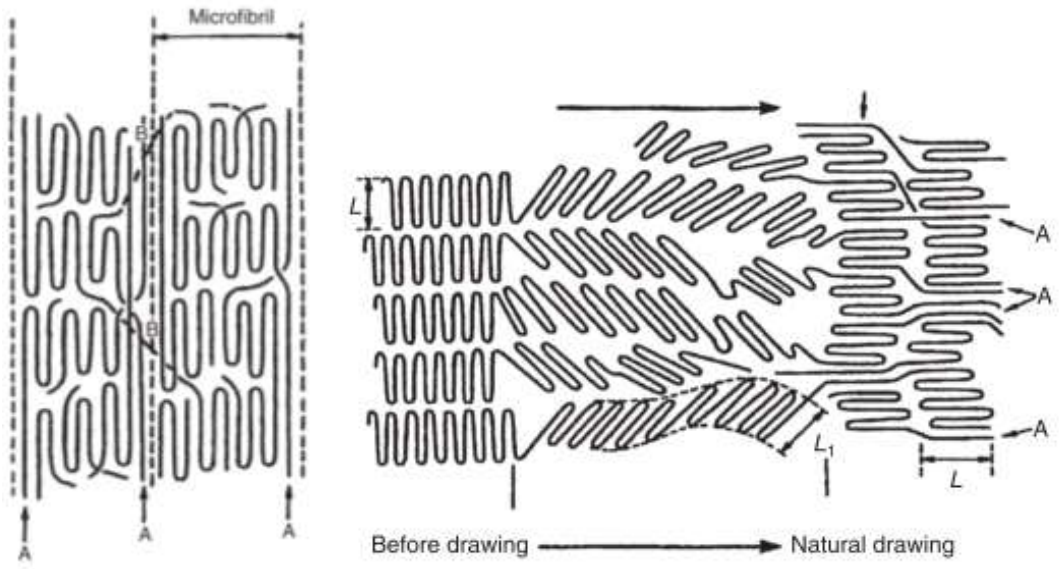
2.3.1.4 Three-phase model

It was recognized that the simple two-phase series model cannot completely explain the observed fibre tensile behavior using a rubbery value for amorphous phase rigidity (Caihong et al., 2014; Choy, Chen, & Young, 1981; Choy, Masayoshi, & Porter, 1983; Hsiue et al., 1989). This lead to the suggestion of taut tie molecules (TTM) or interfibrillar extended chain molecules in to the structure (Choy et al., 1981, 1983; Kobayashi & Keller, 1970; Prevorsek et al., 1974; Wu et al., 1998). These are the molecules transit from multiple crystalline regions to the amorphous region by providing intermolecular coherence (Kobayashi & Keller, 1970; Wang & Hu, 1997b). The models consisting three phase or crystalline, amorphous and interfibrillar or taut tie molecules have also been discussed by many authors (Choy et

al., 1981, 1983, Heuvel & Huisman, 1978, 1981; Huisman & Heuvel, 1989; Liu et al., 2016; Prevorsek et al., 1974; Statton et al., 1970).

Kajiwara and Ohta (2009) stated that drawing is an essential fibre formation process and folded microfibrils contain tie molecules that link the folded crystal. Tie molecules as shown in Figure 2.10(a) connect the folded microfibrils together. The folded parts deform and align in the drawing direction when the fibre is drawn (shown schematically in Figure 2.10(b)). The polymer chains that bind the regions of crystal form the amorphous phase with the ends of the chain. There may be also *mesophase* (the intermediate phase between the phases of crystalline and amorphous) in the fibre structure (Kajiwara & Ohta, 2009).

Although sometimes the presence of a third interfibrillar phase has been adopted to explain specific phenomena, the two-phase approach remains the basis of most of the work.



(a) (b)

Figure 2.10 : Schematic representation of (a) folded microfibrils and (b) drawing process (Kajiwara & Ohta, 2009)

Many models also converged the concepts of two-phase model, fringed micelle model (Bosley & Du, 1967; Fischer & Fakirov, 1976; Vries, 1980), lamellar structure (Dumbleton, 1970b; Prevorsek & Sibilia, 2006; Statton et al., 1970; M. P.

W. Wilson, 1974) and three-phase model to describe the behavior of semi-crystalline polyester fibres.

2.3.2 Models describing the semi-crystalline polyester fibre

As per the model suggested by Samuel (1972), drawn PET consists of highly extended, substantially parallel molecules with few folds. The amount and structural arrangement within a given sample of these regions will depend on manufacturing process of polymer. Both the properties of crystalline and non-crystalline (amorphous) regions are anisotropic and different, their quantity and arrangement will govern the bulk properties of the polymer. The differences between crystallization and a disorientation of the amorphous regions explained many properties such as dyeing behavior, thermal shrinkage behavior and tensile behavior of polyester fibres (Samuels, 1972).

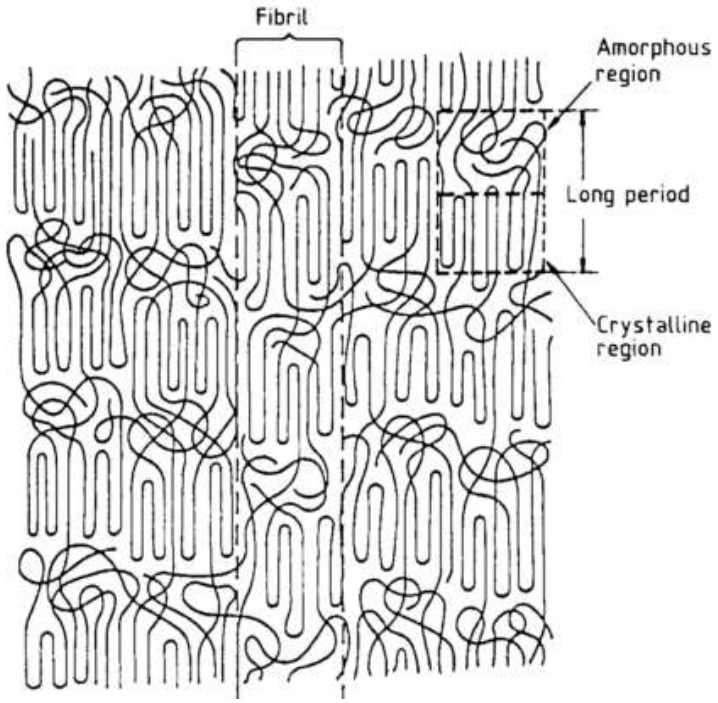


Figure 2.11 : Structural model of drawn PET yarn suggested by Huisman and Heuvel (1989)

Huisman and Heuvel (1989) used a simple two-phase model of crystalline and amorphous regions to investigate the physical structure developed during the production of PET yarns by changing the spinning speed and drawing temperature.

The structural model has ordered (crystalline) regions alternating with less ordered (amorphous) domain, and several crystalline and amorphous regions may run through a single molecule. In addition, it is possible that a molecule folds back to the surface of a crystal to reintroduce it and, depending on the process conditions, the polymer molecules are more or less oriented along the fibre axis and cause the *fibrils* to form. However, as shown in Figure 2.11, these fibrils also have a lateral extension (Huisman & Heuvel, 1989).

Prevorsek and his colleagues (1963 and 1974) used Takayangi model to represent the polymer structure of oriented semi-crystalline polymers which had been processed at high draw ratio, where the chains in the crystalline regions are largely aligned along the draw direction. This model consists of amorphous region, crystalline region and taut tie molecules (Prevorsek et al., 1974; Prevorsek & Tobolsky, 1963). They suggested that at high draw ratio, where the chains in the crystalline regions are largely aligned along the draw direction. This has led the structure of an oriented semi-crystalline polymer can be crudely represented by the Takayanagi model (Figure 2.12).

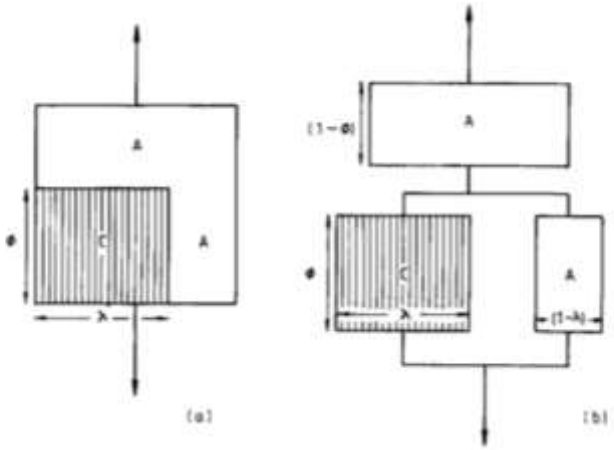


Figure 2.12 : Schematic representation of Takayangi model for highly oriented semi-crystalline polymers: C crystalline block, A amorphous region, T taut tie molecules (Prevorsek et al., 1974; Prevorsek & Tobolsky, 1963)

Prevorsek et al (1974) suggested the structure of melt-spun PET fibres consist of at least three distinct phases; crystallites, amorphous domains separating adjacent crystallites in the microfibril, and amorphous domains separating the microfibrils.

The schematic diagram of model suggested by Prevorsek et al. (1974) is given in the Figure 2.13. The crystallites which form a well-developed macro-lattice are embedded in a three-dimensional network of tie molecules. The crystallite phases that intersect the direction of the polymer chain contain detectable quantities of regular chain folding even at the highest draw ratios. The microfibrils appeared as a coherent unit of the macro-structure (Prevorsek et al., 1974).

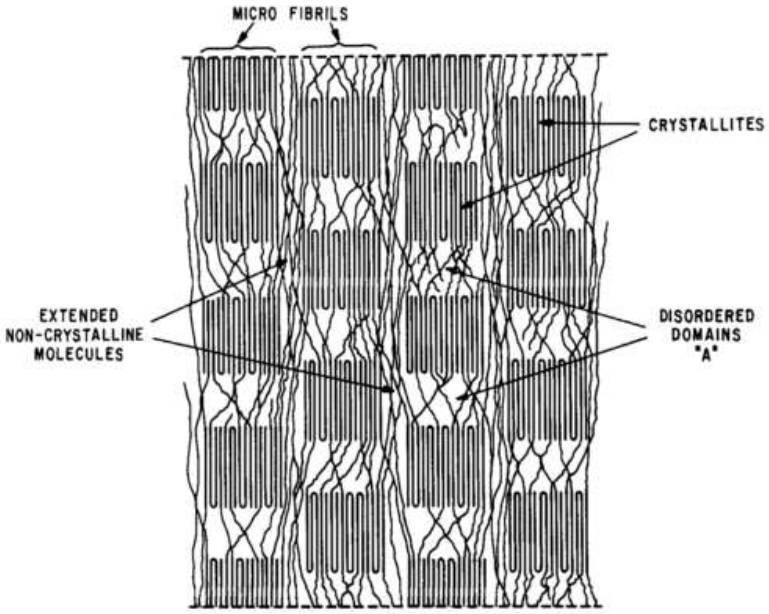


Figure 2.13 : Schematic structure of PET Fibre (Prevorsek et al., 1974)

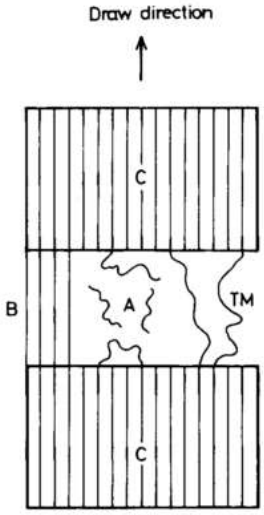


Figure 2.14 : Schematic diagram showing the structure of a highly oriented semi-crystalline polymer as suggested by Choy, Chen and Young (1981).

The model proposed by Choy, Chen and Young (1981) for semi-crystalline polymer consists of crystalline lamellae embedded in an amorphous matrix, each of which consists of crystalline mosaic blocks, amorphous material, tie-molecules joining one crystalline block to another and bridges (Choy et al., 1981). Figure 2.14 presents the suggested model and chain-folded crystalline mosaic blocks, bridges, amorphous regions and tie molecules are represented by (C), (B), (A) and (TM) respectively.

Merino and Pastor (1996) demonstrated a structural model to study the behavior and structural changes that take place annealing of high oriented and crystalline fibres. This model consists of small crystallites which are inter-connected by amorphous regions along with crystalline content.

Although sometimes the presence of a third interfibrillar phase has been adopted to explain specific phenomena, the two-phase approach remains the basis of most recent work. Liu et al. (2016) suggested that crystalline regions alternate with amorphous domains while single molecules transition from multiple crystalline regions to amorphous regions by providing intermolecular fibre coherence (Liu et al., 2016).

2.3.3 DSC analysis to determine structure and morphology of PET

The Differential Scanning Calorimetric (DSC) thermograms can be used to identify the state of the structure and morphology of the polymers. DSC is a thermoanalytical technique in which the difference in the amount of heat required to increase a sample temperature and reference is measured as a function of temperature (Blaine, 2010). A general DSC thermogram of PET is presented in Figure 2.15.

A heat flux curve versus temperature or time is the result of a DSC experiment (Sichina, 2000). Therefore DSC thermograms consist of exothermic and endothermic peaks. When energy is absorbed from the environment in the form of heat, an endothermic reaction occurs. In an exothermic reaction, energy is released into the environment from the system. As the temperature increases the sample eventually reaches its melting temperature. The melting process results in an endothermic peak in the DSC curve.

Polymers are usually characterized by glass-transition temperature (T_g) and the melting temperature (T_m). The amorphous polymers are characterized by their glass transition temperature and crystalline polymers are characterized by their melting temperature. The behavior of the glass transition of semi-crystalline polymers is heavily affected by factors such as molecular weight, amount of crystalline phase and the morphology. The glass transition temperature range of semi-crystalline polymer is generally higher and broader than that of the amorphous polymer.

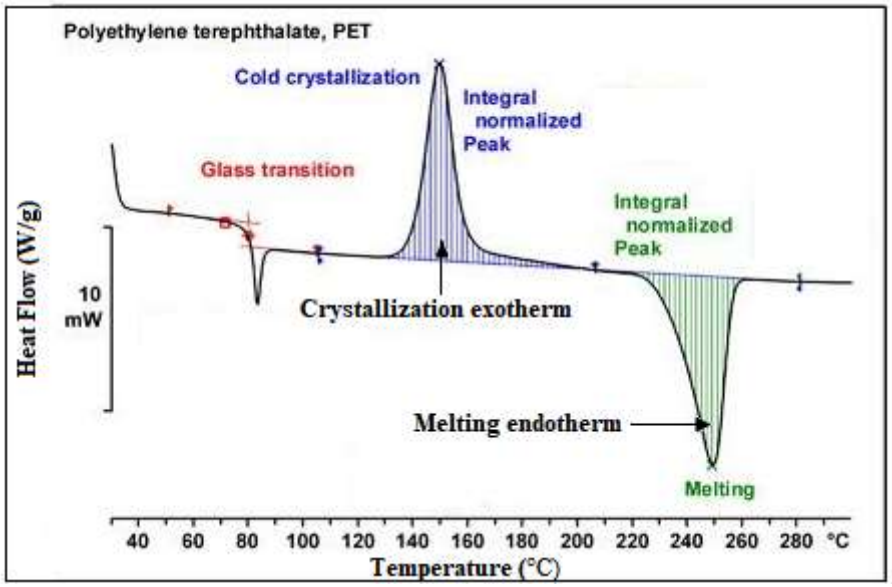


Figure 2.15 : DSC thermogram of PET (Blaine, 2010)

2.4 Polyester Knitted Fabrics

According to textile terms and definitions of the Textile Institute, the term fabric is a manufactured assembly of fibres and/or yarns that has substantial area in relation to its thickness and sufficient inherent cohesion to give the assembly mechanical strength. According to the definition it is important that textile fabrics have to be made out of fibres and /or yarns. Weaving, knitting and non-woven are the three main methods of fabric production.

Knitting can be considered as a process where a yarn is converted to a loop and interconnected with such loops which have been made earlier. This conversion of straight yarn to a loop shaped yarn is done by knitting needles (Spencer, 1996). The

yarn must be fed to knitting needles for the progression of the knitted fabric. If the yarn is fed into the course direction, then the process is called weft knitting. During weft knitting, all the needles in the needle bed are fed by the single yarn which runs horizontally. Therefore the entire needles will catch the same yarn for loop formation during fabric progression (Spencer, 1996). Figure 2.16 presents the simplest weft knitted fabric, known as plain knit. The yarn is bent into loops in a horizontal, or course direction.

Plain fabrics or single jersey fabrics are knitted using one set of needles. This set of needles has their hooks facing towards the same direction. Because of these, during knitting, loops are drawn in the same direction (Spencer, 1996). The result is a fabric with the face loops on one side and the reverse loops on the opposite side. The Figure 2.16 shows how plain fabric is made and the corresponding notation for the *technical face*.

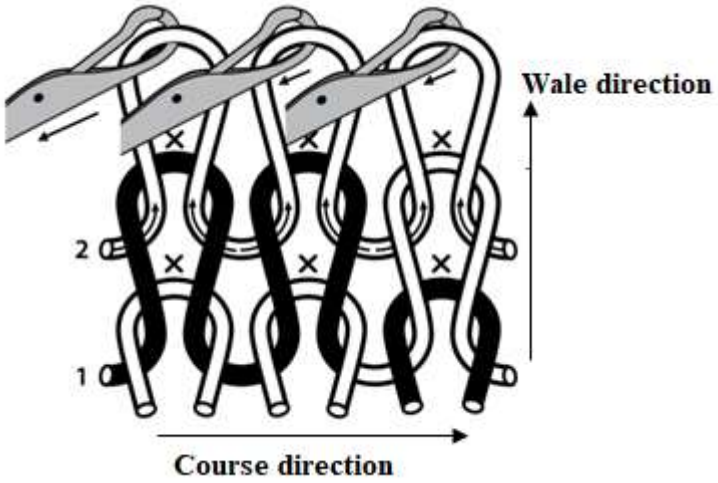


Figure 2.16 : Loop diagram and the technical face of the plain fabric (Spencer, 1996)

Dimensional stability is one of the main characteristics that determine the quality of a fabric or garment. Dimensionally stable fabric shows resistance to permanent stretch and shrink when the fabrics is exposed to mechanical, chemical and thermal agencies (Matlin & Nuessle, 1955). Altering the parameters of fibre, yarn and fabric and by external processing agencies, expected performance in dimensional stability can be achieved (Matlin & Nuessle, 1955).

The mechanisms that affect the dimensions of fabrics are in various forms. Felting

shrinkage and dimensional change due to dry and wet relaxation processes have been discussed critically (Chen, Au, Yuen, & Yeung, 2004; Quaynor, Takahashi, & Nakajima, 2000). These mechanical effects cause to change the loop length or loop shape or both, and change the dimensions of the finished knitted fabrics. Researchers have studied the behavior of the knitted structures theoretically and experimentally, where most studies have focused on the geometry of the plain knitted loop (Chamberlain F.T.I, 1934; Knapton, 1979; Knapton, Truter, & Aziz, 1975; Munden, 1959; Peirce, 1947; Postle, 1968; Postle & Munden, 1967). These models and related experimental studies have eventually developed mathematical relationships between course densities, wale densities, loop shape factor, area density and stitch length, thus establishing well-known knitting constants K_w, K_c, K_s and practical values demonstrating the knitted loop shape (Munden, 1959). Most of these studies have mainly concentrated on wool and cotton (Knapton, Ahrens, Ingenthron, & Fong, 1968; Munden, 1960; Postle, 1974). Although many studies have been carried out on natural fibre knitted fabrics, work on the dimensional stability of thermoplastics knitted fabrics remains limited. This was due to the distortions in thermoplastic polymer fibres such as polyester and nylon in their fibres, yarn and fabric forms at high temperatures (Arghyros & Backer, 1982; Batra, 1976; Haar, 2011; Marvin, 1954). The deformability of the material by thermal exposure is a special feature of the thermoplastic polymer fabric. This has become an advantage when these fabrics are used in 3-dimensional ways such as bra cups, and when the polyester fabric deforms during ironing and hot water washing; it has had a negative effect.

2.5 Heat-Setting of Synthetic Polymer Materials

Researchers have found that distortions in thermoplastic polymer fibres such as polyester and nylon at high temperatures in their fibre and yarn forms (Arghyros & Backer, 1982; Batra, 1976; Haar, 2011; Marvin, 1954). Heat-setting has been identified as the only effective means of stabilizing thermoplastic fabrics (Matlin & Nuessle, 1955). Heat-setting is an important industrial process practiced on yarns, fabrics, and garments of thermoplastic materials or blends of them. The main purpose of heat-setting is to establish stable molecular configurations by supplying

thermal energy to the molecular chains and eliminating instability and relaxing stresses incurred during earlier stages of fibre, yarn and fabric production. Different internal stresses remain in the thermoplastic fibres depending on the different treatment processes performed at different stages of fabric processing (Arghyros & Backer, 1982). Stresses and strains are incurred in thermoplastic filaments due to deformations occurred during spinning, drawing, winding, twisting, texturing, and during the fabric processing.

During heat-setting the fabrics are subjected to higher temperatures than those that are likely to be met in its subsequent processes and heat-setting process is performed under dimensional control (Arghyros & Backer, 1982; Liu et al., 2016; Marvin, 1954). Heat-setting of polyester, requires rearrangement of nonpolar bonds and dipolar interactions associated with the ester groups in the macromolecules (De Boos, Harrigan, & Wemyss, 1986). When the temperature of the fibre is higher than its glass transition temperature (T_g), the vibration of polymer molecules is increased and have a greater freedom and relaxation. If the temperature is much higher, more inter-chain bonds break and greater will be the relaxation from the stresses which are incurred in the material during previous processes. Upon cooling when the material reaches the minimum potential energy level, new intermolecular bonds are formed between the polymer chains at their new orientation (Karmakar, 1999b). The new configuration is thermodynamically more stable with improved dimensional stability due to elimination of stresses and strain during heat treatment.

Polyester may be heat-set by the action of heat alone, although a variety of reagents will plasticize the fibre and facilitate various rearrangements (De Boos et al., 1986). Dry heat, aqueous heat, pressure steam, and boiling water under various conditions are all capable of stabilizing PET yarn to prevent further shrinkage. Heat-setting machines available in the finishing industry may also be classified depending on the type of reagent used to stabilize the polyester (De Boos et al., 1986; Marvin, 1954; Mecklenburgh, 1950; Preston, Nimkar, & Gundavda, 1951a).

The commercial continuous heat-setting of spun polyester yarn can be done using the Superba TVP machine (wet method), Suessen heat-setting unit (dry method) and batch wise heat-setting can be done by using an autoclave (Cullerton et al., 1990).

Fabrics can be heat-set by contact method (fabric is run in contact with heated metal surface), steam-setting method (steaming is carried out in an autoclave fitted with vacuum pump), hydro-setting method (hot water in a high temperature liquor circulating machine), stenter-frame and using selective infra-red emitters method (Karmakar, 1999b). Hot air pin stenter is one of the methods which are widely used in the textile industry for heat-setting of polyester fabrics.

Polyester fabrics are set at various stages from loom state to final finished fabric and further during garment processing. Heat-setting of fabrics can be mainly carried out at three different stages in the processing sequence of fabrics either woven or knitted i.e. in greige condition; after scouring; and after dyeing. Loom state fabrics are heat-set to relieve strains that remain in the fibres and yarn after weaving and knitting. Fabrics are also set after scouring and, where applicable, after dyeing to give the fabric an additional flat stability (Karmakar, 1999b). The procedures used to set fabrics have important effect not only for the flat stability of the fabric, but also for the dyeing properties and subsequent handle and tailoring characteristics of the finished fabric (De Boos et al., 1986).

The effect of heat-setting on PET fibres and film structures and their properties have been reported by a large number of studies (Batra, 1976; Greener, Tsou, & Blanton, 1999; Liu et al., 2016; Lyons & Olson, 1972; Mecklenburgh, 1950; Phillips et al., 2003; Rodgers, 1988). Hearle (1971) highlighted that the new configuration achieved due to heat-setting in the fibre will be retained on cooling, but may be disturbed by subsequent processing treatments (Haar, 2011). Optimum heat-setting involves proper control of four basic factors, namely, the initial high temperature to which the material has to be raised; the time of heat-setting; the tension applied on the material, and the rate of cooling. Heat-setting of fabrics can be done in slack condition (free annealed) as well as at constant length (taut-annealed). The following section will describe the heat setting process of fabrics carried out in hot air pin stenter machine. The Figure 2.17 presents schematic diagram and fabric flow path of hot air pin stenter.

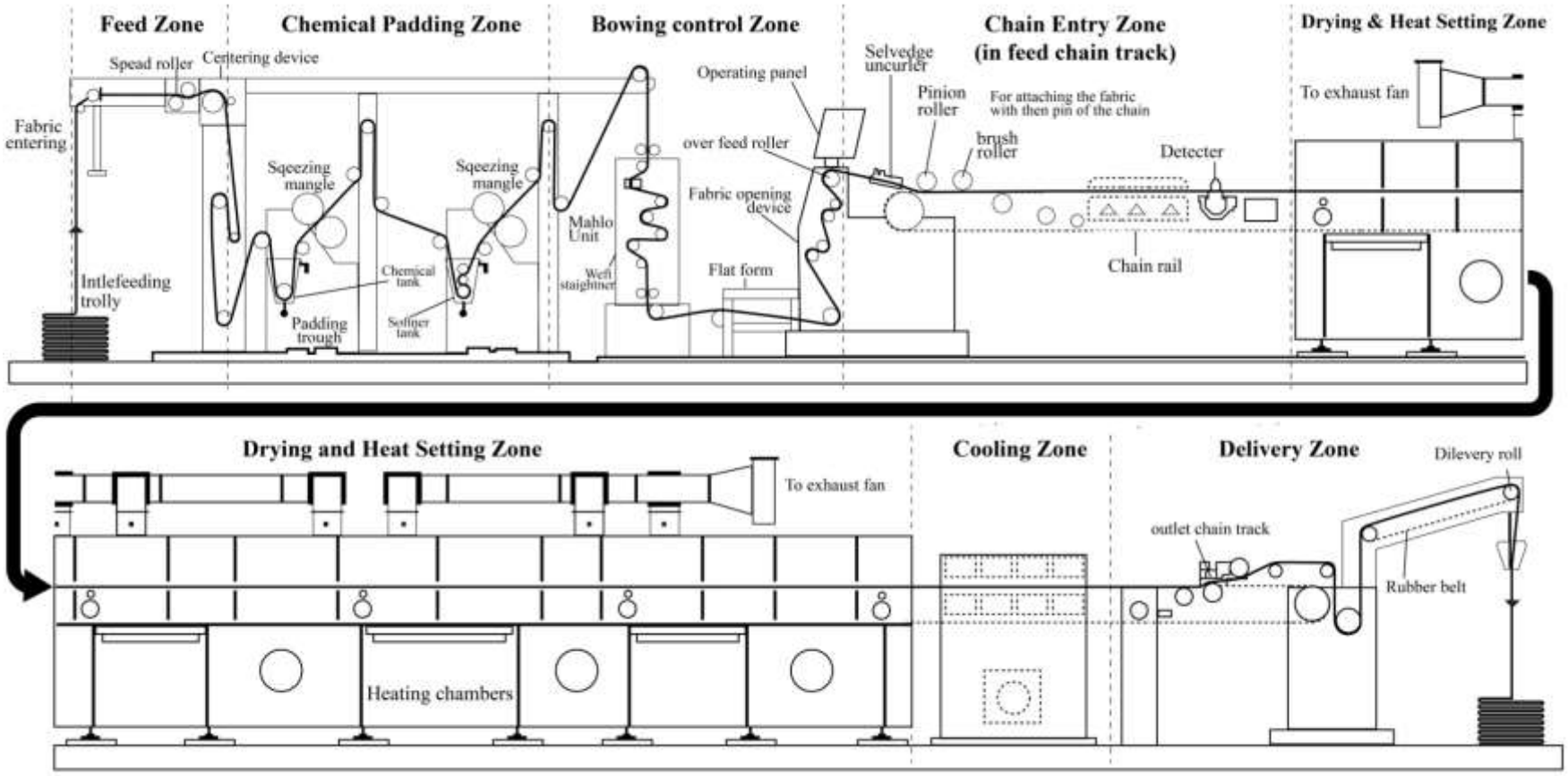


Figure 2.17 : Schematic diagram and fabric flow path of hot air pin stenter (“Heat Setting Stenter (Stenter Machine),” 2017)

2.5.1 Hot-air pin stenter machine

A stenter is a handling system for fabrics requiring precise control of width. Stenter machine simultaneously and continuously captures the fabric in both selvedge and carries it from one point to another. Two endless chains equipped with either clips or pins grasp the selvedge and move the fabric between them in a proper way. With the motor arrangements, the width between the two chains can be adjusted automatically. In a stenter, application of finishing chemicals, drying and stretching, heat-curing and heat-setting operations are usually carried out. A schematic diagram of the stenter machine is presented in Figure 2.17. The following sections described the main zones of hot-air pin stenter.

- **Feed zone**

During the fabric batch change, this part is used to store the fabric. The inlet unit is used to feed the fabric across the machine evenly. Spread rollers are used to remove the curls from the fabric.

- **Chemical padding zone**

Padding mangle includes chemical troughs, guide rollers, and squeezing mangle. The fabric is submerged in the chemical finish and then sent to the squeezing mangle to squeeze out extra chemicals from the fabric.

- **Bowing control zone**

Mahlo device (weft straightener) has two bow and three skew rollers that make the weft yarns straight and correct the skewness and bowing. Dandy rollers which are also called dancing rollers and are used to impart the tension into the fabric for complete stretching. If there is tension in the fabric then they move up and down.

To give over feed or under feed of the fabric to respective chain track, over feed system is used. Main over feed rollers are feeds all the fabric from the padders to the stenter. A schematic diagram of over feed system is presented in Figure 2.18.

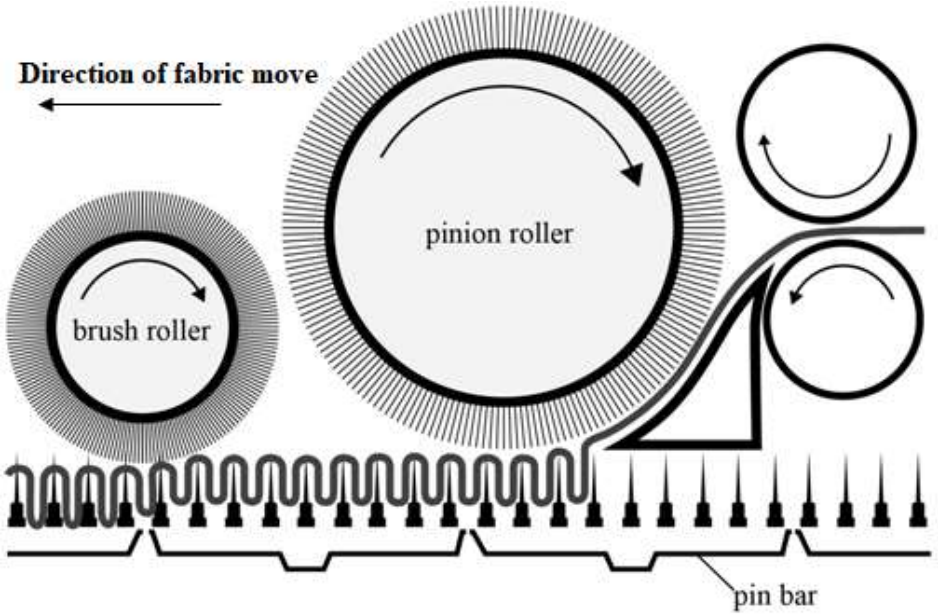


Figure 2.18 : Fabric over feeding system (Swastik, 2012)

During heat-setting over feed rollers are used to maintain the weight / width of the fabric and also imparts the fabric tension. width extension is given to the fabric to achieve the required width measurement in the finally finished fabric. If a knitted fabric is loaded parallel to the courses, not only will the loop shape distortion, it also add to the fabric width at the expense of length and thickness.

The relative movement of interlacing loops will also result in an additional increase in fabric width. In order to prevent extraordinary deformation, the over feed of the fabric is done simultaneous with the width extension (Black, 1974). Most of the stenters make provision for overfeeds - 5 % to + 40 % (Karmakar, 1999b).

Polyester knit fabrics should not be stretched more than 5 % wider than the desired end width. An over feed of up to 20% (generally 6-10 %) is commonly used in knit fabrics or texturised fabrics in order to level out variations in tensions caused by knitting.

- **Chain entry zone**

To aid the fabric pinning or clipping properly, inlet chain tracks are used. These clips and pins are joined to endless chain. Pinion rollers feed the fabric to the pins of stenter and the brush rollers are used to hit the fabric into the clips.

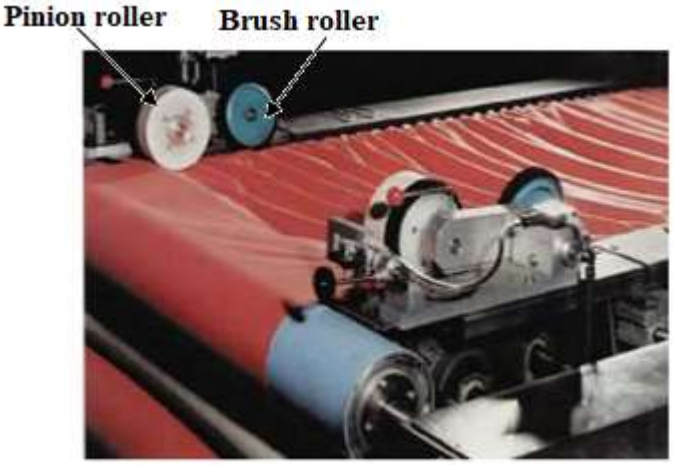


Figure 2.19 : Inlet chain track (Swastik, 2012)

- **Drying and heat-setting zone**

In heating chambers drying, heat-setting and curing processes take place. Heating chamber temperatures are set as per the requirement. There are about 8 to 10 heating chambers. In pin stenter, hot air is usually employed and is directed from above and below by jets onto the material (Haghi, 2011). Air comes from atmosphere and move in the chamber with the help of fans from top to bottom of the chamber. Heated oil is passed through the coils of the chamber so that air becomes hot and dried the fabric as much as it required. Oil is continuously circulated through the chambers and exchanges heat with the air about 100°C. Hot air is passed through the fins of heat exchanger and exchange heat with the fabric. Moist air is pulled from the chamber with the help of blower and exhausted into the atmosphere. The blower sucks hot air from radiator and blow it into the nozzles through which drying occurs. Inside the drying chamber also contains width adjustment spindle and pin/clip chain track.

- **Cooling zone**

After heating chamber, there is a system of cooling of fabric. When the fabric is coming out from chambers its temperature is almost 110°C. Temperature of the fabric is reduced to 70°C by passing it through cooled air. Air is passed through nozzles to create high velocity of air. After that fabric is passed to lapping roller.

- **Delivery zone**

To facilitate de-pinning or de-clipping of fabric from pins/clips and to give proper cleaning of the pins & clips outlet chain tracks are used. Then the fabric is wind on a frame or plaiting of finished fabric in a suitable box/ trolley. The lapping rollers are the rollers that roll the fabric one after the other.

2.5.2 The effect of heat-setting on thermoplastic fibres

The majority of prior research has discussed the effect of heat-setting on thermoplastic fibres and yarns (Batra, 1976; Cullerton et al., 1990; Dennis & Buchanan, 1987; Gupta, 1995; Gupta & Kumar, 1981a; Marvin, 1954; Phillips et al., 2003; Şardağ & Özdemir, 2012; Zhang, Jiang, Wu, Zhou, & Xuan, 1985). Many of the published reports are about quantifying the level of dimensional stability resulting from the filament heat-setting process and to determine the resulted nature of filament structure and morphology (Rudolf et al., 2011; Zhang et al., 1985). Heat-set yarns and fabrics are expected to attain resistance against thermal shrinkage, dimensional changes, curling, and creasing as well as improvements in physical and mechanical properties (Karmakar, 1999b).

Zhang et al. (1985) revealed that the morphology and fine structure of polyester filaments are altered by temperature at heat-setting and by the drawing processes. Their findings showed that the peak shrinkage stress in the heat-set PET fibres at different temperatures are progressively decreases and almost complete relaxation of residual stress was observed with a sample heat-set at 220°C for 4 hrs (Zhang et al., 1985).

Gupta, Ramesh and Gupta (1984) analyzed the structural and morphological changes through wide and low angle X-ray scattering of free and taut annealed PET fibres on heat-setting. Findings revealed that during the temperature ranges from 100°C-180°C; large numbers of small crystallites are formed on the amorphous region of the fibre and increases the glass transition temperature (T_g). In the range from 180°C-250°C, more larger crystallites are formed and caused to decrease the glass transition temperature (Gupta et al., 1984).

Venkatesh (1987) examined the free shrinkage of polyester yarn in oil as a function

of temperature and found that the shrinkages are linearly related to the temperature of heat-setting. 8% and 40% shrinkages were observed for the yarns heat set at 100°C and 225°C respectively (Venkatesh et al., 1978). Thus revealing that during heat-setting, energy stored in the fibre will be released by making structural changes to the fibre especially as shrinkage (Karmakar, 1999b).

If the fabric is heat-set at the presence of steam and called as hydrothermal setting (De Boos et al., 1986). The studies have been done to analyze the effect of hydrothermal and dry heat-setting methods on the stability of wool-polyester blends in subsequent dyeing at elevated temperatures (De Boos et al., 1986). They revealed that the properties of heat-set fabric are depending not only on the agency used to set the fabric (heat or steam) but also on the machinery and conditions that are used. The samples heat-set at constant length (i.e. not allowed to undergo any shrinkage during heat-setting) showed higher residual shrinkage if the heat-setting was performed below 200°C for polyester filaments (Gupta, 1995; Gupta et al., 1984; Rath, Chaki, & Khastgir, 2012).

2.5.3 Effect of temperature and tension during annealing

2.5.3.1 Effect of temperature

Preston, Nimkar and Gundavda (1951) investigated changes in fibre properties after various thermal treatments and found that the amount of change depends on the moisture content and treatment temperature. Samuel (1972) stated that higher the annealing temperature, the more regular the chain folds into the fibre and the amount of non-crystal chains (amorphous) disorientation will depend on the temperature and time of the annealing. In the drawn polymer, the extended polymer state is stable, but once its temperature rises, the extended state returns through the thermal shrinkage process to the folded form. Samuel (1972) showed that the higher the annealing temperature, the higher the expected disorientation and the shrinkage. Several studies suggested that as the polyester yarn temperature increases, the crystalline orientation and the size of the crystal increase (Gupta, 1995; Hearle, Hollick, & Wilson, 2001; Karaka & Dayloglu, 2005; Niu, Wakida, & Ueda, 1992). Trznadel, Pakula and Kryszewski (1988) showed that only the orientation fixed in

equilibrium crystallites can be thermodynamically stable.

Several studies have revealed in addition to relaxing amorphous molecules, micro-crystal formation in the polymer structure is promoted at high temperature (Gupta & Kumar, 1981a; Karmakar, 1999b; Prevorsek & Tobolsky, 1963; Samuels, 1972). The number of crystals increases as the temperature increases, their total number decreases by fusing small crystals at high temperatures and amorphous orientation decreases as the temperature increases (Gupta et al., 1984; Karmakar, 1999b; Samuels, 1972).

Fischer and Fakirov (1976) shown the effect of annealing temperature on the structure of drawn PET. The main effect observed was the increase in order within the crystalline layers arranged perpendicular to the fibre direction. The higher the annealing temperature the larger are the dimensions of the mosaic blocks, both parallel and perpendicular to the chain axes. In addition, the longitudinal mutual order of the mosaic blocks was improved (Fischer & Fakirov, 1976). It is been observed that crystallinity of heat-set partially oriented yarns is increased with the increase of heat-setting temperature (Niu et al., 1992). It has been suggested that amorphous regions play a dominant role in lower temperature shrinking, primarily due to amorphous region disorientation (Gupta, 1995; Hearle et al., 2001; Karaka & Dayloglu, 2005). It was found that the transition from *trans* to *gauche* caused amorphous chain coiling and a physical loss of orientation appeared as a thermal shrinkage.

The findings of earlier researchers revealed that dye diffusivity and saturation values do not vary linearly with heat-setting temperature (Gupta & Kumar, 1976; Marvin, 1954; Mitsuishi & Tonami, 1963; Rodriguez-Cabello et al., 1996). Merian et al. (1963) found that the saturation limit and the average diffusion coefficient of dye showed a minimum value for the fibres heat-set at 150°C, whereas Gupta and Kumar (1976) found that the minimum saturation values for both diffusivity and dye exhibited at a heat-setting temperature close to 175°C.

2.5.3.2 Effect of physical condition during annealing

The physical condition on which heat is applied also has significant effect on the heat-set fabric structure. The annealing of PET can be done either free to relax or held taut at constant length or while stretching. Each of these conditions will cause different structural changes to the fibre. These structural changes will determine the thermal shrinkage behavior of the fibre during subsequent heat treatments.

Mecklenburgh (1950) explained that if the energy is applied while the yarn is prevented from shrinking disorientation still occurs in the yarn, since the liberated chains are moving into positions of less constraint due to the applied thermal energy. However, the author suggested greater yarn stability can be achieved if yarn shrinking is allowed under less severe heat-setting conditions (Mecklenburgh, 1950).

The external tension applied to the fibre during annealing treatment will determine the internal tension of shrinkage caused by the molecules during subsequent heating. If chain refolding is allowed during the annealing process, the potential for subsequent shrinkage and the amount of internal shrinkage tension will be lowered and higher temperatures will be required for further shrinkage to be activated. The refolding of molecules thus appears to be a significant contributor to the shrinkage and shrinkage tension in an oriented fibre during thermal activation (Statton et al., 1970). Prior researches suggest that annealing treatments at high temperatures lead to an increase in regular chain folding; the amount of this folding during annealing treatment is highly sensitive to the applied temperature and the tension conditions (Statton et al., 1970). If a fibre is free to contract, it will have much more regular refolding than one which held at constant length, resulting in very high thermal shrinkage (Statton et al., 1970).

Previous study shown that a significant thermal shrinkage in free end annealing at low temperature range was primarily attributed to two-stage process whereby the fibre shrinks by relaxing the non-crystalline chains or disorientation of amorphous region which can then be incorporated into the crystallite annealing (Wu et al., 1998).

The high orientation of non-crystalline region can help to minimize the distance

between molecular chains and increase cohesive intermolecular forces. Because of high intermolecular interaction, when the fibres are heat treated, large-scale molecular motion can be restricted and extended amorphous molecules can be prevented from recoiling. In the non-crystalline phase, this may result in limited disorientation and limited shrinkage in the fibre (Wu et al., 1998).

At high temperature, taut condition annealing causes the thermoplastic polymers to reach higher orientation along the fibre axis. Gupta (2001) shown that crystallinity, crystal size, crystalline orientation increases as increasing temperature for taut annealed PET fibres.

Keum and Song (2005) revealed that depending on the fibre orientation, the fibres showed two very distinct thermal responses. By taut annealing the partially oriented non-crystalline polymers, it is possible to create non-crystalline chain-extended phase in PET polymers (Keum & Song, 2005).

The finding of Liu et al (2016) revealed that higher spinning speeds and lower heat-setting temperatures resulted in larger number of small crystals in the structure due to two phenomenon; PET molecules at high spinning speed tend to orient polymer molecules along the fibre axis, promoting the crystallization rate and resulting in more crystal nuclei. Low heat-setting temperature restricts crystallization of amorphous molecules and perfection of defective crystals. On the contrary, the PET yarns which underwent low spinning speed and higher heat-setting temperatures resulted in larger crystals. This was attributed to the less crystal nuclei produced at lower spinning speed and the small crystals were able to grow due to the high heat-setting temperatures (Liu et al., 2016).

Liu et al. (2016) demonstrated that heat-setting at taut condition caused to generate two types of tension effects at high temperatures: (1) the internal shrinkage tension caused by the molecules, or (2) the tension or force created by pulling at the ends of a fibre and these discrepancies during annealing would definitely lead to various structural changes.

2.6 Shrinkage Mechanism of Polyester Fibres, Yarns and Fabrics

2.6.1 Thermal shrinkage mechanism of semi-crystalline polyester

The thermal shrinkage of semi-crystalline, oriented, thermoplastic fibres such as nylons and polyesters is well known (Ribnick et al., 1973). When these fibres are exposed to temperatures exceeding the glass-rubber transition but still well below the crystalline melting point, a large decrease in fibre length was observed (Ribnick et al., 1973). The theory regarding the structure of PET fibres and the mechanisms of thermal contraction have been described by many researchers. Molecular disorganization and rearrangement (Matlin & Nuessle, 1955; Prevorsek et al., 1974; Prevorsek & Tobolsky, 1963; Ribnick et al., 1973), disorientations of oriented amorphous chains or extended interfibriller tie molecules (Huisman & Heuvel, 1989; Mody et al., 2001; Pakhomov et al., 1983; Pakuła & Trznadel, 1985; Peterlin, 1977; Prevorsek et al., 1974; Prevorsek & Tobolsky, 1963; M. P. W. Wilson, 1974), recrystallization (Ribnick, 1969), and chain folding (Dismore & Statton, 1966; Dumbleton, 1970b; Dumbleton et al., 1968; Prevorsek & Sibilia, 2006; Statton et al., 1970) are the known mechanisms which described the thermal shrinkage behaviors of polyester polymers.

Many studies on thermal shrinkage behavior of PET fibres and films by previous authors have shown that the overall shrinkage process depends on temperature and duration of the thermal treatment (Gupta et al., 1993; Heuvel & Huisman, 1981; Prevorsek et al., 1974; Prevorsek & Tobolsky, 1963; Ribnick, 1969; Venkatesh et al., 1978; M. P. W. Wilson, 1974). Previous studies have emphasized that thermal shrinkage involves a rapid initial stage of rubber-like contraction of the molecular network, followed by the disorientation in the amorphous phase. It has also been suggested that crystallization can occur simultaneously with amorphous disorientation and, once the crystallization begins, further shrinkage is hindered.

A number of authors have recognized that thermal shrinkages are resulting from annealing at lower temperatures are due to the viscoelastic behavior of PET polymers (Hearle et al., 2001; Statton et al., 1970). The rubber-elastic effect (assisted by rupture of the hydrogen bond and partial crystal melting) appears to be dominated the

viscoelastic effect (due to crystal melting, re-crystallization and increased chain folding) during the initial stage of heating. This was resulted in the build-up of a contractile force, provided the heating rate was sufficiently fast (Bosley & Du, 1967; Choy et al., 1981). Then, depending on the heating rate, the contractile stress reaches a maximum at some temperature, and the viscoelastic effect starts to prevail. There is a rapid stress relaxation of a significant degree which resulting higher thermal shrinkage.

Previous studies have shown that structural changes occur during the annealing of drawn PET and amorphous phase of the fibre control the thermal shrinking. The amorphous polymer molecules have sufficient mobility above the glass-transition temperature to obtain their configuration most likely by coiling up. The higher the temperature of this process the behavior was different to this. In most cases, crystals can be considered as rigid blocks during thermal shrinkage. Based on these arguments they suggested that the yarn shrinkage can be expected to be proportional to the amount of amorphous material available in the structure. Refolding of molecules during thermal activation thus appears to be a significant contributor to the shrinkage tension and shrinkage in an oriented fibre (Mecklenburgh, 1950).

Marvin (1954) conducted one of the earliest studies on thermal shrinking of Terylene filaments, yarn and fabrics. Marvin's findings showed that the possession of shrinkage or retraction property when Terylene yarns and fabrics were exposed to high temperatures. It was found that higher the temperature the yarn or fabric is exposed to, higher the resulting shrinkage, and an approximately linear relationship exists between shrinkage and temperature over the 100°C - 200°C range (Marvin, 1954). Matlin and Nuessle (1955) suggested that the mechanisms for the shrinking of thermoplastic fabrics are largely due to molecular disorganization, which results in fibre contraction and mechanical distortion. Their findings revealed that molecular disorganization is primarily physical in nature and the orientation of the main chains is largely dependent on hydrogen bonding, and the weaker Vander-Waals forces are present in the polymer as few or no covalent cross links exist. Therefore, as the temperature rises, the polymer chains coil up in the amorphous regions to an ever-increasing degree. This phenomenon is seen as a contraction of the fibres, which

causes the yarns to shrink and gross mechanical distortion is the second cause of shrinking (Matlin & Nuessle, 1955).

Prevorsek and Tobolsky (1963) and Prevorsek et al. (1974) conducted a systematic study of fibre properties and morphology as a function the degree of thermal contraction. Results revealed that morphological changes that allowed the contracting of PET fibres by exposing them to different degrees of heat. The relative displacements of microfibril and the contraction of extended interfibrillary tie molecules are the two mechanisms involving high fibre contractions. The first process operates at low levels of contraction; the relative displacement of microfibrils is the overriding factor in shrinkages ranging from 10% to 38%. It also suggested that the contraction above 38% involve in partial melting and re-crystallization leading to the gradual collapse of the three-dimensional fibre structure (Prevorsek et al., 1974; Prevorsek & Tobolsky, 1963). Prevorsek and Tobolsky (1963) also considered shrinking to be the reversal of the process of drawing or orientation. Their findings also suggest the process of molecular disorientation. Structural studies support this conclusion, as X-ray diagrams of fibres or other oriented polymers heated near their melting points showed a complete disorientation of the crystalline regions (Prevorsek & Tobolsky, 1963).

Dismore and Statton (1966) proposed that thermal shrinkage is a re-crystallization of polymers. They heated drawn polyethylene terephthalate, yarns in silicone oil for 1 min. The resulting samples were studied by diffraction from X-rays and mechanical properties were measured. The results suggested that drawn PET consists of substantially parallel highly extended molecules with few folds present and chain folding occurs when the sample was heated (Dismore & Statton, 1966). Dumbleton and colleagues (1968 and 1969) proposed a similar structural rearrangement for thermal shrinkage of polyethylene terephthalate at temperatures above 150°C (Dumbleton, 1969; Dumbleton & Buchanan, 1968).

Ribnick (1969) also demonstrated that thermal shrinkage represents a re-crystallization type of structural arrangement. The thermal shrinkage mechanism proposed by Ribnick (1969) consisted of the three main events; intermolecular bonds formed by polar groups between neighbouring extended chains become free or

loosened by thermal energy, this chain, once released from these bonds, contracts along its length, initially contracting very rapidly, and bonds reform extensively between groups or the same. Ribnick (1969) has shown that the thermal shrinkage of oriented polyester yarns appears to consist of a very fast contraction rate, followed by monotonically decreasing rates until the shrinkage disappears over time. The findings also reveal that contraction increases by increasing temperature as the melting point approaches (Ribnick, 1969). Ribnick (1969) showed that the contraction process can be viewed as an activated one and that a certain number of polar groups must be dissociated thermally before the chain can contract.

Based on the annealing experiments of drawn PET fibres under relaxed conditions, Dumbleton (1969) suggests that chain folding occurs on heating. The result of Statton et al. (1970) infrared structure suggested that the refolding of molecules during thermal activation has a major contribution to shrinkage and shrinkage tension in an oriented fibre (Dismore & Statton, 1966; Statton et al., 1970). The role of chain folding in shrinking drawn poly (ethylene terepthalate) fibres was established by Wilson (1970). Prior research suggests that the overall shrinkage process involves a rapid initial stage that is associated with disorientation in the amorphous regions and this process is primarily responsible for the change in fibre length. If time permits, disorientation is followed by the crystallization stage.

Statton, Koenig and Hannon (1970) showed that the refolding of molecules thus appears to be a significant contributor to the shrinkage and shrinkage tension in an oriented fibre during thermal activation. Dismore and Statton (1970) suggested that by disrupting intermolecular cohesive forces, thermal energy would disrupt polymer chains. With this increased mobility, residual orientation stress in the fibre is relieved and this relaxation process is followed by a rearrangement of the chains in the new configuration at higher temperatures. The new structure appears to be in a more thermodynamically favoured state because of the state of lower free energy (Dismore & Statton, 1966; Statton et al., 1970).

Samuel (1972) concluded that a two-phase model can adequately explain the behavior of several semi-crystalline polymers and that amorphous phase controls the thermal shrinkage. Therefore, the temperatures of annealing used to shrink the fibres

should be in the correct range to give mobility to non-crystalline-oriented chains.

Ribnick et al. (1973) viewed thermal shrinkage process of nylon and polyester as an external indicator of a fundamental polymer chains rearrangement structure (Ribnick et al., 1973). Folding the chain as detected by Infrared spectroscopy was associated with the later crystallization. Authors also observed that the shrinkage process adequately combines the rubber elasticity type of shrinkage approach with later folded chain models (M. P. W. Wilson, 1974).

Nobbs, Bower and Ward (1976) observed for higher drawing ratios, although the shrinkage was dramatically reduced, it was always associated with significant disorientation of amorphous regions. They suggested that disorientation of amorphous regions as the primary shrinkage mechanism for drawn PET fibres (Nobbs et al., 1976).

Fischer and Fakirov (1976) assumed that the main result of the accumulation of defects expelled from the crystals in the disordered regions was the shrinkage or contraction. They also argued that the amount of shrinkage introduced by thermal treatment can sometimes be fully recovered by tension even if the experiments are conducted at temperatures well below the glass transition temperature of the fibre (Fischer & Fakirov, 1976). Bhatt and Bell (1976) demonstrated the possible thermal shrinkage mechanism as the relaxation of some of the chain entanglements due to the strain imposed on the fibre externally (Bhatt & Bell, 1976).

Peterlin (1977) argued that the new folds in the fibre structure cannot be formed and that the observed shrinkage is the result of the contraction of long extended chains formed during drawing. Peterlin first proposed the occurrence of thermal shrinkage resulting in contraction of extended chain molecules (Peterlin, 1977).

Venkatesh et al (1978) explained that when semi-crystalline, oriented thermoplastic fibres such as nylon and polyester are exposed to temperatures exceeding their glass transition temperatures in air or in a fluid medium, shrinkage occurs because these drawn fibres are in a thermodynamically unfavourable condition with built-in stresses and strains during spinning and drawing processes. They also suggested that the chain segments re-crystallize into a structure with higher crystalline perfection

when sufficient energy (thermal or chemical or both) is made available to the polymer system, resulting in partial or complete removal of initial stresses and strains. The dimensional stability and the mechanical, physical and chemical properties are therefore altered (Venkatesh et al., 1978). Pakhomov et al. (1983) investigated the shrinkage mechanism of amorphous PET polymers from geometric and kinetic studies. The studies had evidence to confirm a shrinkage rotational isomer mechanism and concluded that under the action of entropic force a coiling of previously extended polymer molecules are taken place (Pakhomov et al., 1983).

Pakula and Trznadel (1985) discussed the shrinkage force generation mechanism by proposing a model describing the shrinkage phenomenon (Pakuła & Trznadel, 1985). Trznadel and Kryszewski (1988) concluded that the appearance of shrinkage forces is primarily associated with the gradual relaxation of internal stresses frozen in the sample after deformation (Trznadel and Kryszewski, 1988). Entropic nature is the driving force behind yarn shrinkage. They suggest that polymer molecules in the amorphous domains have sufficient mobility above the glass-transition temperature to get their most likely configuration by coiling up. The higher the temperature the coiling up process will promoted and the shrinkage process is more pronounced. The behavior of crystals is contrary to this. In most cases, during thermal shrinkage, the crystals may be considered to behave as rigid blocks. The yarn shrinkage can be expected to be proportional to the amount of amorphous material on the basis of these arguments. The second factor that governs yarn shrinkage is the orientation of the amorphous domains molecular segments (Trznadel & Kryszewski, 1988).

Huisman and Heuvel (1989) observed decreasing shrinkage with increasing spinning speed according to the general structural model of oriented PET fibre, while a significantly lower shrinkage is found for the yarns drawn at the higher temperature. They suggested that entropic nature and molecular segment orientation in amorphous domains are two factors governing the yarn shrinkage. Authors suggested that high amorphous orientation will lead to a large disorientation resulting in a high shrinkage. They have concluded that the shrinkage can be reduced either by increasing the crystallinity or by reducing the amorphous orientation (Huisman & Heuvel, 1989).

Rim and Nelson (1992) performed morphological analysis on high-modulus and low-shrinkage PET fibres (HMLS). Findings revealed that the degree of shrinking and tenacity is controlled by orientation of amorphous region, and interfibrillary regions contribute to the observed behavior of the thermal shrinkage.

Wu, Cuculo and Yoshida (1998) suggested that the external tension applied to a fibre during annealing treatment will determine the internal shrinkage tension caused by the molecules during subsequent heating. If chain refolding is allowed during the annealing process, the potential for subsequent shrinkage and the amount of internal shrinkage tension will be lowered and higher temperatures will be necessary to activate further shrinkage. They also suggested that relatively high but gradually declining shrinkage in the higher temperature region is primarily associated with the decreased disorientation process and a sequential crystallization process (Wu et al., 1998). Mody, Lofgren and Jabarin (2001) stated that the percentage of shrinkage is determined by the amorphous orientation status. The percentage of crystallinity developed in the PET sample and shrinkage arises from the disorientation of the amorphous phase chains (Mody et al., 2001). Moreover, samples with a large degree of regular chain folding are generally more plastic than those with low regularity in folding (Prevorsek & Sibilia, 2006)

Hearle, Hollick and Wilson (2001) observed when thermoplastic cords such as nylon and polyester are subjected to high temperatures they showed a tendency to shrink. This is due to the highly crystalline and oriented polymer chains in a fibre yarn, and the orientation is in the direction of the fibre axis, making the fibre anisotropic in nature. This fibre state, however, is a low entropy state (Hearle et al., 2001). Therefore, whenever yarns undergo thermal treatment, the fibre will tend to go to the state of higher entropy, which is the reason for the observed shrinkage of fibres or thermal disorder due to heat treatment (Rath et al., 2008).

2.7 Standard testing methods available for thermal shrinkage measurement

The primary purpose of textile testing and analysis is to evaluate the performance of textile products and to use test results to predict the performance of the product. There are various types of standard test use to determine the thermal shrinkage of

materials for specific use. To test thermal shrinkage of yarns and fabrics, NFPA 2112, ASTM D4974, ASTM F2894, NFPA 1975-2009 and GB / T 13519-2016 are used. NFPA 2112 is an industry standard for flame resistant garments for industrial personnel protection against flash fire. To comply with the NFPA2112 standard, a garment must pass 4 tests. The tests are the Manikin test, the performance test for heat transfer, the vertical flame test and the shrinkage test. The thermal shrinkage test decides whether a fabric melts drips or separates excessively. The standard NFPA 2112 the test starts with a 15 "square piece of fabric("NFPA 2112 Pass/Fail Test Series Part 4: The Thermal Shrinkage Test," 2019). The fabric specimen is washed three times, and then put horizontally in a 500°F oven for 5 minute duration ("NFPA 2112 Pass/Fail Test Series Part 4: The Thermal Shrinkage Test," 2019). This test standard may not apply to commercial polyester fibres, since melting temperature of polyester is about 260°C. This testing standard is therefore more useful for protective clothing and flame resistant clothing. ASTM D4974 is a main test method for industrial yarn and thread hot-air shrinkage ("ASTM D4974 - 04(2016) Standard Test Method for Hot Air Thermal Shrinkage of Yarn and Cord Using a Thermal Shrinkage Oven," 2016). The NFPA 1975 test method allows quantitative measurement of the dimensional change occurring as a result of a defined heat exposure in a circulating oven with hot air ("NFPA 1975 Standard on Emergency Services Work Apparel," 2019). The thermal stability of specimens by evaluating the blockage inside an oven of folded samples placed between glass plates, under a given weight. ISO 17493/ASTM F2894-12b is a test method and requirement for determining the ability of a fabric to withstand ignition, melt or shrink at 260°C for 5 minutes allows for the measurement of thermal shrinkage of heat-shrinkable polyethylene film for packaging applications ("ASTM F2894 - 12b Standard Test Method for Evaluation of Materials , Protective Clothing and Equipment for Heat Resistance Using a Hot Air Circulating Oven 1," 2015).

2.8 Use of Spandex® in Knitted Fabrics

In order to improve the stretch and recovery properties of knitted fabrics elastomeric yarns co-knitting with other fibres. Polyester/ elastomeric knitted fabrics have gained much attention due to their excellent stretch and recovery and other mechanical

properties. In past, rubber was widely used to convey good stretch and recovery properties to the fabrics. Better recovery, less stress relief, and cheapness have led the rubber being used for manufacturing stretchable fabrics. In 1959, Polyurea copolymer was discovered by chemists C. L. Sandquist and Joseph Shivers at DuPont's Benger Laboratory in Virginia. Compared to rubber, polyurethane fibres are stronger and more powerful, allowing the use of finer yarns than the rubber (N. Wilson, 1967). Polyurethane fibre is refereed as Spandex®, Lycra® or Elastane® by the consumers. The ability of Spandex® yarns to heat-set is an important property that is not possessed by natural rubber (N. Wilson, 1967). Spandex® ® is used in all areas requiring a high degree of permanent elasticity, stretch and recovery, and good dimensional stability. These types of fabrics are used in sportswear and leisurewear, hosiery, underwear and swimwear in the apparel industry (Mani, 2014; Ulrich, 1937).

2.8.1 Chemical structure of Spandex®

Spandex (also known as elastane) is a manufactured fibre in which the fibre forming substance is a long chain synthetic elastomer consisting of at least 85% by weight of segmented polyurethane (N. Wilson, 1967). The fibre has an alternating soft and hard molecular segment polyurea copolymer as presented in Figure 2.20. The hard, crystalline segments with high-melting polyurethane and soft segments have low-melting and amorphous polyesters or polyethers (Karmakar, 1999a). The elastic characteristics of Spandex® fibres are due to the presence of soft molecular segments, made of coiled aliphatic polyesters and polyethers, which uncoil to make it stretch under a load (Salem, 2001). Polyurethane is made from polyether glycol, diisocyanate mixture and chain extender. The four main methods of Spandex fibres production methods are solution dry spinning, solution wet spinning, reaction spinning and melt extrusion (Otaigbe & Madbouly, 2009).

Spandex is compatible with other commonly used fibres such as cotton, nylon, polyester, acetate, polypropylene, acrylic, wool and rayon. Spandex fibres have been added to improve the fabric stretch and recovery properties of the conventional fibres, without changing texture and handle of the material (Ibrahim, 1966, 1968; Senthilkumar & Anbumani, 2011; Tezel & Kavusturan, 2008; N. Wilson, 1967).

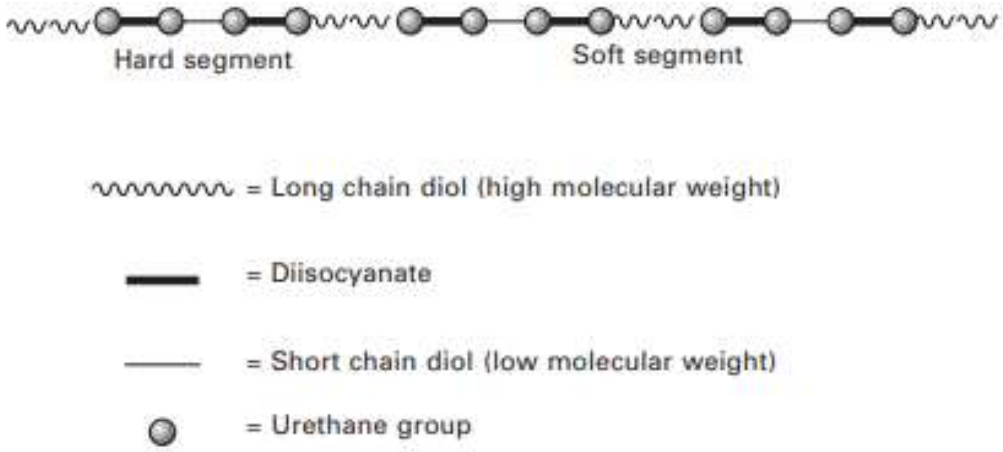


Figure 2.20 : Schematic diagram of the hard and soft segments of polyurathane structure (Otaigbe & Madbouly, 2009).

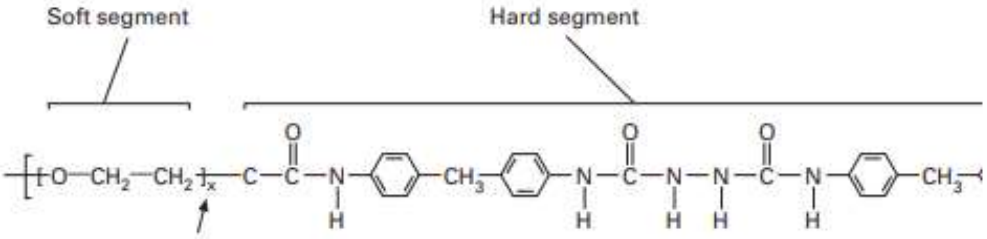


Figure 2.21 : Chemical structure of spandex (Otaigbe & Madbouly, 2009)

In general, Spandex® fibre has a breaking strength of 0.7 g/d, and the pre-break elongation is from 450 to 900 percent and the elastic recovery is 95 percent with a 200 percent extension (Karmakar, 1999a). The Spandex® fibre is white in colour and able to dye with dispersed and acid dyes. It has good chemical resistance and it resists the effect of perspiration. When treated with chlorine, fibre may degrade and become yellow. The soft segment of the fibre has a glass transition temperature lower than 0°C so that the soft components have the freedom to move at room temperature and above. The fibre has moisture regain of about 0.3% to 3% with melting point of 250°C, but starts sticking at 175°C (Karmakar, 1999a).

2.8.2 Knitting with Spandex® yarn

Due to its construction, even without Spandex, the knitted fabrics have their own stretch and recovery. The knit textiles can easily deform or stretch when the individual stitches are compressed or extended. This ability to stretch adds to the

comfort of wearing garments made of knit materials. There is certain recovery of the knit stitches to original dimension when the imposed forces are removed but recovery through knit-stitch rearrangement is not complete because these yarns are not elastomeric. Elastomeric yarns provide the strength to restructure the knit stitches. This residual deformation will permanently deform the garment of knitted fabrics. In order to improve the recovery performance of knit fabrics, a small amount of Spandex fibres with the ground yarn is commonly knitted together. When Spandex yarns are combined with conventional fibres and knitted into a fabric it is needed to ensure that the wearer can comfortably move with fashionable and functional garment, but recover their original shape when allowed to relax.

Spandex yarns are mainly used together with other yarns in circular knitting machines: bare, single, double-covered, core and core folded yarns. Each correctly used Spandex provides high fabric elasticity (Marmarali, 2003). In circular knitting, Spandex is mainly used bare. The feed rate and tensioning of Spandex must be precisely controlled for achieving the desired fabric properties and uniformity.

The process of co-knitting Spandex® is called "plating" (Marmarali, 2003; Senthilkumar & Anbumani, 2011) in circular knitting machine in single jersey fabric constriction (Figure 2.22). Spandex® can be found in polyester / Spandex® knit fabrics in each course or in altering courses that can be classified as full plating and half plating respectively (Patent No. US 6,776,014 B1, 2004). The most uniform appearance in single jersey fabric is obtained by knitting in each course with Spandex® and knitting on each second course creates ridged effect (Patent No. US 6,776,014 B1, 2004). The knitted fabrics containing spandex yarns provide better resilience, extension and immediate recovery compared to 100 % knitted fabrics of the ground yarn (Mukhopadhyay, Sharma, & Mohanty, 2003).

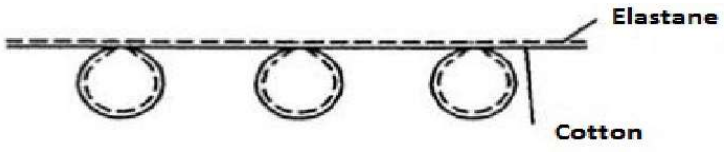


Figure 2.22 : Elastane plated single jersey plain knitted fabric pattern (Abdessalem, Abdelkader, Mokhtar, & Elmarzougui, 2009)

2.8.3 Effect of heat-setting on polyester/Spandex® knitted fabrics

Despite the given advantages, Spandex® fabrics show poor dimensional stability and tend to crease and curl extensively. Fabrics which contains spandex must thus be subjected to thermal treatment which reorganizes and relaxes molecular chains, thereby improving the dimensional stability of knitted fabrics made of polyester /elastane (Karmakar, 1999a). When the Spandex® yarn has been extended, heated and cooled for a certain extension, the yarn does not return to its original length (N. Wilson, 1967).

Heat-setting process sets Spandex® in elongated form and this is called *redeniering*, where a higher-denier Spandex® is drafted or extended to a lower-denier, and then heated to an adequately high temperature to stabilize the Spandex® at the lower denier for an adequate amount of time (Patent No. US 6,776,014 B1, 2004). Thus, heat-setting means that the Spandex® changes permanently at the molecular level to relieve recovery tension mainly in at a new and lower denier. Spandex® heat-setting temperatures are usually between 175°C and 200°C (Patent No. US 6,776,014 B1, 2004). First if heat-setting is not used to "set the Spandex®," the Stretched Spandex® will dissipate in the fabric, after the fabric is knitted and released from the constraints of the circular knitting machine to compress the fabric stitches. So that the fabric is reduced in dimensions compared to what those dimensions would be if the Spandex® were not present. Therefore, the heat-set Spandex® yarn will not significantly compress the knit stitches from the heat-set dimensions. Stretching and heat-setting parameters are chosen to provide weight and elongation within relatively tight limits of the desired fabric basis. Second, the more severe the compression of the stitch, the more the material is longer, exceeding the minimum standards and practical requirements. Excessive elongation in single jersey knitted fabrics for cut and sew applications is generally unwanted. Thirdly, the compressed stitches in the finished fabric are in equilibrium between the recovery forces of Spandex® and the stitch compression resistance of the ground yarn. The washing and drying can reduce the resistance of the ground yarn, probably partly due to agitation of the fabric (Patent No. US 6,776,014 B1, 2004). The Spandex® recovery forces may thus allow washing and drying to further compress knit stitches, resulting in unacceptable levels

of fabric shrinkage. Heat-setting of knit fabrics containing Spandex® relaxes and reduces the recovery force of Spandex®. The thermal setting operation thus improves the fabric stability and reduces the amount that the fabric shrinks after repeated washing (Patent No. US 6,776,014 B1, 2004).

The main elastic factors for the end usage of a Spandex® containing fabric are the amount of stretch available, the power of the fabric in the stretched condition, and its ability to recover quickly to the original dimensions (N. Wilson, 1967). The extensibility of a fabric is mainly controlled by the appropriate fabric construction and denier of the elastomer yarn since these determine the relaxed width of the fabric (Nazir, Hussain, Rehman, & Abid, 2015). Adjusting the stretch is then usually caused by heat-setting when the cloth is extended. This treatment also help to stabilize the fabric, reducing shrinkage during subsequent treatments (N. Wilson, 1967).

2.9 Application of Heat on PET During Garment Manufacturing

The use of polyester fabric for garment manufacturing is also increased during past few decades due to their excellent properties and characteristics. There are many thermal processes involved during garment production process. Among these processes some processes are performed at elevated temperatures with or without applying external pressure on the fabric plane.

Printing is one of such process which is also used in garment panel form to decorating textile fabrics using patterns of pigments, dyes, or other related materials. The Textile Institute in England defines printing as "the production of a design or motif on a substrate by application of a colourant or other reagent, usually in a paste or ink, in a predetermined pattern."

In order to obtain sharply defined, precise and reproducible patterns, traditionally used dye baths are not sufficient due to the capillarity and/or hygroscopicity of fibres and color migration cannot provide sharp and well-defined color patterns. Therefore it is necessary to use special liquids, conventionally called "printing pastes". The main characteristic of printing paste is a high degree of viscosity and has motion resistance (Clarke, 1974).

As the result of high degree of viscosity, the dyestuff applied in well-defined areas to produce the desired pattern cannot migrate to other areas of the fabric. The high viscosity of printing pastes will make the dye adhere to the fabric and fibres surface, but not penetrate and fix on them. Fixation operations will be performed with a heating (curing) or steaming process. Then the removal of excess colour is achieved by the washing process.

The heat transfer printing process is also known as the vapor-phase, dry-heat, sublimation, sublistatic or colourstatic process. Heat transfer is one by which a pre-printed textile, or graphic design on paper or other medium, is used to transfer the dye image to a dye-receptive fabric under controlled time, temperature and pressure conditions through its vapour phase. There is an adequate range of disperse dyes that are sublime in the 180°C region and these have the added property of not being substantive to fibres based on cellulosic. Sublimated dye will be absorbed most of synthetic polymer fibres readily in their vapour phase.

Acetate, certain acrylics, polyester and nylon are the fibres that can be subjected to transfer-printed to an acceptable standard. Other fibres, such as wool, silk and cotton, may not be printed alone, but may be used in mixtures with synthetic polymer fibres, provided that the content of the latter fibres is not less than 75%. The main steps of heat transfer printing is presented in Figure 2.23.

Heat transfer printing and panel sublimation printing are performed directly applying printing paste, heat and pressure during the process. In rubber printing, application of printing paste is performed in ambient temperature but fixation of printing paste will perform at high temperature. Rubber print curing for garment panels are usually performed in industrial drying machines at 170°C for 450 seconds without applying any external tension or pressure on it (free end annealing). Transfer printing, panel sublimation printing, bonding are performed at 160°C, 165 seconds and 200°C for 22 seconds and 24°C for 20 seconds respectively at a pressure of 4 bar in machines specific to these processes.

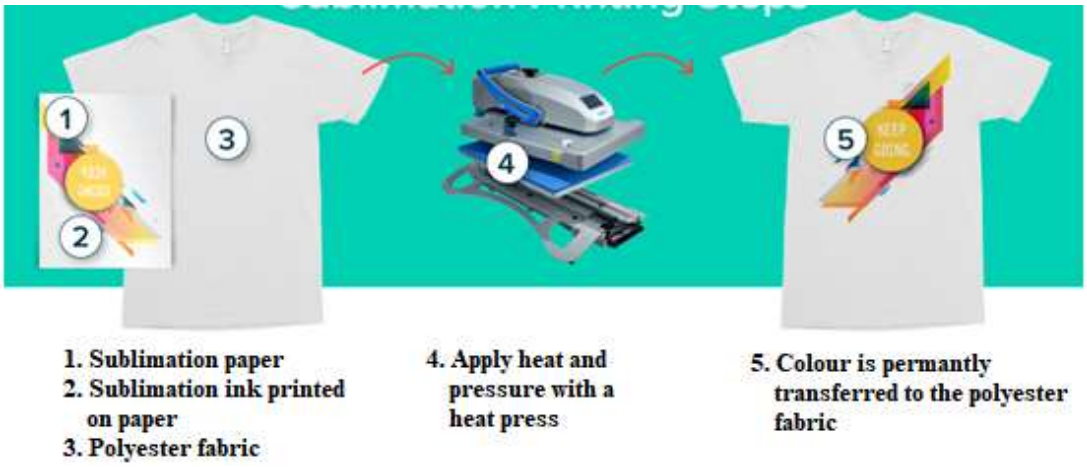


Figure 2.23 : Heat-transfer printing (sublimation) process (Maurer, n.d.)

2.10 Summary

Researchers have observed distortions in thermoplastic polymer fibres such as polyester and nylon at high temperatures in fibres and yarns (Arghyros & Backer, 1982; Batra, 1976; Haar, 2011; Marvin, 1954). The findings also revealed that thermal deformation occurs at temperatures above their glass transition temperatures as these drawn fibres are thermodynamically unstable due to built-in stresses and strains introduced during past processing conditions (Batra, 1976; Venkatesh et al., 1978). These polymer molecules start to vibrate if energy in the form of heat supplied. This will result in intermolecular bond breakage and therefore some parts of the fibre have greater freedom and relaxation. As a result, the dimensional stability and the mechanical, physical and chemical properties are altered (Venkatesh et al., 1978). Depending on the physical conditions maintained during thermal exposure, thermal distortion may be either thermal shrinkage or thermal expansion.

Heat-setting have been identified as a main process which impart dimensionally stability to fabrics containing synthetic fibres. The yarns or fabrics produced from synthetic fibres or blends containing a large proportion of such fibres are usually subjected to a process called heat-setting to impart dimensional stability at elevated temperatures and to prevent further dimensional changes. In general, the temperature of the heat setting is determined by the polymer nature and must be higher than the

maximum temperature expected in subsequent processes (Gupta et al., 1974, 1993; Karmakar, 1999b).

Although high dimensional stability at high temperatures is expected from the heat-set synthetic fabrics, thermal shrinkage behavior is observed when garment panels of synthetic materials are exposed to subsequent or post-heat-setting processes such as print curing and sublimation printing. Though many researchers have critically discussed thermal shrinkage of fibre and polyester yarns (Dumbleton, 1969; Gupta, Jain, Chidambareswaran, & Radhakrishnan, 1994; Long & Ward, 1991; Pakhomov et al., 1983; Pakuła & Trznadel, 1985; Statton et al., 1970) thermal shrinkage behavior of polyester knitted fabrics have been not discussed in details. It was not well understood the thermal distortion behavior of polyester knitted fabrics. The possible reasons could be that the knitted fabric structure is complex due to the configuration of the loop and can easily be distorted due to external factors. The literature will provide better understanding of the background to determine the factors that contribute to the thermal deformation of polyester knitted fabrics due to heat treatments.

3 METHODOLOGY

3.1 Introduction

This research is aiming at studying the thermal behavior of knitted fabrics due to heat-setting and post-heat treatment processes. The fabrics required for the experiments are knitted, exposed to standard heat-setting process and heat-curing process. The methodology executed is identified in six studies and is described in this chapter.

3.2 Materials

The plain knitted fabric is the simplest structure of all knitted fabrics and is the most widely used in garment manufacturing. Therefore this study of the thermal behavior of knitted fabrics is focussed on plain knitted fabrics knitted using 100% polyester yarns. 100% polyester fabrics were required in greige form, for dyeing, for heat-setting and post-heat-setting. These fabrics are produced on an industrial circular knitting machine of 28 gauge and 30-inch in diameter incorporated with positive yarn delivery devices. The thermal effects due to elastomeric yarns into the knitted structure too are analyzed. Spandex® was selected as the elastomeric yarn for the study and the elastomeric yarns were incorporated into the plain knitted structure using plating technique (Senthilkumar & Anbumani, 2011) . Spandex yarn was introduced in each course of the plain knitted fabric when producing 80% polyester/20% spandex plain knitted fabrics.

All the 100% polyester plain knitted fabrics were scoured, bleached and dispersed dyed on a jet dyeing machine (Model:Salavos) at 130°C. Pre-setting of all polyester/ spandex plain knitted fabrics were performed on a hot air pin stenter before disperse dyeing process. The recipes and process conditions followed are the standard practices in the industry in producing fabrics for the export market.

3.3 Heat-Setting Process

Heat-setting is a standard practice on fabrics produced using thermoplastic fibre materials. The fabrics for the experiments on the thermal behavior due to heat-setting and post-heat-setting were processed on industrial hot air pin stenter under

different process conditions as required for the experimental study. The heat-setting process parameters are the temperature, width-wise extension and length over-feed percentages. The initial study on the thermal behavior of polyester fabrics due to heat-setting on 100% polyester was performed at same over feed rate of 25% over-feed in the length direction of the fabric with 5% extension in the width direction. The only variable in this study was the heat-setting temperature. For the Polyester/spandex blended fabrics pre-setting was performed at 198°C prior to dyeing at 30°C. After dyeing, the final setting was performed at 200°C in hot air pin stenter for polyester/spandex blended plain knitted fabric.

The thermal effects due to post-heat treatments are one of the objectives of this study as described in the problem statement. Out of the few post-heat treatments, print curing, bonding, sublimations printing widely used in the apparel manufacturing industry, print heat-curing was selected to study the post heat-treatment effects on polyester fabrics. The criterion used in selecting the post-heat treatment process is described in Chapter 4.

Understanding the thermal behavior of constituting yarns of the fabrics is an important in this study. Although normal heat-setting process is not usual on polyester yarns, the polyester yarns used in this study were heat-set in hank form in same temperature range used for heat-setting the fabrics.

After heat-setting, the heat-set fabric panels and the yarns were subjected to the selected post-heat treatment processes to determine the thermal deformation behavior of the heat-set yarns and fabrics.

3.4 Post-Heat Treatment Process

The post heat treatment processes are usually performed on garment panels to embellish or to impart special feature to the garments. The true impact of the post-heat treatment process parameters on heat-set garment panels cannot be isolated and if the investigation was carried out in the presence of embellishments or special graphics. Therefore, the post heat treatment was performed on the heat-set garment panels without involving the graphics or embellishment. The post-heat treatment process parameters used in this study were determined depending on the experiment

design and the details are presented in the respective chapters. The selected yarn and fabric specifications, knitting machine specifications and parameters, heat-setting machine (hot air pin stenter) and post heat treatment machine parameters that were used for each study are further described in the respective chapters.

The knitted fabrics were kept under relax condition on a flat surface under standard atmospheric conditions as per the ASTM D 1776 before taking any measurement.

Details on each of the six investigations carried out in achieving the objectives of this research are briefly discussed below in relation to the main aim of the research.

3.5 Experiments

Study 1: Significance of thermal shrinkages due to post-heat treatment processes

Most widely used heat treatment processes in the industry are the rubber print curing, sublimation printing, heat transfer printing and bonding. The significance of the thermal effects of these four processes was tested on four commercially used polyester plain knit constructions. The print curing process delivered the highest thermal shrinkage percentage among the selected four processes. Therefore, print curing was selected as the post-heat treatment process for further study on the thermal shrinkage behavior. Yarn and fabric specifications, knitting machine, heat-setting and post-heat treatment machine parameters that were used for the study are described in Chapter 4.

Study 2: Effects of panel parameters and heat-setting temperature on thermal shrinkage

Investigation of the physical effects on the garment panels due to heat base processes is the main focus of this study. Change in dimensions of the garments panel is the significant problem faced by the garment manufactures. Thus the change in dimensions is one of the main focuses of this study. Results of the evaluation of the dimensional change may vary with fabric panel cutting direction and especially the dimensions of the fabrics panel. This study was conducted to investigate whether the test specimen size (cut panel size) has a significant effect on thermal shrinkage behavior of 100% polyester plain knitted fabrics which have been already heat-set

when subjected to further heat application during print curing. The print curing process was used as the post-heat treatment process.

100% polyester plain knitted fabric was heat-set at three different temperatures. For the investigation of the dimensional change due to post-heat treatment the samples were cut adopting two cutting layouts and nine sizes for the specimens. The decision on larger panel size was based on the bed sizes of the industrial print curing machines.

The fabric panels were subjected to print curing process and the resultant thermal shrinkages were measured. As per the statistical analysis of the results of this study and the dimensions of the industrial print-curing machine, 30 x 30 cm^2 was selected as the standard dimensions of fabric panels for further studies. Determination of panel size and panel layout is described in Chapter 5.

Study 3: Thermal behavior of heat treated polyester plain knitted fabrics

The study 3 was designed to study the effect and significance of heat during standard heat-setting process and the post-heat-setting process. The standard heat-setting temperature used on polyester fabrics in the knitted fabric manufacturing industry varies in the range 140°C -170°C. The exact temperature used by the industry may vary with individual organizations and the heat-setting temperature is changed to solve some of the issues faced by the industry; production cost, problems in dimensional stability, dye colour are among the issues. Based on the above issues, the heat-setting of fabric outside the above mention range is not uncommon.

The experiments to study the effect of heat-setting was designed such that the fabrics are heat-set in the range from 130°C-200°C at 10°C intervals and studied the thermal distortions. In order to investigate effect of heat-setting on the chemical structure, heat-set fabrics were analysed using Differential Scanning Calorimetry (DSC) thermograms and the structure and morphology of polyester fibres was analysed. The DSC machine parameters for the experiments are in the chapter 6. The thermal properties of the yarns were studied by analysing the behavior of exothermic and endothermic peaks and calculating the percentage crystallinity from the results of the thermograms. Fabrics heat-set at different temperatures was heat-cured (post-heat

treated) at temperatures from 120°C to 200°C at 20°C intervals and thermal shrinkages were measured. This study is described in the Chapter 6.

Study 4: Comparative study on the thermal shrinkage behavior of polyester yarn and its plain knitted fabrics

The extent to which the thermal shrinkage of thermoplastic yarn affects the thermal shrinkage of the knitted fabric is the focus of this study. Knitted fabric may change its dimensions due to shrinkage of the constituent yarns in the fabric and the change in loop shape. The thermal shrinkage behavior of polyester yarn and the plain-knitted fabric made of the same yarns were analysed after subjecting them to dyeing, heat-setting and subsequent heat-curing processes. The thermal effects on individual yarns in hank, the yarns in the fabrics and on the wale and course densities were investigated.

Plain knit fabrics were produced on circular knitting machines and the yarns used in producing the fabric were subjected to all processes that the fabrics usually undergo. The yarns are processed in hank form. Details of the processes and testing carried out on yarns and fabrics are described in Chapter 7.

Study 5: The influence of over feed during heat-setting on the thermal shrinkage behavior

This study was conducted to investigate the influence of the percentage of overfeed during heat-setting on the thermal shrinkage behavior of heat-set fabrics and when they were exposed to post heat treatment processes. Width extension and overfeed of fabric is imposed during heat-setting to achieve the required width measurement and to prevent unusual deformation of the fabric.

Three polyester plain knitted fabrics with different stitch lengths were subjected to 15%, 20%, 25% and 30% overfeeding while heat-setting at 130°C. The heat-setting temperature for 100% polyester has decreased from 160°C to 130°C in the textile industry to avoid colour fading during the heat-setting process. These fabrics were exposed to heat-curing at 140°C and thermal shrinkage values and structural parameters were statistically analyzed. The detailed study is presented in Chapter 8.

Study 6: Thermal shrinkage behavior of polyester/elastomeric plain knitted fabrics

Physical behavior of knitted fabrics is changed by incorporating elastomeric yarns in polyester plain knitted fabrics. Due to application of heat especially during heat-curing may affect the physical behavior of the fabric; it may even have negative effects on the expected behavior by incorporating elastomeric yarns. The objective of the study 6 is to investigate the thermal behavior of polyester/elastomeric plated plain knitted fabrics. Three fabrics of polyester/spandex were subjected to print curing process and the results were compared against the 100% polyester knitted fabrics. The detailed study is described in the Chapter 9.

3.6 Statistical analysis

Univariate analysis and advanced statistical analysis were performed on data by adopting the following procedures.

The ANalysis of Variance (ANOVA) is used to determine whether the mean of two or more independent variables has statistically significant differences. Multiple linear regression analysis was performed in order to determine the linear relationship among independent and dependent variables. Thus, the linear relationship among continuous dependent variable and categorical independent variables and their interactions were analysed using the backward elimination method at 5% significance level.

Before performing ANOVA, the assumption of normality was evaluated and determined by the values of skew and kurtosis of the distribution to check whether the data satisfied the condition less than ±2.0 and ±9.0, respectively. Furthermore, the assumption of normality was tested based on Shapiro-Wilk's test (Significance level= 0.05) and visual inspection of their histograms was evaluated using normal Q-Q plots and box plots. The Levene's test was performed to test the homogeneity of variance (Significance level= 0.05).

In order to generate the outputs of the above procedures IBM SPSS statistic 20® and Minitab 17 Statistical Software® were used. All data were statistically analysed to interpret the results. Various procedures in SPSS and Minitab statistical software

were used depending on the requirement of the study. Each statistical procedure adopted for the studies are described in the respective chapters.

4 SIGNIFICANCE OF THERMAL SHRINKAGES DUE TO POST-HEAT TREATMENT PROCESSES

4.1 Introduction

This chapter discusses the investigation of significance of the thermal shrinkage on commercially used polyester plain knitted fabrics due to post-heat treatment processes. Four such post-heat treatment processes which are commonly practiced in garment production were selected as the heat treatment processes subsequent to heat-setting. The objective of the studies presented in this chapter was to identify which post-heat treatment process results the highest shrinkage due to the application of heat. The process which shrinks the fabric panel the highest was selected for further studies of this research. It was also investigated whether the thermal shrinkages of test specimens subjected to heat treatment processes are similar to the commercially accepted norms of tolerances or accepted levels of shrinkage. The washing shrinkages of these fabrics were compared with the thermal shrinkages.

4.2 Materials and Methods

4.2.1 Materials and knitting

Four commercial fabric constructions of 100% polyester plain knit fabrics were selected to investigate the effect of heat treatment processes on dimensional changes. The gauge of the knitting machine selected was 28E, which is one of the most commonly used machine gauges for the production of outer wear plain knit fabrics. The other specifications of the knitting machine are; machine diameter-30 inches, number of needles-2580, the number of knitting systems are 90. Four fabrics are denoted as A, B, C and D were produced using yarn counts 100, 155, 100 and 75 denier draw textured polyester yarns. Even though the denier count of fabric A and C are identical, the other parameters are different. The selected yarn counts and number of filaments of the yarns are commonly used yarn constructions in the industry. The yarn and fabric specifications to investigate the effect of post-heat treatment process on fabric shrinkage are presented in the Table 4.1.

Table 4.1 : Yarn and fabric specifications to investigate the effect of post-heat treatment process on fabric shrinkage

Fabric code	Yarn count, denier	No of filaments	Heat-setting temperature, °C	Stitch length, mm	Wales density, per cm	Course density, per cm	Area density, g/100 cm^2
A	100	144	160	2.49	19	28	1.352
B	155	144	160	2.65	16	23	1.555
C	100	144	160	2.33	18	26	1.169
D	75	36	160	2.5	18	28	0.980

4.2.2 Dyeing and heat-setting of fabrics

The fabrics after knitting were scoured, bleached and dyed using dispersed dyes on a jet dyeing machine (Model: Salavos) at 130°C. After dyeing, all the fabrics were heat-set at 160°C, which is the industrial standard heat-setting temperature for polyester knitted fabrics. Heat-setting is carried out with an overfeed of 25% in an industrial hot air pin stenter, maintaining the temperature between 160°C ± 5°C at constant fabric width for 90 Sec. Heat-setting temperatures, time and machine parameters are typical to those that are used commercially.

4.3 Experiments and Testing

The knitted fabrics were kept without tension on a flat surface under standard atmospheric conditions as per ASTM D1776 standard. Since there is no standard test method available to investigate thermal shrinkage of knit or woven fabrics, sample size of 30 X 30 cm^2 was used for all thermal shrinkage testing considering the maximum sample sizes that can be used on commercial machines for the four post-heat treatment processes. Although the standard sample size to test wash shrinkage is 50 X 50 cm^2, this is not practical for thermal shrinkage as most of the industrial machines used for subsequent heat treatment processes in the industry have narrow machine beds.

For each heat treatment (post-heat treatment process), five 30 X 30 cm^2 test specimens were randomly cut keeping the fabric grain and length direction of the fabric specimens parallel. Three pairs of data lines were marked out in each direction on each sample with indelible ink maintaining 1 cm allowance at the edges. These samples were subjected to following heat treatment processes and their

thermal shrinkage in the course direction and thermal shrinkage in the wale directions were measured after conditioning in standard testing atmosphere. Table 4.2 shows the process parameters of selected heat treatment processes.

Table 4.2 : Selected post-heat treatment processes and their process parameters

Process code	Heat treatment process	Machine type	Process parameters		
			Temperature °C	Dwell time, Sec	Pressure, Bar
HTP	Heat Transfer printing process	Heat transfer press machine (Model:Macpi)	160 ±2	22	4
BP	Bonding Process	Heat transfer press machine (Model:Macpi)	165 ±2	20	4
SP	Sublimation printing	Industrial sublimation print machine	200 ±2	24	4
RP	Rubber print curing	Industrial drying machine	170 ±2	90	Atmospheric pressure

All post-heat treatment processes were carried out without any embellishment being applied to them in order to determine the shrinkage of material solely due to heat.

4.3.1 Thermal shrinkage (S_T)

The shrinkages (S_T) in course direction and wale directions of above specimens were calculated after each post-heat treatment using the equation 4.1.

$$S_T = \frac{l_i - l_a}{l_i} \times 100\ (\%) \qquad (4.1)$$

Where l_i is the length between data lines marked in particular direction before thermal application and l_a is the length between the same data lines after subjecting to the thermal application.

Positive value indicates thermal shrinkage and negative value indicates thermal expansion.

4.3.2 Dimensional change due to laundering (DC)

The dimensional stability of samples was determined in accordance with AATCC 135 standard test method. Average dimensional change percentage (% DC) is given

by;

$$Average\ \%\ DC = \frac{l_2 - l_1}{l_1} \times 100\ (\%) \qquad (4.2)$$

Where DC is the average dimensional change, l_1 is the average original dimension and l_2 is the average dimension after laundering.

Measurements were taken after three washes. Negative dimensional change indicates shrinkage and positive dimensional change indicates a growth.

4.4 The Mean Thermal Shrinkage in the Course Direction and Wale Direction of Post-Heat-Treated Fabrics A, B, C and D

The mean thermal shrinkage in the course direction and wale direction values and their standard deviation values of post-heat-treated fabrics A, B, C and D are presented in the Table 4.3.

Table 4.3 : Mean and standard deviation thermal shrinkage measurements of fabrics A, B, C and D subjected to post-heat treatment processes

Fabric type	Post-heat treatment process	% thermal shrinkage (course direction)		% thermal shrinkage (wale direction)	
		Mean	Std. Deviation	Mean	Std. Deviation
A	Bonding	-0.10	0.54	-0.71	0.60
	Heat transfer printing	1.36	0.76	-1.71	0.55
	Rubber print curing	5.19	0.68	0.53	0.57
	Sublimation Printing	3.60	0.62	1.63	0.69
B	Bonding	0.51	0.56	-0.43	0.45
	Heat transfer printing	0.41	0.50	-0.39	0.41
	Rubber print curing	4.24	0.61	0.52	0.53
	Sublimation Printing	3.05	0.34	1.87	0.56
C	Bonding	-0.03	0.47	-0.01	0.51
	Heat transfer printing	0.38	0.45	-1.76	0.57
	Rubber print curing	4.39	0.48	2.47	0.48
	Sublimation Printing	1.71	0.53	1.67	0.55
D	Bonding	0.43	0.53	-0.07	0.31
	Heat transfer printing	0.35	0.50	0.32	0.30
	Rubber print curing	3.45	0.26	1.63	0.24
	Sublimation Printing	1.47	0.48	1.01	0.18

4.5 Statistical Analysis to Determine the Effect of Fabric Type, Post-Heat Treatments and Their Interactions on Thermal Shrinkage

Analysis of Variance (ANOVA) test was conducted to compare the significance of main effect of fabric and post-heat treatment type and their interaction effect on the thermal shrinkage in the course direction and thermal shrinkage in the wale direction values. The descriptive statistics of ANOVA also provides the mean thermal shrinkage in the course direction and thermal shrinkage in the wale directions considering their main effects and interactions. A two-way analysis of variance was conducted on the influence of two independent variables (type of fabric and post-heat treatment process) on the thermal shrinkage in the course direction and thermal shrinkage in the wale directions. The type of fabric included four levels (fabric A, B, C and D) and post-heat treatments consisted of four levels (rubber print curing, heat transfer printing, sublimation printing and bonding). Significant differences at the 95 % level in thermal shrinkage in the course direction and thermal shrinkage in the wale directions caused by changes in levels of the factors are indicated by the F-test.

4.5.1 Statistical analysis of thermal shrinkage in the course direction resulted when fabrics subjected to post-heat treatment processes

The assumption of normality was evaluated for thermal shrinkage in the course direction values to perform ANOVA. The resulted skewness and kurtosis values are presented in the Table 4.4. The results satisfied the assumption as the distributions of thermal shrinkage in the course directions was associated with skew and kurtosis less than ±2.0 and ±9.0, respectively.

Table 4.4 : The results of skewness and kurtosis of thermal shrinkage in the course direction

Dependent variable	Skewness		Kurtosis	
	Statistic	Std. Error	Statistic	Std. Error
% thermal shrinkage (course direction)	-0.07	0.16	-0.30	0.32

Levene's test was performed in order to test the homogeneity of variances. Levene's test indicated that the assumption of homogeneity of variance satisfied for thermal shrinkage in the course directions resulting $F(15,213) = 1.610$, $p = 0.073 > 0.05$.

Furthermore, the assumption of standardized residuals is randomly and normal distributed were evaluated to perform ANOVA. Figure 4.1 show the distribution of standardized residuals of thermal shrinkage in the course directions. The residual values were calculated and tested for approximate normality. The normality distribution showed that standardized residuals have a mean value close to zero and standard deviation close to 1. This revealed that the error terms are normally distributed and fulfil the assumption to perform ANOVA.

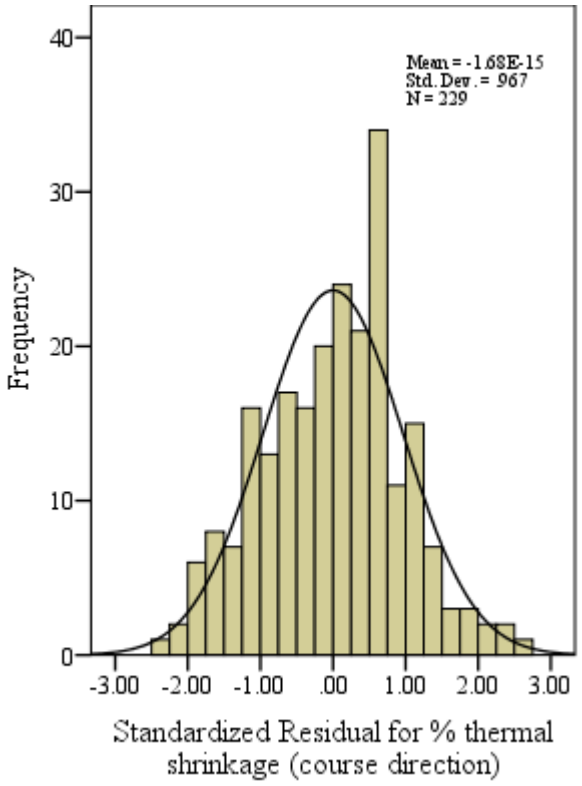


Figure 4.1: The distribution of standardize residuals of thermal shrinkage in the course direction

4.5.1.1 Analysis of variance for thermal shrinkage in the course direction

Three hypothesis tests were performed to test the effect of main independent variables (fabric type and post-heat treatment process) and their interactions (fabric type X post-heat treatment process) for the thermal shrinkage in the course direction. They are denoted as hypothesis test 1, hypothesis test 2 and hypothesis test 3 respectively.

Hypothesis test 1*: H_o: Post-heat treatments do not cause thermal shrinkage in the course direction of fabric panel*

Vs H_1*: Post-heat treatments cause thermal shrinkage in the course direction in the fabric panels*

Hypothesis test 2: H_o*: Fabric type do not cause thermal shrinkage in the course direction in the fabric panel*

Vs H_1*: Fabric type cause thermal shrinkage in the course direction in the fabric panels*

Hypothesis test 3: H_o*: The interaction effect of fabric type and post-heat treatment do not cause thermal shrinkage in the course direction in the fabric panel*

Vs H_1*: The interaction effect of fabric type and post-heat treatment cause thermal shrinkage in the course direction in the fabric panels*

Significance level α=0.05

Table 4.5 show the results of ANOVA to determine the overall impact of fabric type, post-heat treatment processes and their interaction on thermal shrinkage in the course directions. Estimated thermal shrinkage in the course directions resulted due to fabric type and post heat treatment processes are presented in the Table 4.6.

The effect of fabric type, post-heat treatment and interaction effect of fabric type and post-heat treatments were statistically significant at the 0.05 significance level. Therefore, null hypothesis (H_0) of hypothesis tests 1, 2 and 3 were rejected at 5% significance level.

Table 4.5 : Analysis of variance – to determine the overall impact of fabric type and post-heat treatment processes on thermal shrinkage in the course directions (R^2=0.921)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	679.88[a]	15.00	45.33	165.86	0.000
Intercept	820.62	1.00	820.62	3002.88	0.000
Fabric type	39.04	3.00	13.01	47.61	0.000
Post-heat treatment process	598.48	3.00	199.49	730.00	0.000
Fabric type X Post-heat treatment process	42.53	9.00	4.73	17.29	0.000
Error	58.21	213.00	0.27		
Total	1510.73	229.00			
Corrected Total	738.09	228.00			

Table 4.6 : Thermal shrinkage in the course directions resulted due to fabric type and post heat treatment processes

Source		Mean thermal shrinkage (course direction), %	Standard Deviation (SD)
Fabric type	A	2.51	0.073
	B	2.05	0.070
	C	1.61	0.067
	D	1.42	0.067
Post-heat treatment process	Bonding	0.21	0.067
	Heat transfer printing	0.62	0.070
	Rubber print curing	4.32	0.071
	Sublimation Printing	2.46	0.069

The main effect for type of fabric yielded an F ratio of F (3,213) = 47.61, p=0.00 <.α, indicating a significant difference between percentage thermal shrinkage of the fabrics; fabric A (M=2.51, SD=0.07), fabric B (M=2.05, SD=0.07), fabric C (M=1.61, SD=0.07) and fabric D (M=1.42, SD=0.07) (Table 4.6). When considering the effect of fabric type the results revealed that the highest overall thermal shrinkage was observed for fabrics A (M=2.51%) and B (M=2.05%). The fabrics A and B have the highest weight per unit area among the selected four fabrics. The fabrics C and D have resulted comparatively lower overall thermal shrinkage in the course direction.

The main effect for post-heat treatment yielded an F ratio of F (3,213) = 730.00, $p=0.00 < \alpha$, indicate a significant percentage thermal shrinkage difference between post heat treatment processes; bonding (M=0.21, SD=0.07), heat transfer printing (M=0.62, SD=0.07), rubber print curing (M=4.32, SD=0.07) and sublimation printing (M=2.46, SD=0.07) (Table 4.6).

When considering the effect of post-heat treatment, the results revealed that the highest overall thermal shrinkage in the course direction was resulted from rubber print curing (mean= 4.32%) and sublimation printing (mean=2.46%) processes. Dwell time may have significant effect over the thermal shrinkage behavior.

In rubber print curing, the fabric panel was exposed to the treatment without any external constrains. The sublimation printing process has the highest process temperature among the selected four post-heat treatment processes.

The results revealed that the observed thermal shrinkage in the course directions change as the post-heat treatment changes. Further, the results revealed that the observed thermal shrinkage in the course directions change with the fabric type. The interaction effect of the fabric type and the post-heat treatments is significant since the observed significance level is greater than 0.05. The significance level of interaction (Fabric type X post-heat treatment process) is presented in the Table 4.5 and the interaction effect was significant, F (9,229) = 17.29, $p=0.00 < \alpha$. The mean thermal shrinkage in the course direction due to combination effect of fabric type and post-heat treatments are presented in the Table 4.3.

Figure 4.2 graphically represents the mean percentage thermal shrinkage in the course direction of fabrics subjected to four post –heat treatment processes. Rubber print curing, sublimation printing and heat transfer printing caused the fabric panels to shrink while the bonding process caused the thermal expansion of fabric type A and C. In the course direction, the highest thermal shrinkage was observed in all fabric types that were subjected to rubber print curing process (Figure 4.2). During the post-heat treatment processes, pressure was applied perpendicularly to the fabric plane for all other three processes; heat transfer printing, sublimation printing and bonding, and the samples are treated under pressure (Table 4.1).

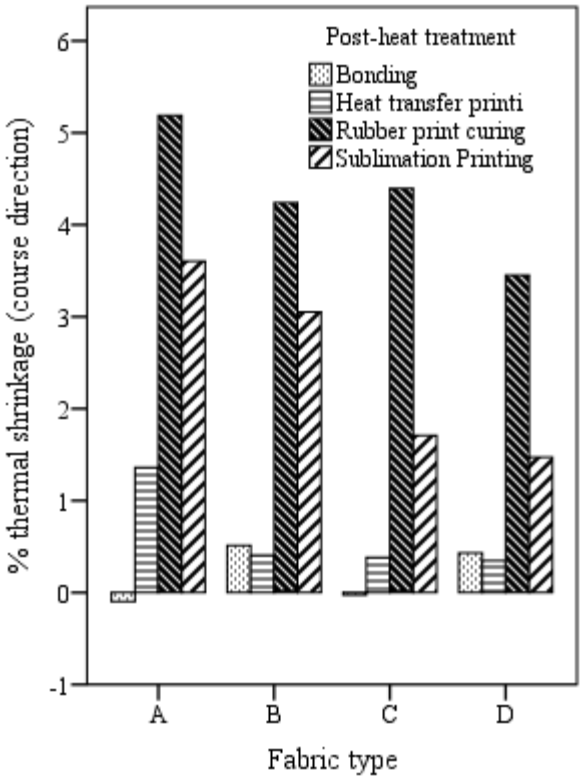


Figure 4.2 : Mean thermal shrinkage in the course direction in relation to fabric type and post-heat treatment processes

As a result, the dimensional changes due to the heat treatment have been hindered by the external restriction caused by the pressure applied on the sample. During the print curing process, the samples are freely moved across a heat chamber on a conveyor belt, and the heat applied has highly affected the changes in the dimensions of the fabric panels. This shows that the post-heat treatment process conditions affect the resulting thermal shrinkage behavior of heat-set fabrics. When overall main effect is considered, rubber print curing has resulted the highest thermal shrinkage in the course direction. The average thermal shrinkages of four fabrics subjected to the rubber printing curing method resulted in significant thermal shrinkage in the course direction relative to the other processes and the average values exceeded the generally accepted thermal shrinkage tolerance level in the garment industry (general tolerance level 3%). It is evidence that rubber print curing has adversely affected the course direction of the fabric panels.

4.5.2 Statistical analysis of thermal shrinkage in the wale direction resulted when fabrics subjected to post-heat treatment processes

The assumption of normality for thermal shrinkage in the wale direction values was evaluated to perform ANOVA. The results are presented in the Table 4.7. The results satisfied the assumption of thermal shrinkage in the wale directions are normally distributed as the distributions of thermal shrinkage in the wale directions were associated with skew and kurtosis less than ±2.0 and ±9.0, respectively.

Table 4.7 : The results of skewness and kurtosis of thermal shrinkage in the wale direction

Dependent variable	Skewness		Kurtosis	
	Statistic	Std. Error	Statistic	Std. Error
% thermal shrinkage (course-wise)	0.20	0.16	1.03	0.32

Figure 4.3 show the distribution of standardized residuals of thermal shrinkage in the wale directions.

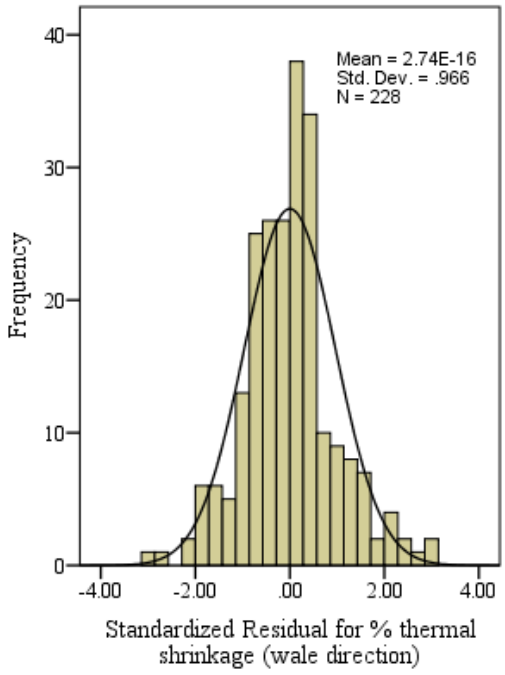


Figure 4.3 : The distribution of standardize residuals (thermal shrinkage in the wale direction)

Levene's test indicated that the assumption of homogeneity of variance had been

satisfied for thermal shrinkage in the wale directions resulting F (15,212) = 1.660, p=0.061 >0.05. The residual values show approximate normality as the mean value close to zero and standard deviation close to 1. This Figure 4.3 confirms that error terms are normally distributed and fulfil the assumption to perform ANOVA.

4.5.2.1 Analysis of variance for thermal shrinkage in the wale direction

Three hypothesis tests were performed to test the effect of fabric type, post heat treatments and their interactions for the thermal shrinkage in the wale direction. They are denoted as hypothesis test 4, hypothesis test 5 and hypothesis test 6 respectively. The hypothesis tests are listed below.

Hypothesis test 4*: H_o: Post-heat treatments do not cause course-wise thermal shrinkage in the fabric panel*

Vs *H_1: Post-heat treatments cause thermal shrinkage in the wale direction in the fabric panels*

Hypothesis test 5: *H_o: Fabric type do not cause thermal shrinkage in the wale direction in the fabric panel*

Vs *H_1: Fabric type cause thermal shrinkage in the wale direction in the fabric panels*

Hypothesis test 6: *H_o: The interaction effect of fabric type and post-heat treatment do not cause thermal shrinkage in the wale direction in the fabric panel*

Vs *H_1: The interaction effect of fabric type and post-heat treatment cause thermal shrinkage in the wale direction in the fabric panels*

Significance level α=0.05

Table 4.8 presents ANOVA results to determine the overall impact of fabric type, post-heat treatment processes and their interactions on thermal shrinkage in the wale directions.

Table 4.8 : Analysis of variance – to determine the overall impact of fabric type, post-heat treatment processes and their interactions on thermal shrinkage in the wale directions (a: R^2=0.866)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	316.98	15	21.13	91.08	0.000
Intercept	38.09	1	38.10	164.18	0.000
Fabric type	19.23	3	6.41	27.62	0.000
Post-heat treatment process	235.88	3	78.63	338.89	0.000
Fabric type X Post-heat treatment process	71.77	9	7.98	34.37	0.000
Error	49.19	212	0.23		
Total	415.76	228			
Corrected Total	366.16	227			

The effect of fabric type, post-heat treatments and their interactions were statistically significant at the 0.05 significance level. Therefore, null hypothesis (H_0) of hypothesis test 4, 5 and 6 were rejected at 5% significance level. Thermal shrinkage in the wale directions values varied with fabric type and post-heat treatment processes are presented in Table 4.9.

Table 4.9 : Thermal shrinkage in the wale directions resulted from the fabric type and post heat treatment processes

Source		Mean thermal shrinkage in wale direction , %	Standard Deviation
Fabric type	A	-0.07	0.067
	B	0.39	0.062
	C	0.59	0.065
	D	0.72	0.062
Post-heat treatment process	Bonding	-0.31	0.063
	Heat transfer printing	-0.88	0.067
	Rubber print curing	1.29	0.063
	Sublimation Printing	1.54	0.063

The main effect for type of fabric yielded an F ratio of F (3,212) = 27.62, p <.001, indicating a significant difference between fabrics. The mean percentage values resulted for the fabric A (M=-0.07, SD=0.07), fabric B (M=0.39, SD=0.06), fabric C (M=0.59, SD=0.06) and fabric D (M=0.72, SD=0.06) resulted a significant difference. Compared to the thermal shrinkage in the course direction, the effect of the fabric type over the thermal shrinkage in the wale direction is lower. For the

fabrics C (mean=0.59%) and D (mean=.0.72%), the highest overall thermal shrinkage in the wale direction was observed. Thermal expansion was observed in fabric A (mean= -0.07%).

The main effect for post-heat treatment yielded an F ratio of F (3,212) = 338.88, $p=0.00 <\alpha$, indicating a significant difference between bonding (M=-0.31, SD=0.06), heat transfer printing (M=-0.88, SD=0.07), rubber print curing (M=1.29, SD=0.06) and sublimation printing (M=1.54, SD=0.06) (Table 4.9). When the effects of post-heat treatments were considered, rubber print curing (mean=1.29%) and sublimation printing (mean=1.54%) have resulted the highest overall thermal shrinkage in the wale direction values. For the fabric panels treated with bonding (mean= -0.88) and heat transfer printing (mean= -0.88) methods, thermal expansions were observed on course-wise direction.

The interaction effect of fabric type and post-heat treatments is significant at 95% confident level resulting F (9,212) = 34.37, $p=0.00<\alpha$. The mean thermal shrinkage in the wale directions resulted from subjecting the fabrics A, B, C and D to post heat treatments are presented in the Table 4.3 and mean thermal shrinkage values are graphically presented in the Figure 4.4.

The impact by the fabric type over the thermal shrinkage in the wale direction is less compared to the thermal shrinkage in the course direction. The findings depicts that the measured thermal shrinkage in the wale directions vary with changes in the post-heat treatment and with the type of fabric. The maximum thermal shrinkage in the course-wise resulted from sublimation printing and the next highest value resulted from rubber print curing process. Bonding and heat transfer printing caused the fabrics A and B to be expanded while sublimation printing and rubber print curing caused the fabrics to shrink.

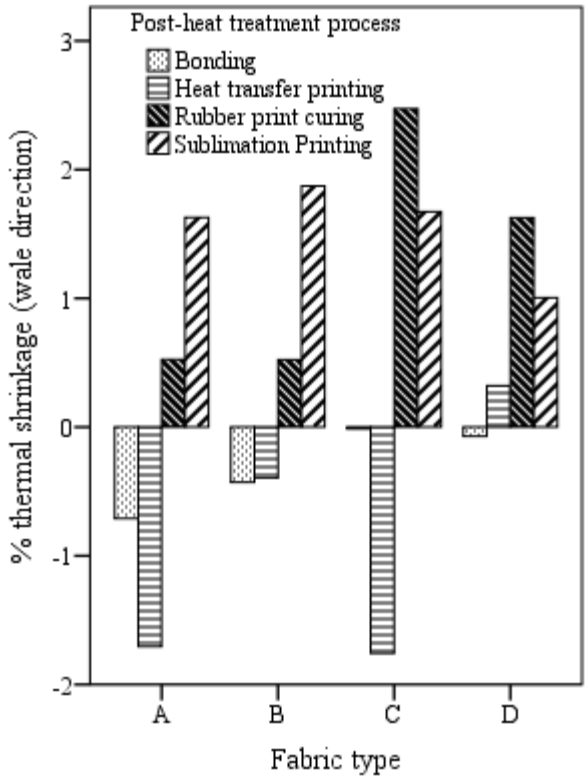


Figure 4.4 : Mean thermal shrinkage in the wale direction in relation to fabric type and post-heat treatment processes

Thermal expansion can be attributed to the pressure on the fabric plane which inhibited thermal shrinkage and facilitated thermal expansion. Thermal shrinkage occurs in place of thermal expansion for the fabric panels sublimated at a relatively high process temperature, even if the pressure is applied. This confirms that the higher annealing temperature cause higher disorientation and hence greater decreases in panel dimensions (Preston, Nimkar, & Gundavda, 1951b; Samuels, 1972). Gupta and colleagues revealed that high thermal shrinkage of thermoplastic yarn at higher temperatures can be expected (Gupta, 1995; Gupta & Kumar, 1981b). This could be a factor for the observed lower thermal shrinkages in the sublimation printing process where the temperature of processing is 200°C, which is the highest temperature among all processing temperatures used in this analysis.

4.5.3 Dimensional changes of fabrics after laundering

Table 4.10 presents the wale and course direction dimensional changes of fabrics A, B, C and D after home laundering.

Table 4.10 : Dimensional changes in fabrics A, B, C and D after home laundering.

Fabric type	Dimensional change (%)- course direction	Dimensional change (%)- wale direction
A	-2.2	-1.8
B	-2.5	-2.2
C	-1.8	-1.5
D	-2.3	-2.2

Wash shrinkage is recommended for most commercial fabrics in order to test the dimensional stability to industrial or domestic washing treatments. The results revealed that laundering caused fabric panels to shrink. Agitation applied during washing has caused better relaxation to knitted stitch by overcoming the frictional forces at four binding points (Postle & Munden, 1967). Anand et al. (2002) stated that agitation and the three-dimensional movement during drying caused considerable change in knitted fabric structure.

4.6 Summary

Rubber print curing led to the most significant thermal shrinkage in the course direction and the second highest thermal shrinkage in the wale direction among rubber print curing, sublimation printing, heat transfer printing and bonding treatment processes. The thermal shrinkage in the course direction even exceeds the accepted thermal shrinkage limits in the garment industry. Thus, the rubber print curing method was chosen as the post-heat treatment process for the rest of the studies of this research.

5 EFFECTS OF PANEL PARAMETERS AND HEAT-SETTING TEMPERATURE ON THERMAL SHRINKAGE

5.1 Introduction

The investigation of the thermal effects on the dimensions of the knitted fabrics is one of the main focuses of this research. The industry currently does not practice the standard test method for assessing thermal shrinkage. Therefore all tests carried out during the research have to be standardized for all the experiments of this research. Dimensions of the fabric panels to be used in experiments and the orientation or the panel layout are established by carrying out several experiments. Though the dimensions for fabrics after dyeing and heat-setting are not restricted, the dimensions of the fabric panel for post-heat treatment are restricted by the bed of the heat-curing machine. The other factors considered in finalizing the standard size were the maximum possible thermal deformations when polyester fabrics are exposed to thermal treatments, compatibility with the available heat treatment machines settings and easy repeatability of the test.

5.2 Materials and Experiments

In order to study the thermal shrinkage behavior at different dimensions of fabric panels, a plain knitted fabric was produced on a circular knitting machine of 28 gauge and 36-inch diameter using 100% polyester draw textured filament yarns of 100 denier with 144 filaments. The fabric was scoured, bleached and dispersed dyed on jet dyeing machine (Model: Salavos) at 130°C. All three processes were carried out in the same dye bath.

After dyeing, the fabric was separated in to three equal lengths and heat-set at three different temperatures of 140°C, 160°C and 180°C with 25% overfeed in an industrial hot air pin stenter. These fabrics are denoted as F-140, F-160 and F-180. The temperature during heat-setting was maintained at an accuracy of ±5°C and fabrics were held taut at constant width with 5% width extension. Heat-setting temperatures, times and machine parameters are typical to those used in

manufacturing fabrics for commercial use. Table 5.1 presents the yarn parameters and the parameters of three fabrics after heat-setting.

Table 5.1 : Yarn specifications and fabric specifications after heat-setting

Fabric code	Yarn count (denier)	No of filaments	Heat-setting temperature (°C)	Stitch length-Greige (mm)	Wale density (per inch)	Course density (per inch)	Area density (g/cm^2)
F-140	100	144	140	2.19	50	67	1.212
F-160	100	144	160	2.19	48	67	1.173
F-180	100	144	180	2.19	47	68	1.169

The knitted fabrics were kept on a flat surface free from tension and conditioned as per standard ASTM D1776.

During manufacturing of garments, the thermal shrinkages caused in the width direction are significant (thermal shrinkage in the course direction). The data presented in the study described in Chapter 4 demonstrated the above fact and showed that the shrinkage in the course direction is considerably higher than the thermal shrinkage in the wale direction. The study presented in this chapter is to determine optimum sample size for thermal shrinkage test. This optimum dimension of the sample should be smaller than the width of the print curing machine. Thus, the optimum sample size is limited by the minimum acceptable sample size. Further, this minimum sample size must produce accurate values for the shrinkage test. Since the shrinkage due to heat is higher in the course direction, the experiment presented in this chapter is limited to the course direction.

Rectangular fabric panels were cut in the width direction (course direction) keeping the dimensions of the length direction (wale direction) to a constant of 30 cm. The range of widths of the rectangular fabrics panels is 3, 6, 10, 15, 21, 28, 35, 45 and 50 cm (specimen sizes are denoted as specimen size 3, 6, 10, 15, 21, 28, 35, 45 and 50).

The fabrics heat-set at 140, 160 and 180°C resulted 0.6, 1.3 and 0% spirality. Due to spirality of the selected knitted fabrics, wales were not perpendicular to courses and therefore two panel layouts were adapted when cutting the fabric specimens. In the cut panel layout 1, fixed dimension was kept parallel to wales and in the cut panel

layout 2, the fixed dimension was kept perpendicular to courses. Figure 5.1 illustrates the two layouts used in cutting fabric panels. For each layout five specimens were cut for each width of the fabric panels.

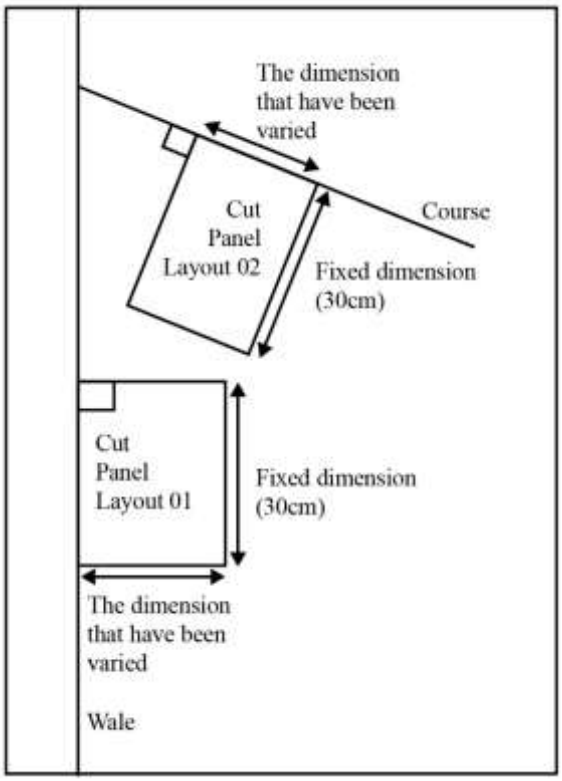


Figure 5.1 : Cut panel layout

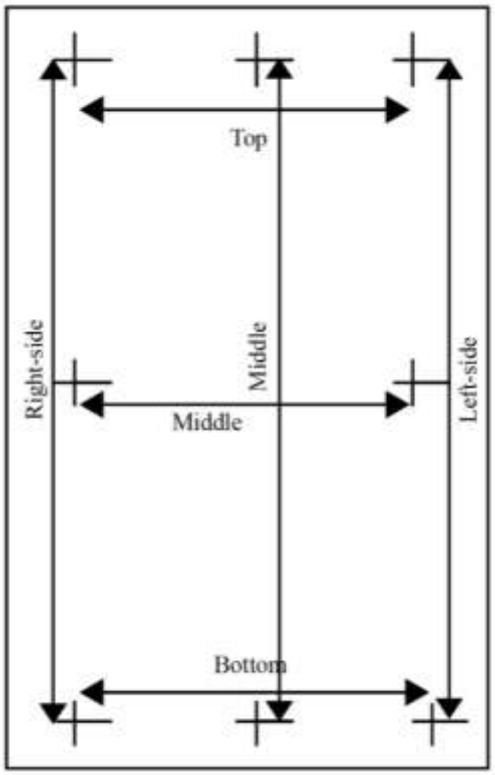


Figure 5.2 : Three pairs of data lines

Three pairs of data lines (Figure 5.2) were marked out in each direction on each sample with indelible ink maintaining 1cm allowance at the edges. The distances between each pair of points were recorded before the heat-curing treatment under standard testing conditions. The samples of both cut layouts were then subjected to post-heat treatment process.

In Chapter 4, print curing was identified as the post-heat treatment process that incur the highest shrinkage on the polyester knitted fabrics, Therefore, print curing is the post-heat treatment process used in the experiments (here after the heat treatment subsequent to heat-setting process will be referred as heat-curing treatment/heat-curing/curing). In the garment industry, the maximum number of different prints that can have on a single garment panel is generally restricted to 5. Assuming that the

same garment panel will be exposed to print curing treatment only for 5 times, the fabric panels were exposed five times to a temperature of 170°C ±2°C for 90 seconds on a print curing machine.

The distances between each pair of points marked on the samples were measured after heat-curing treatment. The fabric panels after heat-curing were conditioned at standard atmospheric conditions; temperature of 21ºC ± 1ºC at a relative humidity of 65% ± 2 for 24 hours with free of tensions on the test specimens before taking the length measurements to calculate the shrinkage. The shrinkage due to heat-curing treatment was calculated in both course direction and wale direction using the equation 5.1.

The thermal shrinkage percentage, S_T is given by,

$$S_T = \frac{(l_i - l_a)}{l_i} X\ 100 \qquad (5.1)$$

Where l_i is the length between data line before thermal application, and l_a is the length between the same data line after heat application.

The (+) value indicates thermal shrinkage and (-) value indicates thermal expansion. The shrinkage at each pair of points was calculated. The average of fifteen pairs (3 pairs of data X 5 specimens) was given as the mean thermal shrinkage in the course direction and average of fifteen pairs of the shrinkage in the wale direction.

The thermal shrinkage in the course direction of top, middle and bottom of the fabric panels were calculated separately for five specimens of each width. The top, middle and bottom data were taken separately for the analysis. The initial length in the wale direction was 30cm (constant). The thermal shrinkage in course direction was measured and calculated to investigate the effects due to the change in width of the fabric panels (3 to 50 cm).

5.3 Statistical Analysis on Fabric Shrinkage

5.3.1 Significance of the thermal shrinkage values among three pairs of points

The shrinkage at three pairs of data points (top, middle, bottom for the course direction and right, middle, left for the wale direction) may have been influence by

their positions. The significance of thermal shrinkages at three pairs of data points was determined in the wale direction and course direction by one-way ANOVA test.

5.3.1.1 Significance of thermal shrinkage in the wale direction of three pairs of data points

The hypothesis test 5.1 was performed in order to analyze the significance among the mean thermal shrinkage in the wale direction at three pairs of data points (left-side, middle and right-side) of the fabric specimens (Figure 5.2) due to curing at 5% significance level.

Hypothesis test 5.1:*H_0: There is no significant different between mean thermal shrinkage in the wale direction at left-side, middle and right-side*

Vs *H_1: Two or more mean thermal shrinkage in the wale direction at left-side, middle and right-side are significantly different from each other*

Significance level α=0.05

Levene's test was performed to verify the homogeneity of variances. Levene's test indicated that the assumption of homogeneity of variance is satisfied for thermal shrinkage in the course direction resulting $F(2,713) = 1.39$, $p>0.05$.

The significance value of one-way ANOVA for thermal shrinkage in the wale direction is represented in Table 5.2. The observed mean thermal shrinkage in the wale direction for each specimen size, cut panel layout and heat-setting temperatures are given in Appendix A1.

Table 5.2 : The one-way ANOVA statistical analysis test for thermal shrinkage in the wale direction

Source of variation	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1.31	2	0.65	0.79	0.45
Within Groups	584.61	713	0.82		
Total	585.92	715			

The resulted significance value is greater than 0.05. Therefore null hypothesis (H_0) is accepted, proving that there is an insignificant differences among the thermal shrinkage in the wale direction at three data points of specimens at 5% significance level ($p>0.05$) according to one-way ANOVA statistical analysis.

5.3.1.2 Significance of thermal shrinkage in the course direction at three pairs of data points

The shrinkage at the top, middle and bottom of the fabric samples may have differences and therefore it is required to statistically test whether the differences are significant. Hypothesis test 5.2 was performed in order to analyze the significance of the mean thermal shrinkage in the course direction of three pairs of data points at top, middle and bottom of the fabric (Figure 5.2) due to heat-curing at 5% significance level.

Hypothesis test 5.2:*H_0: There is no significant different between means at top, middle and bottom thermal shrinkage values in the course direction*

Vs *H_1: Two or more means at top, middle and bottom are significantly different thermal shrinkage value in the course direction*

Significance level $\alpha=0.05$

Before performing ANOVA, Levene's test was performed to verify the homogeneity of variances. Levene's test indicated that the assumption of homogeneity of variance is satisfied for thermal shrinkage in the course direction resulting $F(2,775) = 2.43$, $p>0.05$.

The statistical parameters of the one-way ANOVA for thermal shrinkage in the course direction are presented in Table 5.3. The observed mean thermal shrinkage in the course direction for each specimen size, cut panel layout and heat-setting temperatures are included in Appendix A1.

Table 5.3 : The one-way ANOVA statistical analysis test for thermal shrinkage in the course direction

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	4.51	2	2.26	0.89	0.41
Within Groups	1964.28	775	2.53		
Total	1968.74	777			

The resulted significance is greater than 0.05. Therefore, null hypothesis (H_0) is accepted, revealing that there is an insignificant differences among the thermal shrinkage in the course direction at three data points of specimens at 5% significance level ($p>0.05$) according to one-way ANOVA statistical analysis.

The insignificance of the effect of measuring position over thermal shrinkages in the wale direction and course direction revealed that mean thermal shrinkage of panel in the wale direction and course direction can be represented by the average of the three measurements of thermal shrinkage in the wale direction and course direction respectively.

5.3.2 Mean thermal shrinkage

5.3.2.1 Mean thermal shrinkage in the wale direction

The mean and standard deviations of thermal shrinkage in the wale direction value based on each independent variable are presented in Table 5.4.

The mean thermal shrinkage values in the wale direction were determined considering the heat-setting temperature, cut panel layouts and specimen size. The measured thermal shrinkage in the wale direction reduces as the heat-setting temperature increases.

Figure 5.3 illustrates the scatter plots of thermal shrinkage in the wale direction and specimen size drawn for each heat-setting temperature.

Table 5.4 : Mean values of thermal shrinkage in the wale direction

Heat-setting temperature, °C	Specimen size	Cut panel layout 1		Cut panel layout 2	
		Mean thermal shrinkage, %	Standard deviation	Mean thermal shrinkage, %	Standard deviation
140	3	2.89	0.48	2.92	0.36
	6	2.77	0.31	2.98	0.21
	10	2.80	0.36	3.24	0.59
	15	3.01	0.36	2.56	1.16
	21	3.20	0.29	3.52	0.89
	28	3.01	0.35	2.12	0.46
	35	2.99	0.47	4.01	0.65
	45	2.24	0.70	2.08	0.67
	50	2.17	0.66	2.10	0.80
160	3	3.29	0.52	3.08	0.91
	6	2.63	0.18	3.51	0.34
	10	2.82	0.53	3.69	0.37
	15	2.92	0.71	3.23	0.17
	21	3.21	0.23	3.08	0.50
	28	3.38	0.53	3.25	0.45
	35	2.77	0.46	3.45	0.24
	45	1.83	0.42	1.55	0.80
	50	1.86	0.50	2.19	0.45
180	3	1.38	0.49	1.32	0.29
	6	1.76	0.43	1.55	0.28
	10	2.16	0.33	1.64	0.42
	15	1.57	0.44	1.64	0.44
	21	1.78	0.28	1.76	0.35
	28	1.71	0.35	2.05	0.53
	35	1.54	0.27	1.79	0.46
	45	1.15	0.36	1.16	0.37
	50	0.58	0.42	1.23	0.29

Thermal shrinkage measures as panel size increases and it starts reducing thermal shrinkage after a certain period (about specimen size 28).

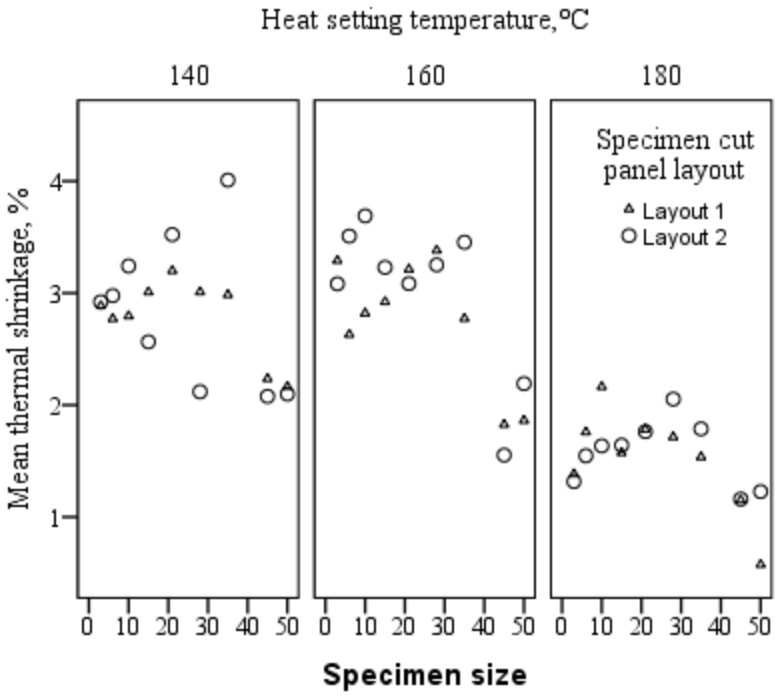


Figure 5.3 : Specimen size Vs. mean thermal shrinkages of layout 1 and layout 2 of fabric heat-set at (a) 140°C, (b) 160°C and (c) 180°C- wale direction

The thermal shrinkage in the wale direction shows random scatter pattern with the size of the specimen. There is no apparent linear relationship observed. A decreasing trend in thermal shrinkage is observed for the increasing heat-setting temperature.

5.3.2.2 Mean thermal shrinkage in the course direction

The mean and standard deviations of thermal shrinkage values in the course direction based on each independent variable are presented in Table 5.5.

Figure 5.4 shows the scatter plots of thermal shrinkage in the wale direction and specimen size drawn for each heat-setting temperature.

Table 5.5 : The mean values of thermal shrinkage in the course direction

Heat-setting temperature, °C	Specimen size	Cut panel layout 1		Cut panel layout 2	
		Mean thermal shrinkage, %	Standard deviation	Mean thermal shrinkage, %	Standard deviation
140	3	6.37	0.33	6.58	0.45
	6	5.44	0.82	6.32	0.93
	10	5.70	0.51	5.64	0.56
	15	5.00	0.39	5.76	0.53
	21	5.11	0.44	5.84	1.19
	28	5.08	0.54	5.78	0.42
	35	5.08	0.75	5.39	0.61
	45	4.12	0.43	4.42	0.46
	50	4.19	0.61	4.14	0.52
160	3	6.21	0.64	5.30	1.56
	6	5.94	0.95	5.33	0.90
	10	5.48	0.64	5.26	0.65
	15	5.27	0.40	4.89	0.48
	21	4.78	0.37	4.56	0.65
	28	4.51	0.42	4.70	0.58
	35	4.43	0.56	4.52	0.43
	45	4.23	0.51	3.97	0.31
	50	3.35	0.58	4.20	0.72
180	3	3.25	0.05	2.66	0.81
	6	2.84	0.44	2.85	0.82
	10	2.54	0.43	2.77	0.76
	15	2.47	0.62	2.50	0.74
	21	2.44	0.28	2.34	0.31
	28	2.31	0.65	2.10	0.29
	35	2.08	0.72	2.09	0.47
	45	1.76	0.44	1.82	0.50
	50	1.28	0.55	1.37	0.43

The mean thermal shrinkages in the course direction display a strong negative linear relationship with the specimen size. In order to evaluate the strength of the relationship among dependent and independent variables, correlation analysis was performed for wale direction and thermal shrinkage in the course direction and their independent variables.

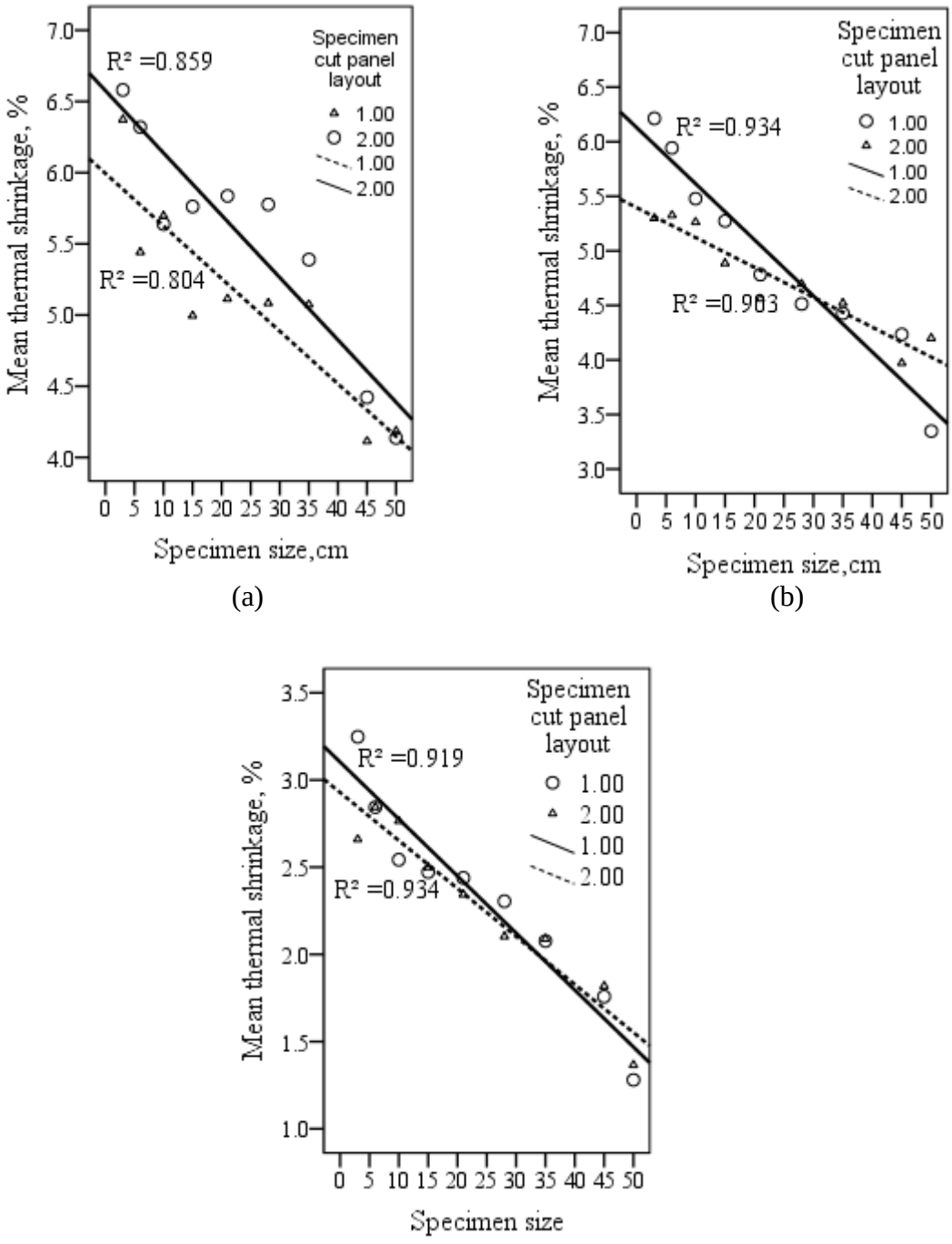


Figure 5.4 : Specimen size vs. mean thermal shrinkages of cut panel layout 1 and cut panel layout 2 of fabric heat-set at (a) 140°C, (b) 160°C and (c) 180°C

5.3.3 Correlation analysis of thermal shrinkage

The correlation analysis was carried out for thermal shrinkage in the course direction, thermal shrinkage in the wale direction, heat-setting temperature, specimen cut panel layout and specimen size in order to provide a better interpretation of the inter-relationships.

5.3.3.1 Correlation analysis of thermal shrinkage in the wale direction

For the correlation analysis of thermal shrinkage in the wale direction, the strength of relationship between dependent variable (thermal shrinkage in the course direction) and independent variables (heat-setting temperature, specimen cut panel layout and specimen size) were evaluated. The strength of the relationship between thermal shrinkage in the wale direction and specimen size cannot be performed as the wale direction panel length was a constant (30 cm). The correlation analyses carried out for thermal shrinkage in the wale direction of heat-cured specimens are presented in Table 5.6.

Table 5.6 : Bivariate linear relationships among variables for thermal shrinkage in the wale direction

Factor		Thermal shrinkage (Wale direction),%	Heat-setting temperature (°C)	Specimen cut panel layout
Thermal shrinkage (Wale direction),%	Pearson Correlation	1	-0.56**	-0.02
	Sig. (2-tailed)		0.00	0.54
Heat-setting temperature (°C)	Pearson Correlation	-0.56**	1	0.03
	Sig. (2-tailed)	0.00		0.44
Specimen cut panel layout	Pearson Correlation	-0.02	0.03	1
	Sig. (2-tailed)	0.55	0.44	

**. Correlation is significant at the 0.01 level (2-tailed).

The heat-setting temperature has a moderate negative correlation with the thermal shrinkage in the wale direction (r=-0.56). The ratio of thermal shrinkage in the wale direction to cut panel layout is very weak (r=-0.02) and is not significant at 5% significant level. The heat-setting temperature is the only significant factor in the wale direction. The moderate negative correlation between thermal shrinkage in the

wale direction and heat-setting temperature (r=-0.56) shows that the material thermal shrinkage in subsequent thermal processes decreases as the temperature of heat-setting increases. The results of correlation analysis of thermal shrinkage in the wale direction and independent variables are confirmed by data presented in the Figure 5.3 as well.

5.3.3.2 Correlation analysis of thermal shrinkage in the course direction

For the correlation analysis of thermal shrinkage in the course direction, the strength of relationships between dependent variable (thermal shrinkage in the wale direction), independent variables (heat-setting temperature, specimen size and cut panel layout) and their 2-way and 3-way interactions (heat-setting temperature x specimen size, heat-setting temperature x cut panel layout, heat-setting temperature x specimen size x cut panel layout) were evaluated. The correlation analyses for thermal shrinkage in the course direction for the heat-cured specimens are presented in Table 5.7.

Table 5.7 presents the Pearson correlation coefficients emanating from the thermal shrinkage in the course direction. Multicollinearity occurs when the independent variables are associated within a regression model. It is a problem because independent variables are supposed to be independent. If the degree of correlation among variables is sufficiently high, it can cause problems by fitting the model and interpreting the results. Therefore the independent variables have to be selected in order to prevent multicollinearity. The correlation analysis revealed 2-way and 3-way interactions are correlated with their independent variables. Therefore heat-setting temperature, specimen size and cut panel lay out were selected as the independent variables for the regression model fitting. The results also revealed that thermal shrinkage in course direction and cut panel lay out are not significant at 95% confidence level (P-value = 0.615).

The results in Table 5.7 revealed that the heat-setting temperature has the strongest negative correlation with the thermal shrinkage (r=-0.78). The correlation between the thermal shrinking of the course direction and the size of the specimen (r=-0.37) is weak and negative. The relationship between thermal shrinkage in the course

direction and sample cut panel layout is very weak (r=0.02) and is not significant at 5% significant level. The negative strong correlation between thermal shrinkage in the course direction and heat-setting temperature depicts that the thermal shrinkage of material in subsequent thermal processes decreases as the heat-setting temperature increases.

Table 5.7 : Bivariate linear relationships among variables for thermal shrinkage in the course direction

		Heat-setting temperature	Cut panel layout	Specimen size	Heat-setting temperature X Cut panel layout	Specimen size X Cut panel layout	Heat-setting temperature X Specimen size	Heat-setting temperature X Specimen size X cut panel layout
Cut panel layout	Pearson correlation	0.01						
	P-Value	0.73						
Specimen size	Pearson correlation	0.00	-0.02					
	P-Value	0.91	0.67					
Heat-setting temperature X Cut panel layout	Pearson correlation	0.30	0.95	-0.01				
	P-Value	0.00	0.00	0.69				
Specimen size X Cut panel layout	Pearson correlation	0.01	0.42	0.85	0.40			
	P-Value	0.88	0.00	0.00	0.00			
Heat-setting temperature X Specimen size	Pearson correlation	0.16	-0.01	0.98	0.03	0.84		
	P-Value	0.00	0.69	0.00	0.40	0.00		
Heat-setting temperature X Specimen size X cut panel layout	Pearson correlation	0.14	0.42	0.84	0.44	0.99	0.86	
	P-Value	0.00	0.00	0.00	0.00	0.00	0.00	
Thermal Shrinkage in course direction	Pearson correlation	-0.78	0.02	-0.37	-0.22	-0.30	-0.48	-0.40
	P-Value	0.00	0.62	0.00	0.00	0.00	0.00	0.00

5.3.4 Multiple linear regression analysis of thermal shrinkage in the course direction

Heat-setting and specimen size have become significantly correlated with the thermal shrinkage in the course direction (Table 5.7). Therefore, multiple linear regression analysis has been conducted to establish the linear relationship between the factors; thermal shrinkage in the course direction, heat-setting temperature, specimen size and cut panel layout. The independent variables; Heat-setting temperature and specimen size are continuous while cut panel layout is categorical. The dependent variable, thermal shrinkage in the course direction is continuous. Categorical variable have discrete values while continuous variables have continuous values. For the regression analysis the categorical variable could be expressed as *dummy* variables. A dummy variable is a numerical variable used to represent subgroups of the categorical variable during regression analysis. A dummy variable is often used to distinguish various treatment groups in a research design. Dummy variable can be treated as any other continuous variable if the categorical variable is expressed in dummy variable.

5.3.4.1 Dummy variable recoding

The number of dummy variables required to demonstrate a categorical variable depends on the number of values that can be taken from the categorical variable. In order to represent a categorical variable which can have k different sub groups, k-1 dummy variables must be defined. The cut panel layout has 2 different levels; the cut panel layout 1 and 2, therefore 1 dummy variable has to be defined.

5.3.4.2 Defining dummy variables for categorical variables

The categorical variable cut panel layout has two values; cut panel layout 1 and cut panel layout 2. Cut panel layout could hence be represented with one dummy variable: CPL_2.

- $CPL_2 = 1$, if cut panel layout 2: $CPL_2 = 0$, otherwise.

For cut panel layout, the reference group consists of cut panel layout 1.

5.3.4.3 Regression equation to express the linear relationship between thermal shrinkage in the course direction, heat-setting temperature, specimen size and cut panel layout

The linear relationship between continuous dependent variables (thermal shrinkage in the course direction), continuous independent variables (heat-setting temperature and specimen size) and categorical independent variables (cut panel layout) as well as their interactions were analyzed with 5% significance level by backward elimination method using Minitab 17® statistical software.

The regression equation resulted from the statistical analysis is shown in Equation 5.2.

Regression Equation;

$$Thermal\ shrinkage\ in\ course\ direction =$$

$$17.133 - 0.07570\ (Heat\ setting\ temperature) - 0.03686\ (specimen\ size) \qquad (5.2)$$

The equation 5.2 can also be written as the equation 5.3. Here the standardized regression coefficients are denoted by "β" values.

$$TS_{Course} = \beta_0 + \beta_1 HT + \beta_2 SS \qquad (5.3)$$

Where;

TS_{Course} : Predicted value of the thermal shrinkage in the course direction

β_0 : Standardized regression coefficient of the constant

β_1 : Standardized regression coefficient of heat-setting temperature

β_2 : Standardized regression coefficient of specimen size

HT : The heat-setting temperature and

SS : The specimen size

β value measures how strongly each independent variable influences the dependent variable. The multiple linear regression equation on data provides heat-setting temperature and the specimen size as two significant variables to predict the

thermal shrinkage in the course direction of a specimen. The regression equation only consists of the heat-setting temperature and the specimen size. The independent variable, cut panel layout was not included in the regression equation. The cut panel layouts, terms of two-way and three-way interaction were eliminated from the backward elimination process at 5% significance level. These results also revealed that the cut panel layout has no significant impact on the thermal shrinkage in the course direction.

The regression coefficients are presented in Table 5.8, where information for each regression coefficient: its value, its standard error, a t-statistic, and the significance of the t-statistic are presented.

Table 5.8: Table of regression coefficients

Term	Standardized Regression Coefficient (β)	Standard Error of Coefficient	T-Value	P-Value	VIF
Constant	17.133	0.291	58.81	0.000	-
Heat-setting temperature	-0.07570	0.00179	-42.24	0.000	1.00
Specimen size	-0.03686	0.00184	-19.99	0.000	1.00

Table 5.8 presents the regression coefficients of the constant, heat-setting temperatures and specimen sizes. The thermal shrinkage value was given as a percentage while heat-setting temperature and sample size was measured in centigrade (°C) and centimeters (cm) respectively. The t-statistics for heat-setting temperature and specimen size are both statistically significant at the 0.05 level.

It is important to confirm how well the regression equation fits the observed data. This is achieved by analyzing the multiple determination coefficients (R^2). R^2 will be high (i.e. close to 1) when the regression equation fits the data well; and vice versa. Table 5.9 summarizes the output of the regression equation.

Table 5.9: Summary output

S	R-squared (R^2)	R-squared (adjusted)	R-squared(predicted)
0.812	74.01%	73.94%	73.82%

The regression equation accounts for explaining 74.01% of the total variability of the data on thermal shrinkage in the course direction which depends on the heat-setting temperature and the specimen size. The coefficient of multiple determinations is 0.74 confirming that the thermal shrinkage in the course direction can be explained by heat-setting temperature and specimen size. This verifies that the regression equation fits the data well.

5.3.4.4 Analysis of variance to determine the significant of heat-setting temperature and specimen size on thermal shrinkage in the course direction

ANOVA test was conducted to compare the significance of main effect of heat-setting temperature and specimen size on the results of thermal shrinkage in the course direction values. Analysis of variance was carried out on 773 individual observations of thermal shrinkage in the course direction due to heat-curing. Significant differences at the 95% confidence level in thermal shrinkage in the course direction caused by changes in levels of the heat-setting temperature and specimen size are indicated by the F-test. The adjusted sum of squares is related to the total variance of the observations and adjusted mean square is obtained by dividing the adjusted sums of square by the respective degrees of freedom (df).

The results of the analysis of variance are presented in Table 5.10.

Hypothesis test 5.3: *H_o: The regression equation does not fit the data well*

Vs *H_1: The regression equation fits the data well*

Significance level $\alpha = 0.05$

Table 5.10: Analysis of variance of thermal shrinkage in the course direction

Source	df	Adjusted Sum of Squares	Adjusted Mean Squares	F-Value	P-Value
Regression	2	1449.5	724.77	1097.74	0.000
Heat-setting temperature	1	1178.1	1178.10	1784.37	0.000
Specimen size	1	263.8	263.78	399.52	0.000
Error	771	509.0	0.66		
Lack-of-fit	51	237.7	4.66	12.37	0.000
Pure Error	720	271.3	0.38		
Total	773	1958.6			

The observed significance values are greater than 0.05. Therefore, the results of the analysis of variance for thermal shrinkage in the course direction reveal that the effect of heat-setting temperature and specimen size are statistically significant. Further, the effect of heat-setting temperature on thermal shrinkage in the course direction was significant, F (1, 773) = 1784.37, P=0.000<α. The results also show that the effect of specimen size on thermal shrinkage in the course direction is significant, F (1,773) =399.52, P=0.000<α.

The occurrence of lack-of-fit test is significant in ANOVA test due to the fact that data contain replicates (multiple observations with identical x-values). Replicates represent "pure error" because only random variation can cause differences between the observed response values (Table 5.10).

5.3.4.5 Diagnostics of regression equation

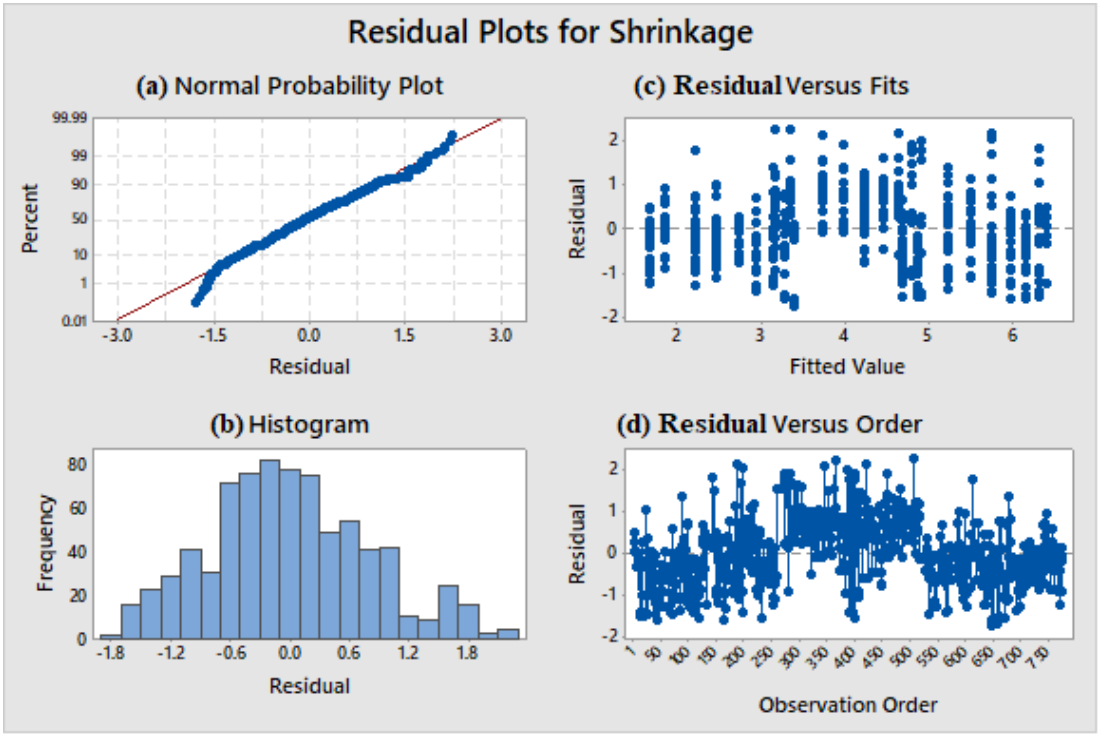


Figure 5.5 : Residual plots (a) Normal Probability plot, (b) Histogram, (c) Residual Versus fits and (d) Residual versus order to verify the regression equation of thermal shrinkage in the course direction

Diagnostics of regression equation are used to evaluate the assumptions of the equation and to investigate whether there are observations with a significant

influence on the analysis. Linear regression assumptions are to check whether the relationship is linear.

The fitness of the regression equation to data was identified by generating random error results, testing error familiarity and error percentage. Figure 5.5 shows the resulting graphs.

In order to verify the assumption that the residuals (errors) are normally distributed, the normal probability plot of residuals was used. The normal probability plot should follow a straight line approximately to confirm the assumption that the errors are normally distributed. The residual histogram displays the residual distribution for all observations. The residual histogram was used to determine if the data is skewed or includes outliers. The histogram for residuals has also resulted in symmetry, and the normal probability plot of errors is also a straight line that only at the two tail ends is slightly deviated from the straight line. The residuals can therefore be considered random. In order to verify the assumption that the residuals are distributed randomly and have constant variance, the residuals versus fits plot was used. In order to verify the assumption that the residuals are independent from each other, the residuals versus order plot was used. The independent residuals do not show any trends or patterns. Completing all hypotheses confirms that the regression equation fits the data well.

5.3.4.6 Validation of the regression equation

For the validation of the resulted regression equation, 100% polyester plain knitted fabric (greige fabric stitch length was 2.5mm) was produced using 75 denier yarn with 36 filaments. The fabric was disperse dyed at 130°C. Then the fabric was heat-set at 150°C with 25% overfeed in an industrial hot air pin stenter while maintaining constant width at 5% width extension.

The cut panel layout 1 was adopted to cut the specimens size ranging from 3 to 50 from the fabric. The fabric panels were exposed to a temperature of 170 ±2°C for 450 seconds for the heat-curing treatment. The thermal shrinkage in the course direction due to heat-curing treatment was measured using the equation 5.2. The multiple linear regression equation developed was validated using observed data. The

comparison of predicted and actual output values was made; percentage errors were calculated and are given in Table 5.11. The predicted values were calculated using the results of multiple linear regression equation 5.2.

Table 5.11: Comparison of predicted and actual values

Heat-setting temperature, °C	Specimen size	Predicted thermal shrinkage in the course direction (Heat-setting temperature 150°C)	Actual thermal shrinkage in the course direction (Mean value) , %	Percentage error
150	3	5.87	5.83	0.57
150	6	5.76	5.58	3.15
150	10	5.61	5.50	1.98
150	15	5.43	5.49	-1.21
150	21	5.20	5.11	1.87
150	28	4.95	4.63	6.87
150	35	4.69	4.82	-2.69
150	45	4.32	4.47	-3.29
150	50	4.14	4.09	1.04

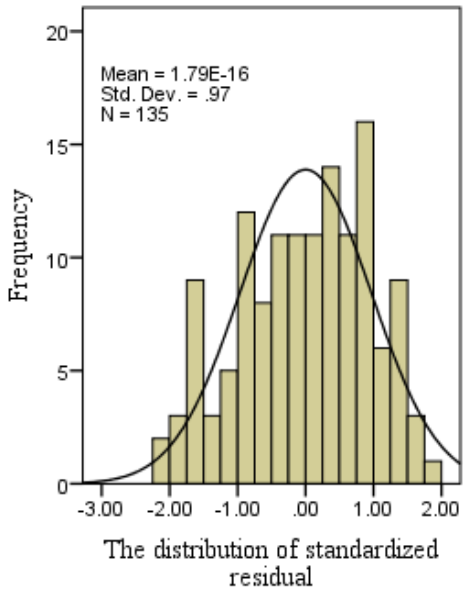


Figure 5.6 : The distribution of standardized residuals

The residual values were calculated and tested for approximate normality. The standardized residuals expected to have a mean value close to zero and standard deviation close to 1. Figure 5.6 shows the distribution of standardized residuals. The results revealed that the data fits the regression equation (equation 5.2) well.

5.4 The Factors to Consider in Determining the Test Specimen Dimensions

5.4.1 Selection of the Cut panel lay out for further thermal shrinkage behavior analysis

The regression equation 5.2 revealed that the heat-setting temperatures, the size of the specimen are important factors affecting the thermal shrinkage in the course direction. The regression equation does not include the layout of the cut panel and its terms of interaction. The cut panel layout has no significant effect over the thermal shrinkage in the course direction, and this confirms the resulting insignificant correlation with the thermal shrinkage in the course direction and the elimination of the cut panel layout variable from the regression equation. Only the independent variables that have statistically significant effects on thermal shrinkage in the course direction are included in the regression equation (Table 5.7 and equation 5.2). Sample preparation processes for cut panel layout 2 consumed more time than the preparation process of cut panel layout 1. Preparation process of cut panel layout 2 required unraveling of courses from the fabric until it reaches a clear course and this process often stretches and deforms the fabric.

5.4.2 Specimen size selection for further thermal shrinkage behavior investigation

One of the key objectives of the standard size is that a specified heat treatment condition must result in the highest possible percentage values of thermal shrinkage. The slightest change of dimension culminated in a higher percentage of thermal shrinkage when the sample size is smaller. As the sample size grows, there is a decline in thermal shrinkage and significantly lower thermal shrinkages for sizes 45 and 50 cm were observed. Larger specimen sizes are difficult to handle and may subjected to permanent creases and wrinkles if the specimen was handled with less care after the post-heat treatment, before it reaches the ambient temperature. Thermal shrinkage in course direction has linear relationship with the specimen size. Therefore considering machine parameters of the post-heat treatments, the specimen size for the standard testing was selected.

5.4.3 The machine parameters of subsequent heat treatments

One of the other factors that affect determination of the standard size for thermal shrinkage testing is the nature of the subsequent heat treatment process. The heating mechanism, dimensions of the heating bed of different equipment for different processes vary. The dimensions of the heating bed are of prime importance in determining the dimensions of the test specimen. Below are the device requirements of widely employed methods for heat treatment.

- Heat transfer press machine (Model: Macpi) –Small (heat treatment bed dimension -29x49cm^2)
- Heat transfer press machine (Model: Macpi) –Large (heat treatment bed dimension -145x49cm^2)
- Print curing dryer: conveyor bed width approximately 230cm
- Sublimation printing machine: maximum width approximately 330cm

Considering the bed dimensions of the heat treating machines, the results of the study on shrinkage behavior of fabric panel of different dimensions and the handling convince with less risk of fabric distortions, the sample size 30 X 30 cm^2 and cut panel layout 1, where the one dimension is cut parallel to wales was selected for the further investigations of thermal shrinkages.

5.5 Summary

Experiments were performed to determine the effects of fabric specimen size, the layout of the panels and the heat-setting temperature on the shrinkage behavior of fabric panels. A decreasing trend in thermal shrinkage in the wale direction is observed for the increasing heat-setting temperature.

The results of the correlation test showed that the thermal shrinking in the course direction is predominantly determined by heat-setting temperatures and by the specimen size. The thermal shrinkage in the wale direction is mainly determined by the heat-setting temperatures. The layout of the specimen has an insignificant impact on thermal shrinkage in course direction and thermal shrinkage in the wale direction.

Since the heat-setting temperature, specimen size and thermal shrinkage in the course direction demonstrated strong correlations; a multiple linear regression test was conducted. Estimated regression coefficients (β) were shown to decrease thermal shrinkage in the course direction for a given heat-setting temperature as the specimen size increases. The regression analysis further showed that the cut panel layout has an insignificant effect on thermal shrinkage in the course direction.

Furthermore, compliance with the existing thermal treatment system settings and the easy repeatability of the experiment were considered for finalizing the standard specimen size. The cut panel layout 1 was chosen as cut panel layout. The other aspect taken into account was that the specimen size must comply with the post-heat treatment environment to obtain the thermal shrinkage related to the thermal exposure. After considering the key criteria for standard specimen size, the specimen size 30 X 30 cm^2 and cut panel layout 1 were chosen for testing thermal shrinkage for the rest of this research.

6 THERMAL BEHAVIOR OF HEAT TREATED POLYESTER PLAIN KNITTED FABRICS

6.1 Introduction

The thermal behavior of polyester plain knitted fabrics when heat treated and after a post-heat treatment process is discussed in this chapter. The techniques such as XRD X-ray diffractometer (XRD), Nuclear Magnetic Resonance (NMR) Spectroscopy and Differential Scanning calorimetry (DSC) are few of the methods which are being used to study the crystalline structure and morphology of polymers. Among these techniques DSC analysis provides a rapid method for determining polymer crystallinity based on the heat required to melt the polymer. The thermal shrinkage behavior of heat-set polyester knitted fabrics is studied using the results of Differential Scanning Calorimetry (DSC) and measuring the shrinkage values after a post-heat treatment process. Differential Scanning Calorimetry (DSC) is a thermoanalytical technique that measures the difference in the amount of heat needed to increase the temperature of the sample and the reference. A heat flux versus temperature curve is one of the results of a DSC experiment. The polymer structure and morphology of polyester heat treated and post-heat treated fabrics were determined by examining the DSC thermograms.

6.2 Materials and Method

6.2.1 Knitting and heat-setting

In order to study the thermal behavior of heat-set and post-heat treated polyester plain knitted fabric, a plain knitted fabric was knitted using 100% polyester yarns, on a knitting machine of 30 inch in diameter; 28 gauge. The fabric was dispersed dyed in a jet dyeing machine (Model:Salavos). Table 6.1 presents the yarn parameters and the parameters of greige and dispersed dyed fabrics. The fabric is denoted as fabric A.

Table 6.1 : Yarn and fabric specifications of fabric A

Yarn specification		Greige fabric specifications		Dyed fabric specifications	
Count (denier)	No of filaments	Greige fabric stitch length (mm)	Yarn count (denier)	Stitch length (mm)	Yarn count (denier)
155	144	2.40	154.89	2.33	160.80

6.2.2 Treatments carried out on fabric A

The fabric A was separated into 8 equal parts of 15 m in length. Those fabric samples were heat-set at 8 different heat-setting temperatures ($T_{heatset}$) ranging from 130°C to 200°C at 10°C intervals having 25% overfeed in an industrial hot air pin stenter machine while holding the fabrics taut at 5% constant width extension for 96 seconds. The heat-set fabric was gradually cooled to the ambient temperature. These heat-setting parameters selected were the most commonly used in commercial fabric production. The fabrics were subjected to standard conditioning after heat-setting as per ASTM D1776 standard. Few yarns from each fabric sample were unravelled after heat-setting and were analysed using the DSC in order to analyse the structure and morphology of polyester molecules of heat-set fabrics.

6.2.3 Differential Scanning Calorimetry (DSC) measurements of fabric A

The thermal characteristics of the heat-set material were analyzed using the differential scanning Calorimetry (DSC Q200). For the analysis, yarn samples from each fabric were taken and each thermogram was recorded from 25°C to 300°C. The mean yarn sample size was 8.82mg (Standard deviation= 0.28mg). The yarn samples were scanned in the nitrogen atmosphere at a heating rate of $10°Cmin^{-1}$.

6.2.3.1 Calculating the percentage of crystallinity

The degree of crystallinity was calculated from the melting enthalpy of samples using equation (6.1) given below. The enthalpy was the integrated area of the primary melting endotherm (coloured area given in Figure 6.1). The melting enthalpy of the ideal crystalline PET of 135 Jg^{-1} was used for the calculations (Rudolf et al., 2011).

$$\text{Percentage crystallinity} = \frac{\text{Enthalpy}}{\text{Melting enthalpy of ideal crystalline PET}} * 100 \qquad (6.1)$$

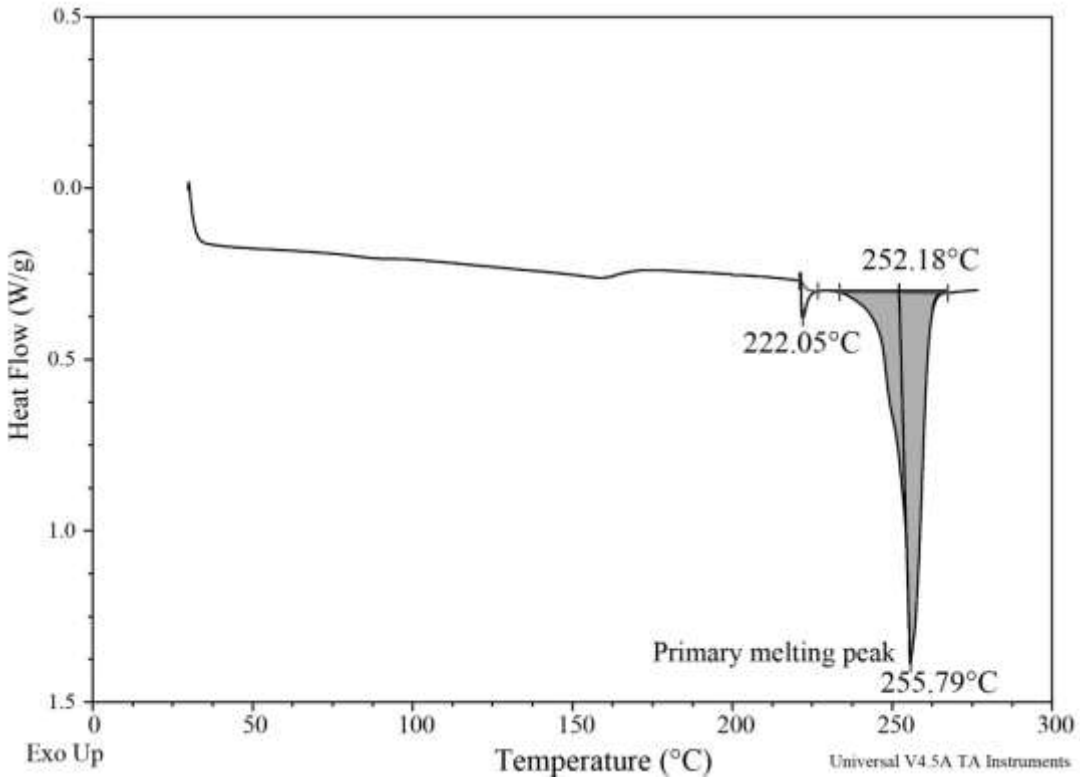


Figure 6.1 : The data derived from DSC thermogram for percentage crystallinity calculation

6.2.4 Post-heat treatments and measuring shrinkage of the yarns in the fabric

Applying heat during heat-setting and post-heat treatments (heat-curing) may shrink the constituent yarns in the fabric and result in fabric shrinking. In order to examine the thermal shrinkage behavior, heat-set fabrics were heat-cured at 20°C intervals at temperatures of 120°C to 200°C. The rubber print curing process which was discussed in the Chapter 4 was used as the post-heat treatment to heat-setting. Hereafter the post-heat treatment is denoted as 'heat-curing'. 30 X 30 cm^2specimens were cut keeping the wales parallel to the grainline of the sample as described in the Chapter 5. Five specimens from each heat-set fabric were subjected to the specific curing temperature. After curing, samples were conditioned in standard atmospheric conditions and DSC thermograms of heat-cured fabric were also recorded for fabrics

heat-set at temperatures 140°C,160°C,180°C and 200°C and heat-cured at a temperature of 200°C.

The effect of heat on the shrinkage of yarns in the fabrics was studied by measuring the stitch lengths of the fabrics. The shrinkage of yarn due to curing was calculated using the equation (6.2). Stitch lengths were measured as per the standard BS EN 14970: 2006.

$$TS_{sl} = \frac{Sl_{hs} - Sl_c}{Sl_{hs}} \times 100 \qquad (6.2)$$

Where, TS_{sl} is the percentage thermal shrinkage of the stitch length, Sl_{hs} is the stitch length after heat-setting and Sl_c is the stitch length after heat-curing. The positive value indicates a thermal shrinkage and negative value indicates a thermal expansion of the stitch length.

6.3 Differential Scanning Calorimetry (DSC) Analysis of Heat-Set Fabrics of Fabric A

6.3.1 Analyse of DSC thermograms of heat-set fabric samples of fabric A

The DSC thermographs of the yarns of heat-set fabric samples are shown in Figure 6.2.

The individual thermograms resulted from scanning of each individual yarn heat-set at different temperatures are presented in Figure 6.2 for comparison purpose. The characteristic shape of all the graphs is similar to all polyester fabrics heat-set at different temperatures ranging from 130°C to 200°C in 10°C intervals.

The sharp endothermic peaks ($M_{primary}$) correspond to the melting of polymer structures (Figure 6.2). Significant change in $M_{primary}$ is not evident in fabrics heat-set at different heat-setting temperatures. A slight bent of all graphs is visible around 160°C, which is also an endothermic curve for pre-melting of the structure. As the severity of the primary melting peak lessen the prominence of other important peaks, more sensitive thermograms were obtained for shorter temperature range of 60°C to 215°C (Figure 6.3).

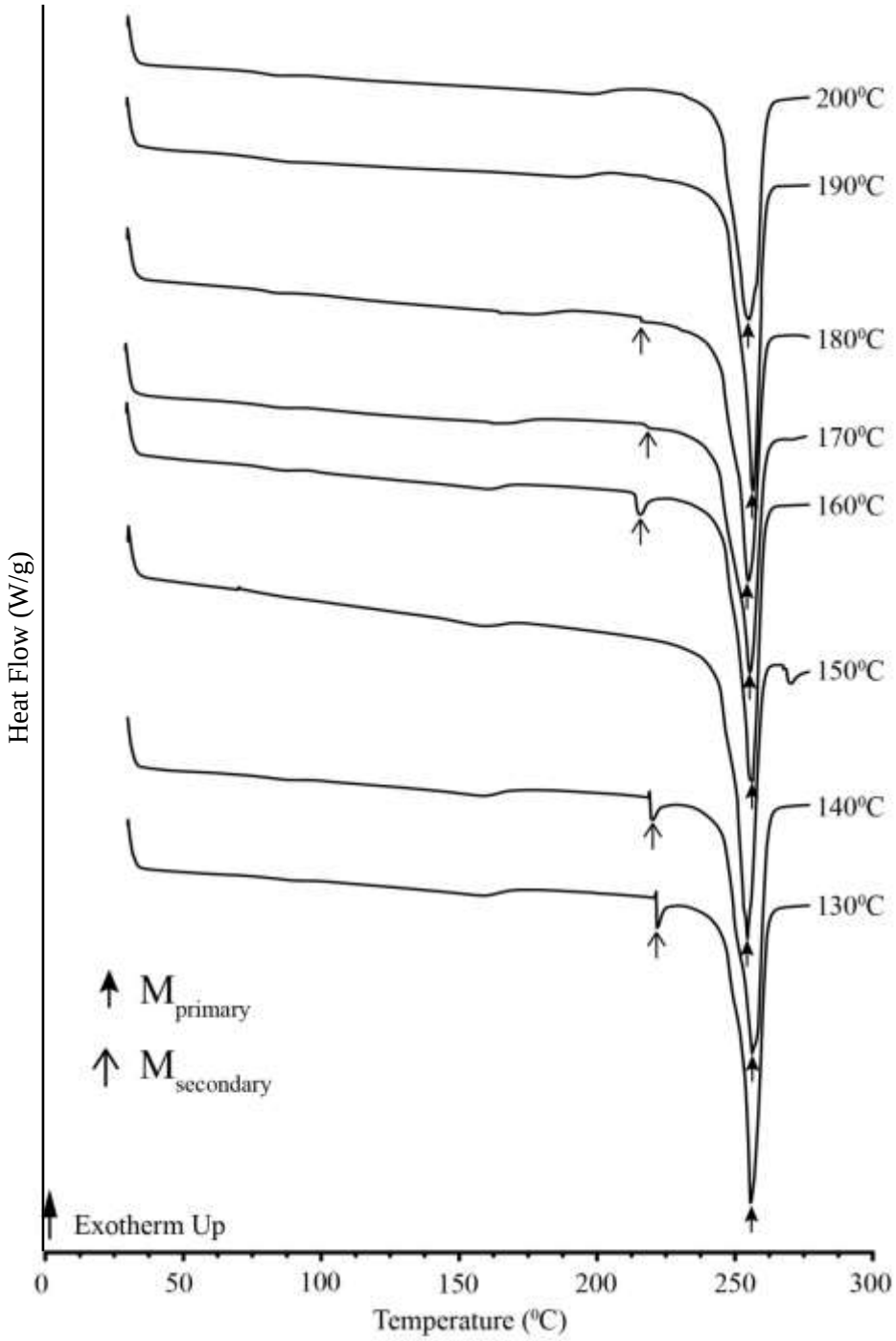


Figure 6.2 : DSC thermograms recorded from 25°C to 300°C of the yarn samples of fabrics heat-set at different temperatures (Heat flow (W/g) Vs. Temperature (°C))

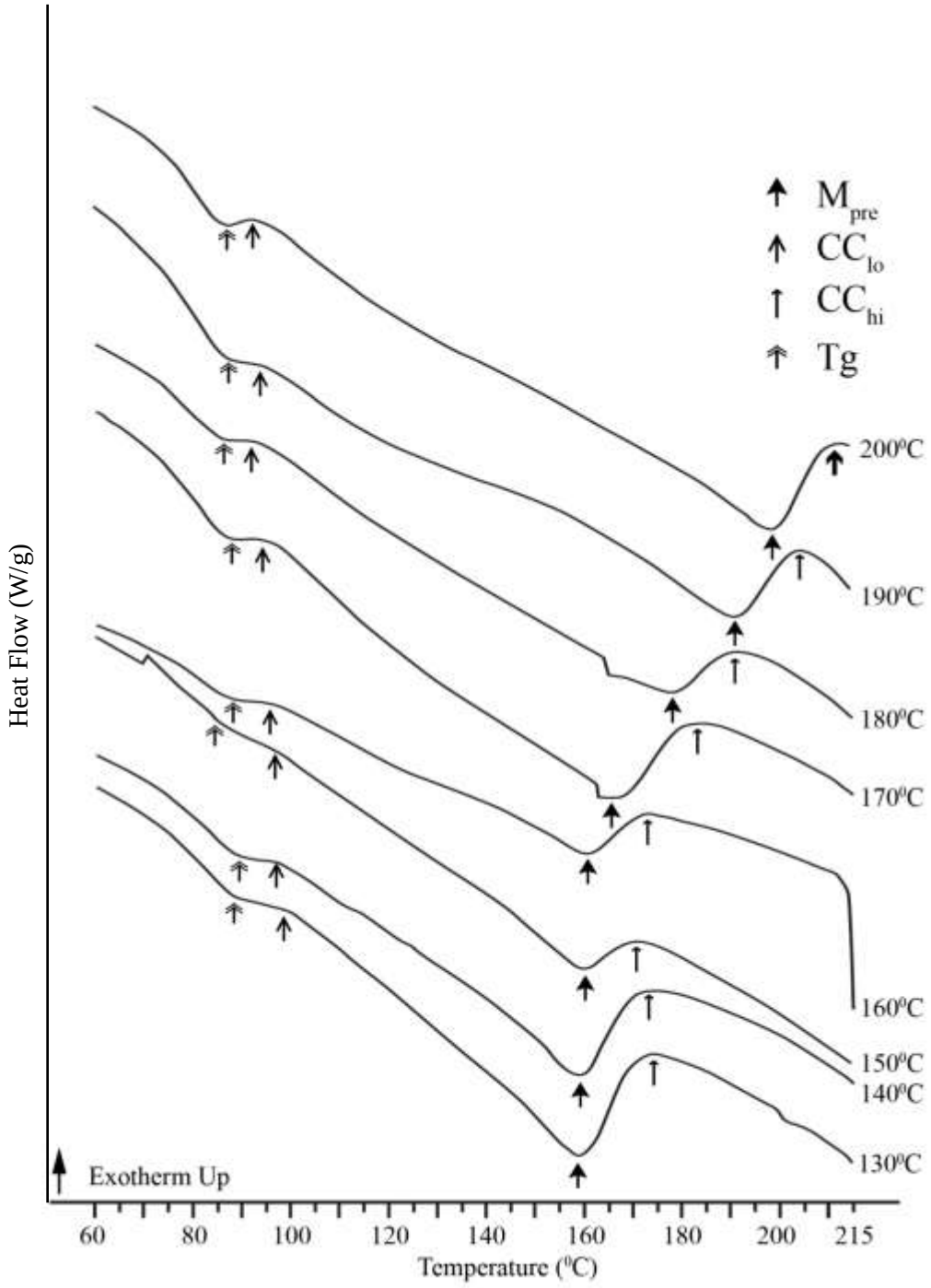


Figure 6.3 : DSC thermograms recorded from 60°C to 215°C of yarns of fabrics heat-set at different temperatures (Heat flow (W/g) Vs. Temperature (°C))

Two exotherm peaks and two endotherm peaks are visible for the thermograms of all heat-set fabrics shown in Figure 6.3. The temperature correspond to glass transition endotherm is denoted as T_g. The temperatures corresponded to low and high cold crystallization peaks, CC_{lo} and CC_{hi}, are denoted by T_{CClo} and T_{CChi} respectively.

The exothermic transitions (T_{CClo} and T_{CChi}) indicate the availability of oriented and isotropic amorphous chains for further crystallization (Aou, Kang, & Hsu, 2005). Secondary endotherms ($M_{secondary}$) in Figure 6.2 and M_{pre} in Figure 6.3 represent the melting of less stable crystals undergoing reorganisation (Fakirov, Fischer, Hoffmann, & Schmidt, 1977; Rath et al., 2012). The secondary and pre-melting endothermic peaks indicate the melting of small size and less perfect crystals (Liu et al., 2016).

At the first small endothermic region correspond to the T_g in the range of 80°C - 90°C, the fusion heat causes glass-rubber transition (Figure 6.3). For all heat-set samples, the presence of less prominent specific heat change is observed. The weak T_g, indicates that the initial structure is nearly crystalline or has a higher orientation in the non-crystalline (amorphous) regions (Miller & Murayama, 1984). Higher crystallization is due to drawing process of yarn during its manufacture (Gupta, 1995; Katayama et al., 1968).

The glass transition region shown in Figure 6.3 is followed by a slight exothermic peak. The slight exothermic peak is also attributed to high molecular orientation in both crystalline and non-crystalline phases (Rodriguez-Cabello et al., 1996). Previous studies show that thermal shrinkage and cold crystallisation are two incidents that happen simultaneously for deformed polymers and may cause an exothermic event just above glass transition temperature (T_g) (Gupta et al., 1994; Manich et al., 2010). The exothermic peak just above the T_g is shifted to the direction of lower temperature with increasing heat-setting temperature. The results suggests that heat-setting has caused the structure to be more oriented (Aou et al., 2005; Rath et al., 2008).

Cayuela and Gacén (1994) revealed that secondary crystallisation that occurred due to a thermal treatment is reflected as a pre-melting endothermic peak in the subsequent DSC analysis thermal curves. This is known as the effective temperature of the thermal treatment and the enthalpy of this melting endotherm is significantly lower than the primary peak (Sichina, 2000). The studies of Buckley and Salem (1990) and Fakirov et al. (1977) revealed that the resultant effective temperature could be the same or much higher than the original heat-setting temperature which it

was subjected. Sichina (2000) revealed that Pre-endothermic peak reflects the annealing processing step and allied with the process of heat-setting. Pre-melting endotherm (M_{pre}) is clearly visible in Figure 6.3, which is the effective temperature of the PET structure (Cayuela & Gacén, 1994).

Pre-melting endotherms of heat-set fabrics spread in a wider range of 155°C -205°C as shown in Figure 6.3. The temperature (T_{pre}) corresponding to pre-melting endotherm (M_{pre}) is the effective temperature of the heat-setting treatment (Fakirov et al., 1977; Gupta et al., 1994; Sichina, 2000). The heat-set fabric will be thermally stable to the extent that the temperature of subsequent thermal treatment is overriding the effective temperature of the heat-set fabric. If the effective temperature is exceeded in subsequent heat applications, significant thermal shrinkage can occur (Cayuela & Gacén, 1994). Figure 6.3 shows that the pre-melting temperature of fabric samples heat-set at 130°C,140°C,150°C and 160°C is on or in the vicinity of 160°C. The positions of the pre-melting peak have shifted to the high-temperature side when heat-setting temperature is increased. Thus the heat-setting has caused the crystalline and amorphous structures to be more oriented. The results reveal that the heat-setting at a higher temperature causes the effective temperature to increase and the structure to be more thermally stable. For any subsequent heat application to be effective, the applied temperature must go beyond the effective temperature.

The exotherm (CC_{hi}) immediately after effective temperature forms secondary crystals and make random amorphous regions available in the structure into new crystals. The exothermic phase is the transition from amorphous form to crystalline form, resulting in an exothermic peak in the DSC signal. Crystallization takes place at CC_{hi}, and the temperature corresponding to the CC_{hi} increases with increasing heat-setting temperature according to Figure 6.3. The increase in temperature corresponding to the CC_{hi} can be attributed to the increased in pre-melting endotherm (M_{pre}).

Fakirov et al. (1977) observed a dual melting behavior during annealing of highly drawn PET fibres. Though dual exothermic event near melting temperatures are visible at low temperatures, the dual melting behavior is not visible in heat-set fibres at high heat-setting temperatures (Figure 6.3). At higher heat-setting temperatures,

the structure has melted without forming the secondary endothermic peaks corresponding to melting of small and less perfect crystals. The observed phenomenon shows that the small crystallites are converted to large crystallites in the heat-setting process and the distribution of the crystallite size becomes narrower (Rath et al., 2008). The findings too indicate that heat-setting at higher temperature has converted the structure into a more crystalline state making the structure more stable.

Table 6.2 presents the temperatures of endothermic and exothermic peaks of heat-set fabrics extracted from DSC graph in Figure 6.2 and 6.3. The temperatures corresponding to pre-melting (M_{pre}), secondary melting ($M_{secondary}$) and primary melting ($M_{primary}$) are denoted by T_{pre}, $T_{secondary}$ and $T_{primary}$ respectively.

Table 6.2 : The temperatures of glass transition, pre-melting, secondary melting, primary melting, low and high temperature cold crystallisation peaks and crystallinity of heat-set fabric samples of fabric A

Heat-setting temperature,°C	T_g, ° C	T_{CClo}, °C	T_{pre}, ° C	T_{CChi}, °C	$T_{secondary}$ °C	$T_{primary}$ °C	Crystallinity, %
130	89	100	159	174	222	256	39.82
140	89	96	159	174	220	256	40.61
150	89	96	160	171	-	255	39.56
160	89	96	160.5	173	216	256	40.00
170	87.5	94.5	166	184	-	256	40.04
180	86	92	178	192	-	255	41.41
190	86	95	191	204	-	256	41.67
200	86	93	198.5	213	-	255	39.99

Percentage crystallinity of the heat-set fabrics was calculated using the equation (6.1). As can be seen in Table 6.2, percentage crystallinity of samples does not increase with increasing heat-setting temperature. Having no effect on crystallinity due to heat-setting even at very high temperatures emphasize that the changes that have taken place at pre-melting (M_{pre}) and secondary melting points ($M_{secondary}$) can not cause any effect to the percentage crystallinity of the structure.

6.4 DSC Analysis of Heat-Cured Fabric (Fabric A)

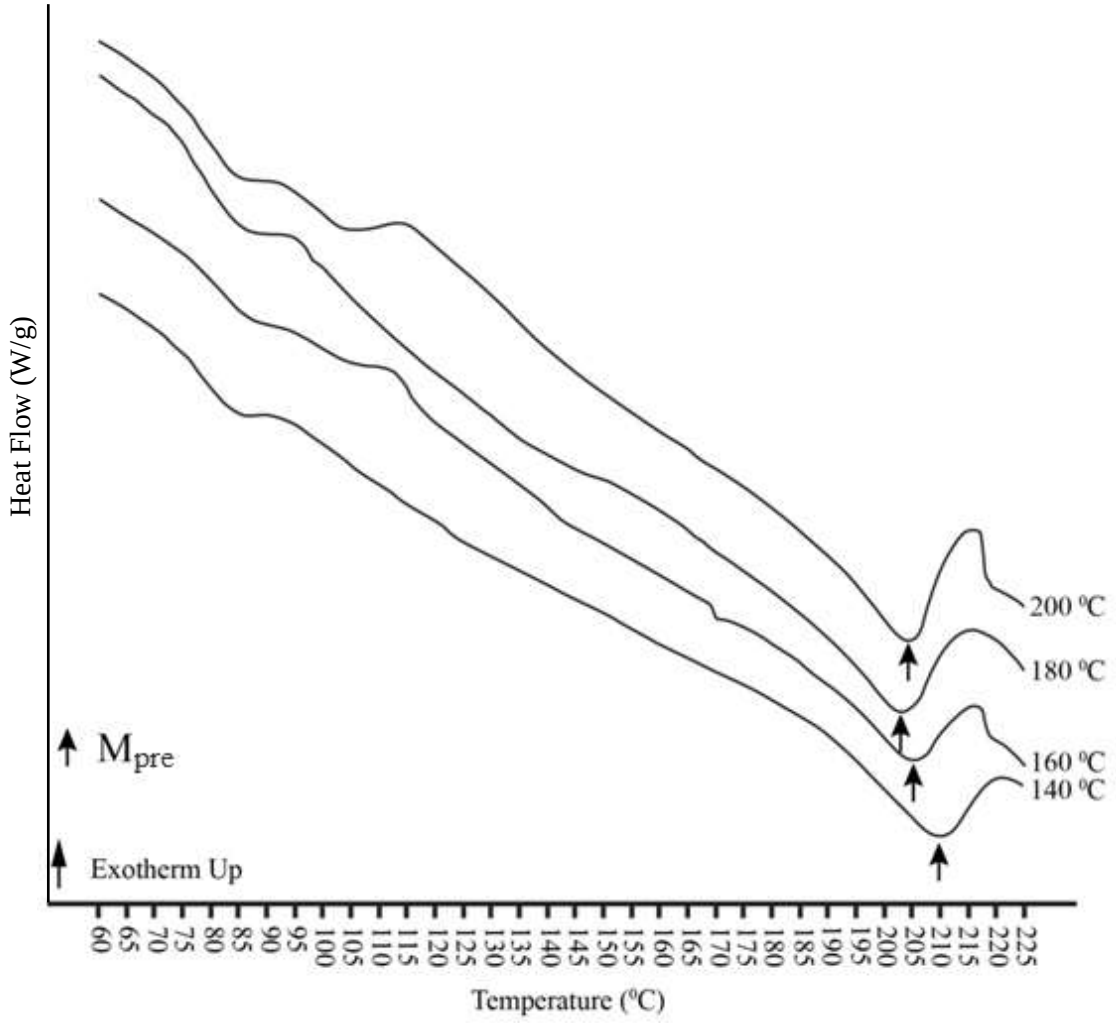


Figure 6.4 : DSC thermograms of yarns from fabrics panels heat-cured at 200°C which have been heat-set at 140°C,160°C,180°C and 200°C temperatures (Heat flow (W/g) Vs. Temperature (°C))

The DSC thermograms recorded from 150°C to 228°C for fabrics heat-set at 140°C,160°C,180°C and 200°C and heat-cured at 200°C are shown in Figure 6.4. A drastic change in the effective temperature (T_{pre}) after curing is observed for fabrics heat-set at low temperatures. The effective temperatures of fabrics heat-set at 140°C, 160°C,180°C and 200°C were 159°C, 160.5°C, 178°C and 198.5°C respectively. After curing process at 200°C, the effective temperatures of the respective fabric samples have been changed to 210.5°C, 205.5°C, 205°C and 204.5°C respectively. The results revealed that the fabric which was exposed to highest heat-setting

temperature has acquired the lowest effective temperature due to subsequent curing. Due to taut annealing at low heat-setting temperature, the polyester polymer structure has not achieved its most probable configuration. During subsequent curing without external physical constraints and thus in a free-to-deform state, the polymer structure is significantly changed, and the most possible configuration and the highest effective temperature may have been achieved. But the higher thermal energy supplied at higher temperatures of heat-setting (200°C) may have allowed the polyester polymer structure to overcome the conditions of taut heat-setting. When such a structure is heat treated subsequently (during heat-curing) more energy is required for a larger change as compared to fabrics heat-set at low temperatures.

Drawing occurs above glass transition temperature and the extended polymer structure is hardened after cooling hence extended state is preferred for the drawn yarns. But once its temperature rises, the extended state returns through the thermal shrinkage process to the folded form(M. P. W. Wilson, 1974). With the increased mobility, residual orientation stress in the fibre is relieved and the relaxation process is followed by a rearrangement of the chains in the new configuration at higher temperatures. The resulted new structure is in a more thermodynamically favoured state because of the state of lower free energy(Bhatt & Bell, 1976; Dismore & Statton, 1966). In addition to relaxing amorphous molecules, micro-crystal formation or secondary crystallization in the polymer structure is promoted at high temperatures (Karmakar, 1999b; Misra & Stein, 1979; Prevorsek & Tobolsky, 1963; Rodriguez-Cabello et al., 1996). These could be the reasons for achieving higher effective temperatures for heat-cured fabric samples at 200°C.

6.5 Significance of the Effective Temperature on Heat-Curing Process

For the yarns of fabrics heat-set at different temperatures (130°C-200°C at 10°C intervals) resulted in specific patterns of DSC thermograms during DSC analysis. The effective temperature (T_{pre}) was one of the variables which varied greatly due to heat-setting.

The heat-setting at low temperature ($T_{heatset}$<=160) resulted in an effective temperature of around 160°C and the effective temperature was increased as the

heat-setting temperature increases above 160°C. Previous studies suggested that the substance was thermally stable as long as the effective temperature of the material in subsequent heat treatments was not exceeded (Cayuela & Gacén, 1994). Therefore, analyzing the behavior of thermal deformation below and above the effective temperature of the material may indicate the relationship between the action of thermal deformation and the effective temperature of the heat-set materials. When there has been a substantial thermal shrinkage above the effective temperature of heat-set fabric for subsequent heat treatment temperatures, it can be argued that the effective temperature influences the subsequent thermal shrinkage behavior.

Among the experimental curing temperatures, 120°C and 140°C were well below the lowest effective temperature (effective temperature for low temperature heat-set materials was approximately 160°C). Therefore, thermal shrinkage values were used to analyze the significance of thermal shrinkage of the stitch length due to the heat-setting process by curing at below 140°C and above 140°C. The formula (6.2) was used to assess the thermal shrinkage percentage of the stitch length owing to heat-curing treatment.

6.5.1 Statistical analysis to assess the impact of effective temperature in subsequent heat treatments of fabric A

The one-way analysis of variance (ANOVA) is used to determine whether there are any statistically significant differences between the mean thermal shrinkages of fabrics heat-cured at different temperatures.

Hypothesis test 6.1 was performed in order to analyse whether there are any statistically significant differences between the mean thermal shrinkages of fabrics heat-set at temperature “T” and heat-cured at 120°C and 140°C.

Hypothesis test 6.2 was performed in order to analyse whether there are any statistically significant differences between the mean thermal shrinkages of fabrics heat-set at temperature “T” and heat-cured at 160°C, 180°C and 200°C.

Levene’s test and standardized residuals plot of error terms were evaluated to verify the assumptions to perform ANOVA. Levene’s test indicated that the assumption of

homogeneity of variance satisfied resulting F (39,377) =1.430, p>0.05 and the residual values showed approximate normality with mean value close to zero and standard deviation close to 1.

Figure 6.5 shows the distribution of standardized residuals of % thermal shrinkage of stitch length due to curing.

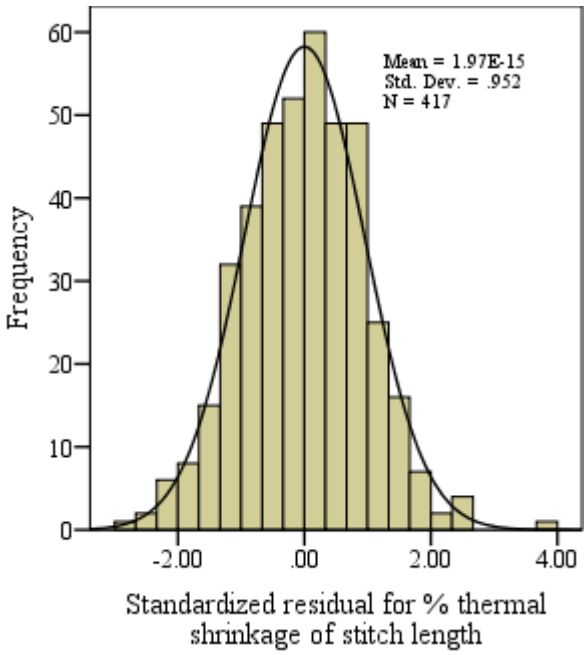


Figure 6.5 : The distribution of standardize residuals of percentage thermal shrinkage of stitch length due to curing

6.5.2 Mean thermal shrinkage of stitch length of heat-set fabrics due to curing

Table 6.3 presents the mean and standard deviation of percentage thermal shrinkage of stitch length of fabrics heat-set at temperatures 130°C, 140°C, 150°C, 160°C, 170°C, 180°C, 190 and 200°C and each heat-cured at 120°C, 140°C, 160°C, 180°C and 200°C.

Table 6.3 : Mean thermal shrinkage, standard deviation and coefficient of variation of heat-set and heat-cured fabrics of fabric A

Heat-setting temperature "T", °C	Curing temperature, °C	Mean thermal shrinkage, %	Std. Deviation, %	Coefficient of Variation, %
130	120	0.34	0.65	191
	140	0.34	0.67	197
	160	-0.26	0.43	-165
	180	1.62	0.51	31
	200	5.96	0.79	13
140	120	0.01	0.72	7200
	140	-1.11	0.67	-60
	160	-1.11	0.53	-48
	180	1.15	0.52	45
	200	4.79	0.71	15
150	120	-0.53	0.71	-134
	140	-0.79	0.47	-59
	160	0.32	0.42	131
	180	1.89	0.67	35
	200	3.56	0.69	19
160	120	-0.19	0.40	-211
	140	-0.49	0.55	-112
	160	-0.79	0.64	-81
	180	0.96	0.44	46
	200	3.92	0.39	10
170	120	-1.04	0.40	-38
	140	-1.04	0.39	-38
	160	-1.04	0.57	-55
	180	0.30	0.77	257
	200	2.03	0.57	28
180	120	-0.28	0.40	-143
	140	-0.61	0.47	-77
	160	0.22	0.34	155
	180	0.26	0.42	162
	200	2.02	0.43	21
190	120	-0.31	0.51	-165
	140	-0.62	0.83	-134
	160	-1.14	0.61	-54
	180	0.39	0.59	151
	200	1.27	0.33	26
200	120	-0.30	0.31	-103
	140	-0.79	0.45	-57
	160	0.40	0.57	143
	180	0.35	0.60	171
	200	0.04	0.40	1000

6.5.3 Analysis of variance test to assess the effect of curing treatment on thermal shrinkage of stitch length

Hypothesis test 6.1 and 6.2 was made to test the significant different between the thermal shrinkage of stitch lengths due to curing below or less than 140°C and above 140°C respectively.

Hypothesis test 6.1: *H_o: There is no significant different between thermal shrinkage of stitch lengths curing ≤140°C for the fabric heat-set at temperature "T"*

Vs *H_1: There is significant different between thermal shrinkage of stitch lengths curing ≤140°C for the fabric heat-set at temperature "T"*

Significance level α=0.05

Hypothesis test 6.2: *H_o: There is no significant different between thermal shrinkage of stitch lengths curing >140°C for the fabric heat-set at temperature "T"*

Vs *H_1: There is significant different between thermal shrinkage of stitch lengths curing >140°C for the fabric heat-set at temperature "T"*

Significance level α=0.05

The one-way ANOVA results for each test is presented in the Appendix 6 and the significant values resulted are presented in Table 6.4.

The results of ANOVA to determine the effect of curing temperatures less than or equal to 140°C on stitch length of heat-set fabrics are presented in Table 6.4. The results of the analysis of variance of the thermal shrinkages of stitch lengths reveal that if the curing temperature is less than or equal to 140°C (curing temperatures were 120°C and 140°C) , the effect of curing temperature on shrinkage of the stitch length is not statistically significant for all heat-set fabrics (Table 6.4). Therefore, the null hypothesis of the Hypothesis test 6.1 is accepted.

Table 6.4 : The significant values resulted from one-way ANOVA tests performed for heat-set and heat-cured fabrics based on the Hypothesis test 6.1 and 6.2.

Heat-set Temperature ,T (°C)	Effect of curing temperature If curing temperature ≤ 140°C	Effect of curing temperature if curing temperature > 140°C
130	NS (P=0. 991)	S (P<0. 000)
140	NS (P=0. 093)	S (P<0. 000)
150	NS (P=0. 340)	S (P<0. 000)
160	NS (P=0. 181)	S (P<0. 000)
170	NS (P=0. 996)	S (P<0. 000)
180	NS (P=0. 114)	S (P<0. 000)
190	NS (P=0. 320)	S (P<0. 000)
200	NS (P=0. 078)	NS (P=0. 248)

When the curing temperature is higher than 140°C (curing temperatures were 160°C,180°C and 200°C) , the effect of curing temperature is statistically significant for all heat-set fabrics except for the fabric heat-set at 200°C where the significant level resulted is higher than 0.05 (Table 6.4). Considering the overall results the alternative hypothesis of the Hypothesis test 6.2 is accepted. The curing temperature has no significant effect on the thermal shrinkage of stitch length of fabric heat-set at 200°C as the effective temperature of this sample due to heat-setting is 198.5°C. This indicates that if curing temperature does not exceed the effective temperature of heat-setting, significant structural change in the yarn cannot be caused. This also revealed that the heat-set fabric structure remains stable as long as the effective temperature does not exceed the effective temperature of heat-setting.

In subsequent curing treatment, the curing temperature below 160°C would therefore not be enough to override the structural stability of polymers set by heat-setting. The resulted thermal shrinkage of the stitch length below 160°C can therefore be attributed to the disorientation of amorphous regions in the polymer structure(Gupta et al., 1993; Nobbs et al., 1976; M. P. W. Wilson, 1974). As the curing temperature increases, significant thermal shrinkage in the stitch length was observed. The observed thermal shrinkage behavior is endorsed by the effective temperatures resulted from DSC analysis. If the curing temperature is more than 160°C, the provided thermal energy could disrupt the stability of the polymer structural by disrupting the secondary crystallization occurred due to heat-setting treatment and

disorientating the oriented amorphous chains of the structure which appears as a thermal shrinkage in the yarn.

6.6 Differential Scanning Calorimetric and Thermal Shrinkage Analysis of Fabric B

A second polyester plain knitted fabric with different yarn and fabric properties to fabric A was knitted and dyed in order to validate the thermal shrinkage behavior observed in fabric A. The second fabric is denoted as fabric B. The fabric B is also heat-set and heat-cured to examine the DSC thermograms and thermal shrinkage behaviors in order to evaluate the relationship between the effective temperature of heat-set fabric and thermal shrinkage behavior. Table 6.5 presents the yarn specifications and properties of greige and dyed fabric B.

Table 6.5 : Yarn and fabric specifications of fabric B

Yarn specification		Greige fabric specifications		Dyed fabric specifications	
Count (denier)	No of filaments	Greige fabric stitch length (mm)	Yarn count (denier)	Stitch length (mm)	Yarn count (denier)
100	144	2.19	100.28	2.11	102.90

6.6.1 Heat treatments carried out for fabric B

Samples from fabric B were set at 8 different heat-setting temperatures ($t_{heatset}$) ranging from 130°C to 200°C at 10°C intervals with 25% overfeeding in an industrial hot air pin stenter machine while keeping the fabrics taut for 96 seconds at 5% constant width extension as did for the Fabric A. The fabrics were gradually cooled to the ambient temperature after the heat-setting process. The fabrics were conditioned in accordance with ASTM standard D1776. Few yarns were unravelled from each fabric sample after heat-setting and analyzed using the DSC to study the structure and morphology of the polyester structure after heat-setting.

Using the Differential Scanning Calorimetry (DSC Q200), the thermal properties of heat-set fabrics (fabric B) were studied. For the study, yarn samples were taken from each fabric sample and their DSC thermograms were recorded from 25°C to 300°C. The mean sample size of the yarn was 8.81 mg (standard deviation= 0.28 mg). The yarn specimens are tested at $10°Cmin^{-1}$ in the nitrogen atmosphere. The

degree of crystallinity was calculated from the equation 6.1 for each heat-set fabric sample and values are reported in Table 6.6.

There was no adequate amount of 140°C and 160°C heat-set fabrics of fabric B for curing treatments since they were used excessively for preliminary studies. Therefore heat-set fabrics 130°C, 150°C, 170°C, 180°C, 190°C and 200°C were subjected to heat-curing at 120°C,140°C, 160°C, 180°C and 200°C. Five 30 x 30 cm^2 specimens of each heat-set fabric were subjected to heat-curing treatment and thermal shrinkage of stitch length due to heat-curing was calculated from the formula 6.2.

6.6.2 Differential scanning calorimetric (DSC) analysis of fabric B

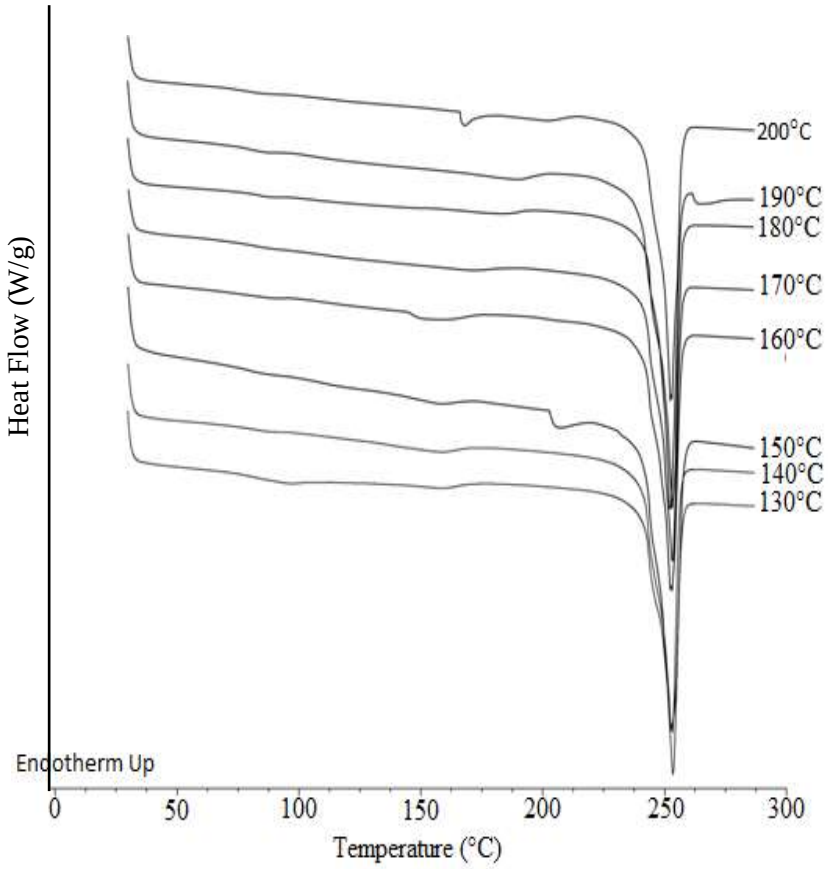


Figure 6.6 : DSC thermograms recorded from 25°C to 300°C of the yarn samples from heat-set fabrics (Heat flow (W/g) Vs. Temperature (°C))

The DSC thermographs of the yarns of heat-set fabric samples of fabric B are shown in Figure 6.6 and the more sensitive thermograms obtained from the DSC

thermograms in Figure 6.6 are stacked and presented in Figure 6.7.

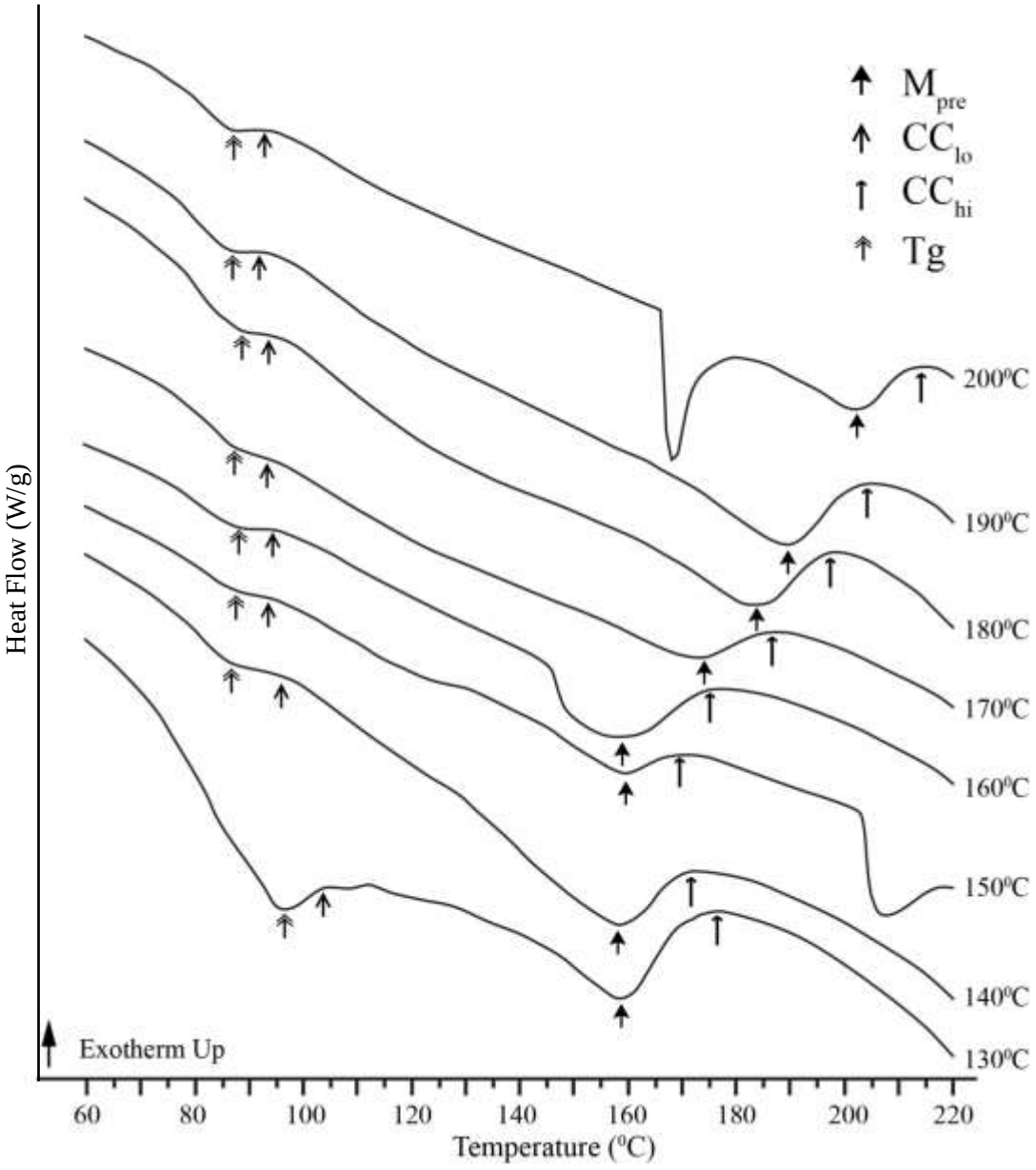


Figure 6.7 : DSC thermograms recorded from 60 °C to 215 °C of yarns from fabrics heat-set at different temperatures (Heat flow (W/g) Vs. Temperature (°C))

For the heat-set fabrics B, the first small endothermic regions correspond to the T_g is in the range of 80-100°C (Figure 6.7). The weak T_g, indicates that the initial structure is nearly crystalline or has a higher orientation in amorphous regions. In all the thermograms, the glass transition region shown in Figure 6.7 is followed by a slight exothermic peak. As observed for the heat-set fabrics of fabric A, the

exothermic peaks just above the T_g of fabric B too are also shifted to the direction of lower temperature with increasing heat-setting temperature confirming that heat-setting has caused the structure to be more oriented.

Pre-melting endotherms which reveal the effective temperature of heat-set fabrics of Fabric B spread in a wider range of 155°C -205°C as shown in Figure 6.7. As in heat-set fabric A, Figure 6.7 shows that the pre-melting temperature of fabric B heat-set at 130°C,140°C,150°C and 160°C are also on or in the vicinity of 160°C. For these yarns also the positions of the pre-melting peak have shifted to the high-temperature side when heat-setting temperature is increased. These results also reveal that the heat-setting at a higher temperature causes the effective temperature to increase (Table 6.6). Crystallization takes place at (CC_{hi}) also have increased with increasing heat-setting temperature. Table 6.5 presents these temperatures of heat-set fabrics extracted from DSC graph in Figure 6.6 and 6.7.

Table 6.6 : The temperatures of glass transition, pre-melting, secondary melting, primary melting, low and high temperature cold crystallisation peaks and crystallinity of heat-set fabric samples of fabric B

Heat-setting temperature °C	T_g °C	T_{CClo} °C	T_{pre} °C	T_{CChi}, °C	$T_{secondary}$ °C	$T_{primary}$ °C	Crystallinity %
130	97	113	158	176.5	-	254	38.11
140	88	97	158	172	-	253	38.84
150	89	96	159	171	207	253	40.29
160	88	96	158	177.5	-	253	39.13
170	90	97	174	187	-	254	39.51
180	89.5	96	183	198	-	254	39.87
190	89	95	190	206	-	253	38.12
200	89	95	202	205	168	253	39.19

6.6.2.1 Determining the crystal structure and crystallinity

Percentage crystallinity of the heat-set fabrics B was calculated using equation 6.1. As can be seen in Table 6.5, percentage crystallinity of samples does not change significantly with increasing heat-setting temperature.

Significance of the effect of effective temperature of heat-setting on subsequent heat-curing process was evaluated by analysing the significance of thermal shrinkage of

stitch length due to curing process at 5% significance level is described in section 6.6.3.

6.6.3 Statistical analysis to assess the impact of effective temperature in subsequent heat treatments of fabric B

In order to verify the assumptions of performing ANOVA, Levene's test and standard residuals plot of error terms were assessed.

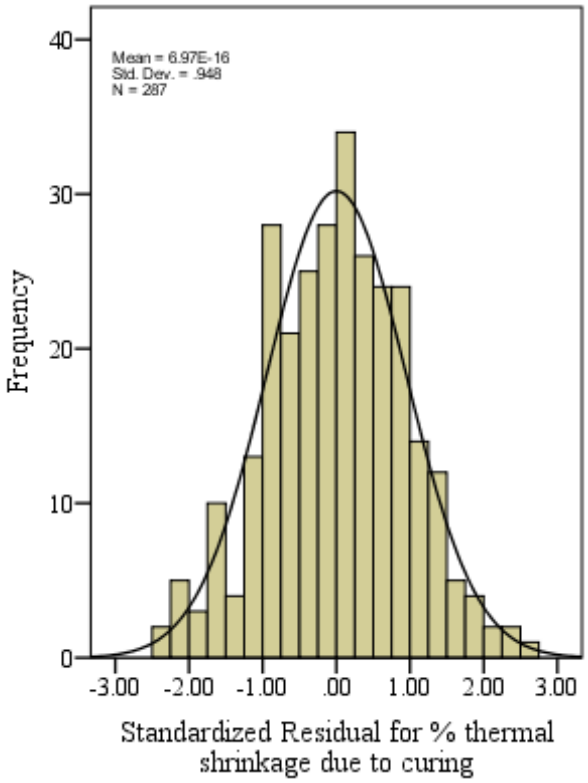


Figure 6.8 : The distribution of standardize residuals of percentage thermal shrinkage of stitch length due to curing

Levene's test showed that the hypothesis of variance homogeneity reached F (29,257) =1.275, p>0.05. The residual values displayed estimated normality with a mean value close to zero and a standard deviation close to 1. Figure 6.8 presents the distribution of standardized thermal shrinkage stitch length residuals owing to heat-curing.

6.6.4 Mean thermal shrinkages of heat-set and heat-cured fabrics of fabric B

Mean thermal shrinkage and standard deviation of stitch length of heat-set fabrics due to curing are presented in Table 6.9. Statistical measurement of the dispersion of data points around the mean in a data series is measured by the percentage of coefficient variance

Table 6.7 : Mean thermal shrinkage, standard deviation and coefficient of variation of heat-set and heat-cured fabrics of fabric B

Heat-setting temperature "T", °C	Curing temperature, °C	Mean thermal shrinkage, %	Std. deviation, %	Coefficient of Variation, %
130	120	1.63	0.26	16
	140	1.87	0.31	17
	160	2.13	0.37	17
	180	3.70	0.39	11
	200	5.62	0.54	10
150	120	-0.69	0.47	-68
	140	-0.33	0.30	-91
	160	0.97	0.36	37
	180	2.11	0.39	18
	200	4.76	0.32	7
170	120	-0.30	0.36	-120
	140	-0.04	0.16	-400
	160	0.23	0.28	122
	180	0.99	0.57	58
	200	3.96	0.38	10
180	120	-0.41	0.20	-49
	140	-0.14	0.37	-264
	160	-0.15	0.54	-360
	180	0.20	0.51	255
	200	2.61	0.38	15
190	120	-0.87	0.31	-36
	140	-0.89	0.33	-37
	160	-1.16	0.56	-48
	180	-0.63	0.49	-78
	200	1.52	0.47	31
200	120	-0.47	0.40	-85
	140	-0.50	0.55	-110
	160	-0.60	0.39	-65
	180	-0.73	0.32	-44
	200	0.20	0.47	235

6.6.5 Analysis of variance for stitch length thermal shrinkage

Hypothesis test 6.3 and 6.4 performed to test the effect of curing temperature on percentage thermal shrinkage of stitch length due to curing of fabric B.

Hypothesis test 6.3: H_o*: There is no significant different between thermal shrinkage of stitch lengths curing ≤140°C for the fabric heat-set at temperature "T"*

Vs H_1*: There is significant different between thermal shrinkage of stitch lengths curing ≤140°C for the fabric heat-set at temperature "T"*

Significance level α=0.05

Hypothesis test 6.4: H_o*: There is no significant different between thermal shrinkage of stitch lengths curing >140°C for the fabric heat-set at temperature "T"*

Vs H1*: There is significant different between thermal shrinkage of stitch lengths curing >140°C for the fabric heat-set at temperature "T"*

Significance level α=0.05

Table 6.7 shows the results of ANOVA to determine the effect of curing temperatures less than or equal to 140°C and curing temperatures more than 140°C for percentage thermal shrinkage of stitch length of heat-set fabrics of fabric B.

Table 6.8 : The ANOVA results of the effect of curing temperature on thermal shrinkage of the yarns in knitted fabric B.

Heat-set Temperature ,T (°C)	Effect of curing temperature If curing temperature ≤ 140°C	Effect of curing temperature if curing temperature > 140°C
130	NS (P=0.083)	S (P<0. 000)
150	NS (P=0.058)	S (P<0. 000)
170	NS (P=0.053)	S (P<0. 000)
180	NS (P=0.065)	S (P<0. 000)
190	NS (P=0.866)	S (P<0. 000)
200	NS (P=0.906)	S (P<0. 000)

The results of the variance analysis of stitch length show that if the curing temperature is below or equal to 140°C, the effect of curing temperature on the stitch length shrinkage is not statistically significant for all heat-set fabrics (Table 6.7). Thus, the null hypothesis of the Hypothesis test 6.3 is accepted.

When the curing temperature exceeds 140°C (curing temperatures were 160°C, 180°C and 200°C), the effect of curing temperature is statistically significant for all heat-set fabrics with P-value less than the significant level as shown in Table 6.7. Hence the alternate hypothesis of Hypothesis test 6.4 s accepted.

These results also revealed that, the thermal energy of curing temperatures below 160°C is enough to override the structural stability of heat-set polyester.

6.7 Summary

The thermal behavior of polyester fabrics after heat-setting and after heat-curing is investigated using DSC analysis and the fabric shrinkage. Analysis was carried out on a fabric knitted using polyester yarns and found that the primary effect of the heat-setting is the change in effective temperature. No significant difference between effective temperatures is observed in low heat-setting temperatures, whereas the effective temperatures rise with the increasing heat-setting temperature. The study on the percentage of shrinkage of yarns due to curing at different temperatures confirmed this behavior.

The analysis carried out on fabric A was repeated for a second fabric (fabric B) in order to establish and accept the observed behavior of polyester fabric A is common to all polyester fabrics manufactured under using similar yarns and similar conditions. Fabric B delivered similar results from the DSC analysis and the thermal shrinkage.

7 COMPARATIVE STUDY ON THE THERMAL SHRINKAGE BEHAVIOR OF POLYESTER YARN AND ITS PLAIN KNITTED FABRICS

7.1 Introduction

The results of the previous chapters revealed that heat treatment processes have caused thermal deformations in polyester knitted fabrics. Heat-based processes on thermoplastic fibre materials are well known to cause the materials to shrink. However, it is yet to be investigated that, whether the contribution of the yarn itself or the knitted fabric structure has more significant impact on the thermal deformation when the knitted fabrics are subjected to heat treatments. Because of the thermal shrinkage of the constituent yarns in the fabric and the change in the loop shape, knitted fabrics can change their dimensions. This chapter focuses on the extent to which the thermal shrinkage of polyester yarn affects the thermal shrinkage behavior of polyester knitted fabrics and the effect of heat on fabric parameters. After dyeing, heat-setting and subsequent heat-curing processes, the thermal shrinkage behavior of polyester yarn and the plain knitted fabric made of the same yarns were analysed. The thermal effects were investigated on yarns, yarns in fabrics, and densities of wale and course of the fabrics. Comparison was made of yarn in hank form and yarn in the knitted stitch. The thermal effects on other parameters of knitted fabric are also discussed.

7.2 Materials and Methods

A 100% polyester plain knitted fabric was produced on 28-gauge single jersey knitting machine using 155 denier 144 filaments polyester yarns. The yarn and the fabric are denoted as “yarn A” and “fabric A” respectively for the study. The yarns used in producing the fabric were subjected to all processes that the fabrics usually undergo. The yarns were processed in hank form. Details of the processes, testing carried out on yarns and fabrics are described in the following sections. Fabric A is the same fabric A, which was referred to in Chapter 6 in the DSC analysis.

7.2.1 Dyeing, heat-setting and subsequent heat-curing of yarns in hank form of yarn A

7.2.1.1 Dyeing yarns

155 denier and 144 filaments Polyester yarn (yarn A) was wound with a minimum tension using a laboratory hank winder of 1 meter in circumference. The yarns in the hank were loosely tied to hold them as a bundle using a separate yarn in few places. The hank was cut at one point that makes 100 yarn samples, each 1 m in length. Nine such bundles, each bundle containing 100 yarns were scoured and dyed at 130°C in a sample dyeing machine.

7.2.1.2 Heat-setting process of yarns

Eight of the above-mentioned dyed yarn bundles were heat treated at temperatures from 130°C to 200°C at 10°C intervals in an industrial drying machine. During heat-setting, yarns were separated in each yarn bundle and relaxed straight on the conveyor belt of the drying machine. A very light weight that will not impede the yarn shrinking during heat treatment was kept on the yarns to stop them from getting entangled due to hot air blow.

7.2.1.3 Heat-curing process of yarns

As mentioned in Chapter 4, the conditions of print curing process were selected for post-heat treatment to test the post-heat treatment behavior of pre-heat-set polyester yarns. Each of the eight yarn bundles which described in the section 7.2.1.2 was divided into 5 yarn bundles comprising 20 yarns. Each yarn bundle, consisting of 20 yarns of a specific heat-set temperature, was subjected to heat-curing at temperatures120°C, 140°C, 160°C, 180°C and 200°C for 5 cycles of 90 seconds in the industrial drying machine.

7.2.1.4 Thermal shrinkage of yarns and the resultant increase in yarn count

As mentioned in Chapter 6, the heat-set polyester yarn glass transition temperatures were observed in the 80°C-100°C temperature range. The selected post-heat treatment temperatures are far greater than the glass transition temperatures of heat-set polyester fabrics. As the transition from glass to rubber is facilitated by the heat-

curing temperatures, thermal deformation of the filaments can also be expected due to post-heat treatment. Changing the length of the yarn will also change the linear density or the yarn count. For this study, percentages thermal shrinkage of yarn and change of yarn count were also calculated. The length measurements and yarn counts were calculated in accordance with the standard BS EN ISO 2060:1995 (ASTM D 1059 – 01).

The changes in length of yarns in hank, followed by the dyeing, different temperatures of heat-setting (130°C,140°C,150°C,160°C,170°C,180°C,190°C and 200°C) and various temperatures of heat-curing (120°C, 140°C, 160°C, 180°C and 200°C) were measured to calculate the average shrinkage or the expansion of the yarns. During dyeing, heat-setting and heat-curing processes, heat is applied as a main process condition; therefore, these processes were generally referred as heat treatment processes for this chapter.

The thermal shrinkage percentage of yarns in hank due to any given heat treatment is calculated by the equation (7.1).

$$TS_Y = \frac{(Yl_i - Yl_a)}{Yl_i} X\ 100 \qquad (7.1)$$

Where, TS_Y is the thermal shrinkage of the yarn, Yl_i is yarn length before the heat treatment and Yl_a is the yarn length after the heat treatment. The (+) values indicate a thermal shrinkage and (-) values indicate thermal expansion of the yarn due to heat treatment.

The percentage increase in yarn count, C_Y is calculated by the equation (7.2)

$$C_Y = \frac{(YC_a - YC_i)}{YC_i} X100 \qquad (7.2)$$

Where YC_a is the count of yarn after the heat treatment and YC_i is the count of yarn before the heat treatment. The (+) values indicate an increase in count and (-) values indicate decreasing in count of the yarn due to heat treatment.

7.2.2 Dyeing, heat-setting and heat-curing of 100% polyester plain knitted fabrics (fabric A)

Plain knitted fabric (fabric A) was made using 155 denier 144 filament polyester yarns (yarn A) on a circular knitting machine. Knitting specifications of the 100% polyester plain fabric were; machine diameter-30 inches, gauge-28; RPM-20, number of positive feeder systems -90, total number of knitting needles-2580. The stitch length of the greige fabric was 2.40 mm.

The fabric was then dispersed dyed at 130°C on the jet dyeing machine. The fabric was then divided into 8 parts of the same length of 15 m. These fabric parts were heat-set at 8 different heat-setting temperatures ($T_{heatset}$) varying from 130°C to 200°C at 10°C intervals with 25% overfeeding in the industrial hot air pin stenter, holding the fabrics to a constant width extension of 5%. The system speed for heat-setting was maintained at 15 m/min so that the fabric was exposed to 90 seconds hot air blow and slowly cooled down to an ambient temperature. The selected heat-setting parameters are the most widely used in the manufacture of commercial fabric. For conditioning ASTM standard D1776 was adopted. The yarn and fabric specifications of fabric A are presented in Table 7.1.

Table 7.1: Yarn and fabric specifications

Fabric code	Yarn specification		Greige fabric specifications		Dyed fabric specifications	
	Count (denier)	No of filaments	stitch length (mm)	Yarn count (denier)	Stitch length (mm)	Yarn count (denier)
A	155	144	2.40	154.89	2.33	160.8

The post heat treatment process to which the fabric was subjected to is the print curing process which was described in the Chapter 4. The process conditions used for heat-curing were similar to those used in the industry.

The temperatures 120°C, 140°C, 160°C, 180° C and 200°C were selected for the heat-curing process. Five specimens from each heat-set fabric was subjected to each heat-curing treatment for five cycles of 90 seconds as described in the Chapter 4 in the same industrial drying machine used to cure the yarns in hank form. The

numbers of curing cycles were selected as five, considering the maximum number of different adornments requiring heat-curing, though this number may vary from 1 to 5 generally in actual industrial practice. In the calculation of thermal shrinkage, five specimens were subjected to each heat-curing temperature and the average shrinkage of the five specimens was reported.

The fabric samples were subjected to standard conditioning as given in ASTM D1776 before taking any measurement.

7.2.2.1 Shrinkage of fabric due to curing (post-heat treatment)

Shrinkages in the course direction (width-wise) and wale direction (length-wise) due to heat-curing were measured on fabric samples of 30 X 30 cm^2. Test specimens were cut with their grain lines parallel to wales and measurements were taken as described in Chapter 5.

7.2.2.2 Thermal shrinkage (S_T)

The shrinkages (S_T) in course direction and wale direction of fabric specimens due to heat-curing were calculated using the equation 7.3.

$$S_T = \frac{l_i - l_a}{l_i} \times 100\ \% \qquad (7.3)$$

Here l_i is the length between data lines marked in particular direction before thermal application and l_a is the length between the same data lines after subjecting to the thermal application.

While the (+) values indicate the thermal shrinkage and (-) values indicate the thermal expansion.

7.2.2.3 Measuring stitch length, count of the yarn in the fabric, the course and wale densities

Course and wale densities of the fabrics were determined according to the standard BS 5441 (ASTM D3775-03) and the change in area was calculated from the results of the shrinkage test and the area shrinkage calculated from the equation 7.4.

$$\text{Area shrinkage} = \frac{(\text{Area inside datalines before curing}) - (\text{Area inside datalines after curing})}{(\text{Area inside datalines before curing})} \text{x}100\% \quad (7.4)$$

The effects of heat on the yarns in the fabrics were studied by measuring the stitch lengths of the fabrics. The stitch lengths of dyed fabric, heat-set, and heat-cured fabrics were measured and calculated as per the international standard BS EN 14970: 2006.

The percentage shrinkage of yarn in fabric after subjecting to dyeing, to different heat-setting temperatures and to different heat-curing temperature were measured to calculate average percentage shrinkage or expansion of stitch length after each process. Thermal shrinkage of yarn in fabric (stitch length) due to a heat treatment was calculated using the equation (7.5).

$$TS_{sl} = \frac{Sl_i - Sl_a}{Sl_i} \times 100 \quad (7.5)$$

Where, TS_{sl} is the percentage thermal shrinkage of the stitch length due to heat treatment, Sl_i is the stitch length before heat treatment and $Sl_{a\ is}$ the stitch length after heat treatment. Here the heat treatments used were dyeing, heat-setting and heat-curing. The (+) value indicates a thermal shrinkage and (-) value indicates a thermal expansion of the stitch length.

If there is a change in the stitch length after a process due to heat, the count of the yarn in the fabric too is changed. If the stitch length is reduced the count of the yarn is increased. Percentage increase in count of the yarn in the fabric after each process, denoted as C_{sl} is calculated by the equation (7.6)

$$C_{sl} = \frac{(SLC_a - SLC_i) * 100}{SLC_i} \quad (7.6)$$

Where SLC_a is the count of yarn in knitted stitch after the heat treatment and SLC_i is the count of yarn in knitted stitch before the heat treatment.

When calculating the % increase in yarn count, (+) values indicates increase in yarn count and (-) values indicate decrease in yarn count.

The thermal effect on yarns in hank and yarns in fabric (stitch length) due to dyeing, and thermal effects of yarn in hank and yarns in fabric due to heat-setting and heat-curing are discussed, and a comparative analysis is presented hereafter in the following sections.

7.3 Thermal Effects on Yarns in Hank and Yarns in Fabric (Stitch Length) Due to Dyeing (Yarn A and Fabric A)

Thermal effects on the yarn in the fabric may happen because of the dyeing process as the dispersed dyeing takes place at high temperatures (130°C). Therefore, the effect of high temperature dyeing on the yarn in hank form and yarns in fabrics is important to identify and the effect on each form is compared. Table 7.2 presents the thermal shrinkage and change in the count of yarns in hank and yarns in fabric due to dyeing process.

Table 7.2 : Thermal shrinkage of yarns and the yarns in the fabric due to dyeing (Standard deviations are indicated in square brackets)

Process status	Yarn length in hank, (cm)	Yarn count in hank, (denier)	Stitch length in fabric,(mm)	Yarn count in fabric,(denier)
Before dyeing	100.41[0.104]	155.60	2.40 [0.178]	154.89
After dyeing	93.07 [0.256]	166.69	2.33 [0.172]	160.80
Thermal shrinkage after dyeing	7.31%	7.13 %	3.30%	3.81%

Due to dyeing, the yarn reduced its length by 7.31% and caused the yarn count to increase by 7.13%. Due to dyeing, the yarn in fabric or stitch length reduced by 3.30% and caused a 3.81% increase in yarn count. The resulting yarn shrinkage in the fabric / stitch length is lower than that of the shrinkage of yarn in hank.

Although the yarn shrinkage in the fabric is relatively low, yarns in the fabric have shrunk significantly (3.3%). Postle (1957) and Munden (1969) stated that the dry relaxation process had no significant effect on the dimensional changes in the thermoplastic knitted fabric, but the dimensional changes in thermoplastic knitted fabrics were significant due to wet relaxation.

Comparatively less yarn shrinkage in the fabric indicates that the longitudinal load on the knitted fabric during dyeing has restricted the yarn shrinkage in the fabric (Gupta, 1995).

Due to dyeing, the yarn in the hank has shrunk to 7.13%. The yarns in the hank form are entirely free to relax from the stresses incurred during previous processes of yarn manufacture. The relaxation from free stresses and thermal deformation behavior due to thermoplastic nature contribute to the shrinkage of yarn (Kobayashi & Keller, 1970; Long & Ward, 1991; Prevorsek et al., 1974; Trznadel & Kryszewski, 1992; M. P. W. Wilson, 1974).

7.4 Thermal Effects of Yarns in Hank and Yarns in Fabric Due to Heat-Setting and Heat-Curing (Yarn A and Fabric A)

In order to compare the effect of the heat-setting and the heat-curing process on the yarn in the hank and the yarn in the fabric, both forms were subjected to similar heat-settings and heat-curing temperatures. The yarn and fabric parameters needed to compare the effects of thermal treatments on each form are summarized in Table 7.3 and Table 7.4.

Mean length shrinkages of yarns in the hank and yarns in fabric (stitch length) due to different heat-setting temperatures (130°C, 140°C, 150°C, 160°C, 170°C, 180°C, 190°C and 200°C) and different post-heat treatment (heat-curing) temperatures (120°C, 140°C, 160°C, 180°C and 200°C) are presented in Table 7.3 and Table 7.4 respectively.

Table 7.3 : Mean length shrinkages of yarn in the hank due to heat-setting and heat-curing process and resultant yarn counts (yarn A)

Heat-setting process -Yarn				Heat-curing process-Yarn					Overall thermal shrinkage (from dyed yarn to curing)
Heat-setting temperature (°C)	Yarn length (cm)	Count (denier)	% length shrinkage heat-setting	Curing temperature (°C)	Yarn length (cm)	Count (denier)	% length shrinkage curing	Standard deviation (shrinkage), %	
130	93.09	165.87	-0.02	120	92.90	165.76	0.21	0.31	0.18
				140	92.60	166.67	0.53	0.41	0.50
				160	91.41	169.16	1.80	0.36	1.78
				180	89.75	170.97	3.59	0.42	3.57
				200	86.78	177.52	6.75	0.17	6.76
140	92.90	166.43	0.18	120	92.82	166.46	0.09	0.39	0.27
				140	92.48	166.53	0.46	0.26	0.64
				160	91.18	169.92	1.85	0.47	2.03
				180	89.19	172.29	4.00	0.47	4.17
				200	87.05	176.79	6.30	0.30	6.47
150	92.61	166.81	0.49	120	92.69	165.92	-0.09	0.41	0.40
				140	92.48	166.49	0.14	0.28	0.63
				160	91.21	168.94	1.52	0.37	2.00
				180	89.96	170.38	2.87	0.42	3.34
				200	87.14	175.59	5.92	0.34	6.38
160	92.44	166.91	0.68	120	92.25	166.44	0.21	0.36	0.88
				140	91.96	167.15	0.52	0.40	1.19
				160	91.40	168.94	1.13	0.08	1.79
				180	89.73	172.14	2.93	0.51	3.59
				200	87.18	175.64	5.70	0.42	6.33
170	90.82	170.02	2.42	120	90.53	171.62	0.32	0.18	2.73
				140	90.50	170.72	0.35	0.48	2.76
				160	90.12	170.86	0.77	0.39	3.17
				180	89.67	171.18	1.26	0.36	3.65
				200	86.73	175.55	4.50	0.29	6.81
180	90.26	170.47	3.02	120	90.06	171.26	0.22	0.45	3.23
				140	89.84	171.17	0.47	0.21	3.48
				160	89.88	171.35	0.42	0.38	3.43
				180	89.52	172.65	0.82	0.40	3.82
				200	87.34	175.37	3.24	0.41	6.16
190	89.17	173.24	4.19	120	89.32	172.63	-0.17	0.51	4.03
				140	88.61	172.87	0.63	0.45	4.79
				160	88.45	174.73	0.81	0.35	4.96
				180	88.32	174.64	0.96	0.40	5.10
				200	87.22	176.53	2.19	0.50	6.28
200	88.11	175.58	5.33	120	87.89	174.60	0.26	0.29	5.57
				140	87.27	176.50	0.95	0.27	6.23
				160	87.93	175.55	0.21	0.65	5.53
				180	87.69	176.54	0.48	0.57	5.78
				200	86.91	177.09	1.37	0.44	6.62

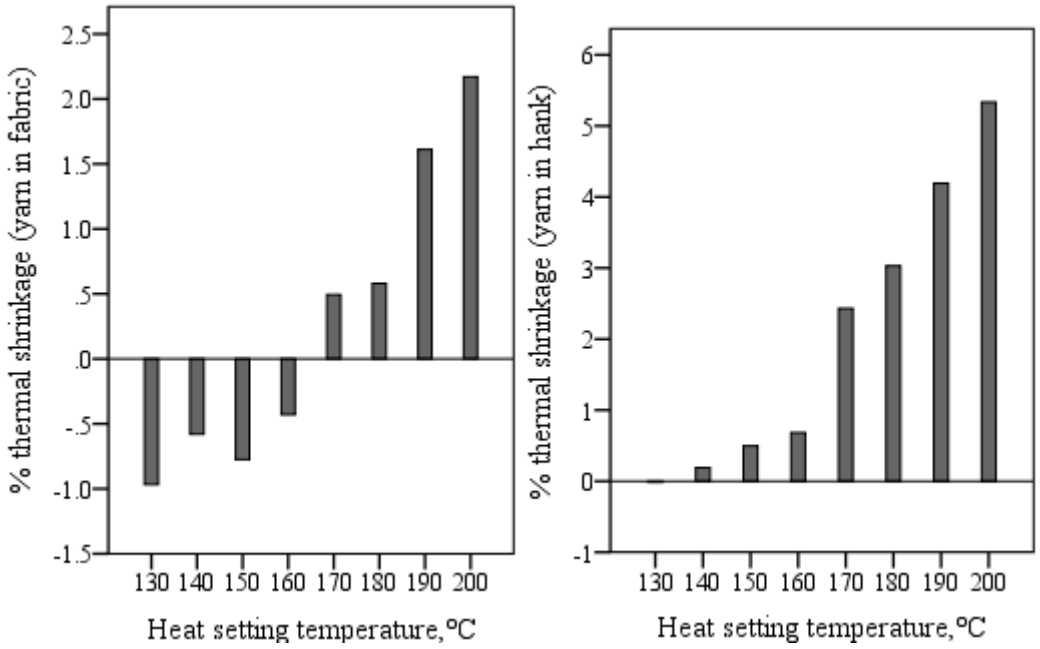
Table 7.4 : Mean shrinkages of knitted stitch (yarns in the fabric) due to heat-setting and post-heat treatment (heat-curing) processes and resultant yarn counts (fabric A)

Fabric (heat-set)				Fabric (heat-cured)					Thermal shrinkage, % overall (from dyeing to curing)
Heat-setting temperature (°C)	Mean stitch length (mm)	Count (denier)	% shrinkage of yarn in fabric heat-setting	Curing temperature (°C)	Mean stitch length (mm)	Count (denier)	% shrinkage of yarn in fabric due to curing	Standard Deviation (shrinkage) %	
130	2.349	159.39	-0.967	120	2.34	159.37	0.34	0.65	-0.62
				140	2.34	161.22	0.34	0.67	-0.62
				160	2.36	159.41	-0.26	0.43	-1.23
				180	2.31	161.17	1.62	0.51	0.67
				200	2.21	168.99	5.96	0.79	5.05
140	2.343	160.91	-0.58	120	2.34	159.93	0.13	0.72	-0.45
				140	2.37	161.06	-1.11	0.67	-1.70
				160	2.37	161.84	-1.11	0.53	-1.70
				180	2.31	162.23	1.15	0.52	0.58
				200	2.23	166.83	4.79	0.71	4.23
150	2.344	160.46	-0.774	120	2.36	159.61	-0.53	0.71	-1.31
				140	2.36	160.33	-0.79	0.47	-1.57
				160	2.34	161.81	0.32	0.42	-0.45
				180	2.30	163.56	1.90	0.67	1.14
				200	2.26	166.37	3.56	0.69	2.82
160	2.336	160.24	-0.430	120	2.34	159.55	-0.19	0.40	-0.62
				140	2.35	160.69	-0.49	0.55	-0.92
				160	2.36	161.00	-0.79	0.64	-1.23
				180	2.31	162.94	0.96	0.44	0.54
				200	2.25	166.81	3.92	0.39	3.50
170	2.315	161.73	0.494	120	2.34	160.92	-1.04	0.40	-0.54
				140	2.34	160.80	-1.04	0.39	-0.54
				160	2.34	160.80	-1.04	0.57	-0.54
				180	2.31	162.99	0.30	0.77	0.80
				200	2.27	165.87	2.03	0.57	2.51
180	2.313	161.48	0.580	120	2.32	161.41	-0.30	0.40	0.28
				140	2.33	162.83	-0.61	0.47	-0.02
				160	2.31	162.61	0.22	0.34	0.80
				180	2.32	161.51	0.26	0.42	0.32
				200	2.27	166.04	2.03	0.43	2.60
190	2.290	162.78	1.612	120	2.30	163.46	-0.31	0.51	1.31
				140	2.31	164.56	-0.83	0.83	0.80
				160	2.31	162.96	-1.14	0.61	0.49
				180	2.28	163.81	0.39	0.59	2.00
				200	2.26	166.11	1.27	0.33	2.86
200	2.276	164.5	2.171	120	2.28	164.70	-0.31	0.31	1.87
				140	2.29	164.78	-0.79	0.45	1.40
				160	2.27	164.76	0.40	0.57	2.56
				180	2.27	165.07	0.35	0.60	2.51
				200	2.28	164.61	0.04	0.40	2.21

7.4.1 Comparison of mean thermal shrinkage behavior of yarn in hank and yarn in fabric due to process of heat-setting (yarn A and fabric A)

Figures 7.1 (a) and Figure 7.1(b) show comparisons between the thermal shrinkage of the length of the yarn in the hank and the shrinkage of the stitches in the fabric at different heat-setting temperatures. Although heat-setting is usually performed on fabrics, heat-setting was performed for the yarns in the hank too, to compare the thermal effects on yarn in both forms.

Thermal shrinkage of yarn in hank and yarns in fabrics due to heat-setting are presented in Figure 7.1(a) and Figure 7.1(b) respectively.



(a) (b)

Figure 7.1: Thermal shrinkage of (a) yarn in hank and (b) yarn in fabric due to heat-setting (yarn A and fabric A)

Both thermal expansions and thermal shrinkages were observed in the yarns in hank form and yarns in the fabric. The lowest heat-setting temperature, 130°C after the dyeing process is also much higher than the glass transition temperature of polyester; which is occurred between 80-100°C. Thus, the yarns in hank and fabric could undergo a glass-rubber transition that will soften the fibres and could facilitate thermal deformation. Due to the free end annealing, the yarns in the hank form are

free to change their dimensions easily. The yarn has therefore shrunk considerably, and the shrinkage is as high as 5.33% when heat-setting was performed at 200°C. There was a very small thermal expansion in the yarn heat-set at 130°C in hank form. The yarns in the fabric are subjected to tension due to external forces applied by width wise extension applied in the stenter, resulting in expansions below 160°C and thermal shrinkages at temperatures above 160°C. Although the fabric shrinkage is comparatively low, both Figures 7.1(a) and Figure 7.1(b) show that the thermal shrinkage increases as the temperature increases. The studies of Statton et al. (1970) regarding PET fibre infrared annealing treatments at elevated temperatures have shown that at higher annealing temperatures, the folding of the fibre chain is more regular and thus the thermal shrinkage will be more regular. If a fibre is free to contract, the amount of thermal shrinkage will be much greater than the one held at a constant length. Stretching may prevent refolding at low temperatures, but stretching at higher temperatures could not prevent refolding and thermal shrinkage (Statton et al., 1970).

Thermal expansion and thermal shrinkage are physically coupled to the structure, and both changes may result in structural relaxation (Riesen & Schawe, 2000). Thermal shrinkage in oriented fibres however generally superimposes the thermal expansion. The thermal expansion along the fibres have been shown to increase significantly at the glass transition temperature (glass-rubber transition) associated with large-scale micro-brownian motion of chain molecules (Choy et al., 1983).

Choy, Masayoshi and Porter (1983) too observed thermal expansion, and the effect was described as a result of the local movement of amorphous regions in small segments of molecular chains in drawn fibres. Thus, during free-end annealing, both thermal expansion and shrinkage are observed as heat effects on thermoplastic materials. The significant effect at higher temperatures is the thermal shrinkage. Although very small thermal expansion was observed on free-end yarn annealing at 130°C in the hank, the dominant effect is thermal shrinkage at higher temperatures, particularly above 160°C. The width-wise extensions at the stenter on the knitted fabric cause the knitted stitches to stretch as compared to the free end annealing of yarns in the hank form.

In these experiments, heat-setting of fabrics was performed with a width-wise extension of 5 percent and overfeed of 25% in the length direction. In commercial fabric production, width-wise extension and overfeeding are imposed in order to achieve the final finished fabric dimensions requested by the customer. Heat-setting of tensioned fabrics has caused the yarns in the fabric to stretch at low heat-setting temperature resulting in thermal expansions. Because of the external force applied to the yarns in the fabric, although the thermal energy forces the yarn to shrink, it is restricted, and a thermal expansion is observed at low heat-setting temperature. Larger thermal energy overcomes the forces of width-wise at high heat-setting temperatures and causes the yarns to shrink.

7.4.2 Thermal effects of heat-curing on the yarn in hank and yarn in fabric

Table 7.3 and Table 7.4 presents the shrinkage of the yarns in the hank A and yarn in fabric A due to heat-setting and heat-curing respectively.

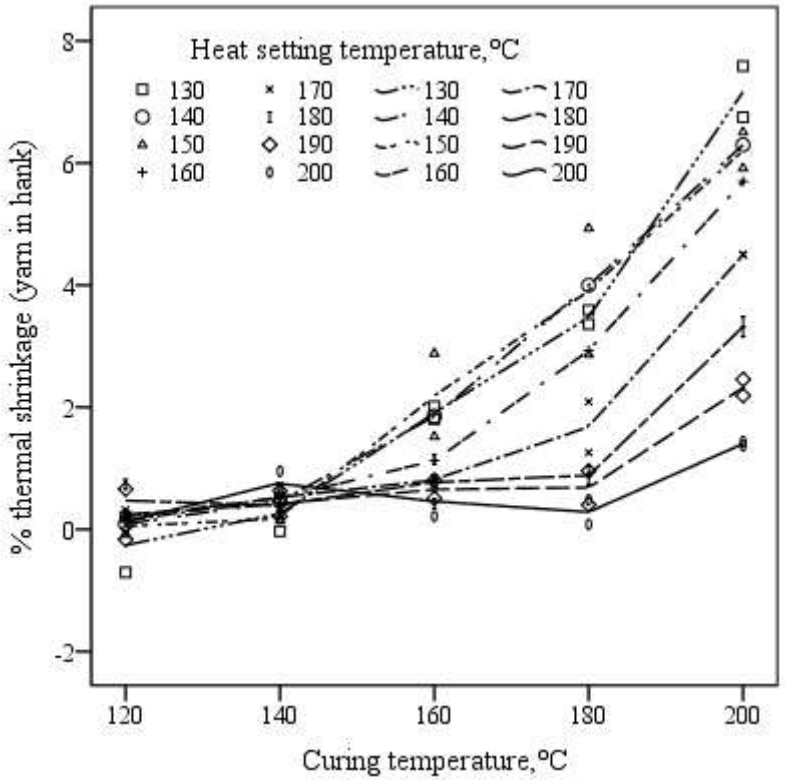


Figure 7.2 : Thermal shrinkage behavior of yarn in hank due to heat-curing (yarn A)

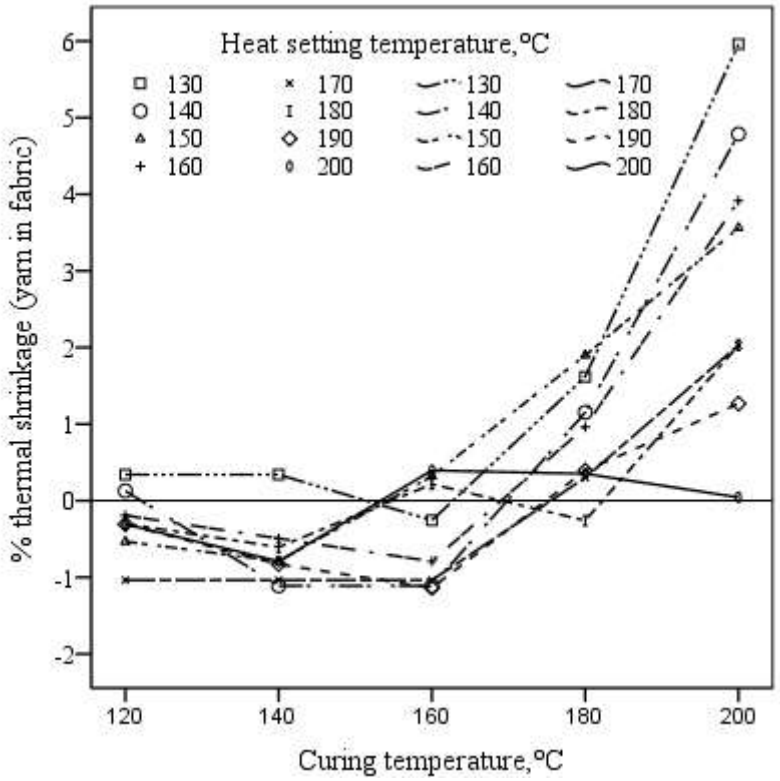


Figure 7.3 : Thermal shrinkage of behavior of yarn in fabric due to heat-curing (fabric A)

Figure 7.2 and Figure 7.3 present the thermal shrinkage behavior of yarns in hanks and yarns in fabrics for a better comparison of the thermal shrinkage behavior due to heat-curing treatment. The results revealed that the thermal shrinkage is increasing as the heat-curing temperature increases. For both the yarn in hank and yarn in fabric forms, thermal expansion is observed at low curing temperatures. The thermal shrinkages of yarn in hank, yarn in fabric and fabric panel dimensions were compared in to make a better comparison.

Before comparing the thermal shrinkage behavior of yarn in hank and yarn in fabric, it is important to check whether the resulting lengths of yarn in hank and yarn in fabric are statistically different due to curing treatment at different temperatures. The assumptions can be verified by performing analysis of variance of yarn lengths in hank and yarn in fabric subject to heat-curing. Section 7.5 describes the process of statistical analysis to verify the how significant the change of yarn lengths in hank and yarn in fabric due to curing treatment.

7.5 Statistical Analysis to Evaluate the Effect of Heat-Curing Treatment on Yarn Length in Hank and Yarns in Fabric (Yarn A and Fabric A)

Variance analysis (ANOVA) tests were conducted to evaluate the effect of heat-curing temperature on heat-cured yarn lengths in hank and yarns in fabrics. The factors are the heat-setting temperature that includes eight levels (130°C, 140°C, 150°C, 160°C, 170°C, 180°C, 190°C and 200°C) and heat-curing temperature that includes five levels (120°C,140°C,160°C,180°C and 200°C). The F-test indicates significant difference at the 95% level in length of yarn in hank and yarn in fabric (stitch length) caused by changes in factor levels.

7.5.1 Statistical analysis to assess the effect of heat-setting and heat-curing temperature on the length of yarns in hank due to curing

To verify the assumptions of ANOVA, the Levene's test and standard residual error plot were evaluated.

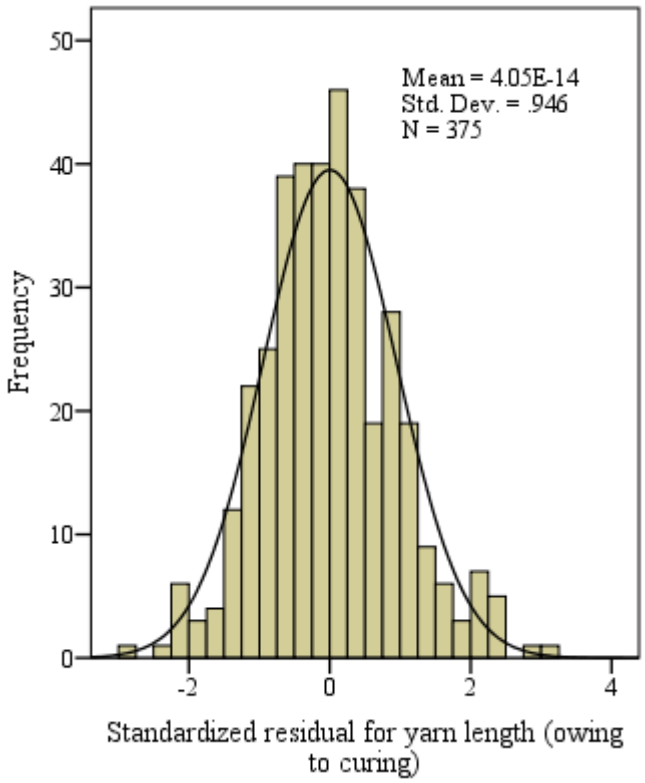


Figure 7.4 : The distribution of standardize residuals for length of heat-cured yarns in hank (yarn A)

Results of Levene's test verified that the hypothesis of homogeneity of variance reached F (39,335) =1.296, p>0.05. The residual values displayed estimated normality with a mean value close to zero and a standard deviation close to 1. The distribution of standardized residues for stitch length due to heat-curing is presented in Figure 7.4. The significance of heat-curing temperature on the change in length of yarn in hank is tested using ANOVA.

7.5.1.1 Analysis of variation (ANOVA) of yarn lengths in hank due to heat-curing

Hypothesis test 7.1 was conducted to test the significance effect of heat-curing temperatures on lengths of yarn in hank that were subject to heat-setting and subsequent heat-curing treatment. The ANOVA results are presented in Table 7.5.

Hypothesis test 7.1*: H_o: There is no significant difference between length in yarn in hank which were heat-set and heat-cured at different temperatures*

Vs *H_1: There is significant difference between lengths in yarn in hank which were heat-set and heat-cured at different temperatures*

Significance level $\alpha=0.05$

Table 7.5 : The ANOVA results to determine the overall impacts of heat-curing temperatures on yarn length of heat-set and heat-cured yarn in hank

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1516.681[a]	39	38.889	281.117	0.000
Intercept	2861103.053	1	2861103.053	20681898.18	0.000
Heat-setting temperature	445.247	7	63.607	459.790	0.000
Curing temperature	737.186	4	184.297	1331.214	0.000
Heat-setting temperature X Curing temperature	223.099	28	7.968	57.598	0.000
Error	46.343	335	0.138		
Total	3019294.900	375			
Corrected Total	1563.024	374			

a.R Squared = 0.912

The effect of heat-curing temperature on the length of yarn in hank is statistically significant at 0.05 significance level (p-value is less than 0.05). Therefore, the alternative hypothesis (H_1) is accepted. There is a significance difference between the lengths of yarn in hank which was subjected to heat-setting and heat-curing at different temperatures. Furthermore, there is a significant difference between the lengths of yarns resulted from various heat-setting and subsequent heat-curing treatments. The results revealed that heat-curing significantly caused changes in the length of the yarn in hank that ultimately resulted in thermal shrinkage as a significant difference.

7.5.2 Statistical analysis to evaluate the effect of heat-curing on the length of yarns in fabric

Figure 7.5 presents the distribution of standardized residuals of stitch lengths owing to heat-setting and subsequent heat-curing.

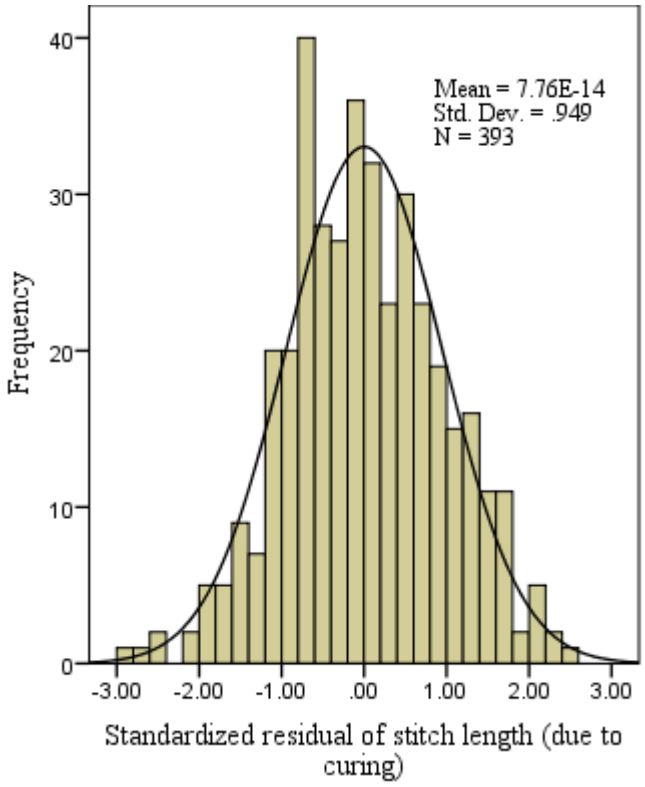


Figure 7.5 : The distribution of standardize residuals stitch lengths fabrics (fabric A)

In order to perform ANOVA, Levene's test was performed and standardized residual plot of length of yarn in heat-cured fabrics were analysed.

Results of Levene's test verify that the hypothesis of variance homogeneity resulted F (39,353) =1.365, p>0.05. The residual values displayed estimated normality with a mean value close to zero and a standard deviation close to 1.

7.5.2.1 Analysis of variance of length of yarn in fabric (stitch length) that are subjected to heat-setting and heat-curing (fabric A)

The significance of heat-setting and heat-curing temperatures on stitch lengths of heat-cured fabrics were analysed using ANOVA (Table 7.6). Hypothesis test 7.2 was performed in order to analysis the effect and significance of the heat-setting and heat-curing temperature on the length of yarn in heat-set and heat-cured fabrics (stitch length).

Hypothesis test 7.2*: H_o: There is no significant difference between the stitch lengths of fabrics that was heat-set and heat-cured at different temperatures*

Vs *H_1: There is significant difference between the stitch lengths of fabrics that was heat-set and heat-cured at different temperatures*

Significance level α=0.05

Table 7.6 : The ANOVA results to assess the overall effects of heat-setting and heat-curing temperatures on stitch lengths of heat-curing fabrics

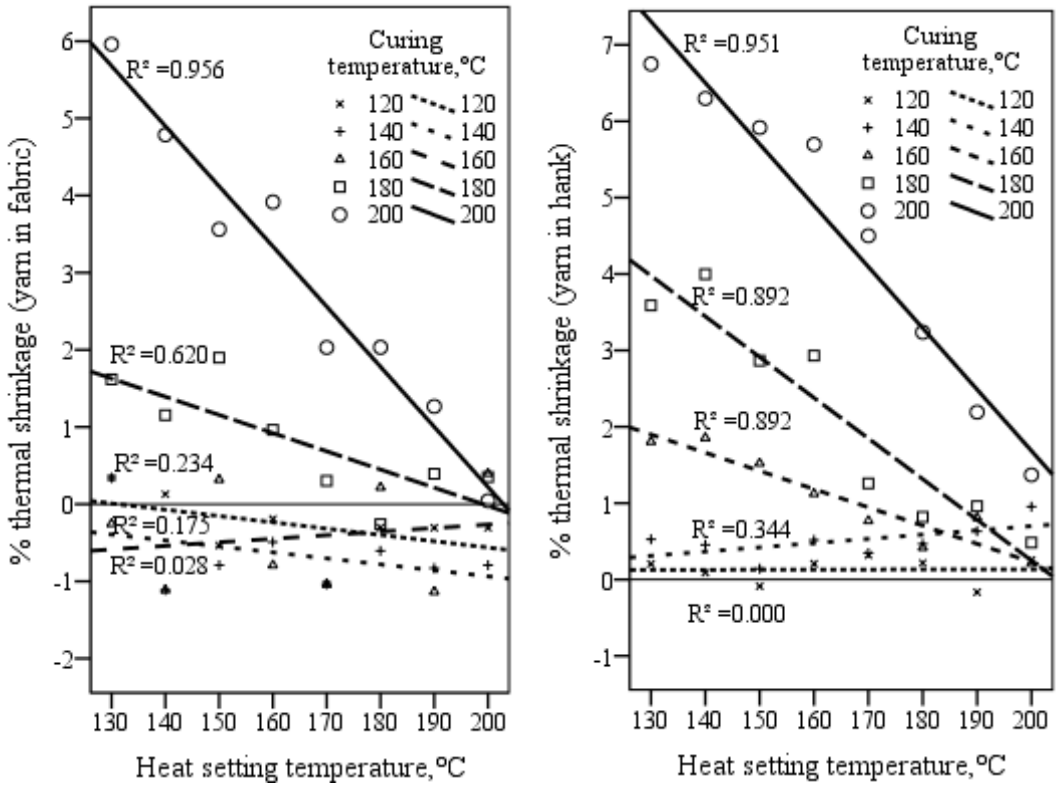
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	0.006[a]	39	0.000	93.491	0.000
Intercept	20.897	1	20.897	12889884.64	0.000
Heat-setting temperature	0.001	7	0.000	81.456	0.000
Curing temperature	0.004	4	0.001	581.269	0.000
Heat-setting temperature X Curing temperature	0.001	28	0.000043	26.536	0.000
Error	0.001	353	0.000002		
Total	20.968	393			
Corrected Total	0.006	392			

a. R Squared= 0.912

The results of the variance analysis for the stitch length showed that the effects of heat-setting temperature and heat-curing temperatures are statistically significant at 95% confident level resulting P-value is less than 0.000 (Table 7.6). The alternative hypothesis (H_1) is therefore accepted. The results revealed that the curing caused significant changes in the stitch lengths and eventually changes in the resulting thermal shrinkage values.

7.6 Comparison of Heat Treatment Effect for Yarn in Fabric and Yarn in Hank

In order to obtain a better understanding of the thermal shrinkage behavior of yarn in hank and yarn in fabric, the thermal shrinkage due to curing was compared graphically. Figure 7.6(a) and Figure 7.6(b) present the thermal shrinkage behavior of yarn in hank and yarn in fabric at different heat-setting and heat-curing temperatures respectively.



(a) (b)

Figure 7.6 : Thermal shrinkage behavior of (a) yarn in hank and (b) yarn in fabric at different heat-setting and heat-curing temperatures (yarn A and fabric A)

The data in Table 7.3 shows that, at low curing temperatures, there is no trend in thermal shrinkage due to curing of the yarns heat-set throughout the range 130°C to 200°C. In the case of fabrics, fabrics heat-set at temperatures of 150°C and 190°C and cured at 120°C, negative values (extension of yarn length) are also observed. The treatment at 140°C also does not indicate any particular trend. For the given data, the R^2 values for the fitted trend lines indicate 0.0 for the yarn cured at 120°C and 0.337 for the yarns cured at 140°C (Figure 7.6(a)). Clear trends with high R^2 values were demonstrated at 160°C and above for curing temperatures for both yarn in hank and yarn in fabric. Such results also show that the temperature of 160°C is crucial to the thermal behavior of polyester and support the findings described in Chapter 6 of the DSC analysis.

Low curing temperatures caused the yarn length in the fabric to increase (expand) but showed little or no shrinkage (Table 7.4 and Figure 7.6(b)). Further, yarn expansions are found in the fabric in contrast with the deformation of the yarn in the hank due to curing at curing temperatures 120°C and 140°C. As stated in Table 7.4 and Figure 7.6(b), the thermal deformation behavior of PET yarns below 160°C is unpredictable and could be a thermal shrinkage or an expansion.

Taut condition thermal treatment during heat-setting also leads to a greater orientation along the fibre axis in polyester (Rodriguez-Cabello et al., 1996). In amorphous areas, the high orientation reduces the distance between molecular chains and increases intermolecular cohesive forces (Wu et al., 1998). As fibre is heated during curing treatment (post heat treatments) due to high intermolecular interactions, large molecular motion may be limited, and large-scale amorphous molecules may be prevented from recoiling, resulting in limited shrinkage in subsequent heat treatments (Wu et al., 1998). However, during low heating rates, the rubber-elastic effect, which is supported by rupture of the hydrogen bonds and partial crystal melting, appears to dominate. Relaxation by breaking up of hydrogen bonds (physical links) result in intermolecular slippage. Physically, this intermolecular slip in the yarn is apparent as thermal expansion of the yarn (Trznadel & Kryszewski, 1992).

As illustrated in Figure 7.6(b), the yarns heat-set at higher temperatures show lower thermal shrinkage during the subsequent curing process. This is reflective of the thermal stability of the yarn at higher temperatures.

As shown in Figures 7.6(a) and 7.6(b), the yarn shrinkage is encouraged during the heat-setting process by increasing the temperature and making the yarn dimensions stable at higher temperature. The curing shrinkage values depend on the temperature of the heat-setting. The thermal history is therefore a determining factor for thermal shrinkage due to curing. However, the shrinkage caused at low heat-curing temperatures is very low regardless of the heat-setting temperature.

The result shows that thermal history has less impact when the curing temperature is low and the shrinkage in generally depends on the thermal history. So far, the thermal shrinkage behavior in yarn form (yarn in hank and yarn in fabric) has been discussed. Comparing and explaining the thermal deformation of yarn in hank and yarn in fabric (stitch length) due to dyeing, heat-setting and subsequent heat-curing treatments were carried out. Due to thermal treatments apart from the yarn in the knitted fabric, fabric length and width measurements can also distort. The following section 7.7 discusses the dimensional stability of the fabrics due to heat-setting and heat-curing and the relativity of yarn in hank to thermal shrink.

7.7 Effect of Heat-Setting and Post-Heat Treatments on Course and Wale Direction Thermal Deformations of Fabric A

In the textile and clothing industry, changes in fabric panel dimensions are a major concern. The knitted stitch is the construction block of any knitted fabric. The thermal deformations of constitution yarns in knitted fabric may also lead to a serious deformation of the fabric panel. Therefore, it is important to analyse the thermal shrinkage behavior, the width and length of the dimensions of the fabric in order to analyse the thermal deformation contribution of the knitted yarn to fabric dimensions.

7.7.1 Course direction (width-wise) and wale direction (length-wise) thermal shrinkage of fabric due to heat-setting (fabric A)

The fabric is deformed width-wise and lengthwise due to heat-setting at the hot air pin stenter in order to obtain the customer requested width and length measurements. The density of the wales and the courses are two parameters that give an indication of the thermal deformation of the fabric due to heat-setting. Due to the fabric extension in width direction during heat-setting (5 percent extension), the loop structure is distorted as illustrated in Figure 7.7.

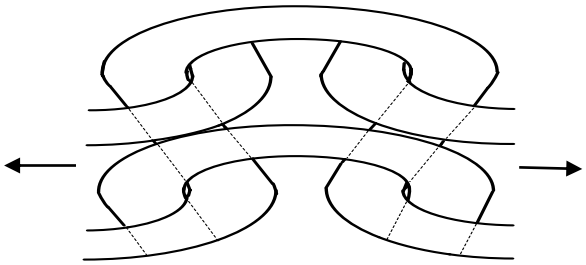


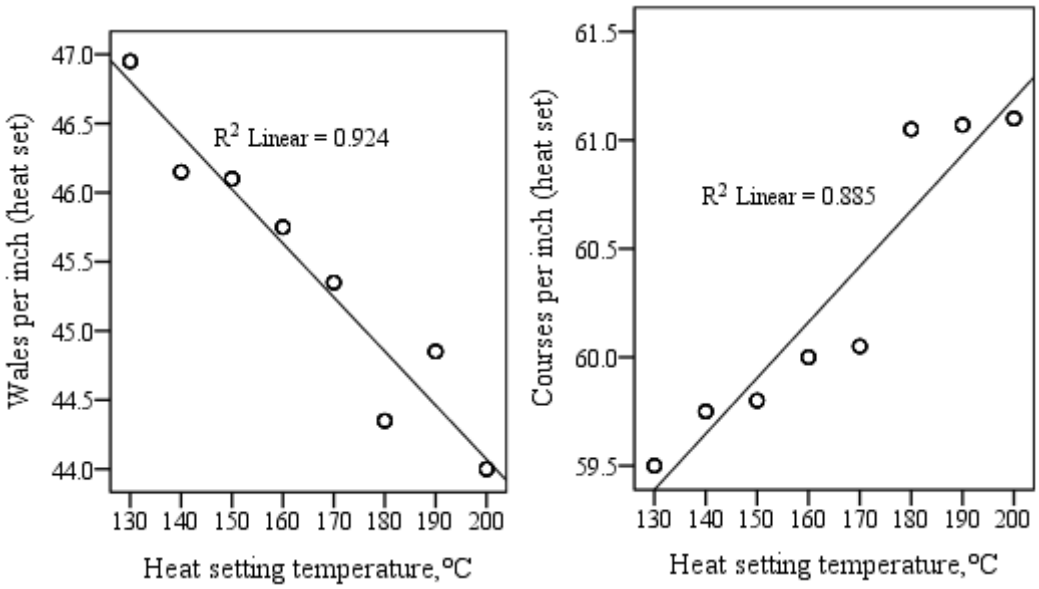
Figure 7.7 : knitted loop distortion due to width-wise extension at the stentering machine

Table 7.7 : wale density and course density of heat-set fabrics of fabric A

Fabric code	Heat-setting temperature, °C	Wales per inch (heat-set)	Courses per inch (heat-set)
A	130	46.95	59.50
A	140	46.15	59.75
A	150	46.10	59.80
A	160	45.75	60.00
A	170	45.35	60.05
A	180	44.35	61.05
A	190	44.85	61.07
A	200	44.00	61.10

Table 7.7 presents the wale and course densities resulted from heat-setting of Fabric A at different heat-setting temperatures. Since the loop is distorted by the width-wise extension in the stenter, it decreases its natural wale density and increases its course density. The tendency to increase the wale density after the release of the external force and reduction of the course density is independent of the heat-setting temperature. The fabric is extended by equal quantity (5%) for all fabrics heat-set

at different temperatures. The change in wale and course densities measured before and after heat-setting of the fabrics. Figure 7.8(a) and Figure 7.8(b) show the thermal effects on wale and course densities respectively.



(a) (b)

Figure 7.8 : Change of wale and course densities of the fabrics due to heat-setting (fabric A)

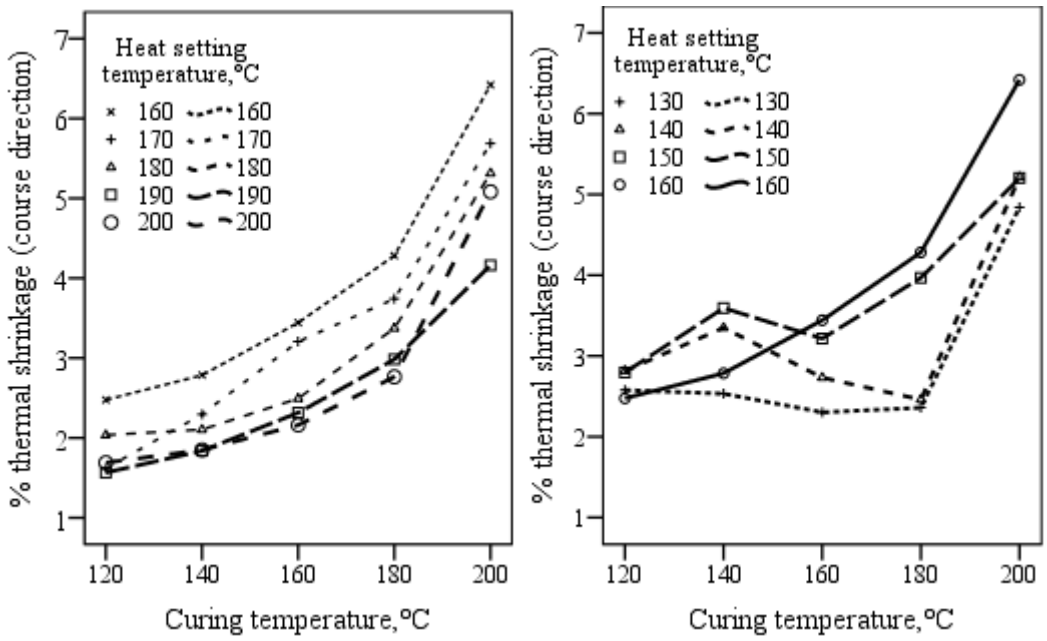
When fabrics were heat-set at 200°C, the wale density decreased by 6.3% compared to the fabric heat-set at 130°C, while the course density increased by 2.7%. These data show very clearly the significance of heat-setting temperature on the dimensional stability of knitted fabrics. The fabric heat-set at low temperatures has a better chance of shrinking and thus shows a larger shrinkage giving higher value for wale density. The heat-setting of the fabrics at 200°C makes the fabric highly stable and therefore shrinks less, showing low shrinkage resulting in lower value for wale density. Therefore, the fabrics from the extended state to the relaxed state off from the stentering machine cause the fabrics to shrink and increase their wale density.

Off the stenter, the tendency to increase the length of the fabric is high since the fabric was under widthwise extension in the stenter. If the width extension is removed, fabric tends to relax by deforming the fabric by increasing the fabric length and decreasing the fabric width.

This increase in length is more at low temperature and less at high temperature. The fabric becomes more stable at high heat-setting temperatures and the change in the length of the fabric off the stenter is lower and stabilized with higher courses per inch (Figure 7.8(b)).

7.7.2 Effect of curing temperature on width and length dimensions of fabric A

Thermal shrinkages in course direction and wale direction caused by heat-curing of heat-set fabric structures are shown in Figure 7.9 and Figure 7.10 respectively. For the purpose of clarity in interpretation, heat-set fabrics of 130°C to 160°C and 160 to 200°C are shown as two separate graphs in Figures 7.9 and 7.10 respectively.



(a) heat-setting temperature 130-160°C (b) heat-setting temperature 160-200°C

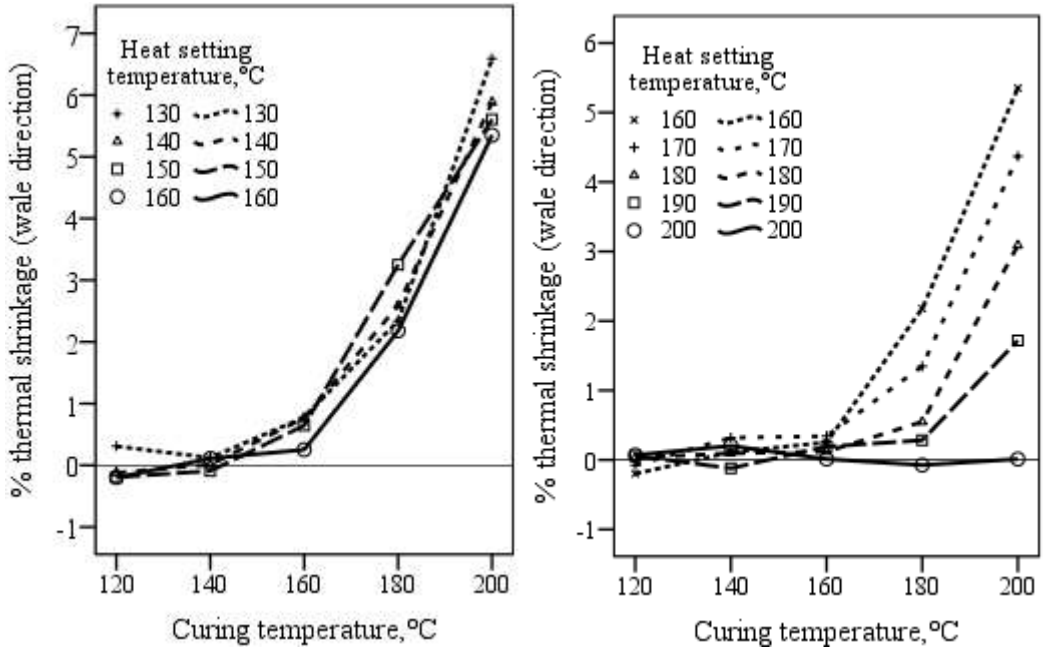
Figure 7.9 : Course direction shrinkage due to curing of heat-set fabrics (fabric A)

For the fabrics heat-set at temperatures 130°C to 160°C, for all curing temperatures, the course direction shrinkage due to curing is more than 2%. The fabrics are free to shrink during curing as no external stresses are applied to the fabrics. There was no trend is observed for the change in shrinkage due to curing at temperatures below 160°C. Analysis of the shrinkage of yarns in the fabric (discussed above section 7.4.2) also revealed ad-hoc behavior at low temperature heat-setting.

Table 7.8 : Mean thermal shrinkage percentages in course direction and wale direction due to curing treatment of fabric A

Heat-setting temperature, °C	Curing temperature, °C	Thermal shrinkage (course direction), %		Thermal shrinkage (wale direction), %	
		Mean thermal shrinkage, %	Std. Deviation	Mean thermal shrinkage, %	Std. Deviation
130	120	2.58	0.43	0.31	0.31
	140	2.53	0.33	0.12	0.66
	160	2.30	0.44	0.78	0.46
	180	2.36	0.36	2.34	0.47
	200	4.84	0.59	6.59	1.34
140	120	2.82	0.53	-0.12	0.70
	140	3.35	0.34	0.01	0.46
	160	2.73	0.48	0.77	0.66
	180	2.46	0.34	2.59	0.42
	200	5.21	0.59	5.89	0.74
150	120	2.80	0.50	-0.19	0.43
	140	3.59	0.45	-0.09	0.70
	160	3.22	0.20	0.64	0.33
	180	3.97	0.78	3.25	1.49
	200	5.20	0.80	5.61	1.00
160	120	2.48	0.48	-0.20	0.32
	140	2.79	0.77	0.11	0.65
	160	3.44	0.26	0.25	0.47
	180	4.28	0.98	2.18	0.67
	200	6.42	0.81	5.35	0.89
170	120	1.62	0.57	-0.08	0.48
	140	2.30	0.51	0.32	0.50
	160	3.21	0.25	0.34	0.46
	180	3.74	0.36	1.35	0.38
	200	5.69	0.50	4.37	0.69
180	120	2.04	0.31	0.03	0.43
	140	2.10	0.36	0.10	0.30
	160	2.49	0.34	0.12	0.40
	180	3.37	0.32	0.55	0.38
	200	5.31	0.59	3.09	0.36
190	120	1.57	0.25	0.06	0.32
	140	1.84	0.47	-0.12	0.46
	160	2.32	0.49	0.19	0.23
	180	2.98	0.62	0.28	0.46
	200	4.16	0.62	1.72	0.40
200	120	1.69	0.46	0.07	0.51
	140	1.85	0.30	0.20	0.34
	160	2.16	0.45	0.01	0.30
	180	2.77	0.72	-0.07	0.19
	200	5.08	0.64	0.01	0.48

Figure 7.9(b) shows that the shrinkage in the course direction increases with increasing curing temperatures showing a clear pattern for fabric heat-set at 160°C, 170°C, 180°C, 190°C and 200°C. These results show that 160°C is an important temperature of heat-set polyester.



(a) heat-setting temperature 130°C-160°C (b) heat-setting temperature 160°C-200°C

Figure 7.10 : Wale direction shrinkage due to curing of heat-set fabrics (fabric A)

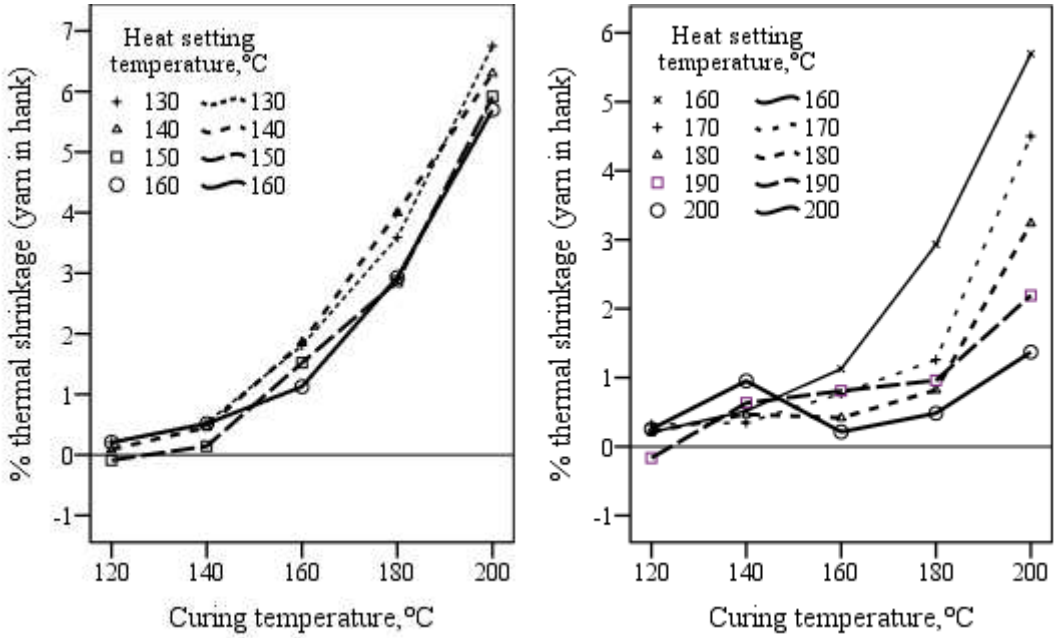
Wale direction shrinkage / expansion due to curing are very low for all fabrics below 160°C curing temperature; the thermal effect is either shrinkage or expansion up to 160°C. During heat-setting, the lengthwise compression of the fabrics is due to the extension of the width. Therefore, expansion of the wale direction during curing can be expected. However, fabric experiences extremely low shrinkage or expansion due to the effect of low heat (below 160°C). However, all fabrics shrink in wale direction beyond the curing temperature of 160°C, although a clear difference between heat-setting temperatures below 160°C is not observed.

Thermal shrinkage is observed in course direction, despite the fact that thermal expansion is logical in wale direction due to over-feed and widthwise extension. The findings reveal that the loop configuration is set at high heat-setting temperatures and

further heat causes the structures to shrink due to yarn shrinkage at high curing temperatures. In addition to curing temperatures of 160°C (Figure 7.10(b)), there is a significant reduction in the shrinkage of the wale direction with higher curing temperatures. Heat-set fabrics at high temperatures show relatively low shrinkages.

7.7.3 Comparison of the thermal shrinkage of yarn in hank and wale direction of fabric (yarn A and fabric A)

The resulting trends in the wale direction for thermal shrinkage of fabrics due to curing can be compared with the thermal shrinkage of yarns in hank due to curing (Figure 7.11). Figure 7.11(a) and Figure 7.11(b) presents the percentage of yarn in the hank form due to heat-curing (post-heat treatment); Figure 7.11(a) shows heat-setting temperature from 130°C to 160°C and Figure 7.11(b) shows heat-setting temperatures from 160°C-200°C.



(a) heat-setting temperature 130-160°C (b) heat-setting temperature 160-200°C

Figure 7.11 : Shrinkages due to heat-curing of yarns (in the hank) those have been heat-set at different temperatures (yarn A)

The shrinkage of the yarns increases with increasing curing temperature for yarns heat-set at different heat-setting temperatures. No significant difference due to heat-curing is observed in shrinkages of yarns heat-set at 130°C to 160°C, though a slight reduction in shrinkages is observed with increasing heat-setting temperature (Figure 7.11(a)). However, the shrinkages due to curing of yarns at and above 160° decrease with the increasing heat-setting temperature (Figure 7.11(b)). As discussed in the DSC analysis in the Chapter 6, Heat-setting causes the effective temperature of PET to increase. The finding of thermal shrinkage behavior of yarn revealed that the thermal deformations are significant only above the effective temperature. The results also revealed that when the effective temperature is high, the shrinkage due to a subsequent heat application is low. The graphs of Figure 7.10(a), Figure 7.10(b), Figure 7.11(a) and Figure 7.11(b) reveal that wale direction thermal shrinkage of fabric and the yarns in hank due to curing show almost identical trends.

As per the observed results, when yarns in the hank are cured at 200°C, the percentage of wale direction shrinkage values due to curing fabrics at 200°C are not significantly different from the percentage shrinkage values. This reveals that the shrinkage in yarn has caused the shrinkage in the course direction. The significance level is analyzed statistically below. Table 7.9 presents the yarn and fabric shrinkage values when curing at 200°C and the statistical analysis is presented in Table 7.10.

Table 7.9 : Percentage wale direction fabric shrinkage and percentage shrinkage of the yarn in the hank when curing is performed at 200°C (yarn A and fabric A)

Heat-setting temperature, °C	130	140	150	160	170	180	190	200
% wale direction shrinkage of fabric (curing at 200°C)	6.59	5.89	5.61	5.35	4.37	3.09	1.72	0.01
% shrinkage of the yarn in the hank (curing at 200°C)	6.75	6.3	5.92	5.7	4.5	3.24	2.19	1.37

In order to test the hypothesis that curing at 200°C has a similar effect on thermal shrinkage behavior of wale direction in fabric and the yarns in hank, one-way ANOVA was performed for each heat-setting temperature. Based on the Levene's F test, the assumption of homogeneity of variances was checked and fulfilled.

The result of Levene's test for each heat-setting temperature is presented in the Appendix A2. Hence equal variances were assumed for the analysis. Hypothesis test 7.3 was performed to evaluate the significance difference between the wale direction thermal shrinkage of yarn in fabric and yarn in hank thermal shrinkage at 200°C curing temperature.

Hypothesis test 7.3: H_o: *The mean wale direction percentage of thermal shrinkages of fabric and curing the yarn in the hank at 200°C are equal*

Vs. H_1: *The mean wale direction percentage of thermal shrinkages of fabric and curing the yarn in the hank at 200°C are not equal*

Significance level $\alpha = 0.05$

Table 7.10 : The significance values resulted from analysis of variance perform for each heat-setting temperature for wale direction thermal shrinkage of fabric and yarns in hank (yarn A and fabric A)

Heat-setting temperature°C, T	P-value
130	0.729
140	0.083
150	0.272
160	0.173
170	0.713
180	0.375
190	0.063
200	0.000

Table 7.8 shows that except at heat-setting temperature 200°C, the resulted P-value are higher than the significance level α= 0.05. This indicates that the thermal shrinkage of wale direction of fabric and yarn in hank curing at 200°C are not significantly different. This reveals that thermal shrinkages resulted due to curing has not changed significantly due to the form of yarn; either yarn in hank or yarn in knitted fabric. It is evident that the wale direction shrinkage of the fabric is highly correlated to the shrinkage behavior of the yarns in hank.

DSC results showed that the effective temperature of fabric heat-set at 200°C resulted in 198.5°C. This caused the yarns in the fabric more structurally stable thus

resulting in very low thermal deformation. The structural stability also provide evidence by resulting very low wale direction thermal shrinkages for the fabrics heat-set at 200°C and subjected to curing below or the same heat-setting temperature (Figure 7.11(b)).

7.7.4 The effect of curing temperature on area shrinkage of the fabric A

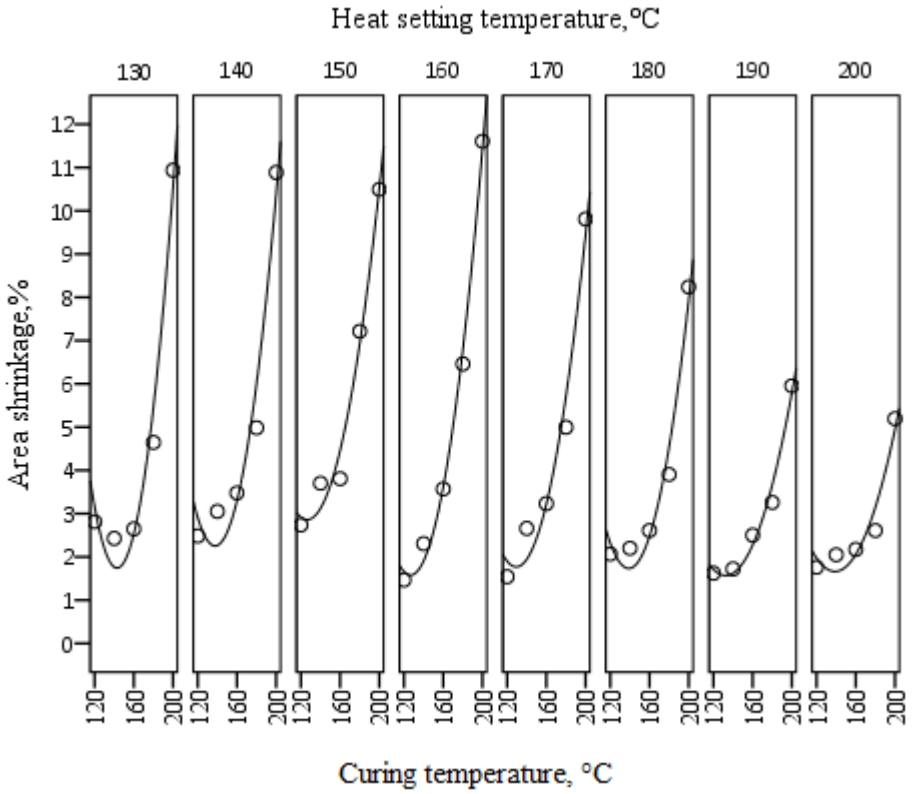


Figure 7.12 : The effect of heat-curing temperature on area shrinkage of heat-set fabrics (fabric A)

Fabrics heat-set at temperatures up to 160°C and if heat-cured at high temperature, the area shrinkage can be as high as 12%. The area shrinkage of the fabrics due to heat-curing as shown in Figure 7.12 is a good indication to the garment manufacturer to decide on heat-curing temperatures and resultant allowance that should be given during cutting of garment panels.

7.8 Thermal Shrinkage Behavior of Yarn B and Fabric B

A second polyester plain knitted fabric with different yarn and fabric parameters (yarn count 100 denier and greige fabric stitch length 2.19) to yarn A and fabric A was knitted in order to validate the thermal shrinkage behavior observed in yarn A and fabric A.

The second yarn and fabric are denoted as “yarn B” and “fabric B”. The fabric B is the same fabric B which was describes in the Chapter 6. The yarn B and fabric B also dyed, heat-set and heat-cured to examine the thermal shrinkage behaviors and to evaluate the relationship between the thermal shrinkage behavior and the yarn and fabric properties.

The process parameters and testing procedures were used for the yarn A and fabric A was adopted for dyeing, heat-setting and heat-curing processes of yarn B and fabric B.

There were no adequate 140°C and 160°C heat-set materials of fabric B available for curing because they were excessively used for the initial studies. Table 7.11 presents the yarn specifications and properties of greige and dyed fabric B.

Table 7.11 : Yarn and fabric specifications of fabric B

Fabric code	Yarn specification		Greige fabric specifications		Dyed fabric specifications	
	Count (denier)	No of filaments	stitch length (mm)	Yarn count (denier)	Stitch length (mm)	Yarn count (denier)
B	100	144	2.19	100.28	2.11	102.90

The thermal effect on yarns in hank and yarns in fabric (stitch length) due to dyeing, heat-setting and heat-curing are discussed, and a comparative analysis is presented hereafter in the following sections.

7.8.1 Thermal shrinkage behavior of yarn in hank and yarn in fabric B due to dyeing

The thermal shrinkage and change in count of yarns in hank and yarns in fabric due to the dyeing process are presented in Table 7.12.

Table 7.12 : Thermal shrinkage of yarns and the yarns in the fabric B due to dyeing (Standard deviations are indicated in square brackets)

Process status	Yarn length in hank (cm)	Yarn count in hank,(denier)	Stitch length in fabric,(mm)	Yarn count in fabric,(denier)
Before dyeing	100.12	98.70	2.19	100.28
After dyeing	92.59	106.66	2.11	102.90
Thermal shrinkage after dyeing	7.52%	8.06%	3.65%	2.61%

The yarn B decreased its length by 7.52% due to dyeing and caused the yarn count to increase by 8.06%. The yarn in fabric or stitch length decreased by 3.65% due to dyeing and caused an increase in yarn count of 2.61%. The resulting shrinkage of yarn in fabric is lower than that of yarn in hank shrinkage; similar behavior to fabric A.

7.8.2 Thermal effects of yarns in hank and yarns in fabric due to heat-setting and post heat treatment (heat-curing) Fabric B

Table 7.13 and Table 7.14 present the mean length shrinkage of yarns in hank and yarns in fabric due to different heat-setting temperatures (130, 140, 150, 160, 170, 180, 190 and 200°C) and to different post-heat treatment (heat-curing) temperatures (120, 140, 160, 180 and 200°C).

Table 7.13 : Mean length shrinkages of yarn in the hank due to heat-setting and heat-curing process and resultant yarn counts (yarn B)

Heat-setting process -Yarn				Heat-curing process-Yarn					
Heat-setting temperature (°C)	Yarn length (cm)	Count (denier)	% length shrinkage	Curing temperature (°C)	Yarn length (cm)	Count (denier)	% length shrinkage curing	Standard Deviation (shrinkage),%	Overall thermal shrinkage (from dyed yarn to curing)
130	92.27	107.52	0.35	120	92.92	107.11	-0.70	0.46	-0.36
				140	92.19	107.11	0.09	0.42	0.43
				160	90.41	109.50	2.02	0.78	2.35
				180	89.17	111.17	3.36	0.40	3.69
				200	86.10	114.75	6.69	0.63	7.01
140	92.86	106.97	-0.29	120	92.05	108.67	0.87	0.74	0.58
				140	91.56	108.62	1.41	0.56	1.12
				160	89.49	110.93	3.63	0.64	3.35
				180	89.19	112.90	3.96	0.47	3.68
				200	85.88	115.32	7.52	0.60	7.25
150	91.97	107.74	0.67	120	91.79	108.44	0.19	0.66	0.86
				140	91.59	108.36	0.41	0.82	1.08
				160	89.32	111.63	2.88	0.65	3.54
				180	88.07	114.13	4.24	0.53	4.89
				200	85.74	114.62	6.77	0.80	7.40
160	91.74	108.40	0.92	120	90.96	109.48	0.85	0.71	1.76
				140	91.26	107.97	0.53	0.71	1.44
				160	90.28	109.84	1.60	0.22	2.50
				180	89.73	110.88	2.19	0.51	3.09
				200	87.41	112.79	4.72	0.58	5.59
170	90.52	109.64	2.24	120	90.78	109.82	-0.29	0.91	1.96
				140	89.95	109.91	0.63	0.76	2.85
				160	89.76	110.17	0.84	0.52	3.06
				180	89.65	111.71	0.96	0.53	3.18
				200	86.02	113.65	4.97	0.71	7.10
180	89.97	109.99	2.83	120	89.31	110.96	0.74	0.40	3.55
				140	89.68	110.61	0.32	0.47	3.15
				160	89.88	111.52	0.10	0.38	2.93
				180	89.57	111.09	0.44	0.36	3.26
				200	86.91	112.73	3.40	0.63	6.14
190	88.75	111.42	4.15	120	88.16	111.02	0.67	0.49	4.79
				140	88.46	111.48	0.33	0.73	4.46
				160	87.96	111.88	0.89	0.56	5.00
				180	88.21	111.51	0.60	0.70	4.73
				200	86.56	113.75	2.46	0.80	6.51
200	87.04	113.65	6.00	120	87.66	112.92	-0.71	0.65	5.32
				140	86.8	114.69	0.28	0.35	6.25
				160	86.43	115.19	0.70	0.62	6.65
				180	86.83	113.7	0.25	0.42	6.23
				200	85.79	115.87	1.44	0.64	7.35

Table 7.14 : Mean thermal shrinkages of yarns in the fabric B due to heat-setting and heat-curing processes (fabric B)

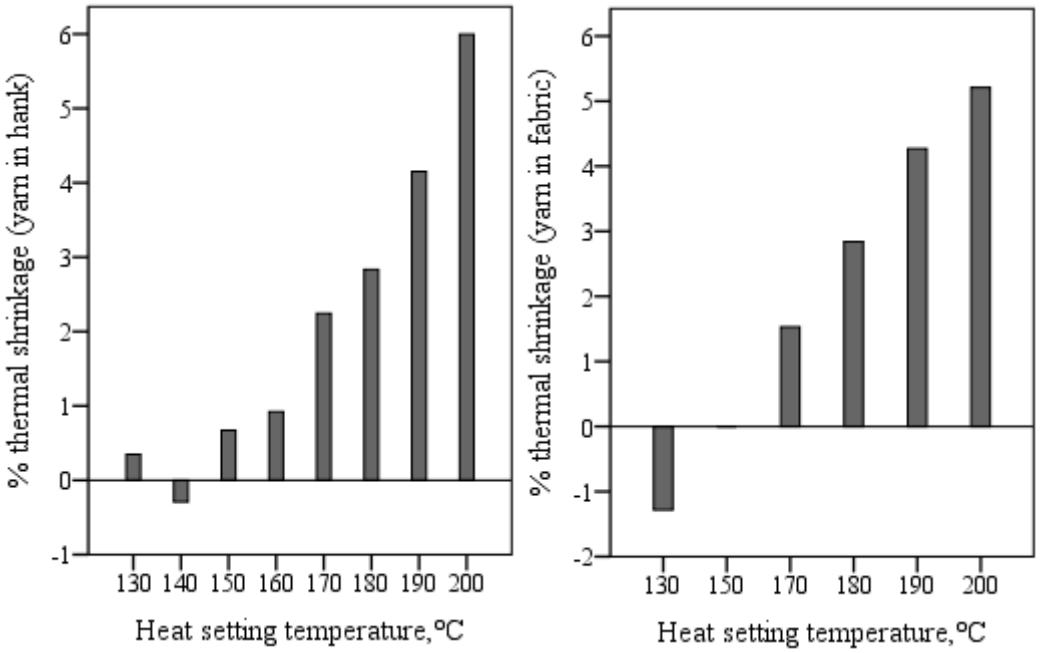
Fabric (heat-set)				Fabric (heat-cured)					Thermal shrinkage, % overall (from dyeing to curing)
Heat-setting temperature (°C)	Mean stitch length (mm)	Count (denier)	% shrinkage of yarn in fabric	Curing temperature (°C)	Mean stitch length (mm)	Count (denier)	% shrinkage of yarn in fabric	Standard Deviation (shrinkage), %	
130	2.137	101.50	-1.28	120	2.102	106.11	1.63	0.26	0.38
				140	2.097	105.47	1.87	0.31	0.62
				160	2.091	104.14	2.13	0.37	0.90
				180	2.058	107.14	3.70	0.39	2.46
				200	2.017	108.97	5.62	0.54	4.41
150	2.110	103.65	0.00	120	2.124	104.21	-0.69	0.47	-0.66
				140	2.117	103.58	-0.33	0.30	-0.33
				160	2.089	103.80	0.97	0.36	1.00
				180	2.066	106.75	2.11	0.39	2.09
				200	2.009	109.73	4.76	0.32	4.79
170	2.078	106.00	1.53	120	2.084	104.89	-0.28	0.36	1.23
				140	2.078	105.19	-0.02	0.16	1.52
				160	2.073	105.50	0.24	0.28	1.75
				180	2.057	106.24	1.00	0.57	2.51
				200	1.995	108.69	3.97	0.38	5.45
180	2.050	106.40	2.84	120	2.058	107.03	-0.41	0.20	2.46
				140	2.053	105.93	-0.14	0.37	2.70
				160	2.053	105.30	-0.15	0.54	2.70
				180	2.046	107.33	0.20	0.51	3.03
				200	1.997	108.73	2.61	0.38	5.36
190	2.020	106.80	4.27	120	2.037	107.25	-0.87	0.31	3.46
				140	2.038	108.16	-0.89	0.33	3.41
				160	2.045	108.00	-1.24	0.56	3.08
				180	2.033	107.53	-0.63	0.49	3.65
				200	1.989	108.91	1.52	0.47	5.73
200	2.000	108.18	5.21	120	2.009	108.97	-0.47	0.40	4.79
				140	2.010	110.15	-0.50	0.55	4.74
				160	2.012	110.34	-0.60	0.39	4.64
				180	2.015	108.66	-0.73	0.32	4.50
				200	1.996	109.82	0.20	0.47	5.40

7.8.2.1 Comparison of the mean thermal shrinkage behavior of yarn in hank and yarn in fabric due to the heat-setting process (yarn B and fabric B)

Both thermal expansions and thermal shrinkages are observed in the yarn in the hank form and yarns in the fabric. In the yarns in hank and yarns in the fabric, both thermal expansions and thermal shrinkages are observed.

Thermal shrinkage of yarn in hank and yarns in fabrics due to heat-setting are

presented in Figure 7.13(a) and Figure 7.13(b) respectively.



(a) (b)

Figure 7.13 : Thermal shrinkage of (a) yarn in hank and (b) yarn in fabric due to heat-setting (yarn B and fabric B)

Due to free end heat-setting, yarns in hank may change their dimensions easily. Therefore, the yarn has shrunk significantly and the shrinkage is as high as 6%. The yarn in fabric B was reduced in length than the fabric A and resulted in a thermal shrinkage of 5.21% at 200°C. Both Figures 7.13(a) and 7.13(b) show the increase in thermal shrinkage as the temperature in the heat-setting increases and that conform to the results obtained for yarn A and fabric A. The results of yarn B and fabric B also confirm that significant effect at higher temperatures of heat-setting is the thermal shrinkage. Although very small thermal expansion was observed on free-end yarn annealing at 140°C in the hank, the dominant effect is thermal shrinkage at higher temperatures, particularly above 160°C.

7.8.2.2 Comparison of thermal effects of heat-curing treatment on yarn in hank and yarn in fabric (yarn B and fabric B)

Figures 7.14 and 7.15 demonstrate the thermal shrinkage behavior of heat-set and heat-cured yarns in hank (yarn B) and yarns in fabric B.

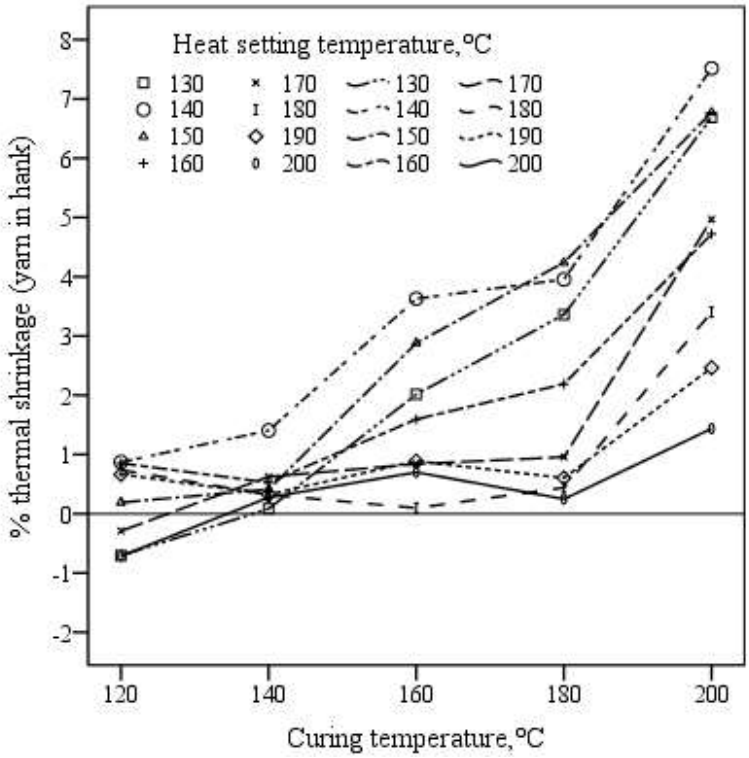


Figure 7.14 : Thermal shrinkage of yarn in hank due to heat-curing (yarn B)

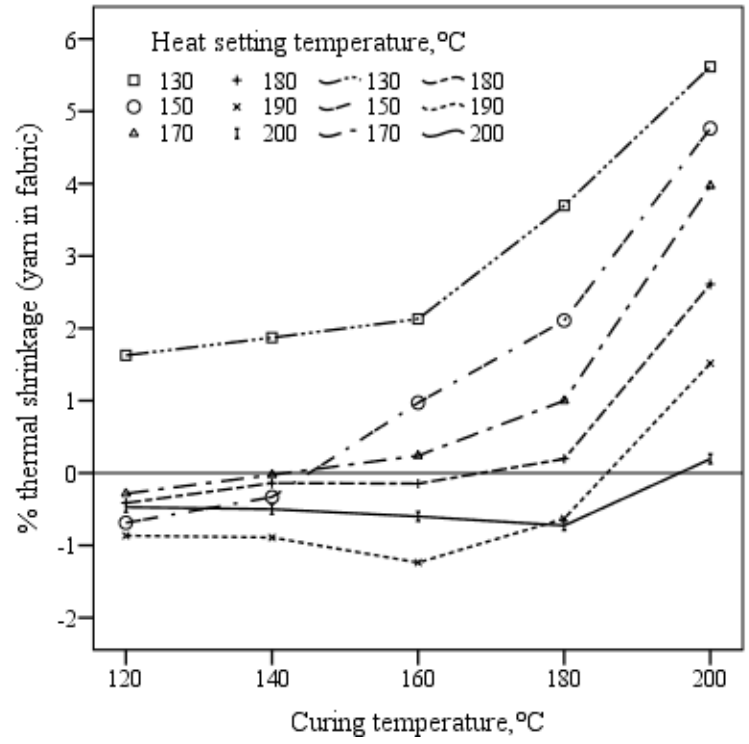


Figure 7.15 : Thermal shrinkage of yarn in fabric due to heat-curing (fabric B)

Similar increasing thermal shrinkage behavior as in yarn A and fabric A was observed for the yarn B and fabric B as well.

7.8.3 Statistical analysis to evaluate the effect of heat-setting temperature and heat-curing temperature on yarn length in hank and yarns in fabric due to curing (yarn B and fabric B)

Variance analysis (ANOVA) tests were conducted to assess the impact of heat-setting temperature and heat-curing temperature on yarn in hank and yarn in fabrics. The heat-setting temperature includes eight levels (130,140,150,160,170,180,190 and 200°C) and five levels for heat-curing temperature (120,140,160,180 and 200°C) of yarn in hank form. The heat-setting temperature includes six levels (130,150,170,180,190 and 200°C) and five levels (120,140,160,180 and 200°C) of heat-curing temperature for yarn in fabric form. The F-test shows significant differences in the length of yarn in hank and yarn in fabric (stitch length) at the 95% confidence level caused by changes in factor levels.

7.8.4 Statistical analysis to assess the effect heat-curing temperature on the length of yarns in hank (yarn B)

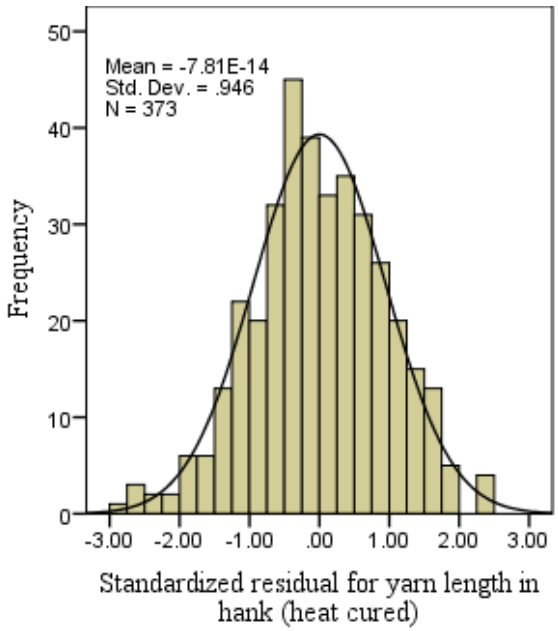


Figure 7.16 : The distribution of standardize residuals for yarn in hank (yarn B)

The Levene's test and standard residual error plot were evaluated to perform ANOVA. Results of Levene's test verify that the hypothesis of homogeneity of variance reached F (39,333) =1.423, p>0.05. The residual values showed estimated normality with an approaching zero mean value and a near1 standard deviation. Figure 7.16 shows the distribution of standardized stitch length residues due to heat-setting and subsequent heat-curing. The significance of heat-setting and heat-curing temperature on the change in yarn lengths in hank is tested using ANOVA.

7.8.5 Analysis of variation of yarn in hank due to heat-curing (yarn B)

Hypothesis test 7.4 was performed to test the significant effect of heat-setting and heat-curing temperatures on yarn lengths in hank subject to heat-setting and subsequent heat-curing treatment. Results of ANOVA test are presented in Table 7.15.

Hypothesis test 7.4*: H_o: There is no significant difference between lengths in yarns in hank which were heat-set and heat-cured at different temperatures*

Vs *H_1: There is significant difference between lengths in yarns in hank which were heat-set and heat-cured at different temperatures*

Significance level α=0.05

Table 7.15 : Results of ANOVA to determine the overall effects of heat-setting and heat-curing temperatures on heat-cured yarn in hank (yarn B)

Source	Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1500.330[a]	39	38.470	128.184	0.000
Intercept	2799098.971	1	2799098.971	9326747.067	0.000
Heat-setting temperature	385.297	7	55.042	183.404	0.000
Curing temperature	804.249	4	201.062	669.950	0.000
Heat-setting temperature X Curing temperature	231.218	28	8.258	27.515	0.000
Error	99.938	333	0.300		
Total	2958835.730	373			
Corrected Total	1600.268	372			

a. R Squared = 0.938

The effect of heat-setting and heat-curing temperature on yarn length in hank is statistically significant at a significance level of 0.05. The alternative hypothesis (H_1) is therefore accepted. There is a significant difference between the lengths of yarn in hank that has been subjected to heat-setting and heat-cured at different temperatures.

7.8.6 Statistical analysis to evaluate the effect heat-curing temperatures on the length of yarns in fabric B

In order to perform ANOVA, Levene's test was performed and standardized residual plot of length of yarn in heat-cured fabrics were analysed. Levene's test results verify that F (29,258) = 1,235, p>0.05. The residual values showed estimated normality with a near zero mean value and a near 1 standard deviation. Figure 7.17 presents the distribution of standardized stitch length residuals due to heat-setting and subsequent heat-curing.

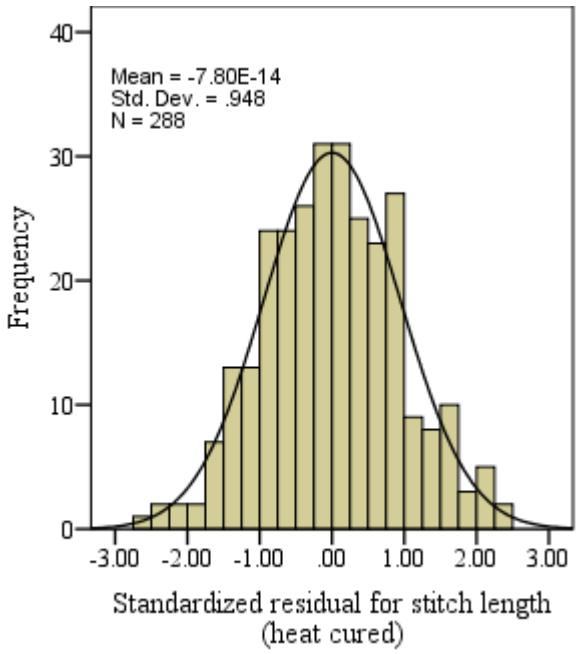


Figure 7.17 : The distribution of standardize residuals for stitch length (heat-cured fabric B)

7.8.6.1 Analysis of variance of yarn length in fabric (length of stitch) subject to heat-curing (fabric B)

Statistical analysis was performed to verify whether curing treatment caused significant change in yarn length of fabric. ANOVA (Table 7.16) has been used to analyze the significance of heat-setting and heat-curing temperatures on stitch lengths of heat-cured fabrics. Hypothesis test 7.5 was conducted to analyze the effect and significance of heat-setting and heat-curing temperature on yarn length in heat-set and heat-cured fabrics (stitch length).

Hypothesis test 7.5*: H_o: There is no significant difference between the stitch lengths of fabrics that was heat-set and heat-cured at different temperatures*

Vs *H_1: There is significant difference between the stitch lengths of fabrics that was heat-set and heat-cured at different temperatures*

Significance level α=0.05

Table 7.16 : The ANOVA findings to analyze the overall effects of heat-setting and heat-curing temperatures on stitch lengths of heat-cured fabric (yarn B and fabric B)

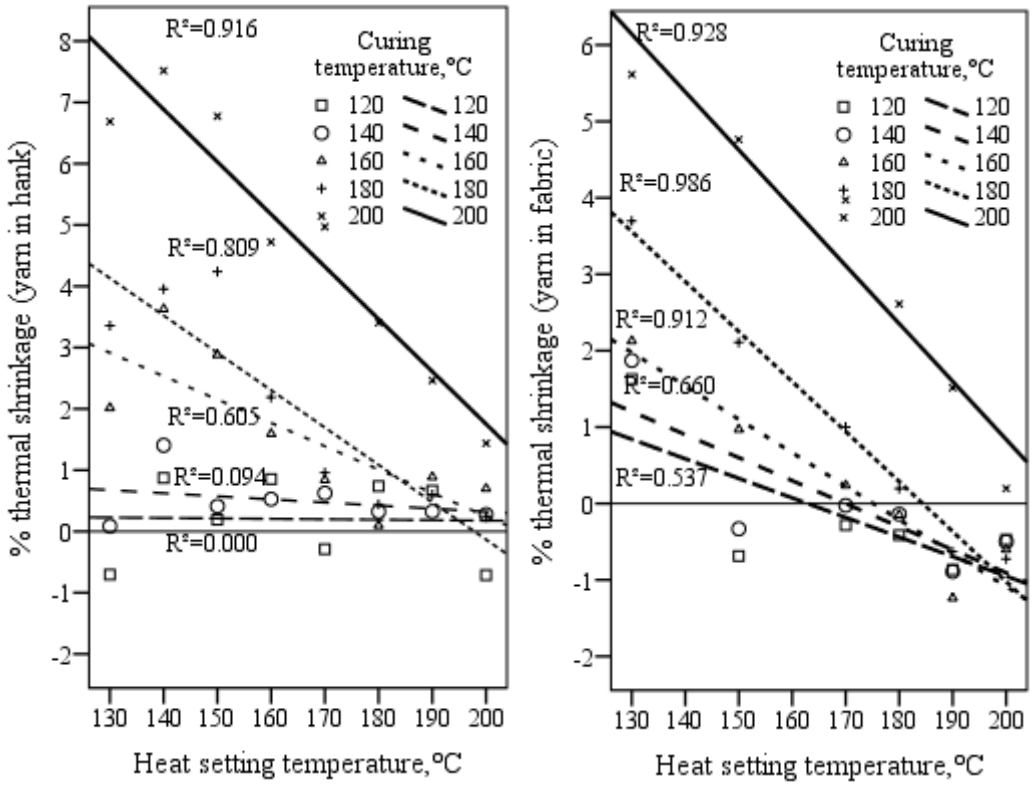
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	0.004[a]	29	0.000	206.909	0.000
Intercept	11.969	1	11.969	17278295.081	0.000
Heat-setting temperature	0.002	5	0.000	536.043	0.000
Curing temperature	0.002	4	0.000	655.177	0.000
Heat-setting temperature X Curing temperature	0.000	20	2.328E-005	33.606	0.000
Error	0.000	258	6.927E-007		
Total	12.091	288			
Corrected Total	0.004	287			

a. R Squared = .959 (Adjusted R Squared = .954)

The results of the variance analysis of stitch length revealed that the effects of heat-setting temperature and heat-curing temperatures are statistically significant at a confident level of 95% resulting in a P-value of less than 0.000 (Table 7.16).

7.9 Comparison of the Effect of Heat Treatments on Yarns in Fabric and Yarn in Hank (Yarn B and Fabric B)

Figure 7.18(a) and Figure 7.18(b) present the thermal shrinkage behavior of yarn in hank and yarn in fabric at different heat-setting and heat-curing temperatures respectively.



(a) (b)

Figure 7.18 : Thermal shrinkage behavior of (a) yarn in hank and (b) yarn in fabric at different heat-setting and heat-curing temperatures (yarn B and fabric B)

The R^2 values for the fitted trend lines are, 0.0 for the yarn cured at 120°C and 0.094 for the yarn cured at 140°C (Figure 7.18(a)). The similar behavior in yarn in hank of yarn A was observed. Clear trends with high R^2 values for curing temperatures were shown at 160°C and above. Such results also show that 160°C temperature is crucial to polyester thermal behavior and support the findings described in the DSC analysis Chapter 6. Low temperatures of curing caused the yarn length in the fabric to increase when heat-setting temperatures of the fabrics are high. This behavior is

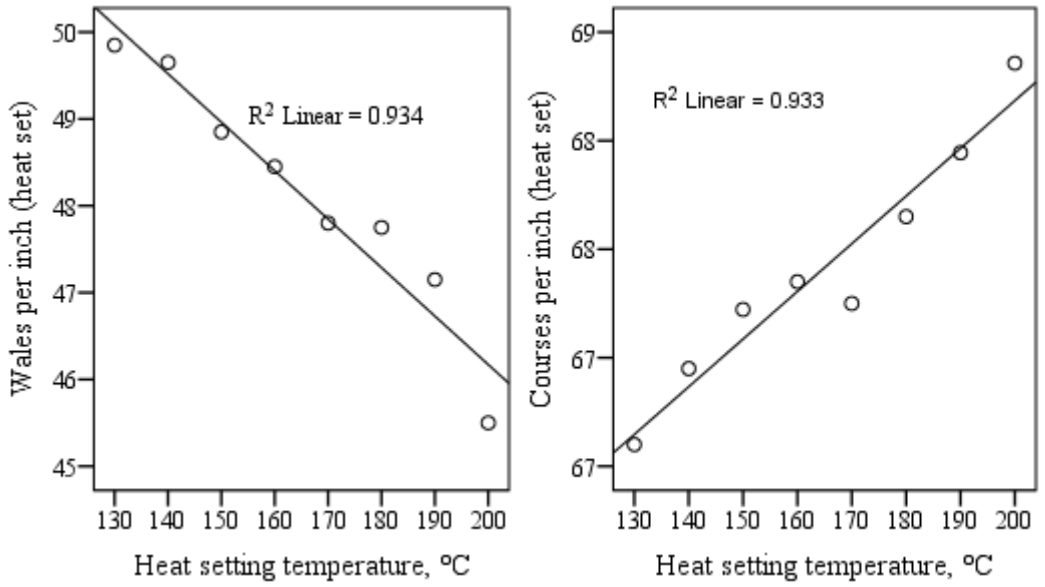
similar to the behavior of Fabric A (Table 7.14 and Figure 7.18(b)). In contrast to the deformation of the yarn in the hank due to curing, yarn expansions are found in the fabrics B as well. The thermal deformation behavior of PET yarns below 160°C, as stated above, is unpredictable and can be either a thermal shrinkage or an expansion.

7.10 Course Direction (Width-wise) and Wale Direction (Length-wise) Thermal Shrinkage of Fabric B Due to Heat-Setting

The density change measured before and after heat-setting of the fabrics of fabric B as well. Table 7.17 present wale and course densities of heat-set fabrics of fabric B.

Table 7.17 : Wale and course densities of heat-set fabrics of fabric B

Fabric code	Heat-setting temperature, °C	Wales per inch (heat-set)	Courses per inch (heat-set)
B	130	49.85	66.60
B	140	49.65	66.95
B	150	48.85	67.22
B	160	48.45	67.35
B	170	47.8	67.25
B	180	47.75	67.65
B	190	47.15	67.94
B	200	45.5	68.36



(a) (b)

Figure 7.19: Change in wale and course densities of the fabrics (fabric B)

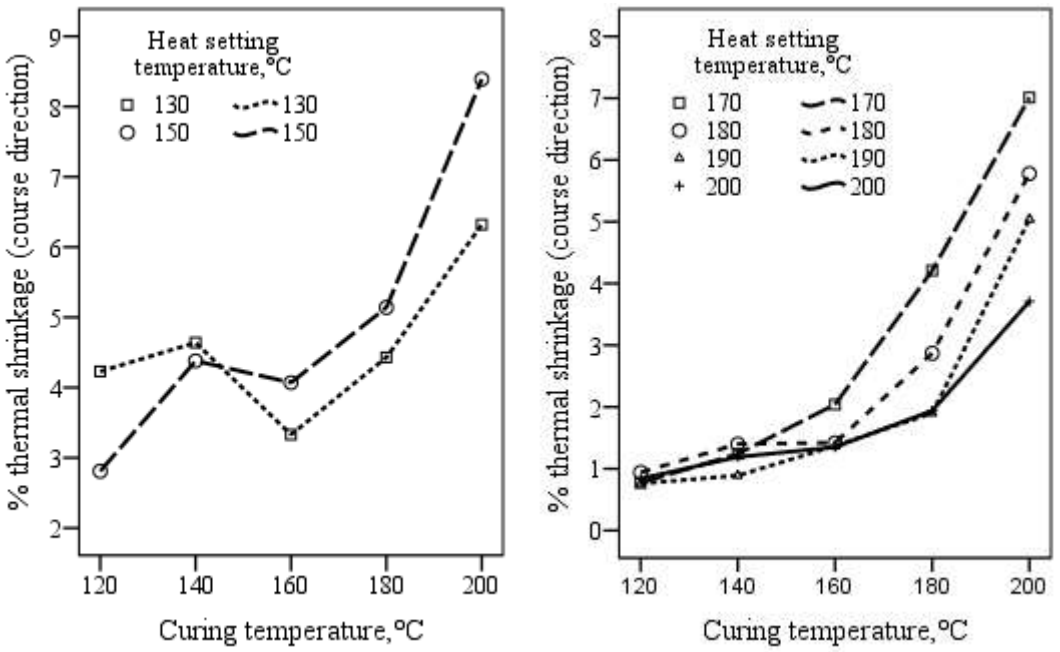
Figure 7.19(a) and Figure 7.19(b) show the thermal effects on wale and course densities respectively. When fabrics were heat-set at 200°C, the wale density decreased by 9.56% compared to the fabric heat-set at 130°C, while the density of the course increased by 2.64%. The significance of heat-setting temperature on the dimensional stability of the high heat set fabrics are shown very clearly by these data. Similar trends were observed for fabrics A as for wale and course densities of heat-set fabrics.

7.10.1 Effect of curing temperature on width and length dimensions of fabric B

Table 7.18 : Mean thermal shrinkage percentages in course direction and wale direction due to curing treatment of fabric B

Heat-setting temperature, °C	Curing temperature, °C	Thermal shrinkage (course direction), %		Thermal shrinkage (wale direction), %	
		Mean	Std. Deviation	Mean	Std. Deviation
130	120	4.23	1.10	0.36	0.89
	140	4.64	0.59	0.36	0.61
	160	3.33	0.51	1.38	0.41
	180	4.43	0.92	3.48	0.45
	200	6.32	0.98	6.03	0.77
150	120	2.81	0.33	0.88	0.26
	140	4.38	0.45	1.25	0.41
	160	4.07	0.90	2.22	0.39
	180	5.14	0.28	3.53	0.36
	200	8.39	0.17	6.53	0.23
170	120	0.77	0.26	0.58	0.26
	140	1.24	0.21	0.62	0.46
	160	2.04	0.41	1.29	0.33
	180	4.21	0.36	2.11	0.50
	200	7.01	0.46	5.31	0.74
180	120	0.94	0.32	0.06	0.44
	140	1.40	0.29	0.46	0.46
	160	1.42	0.25	0.66	0.25
	180	2.87	0.37	1.39	0.12
	200	5.78	0.58	3.97	0.78
190	120	0.76	0.28	0.40	0.23
	140	0.89	0.37	0.40	0.29
	160	1.37	0.47	0.48	0.46
	180	1.90	0.44	0.91	0.25
	200	5.04	0.63	3.18	0.34
200	120	0.84	0.32	0.31	0.32
	140	1.19	0.31	0.61	0.20
	160	1.35	0.24	0.50	0.20
	180	1.94	0.21	1.11	0.85
	200	3.71	0.26	1.85	0.79

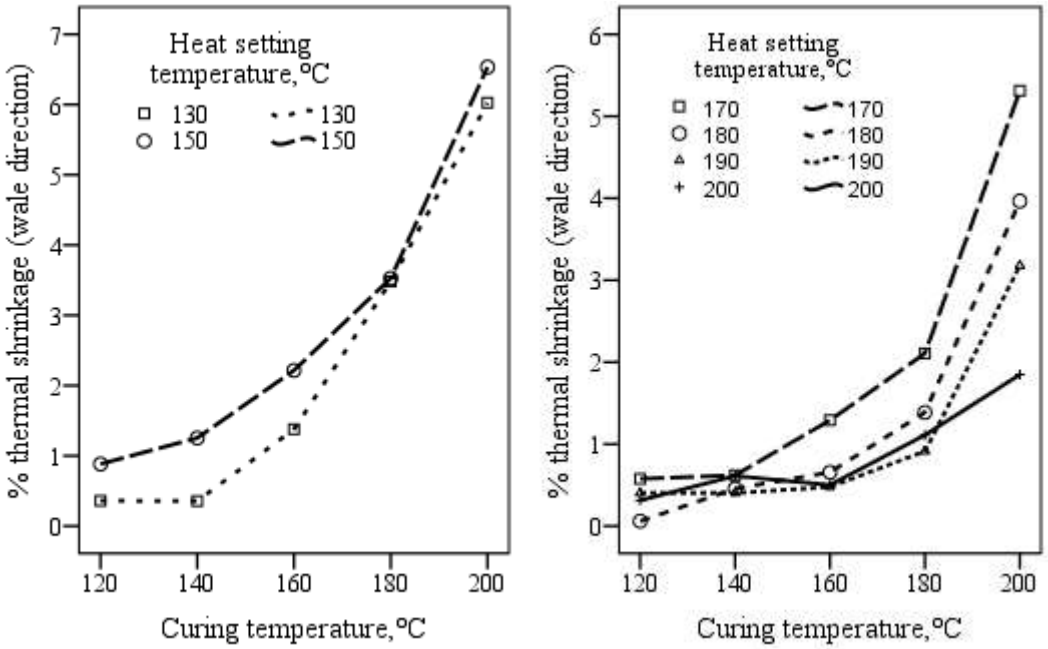
Thermal shrinkages resulted by curing treatment in course direction and wale direction of heat-set fabrics are presented in Figure 7.20 and Figure 7.21 respectively. As in fabric A, heat-set fabrics of 130°C and 150°C and 170 to 200°C are shown as two separate graphs in Figures 7.21 and 7.22 for clarity.



(a) heat-setting temperature 130°Cand 150°C (b) heat-setting temperature 170-200°C

Figure 7.20 : Course direction shrinkage due to curing of heat-set fabrics (fabric B)

As for the fabric A, the fabrics heat-set at temperatures 130°Cand 150°C, for all curing temperatures, the course direction shrinkage due to curing is more than 2%. No trend is observed for the change in shrinkage due to curing at temperatures below 170°C. Figure 7.20(b) shows that the shrinkage in the course direction increases with increasing curing temperatures showing a clear pattern for fabrics heat-set at 170°C, 180°C, 190°C and 200°C.



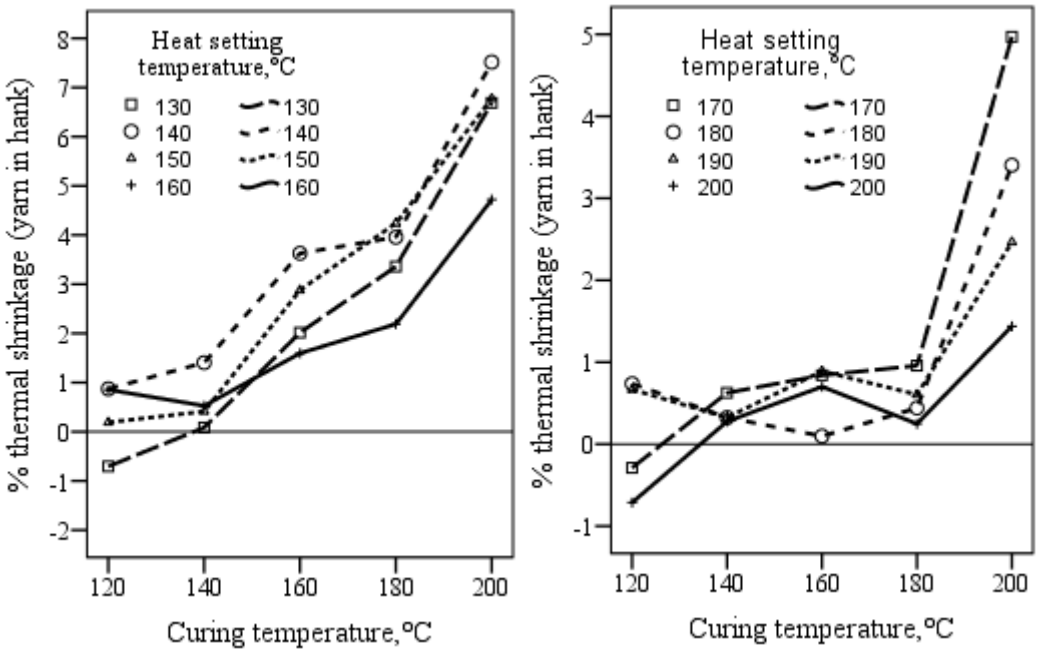
(a) heat-setting temperature 130°C and 150°C (b) heat-setting temperature 170°C to 200°C

Figure 7.21 : Wale direction shrinkage due to curing of heat-set fabrics (fabric B)

There is a significant reduction in the shrinkage of the wale direction with higher curing temperatures. Heat-set fabrics at high temperatures show relatively low shrinkages.

7.10.2 Comparison of the thermal shrinkage of yarn in hank and wale direction of fabric

As for fabric A, the resulting trends for thermal shrinkage of fabrics due to curing in the wale direction can be contrasted with the thermal shrinkage of yarns due to curing in hank (Figure 7.22). Figure 7.22(a) and Figure 7.22(b) display the percentage of yarn in the hank as a result of heat-curing (post-heat treatment); Figure 7.22(a) shows temperature setting from 130°C to 160°C and Figure 7.23(b) shows temperature setting from 160°C to 200°C.



(a) heat-setting temperature 130-160°C (b) heat-setting temperature 170-200°C

Figure 7.22 : Shrinkage due to heat-curing of the yarns (in the hank) at different temperatures (yarn B)

The shrinkage of the yarns increases with increasing curing temperature for yarns heat-set at different heat-setting temperatures. No significant difference due to heat-curing is observed in shrinkages of yarns heat-set at 130°C to 160°C, though a slight reduction in shrinkages is observed with increasing heat-setting temperature (Figure 7.22(a)).

The graphs of Figure 7.21(a), Figure 7.21(b), Figure 7.22(a) and Figure 7.22(b) reveal that the yarns in hank and wale direction thermal shrinkage of fabric due to curing show the almost identical trends as observed for yarn and fabrics A. Hence the statistical analysis is performed for yarns and fabrics of fabric B to verify the findings. Table 7.18 presents the yarn and fabric shrinkage values when curing at 200°C and the statistical analysis is presented in Table 7.19.

Table 7.19 : Percentage fabric shrinkage in wale direction and percentage shrinkage of the yarn in the hank when curing is performed at 200°C (yarn B and fabric B)

Heat-setting temperature, °C	130	150	170	180	190	200
% wale direction shrinkage of fabric (curing at 200°C)	6.02	6.53	5.31	3.97	3.18	1.85
% shrinkage of the yarn in the hank (curing at 200°C)	6.69	6.77	4.97	3.41	2.46	1.44

In order to test the hypothesis that curing at 200°C has a similar effect on thermal shrinkage behavior of wale direction in fabric and the yarns in hank, two-way ANOVA was performed for each heat-setting temperature. Based on the Levene F test, the assumption of homogeneity of variances was checked and fulfilled. Results of Levene's test verify that the hypothesis of variance homogeneity resulted F (13,137) =1.172, p>0.05. The residual values displayed estimated normality with a mean value close to zero and a standard deviation close to 1. Figure 7.23 presents the distribution of standardized residuals for thermal shrinkage percentage of wale direction of fabric and yarn in hank heat-cured at 200°C.

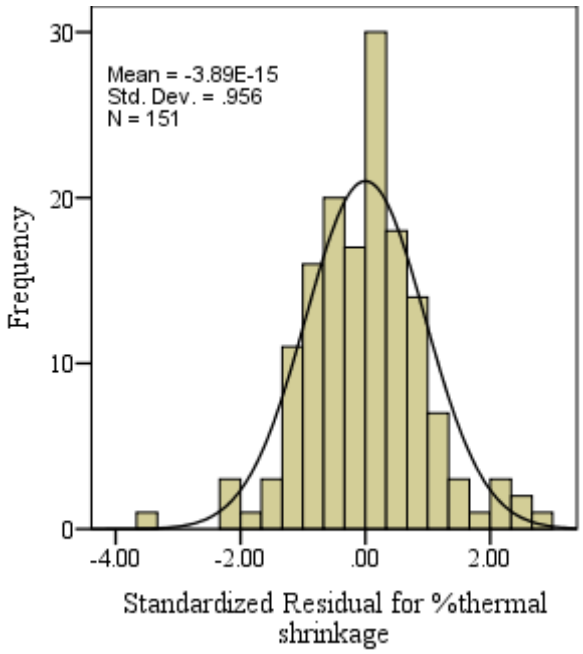


Figure 7.23 : Standardized residual for thermal shrinkage of yarns in hank and thermal shrinkage in wale direction of fabric heat-cured at 200°C (yarn B and fabric B)

Hypothesis test 7.6 was performed to evaluate the significance difference between the thermal shrinkage in wale direction of fabric and thermal shrinkage of yarn in hank at 200°C curing temperature.

Hypothesis test 7.6: *H_o: There is no significant difference between the mean percentage of thermal shrinkage in wale direction of fabric and curing the yarn in the hank at 200°C*

Vs. H_1: There is significant difference between the mean percentage of thermal shrinkage in wale direction of fabric and curing the yarn in the hank at 200°C

Significance level $\alpha = 0.05$

Table 7.20 : The analysis of variance performed for thermal shrinkage of the fabric in the wale direction and yarns in hank when heat-cured both at 200°C

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	523.961[a]	13	40.305	86.984	0.000
Intercept	3223.737	1	3223.737	6957.366	0.000
Type	1.061	1	1.061	2.290	0.132
Heat-setting temperature	503.496	7	71.928	155.233	0.000
Type X Heat-setting temperature	6.803	5	1.361	2.937	0.015
Error	63.480	137	0.463		
Total	3779.842	151			
Corrected Total	587.441	150			

a. R Squared = .892 (Adjusted R Squared = .882)

ANOVA results revealed that the “type” has no significant effect over the thermal shrinkage since the observed significant level is higher than 0.05 (p=0.132). This reveals that thermal shrinkages resulted due to curing has not changed significantly due to the form of yarn; either yarn in hank or yarn in knitted fabric. It is evident that the wale direction shrinkage of the fabric is highly correlated to the shrinkage behavior of the yarns in hank.

7.10.3 The effect of curing temperature on area shrinkage of the fabric B

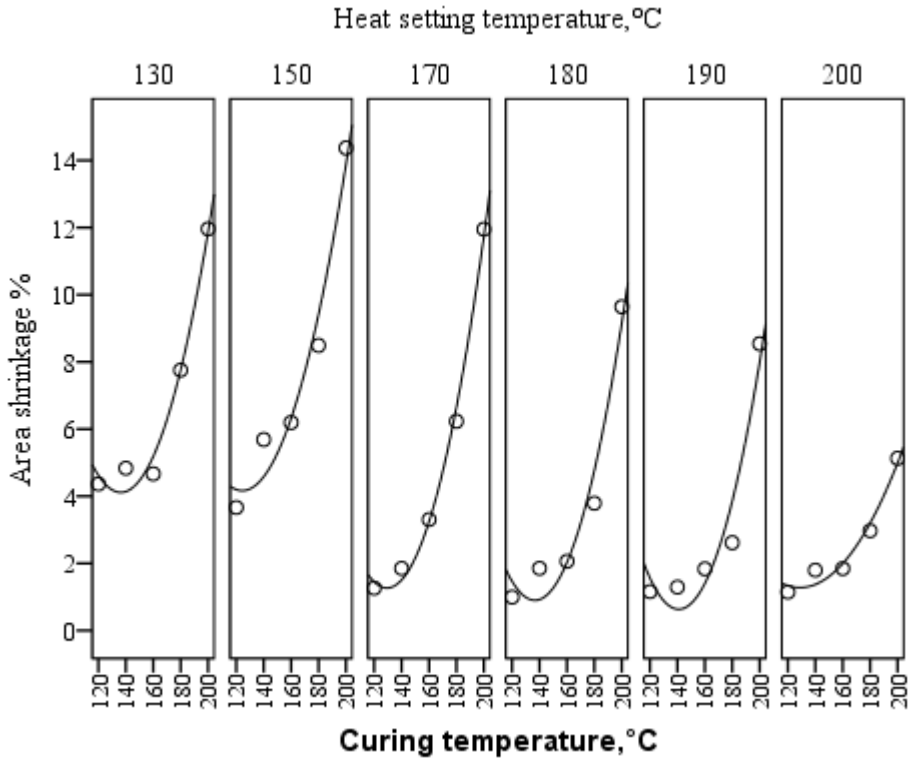


Figure 7.24 : The effect of heat-curing temperature on area shrinkage of heat-set fabrics (fabric B)

Fabrics heat-set at temperatures 130°C and 150°C and if heat-cured at high temperatures, the area shrinkage have reached as high as 14%.

7.11 Summary

This chapter focuses on the extent to which the thermal shrinking polyester yarn affects the thermal shrinkage behavior of polyester knitted fabrics and the effect of heat on fabric parameters. The thermal shrinkage behavior of polyester yarn and the plain knitted fabric made of the same yarns were analyzed after dyeing, heat-setting and subsequent heat-curing processes. The thermal effects on yarns, yarns in fabrics and wale and course densities were analyzed.

Course direction thermal shrinkage is highly associated with the width-wise extension applied during heat-setting and wale direction shrinkage is highly correlated with the yarn shrinkage behavior in hank form. Remarkable change in

polyester thermal behavior at 160°C was observed. In order to validate the results of the yarn A and fabric A, same experiments were performed for a second yarn and fabric B. The result of yarn B and fabric B also confirms the finding of yarn A and fabric A.

8 THE INFLUENCE OF OVER FEED DURING HEAT-SETTING ON THE THERMAL SHRINKAGE BEHAVIOR

8.1 Introduction

In previous chapters the effects of heat-setting temperature and heat-curing temperature on thermal shrinkage behavior was discussed. Temperature is one parameter to adjust during heat-setting and the two other important parameters are the width extension and over feed during heat-setting. The effect of percentage of over feed is discussed in this Chapter for 100% polyester knitted fabric. Heat-setting is a general practice for synthetic fabrics during fabric processing to achieve the required width measurement in the finally finished fabric. Width extension and over feed of fabric is done during heat-setting to achieve the required width measurement and to prevent extraordinary deformation of fabric due to width extension respectively. Since the over feeding is an important heat-setting parameter, the influence of the percentage of over feed during heat-setting towards the thermal shrinkage behavior of heat-set fabrics and when they were exposed to post-heat treatment processes are discussed in this chapter.

8.2 Materials and Method

Three plain knit fabrics (denoted as F_1, F_2 and F_3) with three stitch lengths (2.64mm, 2.83mm and 3.03mm) were produced on 28 gauge single jersey knitting machine using 155 denier 144 filament polyester yarns. The yarn and fabric specifications are presented in Table 8.1.

The fabrics were scoured and disperse dyed on a jet dyeing machine at 130°C. Afterwards the fabric was separated into 4 equal parts of 15m in length. Each dyed fabric was heat-set at 130°C ± 5°C for 90 seconds, which is the current industrial standard heat-setting temperature for polyester knitted fabrics. Heat-setting was done varying the over feed value as 15%,20%,25% and 30 % in industrial hot air pin stenter with 5% width extension. Heat-setting temperatures, duration and machine parameters are similar to those of commercially used values of parameters.

Heat-set fabrics were then subjected to heat-curing process. The process conditions

used were similar to those used in the industry for heat-curing process described in Chapter 4. Shrinkage in wale direction and course direction were measured on fabric samples of 30 x 30 cm^2 after subjecting to heat-curing treatment. Test samples were cut with their grainlines parallel to wales as described in Chapter 5. In order to calculate the average shrinkage or expansion percentage, the shrinkage percentage of each fabric sample was determined after being exposed to heat-curing temperature.

The heat-curing was carried out at 140°C for 5 cycles of 90 seconds in the industrial drying machine. Five specimens were subjected to heat-curing temperature and the average of the five specimens was recorded in calculating mean thermal shrinkage in the course direction and the wale direction. Fabrics subjected to standard conditioning after heat-setting and heat-curing before any measurement in accordance with ASTM D1776. Stitch length of dyed fabrics of F_1, F_2 and F_3 are denoted by L_1, L_2 and L_3 respectively. The stitch lengths of dyed fabrics are also referred to as "initial stitch lengths" for the analysis.

Table 8.1 : Yarn and fabric specifications

Fabric code	Yarn count (Denier)	No of filaments	Stitch length (greige) (mm)	Initial stitch length (dyed) (mm)
F_1	100	144	2.64	2.54
F_2	100	144	2.83	2.73
F_3	100	144	3.03	2.94

8.2.1 Measuring fabric parameters

8.2.1.1 Shrinkage of fabric due to heat-curing (post-heat treatment)

The shrinkage in the course direction and the wale direction of fabric specimens was calculated after the heat-curing treatment. Thermal shrinkage percentages, S_T is given by;

$$S_T = \frac{L_o - L_T}{L_o} \times 100\ \% \qquad (8.1)$$

Where L_o is the length between data lines marked in a particular direction before thermal application and L_T is the length between the same data lines after subjecting to the thermal application.

8.2.1.2 Wale densities (WPI), course densities (CPI) and stitch length

The stitch lengths of heat-set and heat-cured fabrics were measured and calculated as per the international standard BS EN 14970: 2006. Course and wale densities (courses per inch and wales per inch) of the fabrics were determined according to ASTM D3775-03.

8.3 Structural Analysis of Heat-set Fabrics and Heat-cured Fabrics

In order to analyze the effect of percentage of over feed over the structural parameters of heat-set and heat-cured fabrics, WPI, CPI and stitch lengths of heat-set and Heat-cured fabrics were measured. Table 8.2 demonstrates the mean values of WPI, CPI and stitch lengths of heat-set fabrics and heat-cured fabrics with regard to the initial stitch length and the percentage of over feed.

Table 8.2 : WPI, CPI and stitch lengths of heat-set fabrics and heat-cured fabrics

Initial stitch length, mm	Over feed , %	Heat-set fabrics			Heat-cured fabrics		
		WPI	CPI	Stitch length, mm	WPI	CPI	Stitch length , mm
2.54	15	38.80	52.60	2.543	41.40	57.30	2.553
	20	38.77	52.63	2.556	41.57	57.37	2.559
	25	39.00	54.13	2.554	41.87	57.65	2.545
	30	38.40	56.57	2.534	42.14	57.77	2.561
2.73	15	37.50	46.63	2.731	39.81	52.21	2.740
	20	37.43	47.54	2.734	39.08	52.50	2.755
	25	38.04	49.36	2.736	39.03	52.70	2.751
	30	37.18	50.58	2.744	39.27	52.93	2.744
2.94	15	36.50	42.63	2.955	37.03	48.53	2.949
	20	36.00	43.90	2.974	37.00	48.78	2.964
	25	36.18	45.78	2.911	37.25	48.45	2.915
	30	35.50	46.08	2.960	36.93	49.30	2.929

The mean WPI, CPI and stitch densities of heat-set and heat-cured fabrics F1, F2 and F3 at different percentages of over feed are graphically presented in Figure 8.1 and Figure 8.2. In order to identify the relationship among the parameters correlation analysis was performed. The correlation analysis carried out for independent variables (percentage of over feed and initial stitch length) and dependent variables (WPI, CPI, stitch density and stitch length) in order to provide a better interpretation of the inter-relationships.

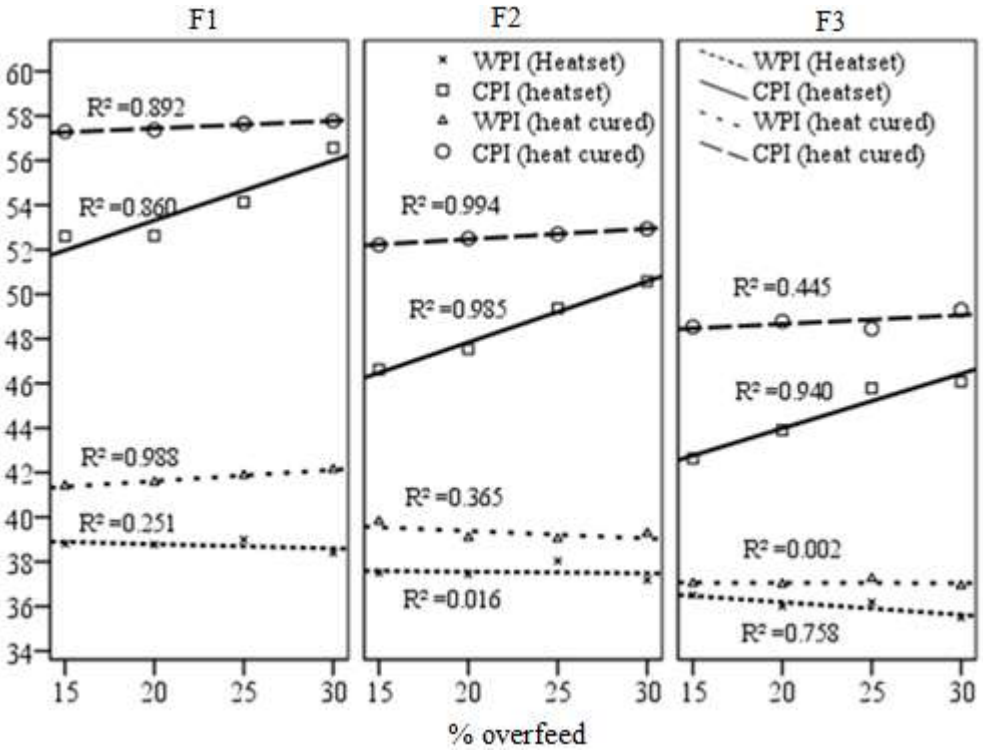


Figure 8.1: Change of WPI and CPI of heat-set fabrics and heat-cured fabrics with percentage of over feed

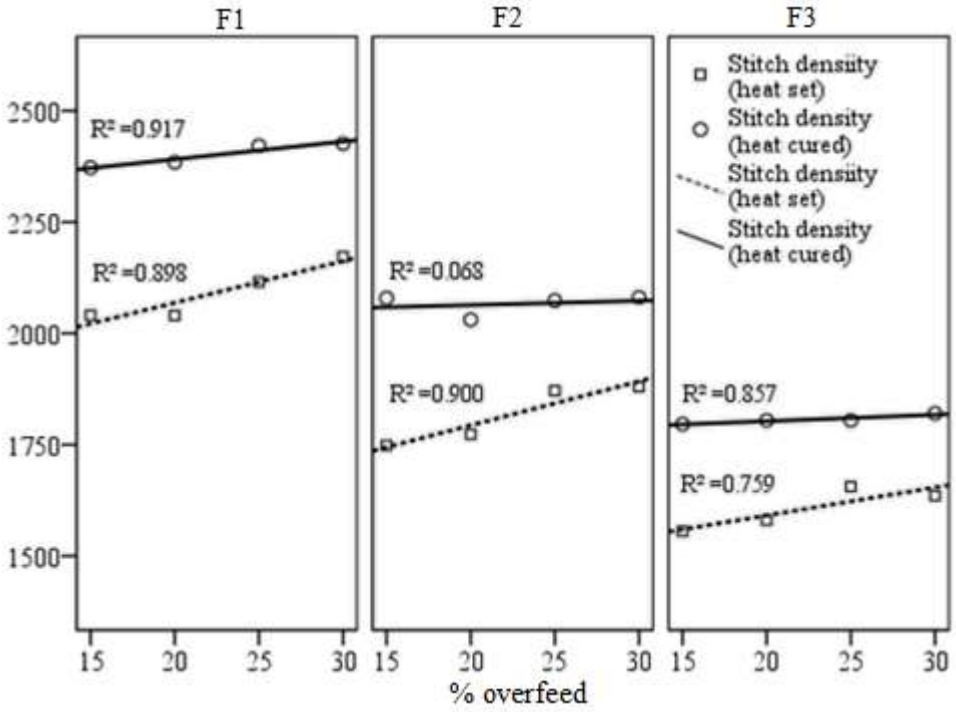


Figure 8.2 : Change of stitch densities of heat-set fabrics and heat-cured fabrics with percentage of over feed

The correlation analysis between percentage of over feed, initial stitch length and structural parameters of heat-set fabrics were discussed in the section 8.3.1.

8.3.1 Correlation analysis

For the correlation analysis of between independent variables (percentage of over feed and initial stitch length) and dependent variables (WPI, CPI, stitch density and stitch length) of heat-set fabrics were evaluated and presented in Table 8.3. Table 8.3 presents the bivariate correlation analysis between structural parameters of the heat-set fabrics (WPI, CPI, stitch length and stitch density) and independent variables (initial stitch length and percentage of over feed).

Table 8.3: Bivariate correlation analysis between heat-set fabric structural parameters (WPI, CPI, stitch length and stitch length) and independent variables (over feed and initial stitch length)

Source	Pearson correlation and significance	Over feed, %	Initial stitch length, mm
WPI (heat-set)	Pearson Correlation	-0.139	-0.826**
	Significance	0.056	0.000
CPI (heat-set)	Pearson Correlation	0.335**	-0.920**
	Significance	0.000	0.000
Stitch length (heat-set)	Pearson Correlation	-0.068	0.988**
	Significance	0.381	0.000
Stitch density (heat-set)	Pearson Correlation	0.214	-0.951
	Significance	0.004**	0.000**

**. Correlation is significant at the 0.01 level (2-tailed).

There is a weak correlation between the percentage of over feed and CPI of heat-set fabric (r=0.335) and the correlation is significant at 95% confident level. It suggests that the CPI of the heat-set fabrics is increasing as the percentage of over feed increases. Percentage of over feed does not have any significant effect on the WPI or stitch length of heat-set fabrics. The initial stitch length has a negative correlation with the WPI and CPI of heat-set fabric. The WPI and CPI of heat-set fabrics decrease as the initial stitch length increases. As the initial stitch length increases, the stitch density of heat-set fabric decreases. For a given initial stitch length, the stitch density increases as the percentage of over feed increases.

Initial stitch lengths of fabrics and percentages of over feed may effect the heat-curing treatment as well. Hence the correlation analysis among structural parameters of heat-cured fabrics, initial stitch length and percentage of over feed were also analyzed.

8.3.2 The effect of initial stitch length and percentage of over feed on structural parameters of heat-cured fabrics

Table 8.4 presents the bivariate correlation analysis of structural parameters of the heat-cured fabric (WPI, CPI, stitch length and stitch density) and independent variables (initial stitch length and percentage of over feed).

Table 8.4 : Bivariate correlation analysis among heat-set and heat-cured WPI, CPI and stitch length, percentage of over feed and initial stitch length

Sources		Over feed	Stitch length (dyed)
WPI (Heat-cured)	Pearson Correlation	0.007	-0.889**
	Significance	0.920	0.000
CPI (Heat-cured)	Pearson Correlation	0.035	-0.976**
	Significance	0.640	0.000
Stitch length (heat-cured)	Pearson Correlation	-0.078	0.990**
	Significance	0.316	0.000
stitch density (heat-cured)	Pearson correlation	0.031	-0.976
	Significance	0.682	0.000**

**. Correlation is significant at the 0.01 level (2-tailed).

As the initial stitch length of fabric increases, stitch lengths of heat-cured fabric were also increased. Stitch lengths of heat-cured fabrics have strong positive correlations with the initial stitch length (0.990). The WPI and CPI of heat-cured fabrics decrease as the initial stitch length increases and the heat-cured WPI and CPI show strong negative correlations with the initial stitch length. The significance of correlation between WPI, CPI, stitch length and stitch densities are less than 0.05, which show significant correlations. The results revealed that percentage of over feed has no significant effect on the WPI, CPI, stitch length and stitch density of heat-cured fabrics.

8.3.3 Analysis of variance of thermal shrinkage of stitch length due to heat-curing treatment

It is important to analyze whether initial stitch length and percentage of over feed have significant effect over the stitch length of heat-cured fabrics. Therefore analysis of variance test was performed refer where you present this, are you referring to text above or below. The effect of initial stitch length and percentage of over feed over thermal shrinkage behaviors of stitch length of heat-cured fabrics were analyzed using hypothesis test 8.1, hypothesis test 8.2 and Analysis of Variance test (ANOVA).

Hypothesis test 8.1: *H_0: There is no significant effect of initial stitch length in the thermal shrinkage of heat-cured fabric stitch lengths*

Vs *H_1: There is significant effect of initial stitch length in the thermal shrinkage of heat-cured fabric stitch lengths*

Significance level α=0.05

Hypothesis test 8.2: *H_0: There is no significant effect of percentage of over feed in the thermal shrinkage of heat-cured fabric stitch lengths*

Vs *H_1: There is significant effect of percentage of over feed in the thermal shrinkage of heat-cured fabric stitch lengths*

Significance level α=0.05

The ANOVA results are presented in Table 8.5. The ANOVA results revealed that the initial stitch length has significant effect over the thermal shrinkage of stitch lengths of heat-cured fabrics since the significance level is less than 0.05. Therefore the null hypothesis (H_0) was accepted in the hypothesis test 8.1. However, the effect of percentage of over feed has insignificant effect over the thermal shrinkage behavior of heat-cured fabrics with the significance value P =0.388. Therefore, alternative hypothesis (H_1) of hypothesis test 8.2 was accepted. The results demonstrate that the influence of percentage of over feed on the stitch length of the fabric specimens during curing treatment is insignificant. The different in initial stitch length has caused a significant impact on stitch length of heat-cured fabric

specimens.

Table 8.5 : Analysis of variance of thermal shrinkage of stitch length due to heat-curing

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	48.348[a]	11	4.395	7.534	0.000
Intercept	1.253	1	1.253	2.147	0.145
Initial stitch length	19.143	2	9.572	16.407	0.000
Percentage of over feed	1.773	3	0.591	1.013	0.388
Initial stitch length X Over feed	31.710	6	5.285	9.059	0.000
Error	94.510	162	0.583		
Total	145.507	174			
Corrected Total	142.858	173			

8.4 Mean Thermal Shrinkage in Course Direction and Wale Direction Due to Heat-curing Treatment

Thermal shrinkage behavior of heat-set fabric specimens when they were subjected to subsequent heat-curing treatment was analysed. The course direction and wale direction thermal shrinkages of heat-cured fabric specimens were measured. Table 8.6 presents the mean and standard deviations of the thermal shrinkage in course direction and wale direction of heat-cured fabrics.

Table 8.6 : Mean and standard deviation of thermal shrinkages in the course direction and wale direction of heat-cured fabrics

Initial stitch length, mm	Over feed, %	Thermal shrinkage (course direction), %		Thermal shrinkage (wale direction), %	
		Mean	Std. Deviation	Mean	Std. Deviation
2.54	15	3.51	0.73	8.41	1.06
	20	3.82	0.81	6.91	0.77
	25	3.68	0.69	4.72	1.15
	30	3.81	0.77	2.58	0.71
2.73	15	3.53	0.93	10.33	1.18
	20	2.49	0.59	8.59	1.12
	25	2.11	0.62	6.65	1.19
	30	3.93	0.73	4.56	0.74
2.94	15	-0.34	0.78	10.41	1.11
	20	0.00	0.73	9.80	1.07
	25	1.53	0.48	6.86	0.97
	30	1.03	1.61	6.71	1.83

8.5 Correlation Analysis of Thermal Shrinkages in the Course and Wale Direction of Heat-cured Fabrics

A better interpretation of the inter-relationship was given by the correlation analysis performed for thermal shrinkage in course direction and wale direction of heat-cured fabric specimens and independent variables; initial stitch length and percentage of over feed.

Table 8.7: Bivariate correlation analysis among variables initial stitch length, percentage of over feed, course direction thermal shrinkage and wale direction thermal shrinkage of heat-cured fabric specimens

Source		Initial stitch length	Over feed	Course direction thermal shrinkage	Wale direction Thermal shrinkage
Initial stitch length, mm	Correlation	1	-0.039	-0.783**	0.506**
	Significance		0.578	0.000	0.000
Over feed,%	Correlation	-0.039	1	0.227**	-0.756**
	Significance	0.578		0.001	0.000
Course direction thermal shrinkage, %	Correlation	-0.783**	0.227**	1	-0.570**
	Significance	0.000	0.001		0.000
Wale direction Thermal shrinkage, %	Correlation	0.506**	-0.756**	-0.570**	1
	Significance	0.000	0.000	0.000	

**. Pearson correlation is significant at the 0.01 level (2-tailed).

The correlation coefficients received from the analysis are presented in Table 8.7. An analysis of variance was performed for the thermal shrinkage in the course direction and wale direction obtained for the heat-cured specimens.

The bivariate linear relationship between the variables were considered (Table 8.7), and the results reveal that the correlation between percentage of over feed and wale direction thermal shrinkage is strong negative and significant at 95% confidence level. The results also show that the percentage of over feed has a negative effect on the thermal shrinkage in the wale direction. As the percentage of over feed increases the thermal shrinkage of the wale direction has been reduced. These results reveal that the thermal shrinkage of the wale direction increases as the stitch density of the heat-set fabric increases. The over feed has low positive correlation (r = 0.227) with

course direction thermal shrinkage. The higher percentage of over feed caused to decrease the observed thermal shrinkage in the course direction.

The initial stitch length has strong negative correlation with the thermal shrinkage in the course direction (r= -0.783). A negative strong correlation between course direction thermal shrinkage and initial stitch length revealed that as the stitch length increases the thermal shrinkage in the course direction due to post heat treatments decreases. The stitch length of the fabric before heat-set has moderate positive correlation with the thermal shrinkage in the wale direction (r= 0.506). A positive moderate correlation between the thermal shrinkage in the wale direction and initial stitch length revealed that as initial stitch length increases the thermal shrinkage in the direction due to curing is also increasing. The correlation results also revealed that as the thermal shrinkage in the wale direction increases the thermal shrinkage in the course direction decreases and vice-versa.

8.6 Multiple Linear Regression Analysis of Thermal shrinkages in the Course and Wale Directions

It was revealed that the initial stitch length and percentages of over feed are two significant factors which determined thermal shrinkage in the course direction and the wale direction. Therefore regression analysis is performed to depict the linear relationships among independent and dependent variables. The sections 8.6.2 and 8.6.3 describe the steps of multiple linear regression analysis performed for thermal shrinkage in the course direction and in the wale direction respectively.

As given in Table 8.3, stitch length of the fabric and percentages of over feed are significantly correlated with the thermal shrinkage in the thermals shrinkages of course direction and wale directions. Thus, multiple linear regression analyses was performed to establish the linear relation between the factors: thermal shrinkage of course direction, initial stitch length and percentage of over feed and the factors: thermal shrinkage of wale direction, initial stitch length and percentage of over feed. All the independent variables; the stitch length and over feeding percentage are categorical and the dependent variable, the thermal shrinkages are continuous variables. All categorical variables with sub groups could be expressed as dummy

variables for regression analysis. The dummy variable can be used as any other continuous variable in regression equation, as explained in Chapter 5, by expressing the categorical variable as a dummy variable.

8.6.1 Dummy variable recoding for categorical variables

Initial stitch length of the fabrics and percentage of over feed are two independent categorical variables which significantly affect the thermal shrinkages in the course and wale direction. There are three distinct values or subgroups in initial stitch length. Therefore, 2 dummy variables must be defined and there are four subgroups in the percentage of over feed. Therefore, it is necessary to define 3 dummy variables. The initial stitch length of fabric could thus be represented by two dummy variables: as SL_2 and SL_3.

Here;

- $SL_2 = 1$, if stitch length L_2; $SL_2 = 0$, otherwise.
- $SL_3 = 1$, if stitch length L_3; $SL_3 = 0$, otherwise.

The reference group for stitch length is SL_1.

The categorical variable percentage of over feed have 4 values 15%, 20%, 25%; Percentage of over feed hence can be represented by 3 dummy variables: OF_{20}, OF_{25} and OF_{30}.

Here;

- $OF_{20} = 1$, if percentage of over feed 20: $OF_{20} = 0$, otherwise.
- $OF_{25} = 1$, if percentage of over feed 25: $OF_{25} = 0$, otherwise.
- $OF_{30} = 1$, if percentage of over feed 30: $OF_{30} = 0$, otherwise.

For percentage of over feed, the reference group consists of 15% (OF_{15}).

8.6.2 Regression equation to express the relationship between thermal shrinkage in the course direction, initial stitch length and percentage of over feed

Using Minitab 17® statistical software, the linear relationship between continuous dependent variable (course direction thermal shrinkage) and categorical, independent variables (fabric initial stitch length and percentage of over feed) as well as their interactions with the 5% significant level were analyzed by backward elimination method.

The regression equation from the statistical analysis is shown in Equation 8.2.

Regression Equation

$$Thermal\ shrinkage\ in\ course\ direction = 3.441 + 0.0\ SL_1 - 0.690SL_2 - 3.289SL_3 + 0.0OF_{15} - 0.033\ OF_{20} + .276\ OF_{25} + 0.816\ OF_{30} \quad (8.2)$$

The fitted multiple linear regression equation revealed that initial stitch length and over feeding during heat-setting were the two significant variables to predict the course direction thermal shrinkage. The two-way interaction term has been eliminated at a 5% significant level from the backward elimination process. The fabric stitch lengths before heat-set SL_1 and percentage of over feed 15 were the reference levels and their coefficients are set to 0.

The equation 8.2 can be written as the equation 8.3.

$$Thermal\ shrinkage\ in\ course\ direction = \beta_0 + \beta_{11}SL_1 - \beta_{12}SL_2 - \beta_{13}SL_3 + \beta_{215}OF_{15} - \beta_{220}OF_{20} + \beta_{225}OF_{25} + \beta_{230}OF_{30} \quad (8.3)$$

Here the standardized regression coefficients are denoted by "β". β value measures how strongly each independent variable influences the dependent variable.

The equation 8.3 can be simplified and written as the following equation 8.4;

$$TS_{Course} = \beta_0 + \beta_{1i}SL_i + \beta_{2j}SS_j \qquad (8.4)$$

Where;

TS_{Course} : Predicted value of the course direction thermal shrinkage

β_0 : Standardized regression coefficient of the constant

β_{1i} : Standardized regression coefficient of i^{th} level of dummy variable representing initial stitch length

β_{2j} : Standardized regression coefficient of j^{th} level of dummy variable representing percentage of over feed

SL_i : The i^{th} level of dummy variable representing initial stitch length and

OF_j : The j^{th} level of dummy variable representing percentage of over feed

Stitch length has three levels (i=1, 2 and 3) and percentage of over feed has 4 levels (j=15, 20, 25 and 30). The regression coefficients of SL_1 and the regression coefficient OF_{15} were set to 0 since they are reference levels.

The multiple linear regression equation revealed that stitch length and percentages of over feed are two significant variables which predict the thermal shrinkage in the course direction. The coefficient of regression of each dummy variable is compared in analysis with the reference group.

In order to compare the coefficient of regression effect over the thermal shrinkage in the course direction, the regression coefficients are tabulated. The tables of regression coefficients show the following information: regression coefficient value, standard error of regression coefficient, a t-statistic, and the t-statistical significance and the p-value.

Table 8.8 : Regression coefficient of constant

Term	Standardized Regression Coefficient (β_0)	Standard Error of Coefficient	T-Value	P-Value	VIF
Constant	3.441	0.174	19.74	0.000	-

Table 8.9 : Regression coefficients of stitch lengths

Term	Standardized Regression Coefficient (β_{1i})	Standard Error of Coefficient	T-Value	P-Value	VIF
SL2	-0.690	0.183	-3.78	0.000	1.41
SL3	-3.289	0.169	-19.43	0.000	1.42

Table 8.10 : Regression coefficients of percentage of over feed

Term	Standardized Regression Coefficient (β_{2j})	Standard Error of Coefficient	T-Value	P-Value	VIF
OF_{20}	-0.033	0.191	-0.17	0.862	1.44
OF_{25}	0.276	0.203	1.36	0.176	1.41
OF_{30}	0.816	0.193	4.23	0.000	1.43

Tables 8.8, 8.9 and 8.10 present the regression coefficients of the constant, initial stitch length and percentage of over feed. The thermal shrinkage value was given as percentages while initial stitch length and over feed are measured in millimeters (mm) and percentage (%) respectively.

As per the regression coefficients, the p-value of percentages of over feed of 20 and 25 are not significant at 95% confidence level. When percentage of over feed is 30, over feed has effect over the thermal shrinkage in the course direction. This behavior also revealed by the correlation analysis presented in Table 8.7 by resulting weak positive correlation (0.227) between the thermal shrinkage in the course direction and the percentages of over feed.

The coefficients of the initial stitch length (β_{1i}) become more negative with increasing initial stitch length (Table 8.9). The resulting course direction thermal shrinking is therefore decreased significantly for a given percentage of over feed as the initial stitch length increases.

Further, increasing percentage of over feed increases the negative value of coefficients of over feed (β_{2j}) (Table 8.10). As the percentage of over feed increases, the resulting course direction thermal shrinkage is significantly reduced for a given initial stitch length.

It is important to confirm how well the regression equation fits the observed data. This is achieved by analyzing the multiple determination coefficients (R^2). R^2 will

be high (i.e. close to 1) when the regression equation fits the data well; and vice versa. Table 8.11 summarizes multiple determination coefficient of regression equation of course direction thermal shrinkage.

Table 8.11 : Multiple determination coefficient of regression equation of course direction thermal shrinkage

S	R-squared (R^2)	R-squared (adjusted)	R-squared(predicted)
0.996	70.82%	70.08%	69.04%

The model accounts for explaining 70.82% of the total variability of the data on course direction thermal shrinkage which depends on the initial stitch length and percentage of over feed (Table 8.11). This confirms that the regression equation fits the observed data well.

8.6.2.1 Analysis of variance to determine the significant of initial stitch length and percentage of over feed on direction thermal shrinkage

ANOVA test was conducted to compare the significance of main effect of initial stitch length and percentage of over feed of thermal shrinkage in the course direction. Analysis of variance was carried out on 202 individual observations of course direction thermal shrinkage due to heat-curing. Significant differences at the 95% level in course direction thermal shrinkages caused by changes in levels of the initial stitch length and percentages of over feed are indicated by the F-test. The adjusted sum of squares is relating to the total variance of the observations and adjusted mean square is obtained by dividing the adjusted sums of square by the respective degrees of freedom (df).

Hypothesis test 8.3 was performed and the results of the analysis of variance are presented in Table 8.12.

Hypothesis test 8.3 : *H_o: The regression equation represents the thermal shrinkage in the course direction does not fit the data well*

Vs *H_1: The regression equation represents thermal shrinkage in the course direction fits the data well*

Significance level $\alpha = 0.05$

Table 8.12 : Analyses of variance results to determine the effect of initial stitch length and percentage of over feed on course direction thermal shrinkage

Source	DF	Adjusted Sum of Squares	Adjusted Mean Squares	F-Value	P-Value
Regression	5	474.47	94.89	95.64	0.000
Initial stitch length	2	435.39	217.69	219.40	0.000
Percentage of over feed	3	24.04	8.02	8.08	0.000
Error	197	195.47	0.99		
Lack-of-fit	6	52.31	8.72	11.63	0.000
Pure Error	191	143.16	0.75		
Total	202	669.94			

The results of the analysis of variance for course thermal shrinkage in the direction are presented in Table 8.12 and the results reveal that the effect of initial stitch length and percentages of over feed are statistically significant with a p-value is less than the significance level 0.05. Therefore, the results of the analysis of variance for course direction thermal shrinkages revealed that the effect of initial stitch length and percentages of over feed are statistically significant. Further, the effect of initial stitch length on thermal shrinkage in the course direction was significant, $F(2, 202) = 219.40$, $P=0.000<0.05$. The results also show that the effect of percentage of over feed on course direction thermal shrinkage is also significant, $F(3,202) =8.08$, $P=0.000<0.05$. Due to the fact that data contains replicates (multiple observations with identical x-values), the occurrence of lack-of-fit test is significant in the ANOVA test.

8.6.2.2 Diagnostics of regression equation of the thermal shrinkage in the course direction

Regression equation diagnostics are used to assess the assumptions of equation and to investigate whether there are observations that have a significant impact on the analysis. The assumptions of linear regression are to check whether the relationship is linear. The fitness of the regression equation to data was identified by generating results of random errors, testing the familiarity of errors and percentage of errors. The resulting graphs are shown in Figure 8.3.

The normal probability plot of residuals was used to verify the assumption that the residuals (errors) are normally distributed. The residual histogram was used to determine whether the data were skewed or whether outliers were included. Symmetry has also resulted in the histogram for residuals, and the normal probability plot of errors is also a straight line. Therefore, the residuals can be considered random. The residuals versus fits plot was used to check the assumption that the residuals are distributed randomly and have constant variance.

The residuals versus the order plot were used to verify the assumption that the residuals are independent from each other. There are no trends or patterns in the independent residuals. Completing all hypotheses confirms that the equation of regression fits well with the data.

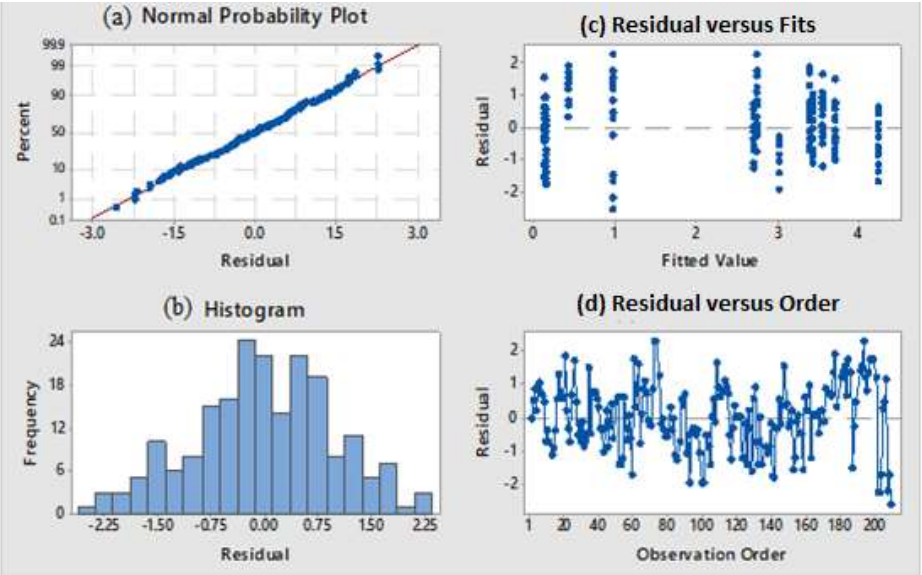


Figure 8.3 : Residual plots (a) Normal Probability plot, (b) Histogram, (c) Residual versus fits and (d) Residual versus order to verify the regression equation of course direction thermal shrinkage

8.6.3 Regression equation to express the relationship between the thermal shrinkage in the wale direction, initial stitch length and percentage of over feed

Using Minitab 17® statistical software, the linear relationship between continuous dependent variable (wale direction thermal shrinkage) and categorical, independent variables (fabric initial stitch length and percentage of over feed) as well as their interactions with the 5% significant level were analyzed by backward elimination method.

The regression equation from the statistical analysis is shown in Equation 8.5.

Regression Equation

$$Thermal\ shrinkage\ in\ wale\ direction = 8.006 + 0.0\,SL_1 + 1.868SL_2 + 2.887SL_3 + 0.0OF_{15} - 1.146OF_{20} - 3.513OF_{25} - 4.739OF_{30} \quad (8.5)$$

The fitted multiple linear regression model revealed that the initial stitch length and percentage of over feeding were the two significant variables to predict the thermal shrinkage in the wale direction. The two-way interaction term has been eliminated at a 5% significant level from the backward elimination process. The initial stitch length of the fabric before heat-set SL_1 and OF_{15} were the reference levels and their coefficients are set to 0.

The equation 8.5 can be written as the equation 8.6.

$$Thermal\ shrinkage\ in\ wale\ direction\ = \beta_3 + \beta_{41}SL_1 - \beta_{42}SL_2 - \beta_{43}SL_3 + \beta_{515}OF_{15} - \beta_{520}OF_{20} + \beta_{525}OF_{25} + \beta_{530}OF_{30} \quad (8.6)$$

Here the standardized regression coefficients are denoted by "β".

The equation 8.6 can be simplified and written as the following equation 8.7;

$$TS_{Wale} = \beta_3 + \beta_{4i}SL_i + \beta_{5j}SS_j \qquad (8.7)$$

Where;

TS_{Wale} : Predicted value of the wale direction thermal shrinkage

B_3 : Standardized regression coefficient of the constant

B_{4i} : Standardized regression coefficient of i^{th} level of dummy variable representing initial stitch length

B_{5j} : Standardized regression coefficient of j^{th} level of dummy variable representing percentage of over feed

SL_i : The i^{th} level of dummy variable representing fabric initial stitch length and

OF_j : The j^{th} level of dummy variable representing percentage over feed

The initial stitch length has three levels (i=1, 2 and 3) and percentage of over feed has 4 levels (j=15, 20, 25 and 30). The regression coefficients of SL_1 and the regression coefficient OF_{15} were set to 0 since they are reference levels.

The multiple linear regression equation on the data provides initial stitch length and percentages of over feed, two significant variables to predict a thermal shrinkage in wale direction as well. The regression coefficients were estimated in order to compare their effect of the thermal shrinkage in the wale direction.

Table 8.13 : Regression coefficient of the constant

Term	Standardized Regression Coefficient (β_3)	Standard Error of Coefficient	T-Value	P-Value	VIF
Constant	8.006	0.198	40.46	0.000	-

Table 8.14 : Regression coefficients of initial stitch lengths

Term	Standardized Regression Coefficient (β_{4i})	Standard Error of Coefficient	T-Value	P-Value	VIF
SL_2	1.868	0.207	9.02	0.000	1.42
SL_3	2.887	0.190	15.18	0.000	1.42

Table 8.15 : Regression coefficients of percentages of over feed

Term	Standardized Regression Coefficient (β_{5j})	Standard Error of Coefficient	T-Value	P-Value	VIF
OF_{20}	-1.146	0.216	-5.30	0.000	1.46
OF_{25}	-3.513	0.228	-15.40	0.000	1.43
OF_{30}	-4.739	0.219	-21.68	0.000	1.46

Table 8.14, 8.15 and 8.16 present the regression coefficients of the constant, the initial stitch length and the percentage of over feed. As per the regression coefficients, the p-value of percentages of over feed and initial stitch lengths are significant at 5% significance level.

The coefficients of initial stitch length (β_{4i}) become positive with increasing initial stitch length (Table 8.15). The resulting thermal shrinking in the wale direction is therefore increases significantly for a given percentage of over feed as the initial stitch length increases.

Furthr, increasing percentage of over feed increases the negative value of coefficients of over feed (β_{5j}). As the percentage of over feed increases, the resulting thermal shrinkage in the wale direction is significantly reduced for a given initial stitch length.

It is important to confirm how well the regression equation fits the observed data. Table 8.16 presents the multiple determination coefficient of regression equation of the thermal shrinkage in the wale direction.

Table 8.16 : Multiple determination coefficient of regression equation of the thermal shrinkage in the wale direction

S	R-squared (R^2)	R-squared (adjusted)	R-squared(predicted)
1.1294	80.89%	80.41%	79.74%

The model accounts for explaining 80.41% of the total variability of the data on the thermal shrinkage in the wale direction which depends on the initial stitch length and the percentage of over feed (Table 8.16). This confirms that the regression equation fits the data well.

8.6.3.1 Analysis of variance to determine the significant of initial stitch length and percentage of over feed on wale direction thermal shrinkage

ANOVA test was conducted to compare the significance of main effect of the initial stitch length and the percentage of over feed on the thermal shrinkage in the wale direction . Analysis of variance was carried out on 202 individual observations of the thermal shrinkage in the wale direction due to heat-curing. Significant differences at the 95% level in wale direction thermal shrinkages caused by changes in levels of the initial stitch length and percentages of over feed are indicated by the F-test.

The hypothesis test 8.4 and the results of the analysis of variance are presented in Table 8.17.

Hypothesis test 8.4: H_o*: The regression equation represents the thermal shrinkages in the wale direction does not fit the data well*

Vs H_1*: The regression equation represents the thermal shrinkages in the wale direction fits the data well*

Significance level $\alpha = 0.05$

Table 8.17 : Analyses of variance results to determine the effect of initial stitch length and percentage of over feed on the thermal shrinkage in wale direction

Source	DF	Adjusted Sum of Squares	Adjusted Mean Squares	F-Value	P-Value
Regression	5	1079.92	215.99	169.31	0.000
Initial stitch length	2	295.27	147.64	115.73	0.000
Percentage of over feed	3	735.00	245.00	192.06	0.000
Error	200	255.13	1.28		
Lack-of-fit	6	45.97	7.66	7.11	0.000
Pure Error	194	209.16	1.08		
Total	205	1335.06			

The results of the analysis of variance for the thermal shrinkages in the wale direction are presented in Table 8.17 and the results reveal that the effect of initial stitch length and percentages of over feed are statistically significant with a p-value less than 0.05.

Further, the effect of initial stitch length on the thermal shrinkage in the wale direction was significant, F (2, 205) = 115.73, P=0.000< α = 0.05. The results also show that the effect of percentage of over feed on the thermal shrinkage in the wale direction is significant, F (3,205) =192.06, P=0.000< α = 0.05.

8.6.3.2 Diagnostics of regression equation represent the thermal shrinkages in the wale direction

The fitness of the regression equation to data was identified by generating results of random errors, testing the familiarity of errors and percentage of errors. The resulting graphs are shown in Figure 8.4. Symmetry has also resulted in the histogram for residuals, and the normal probability plot of errors is also a straight line. Therefore, the residuals can be considered random. There are no trends or patterns in the independent residuals. Completing all hypotheses confirm that the equation of regression fits well with the data.

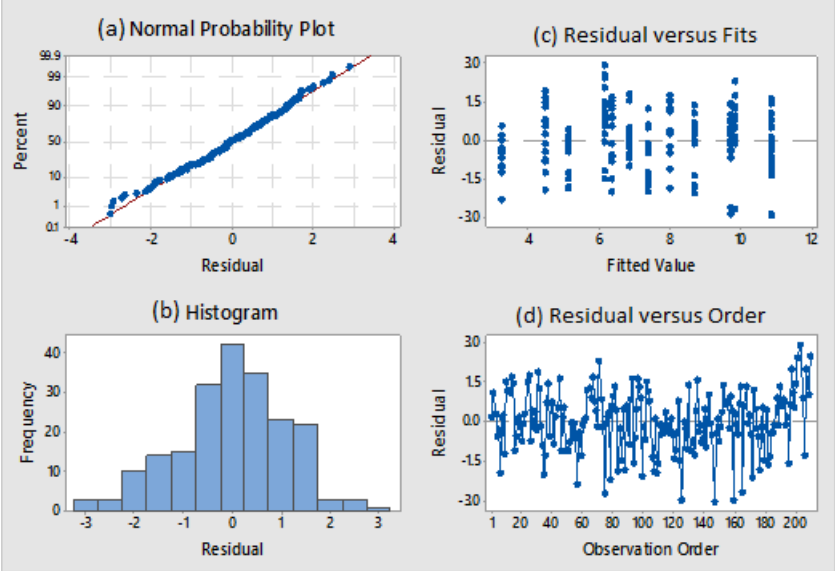
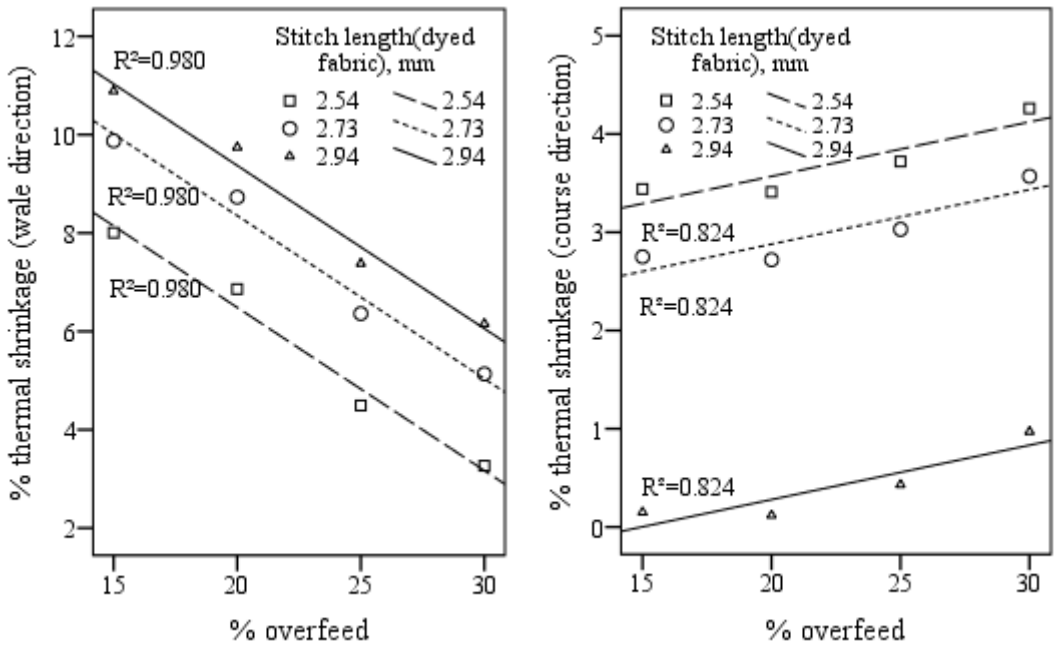


Figure 8.4 : Residual plots (a) Normal Probability plot, (b) Histogram, (c) Residual versus fits and (d) Residual versus order to verify the regression equation of the thermal shrinkage in the wale direction

8.7 Thermal Shrinkage Behavior of Heat-cured Fabrics in the Course and Wale Directions

Estimated thermal shrinkages in the course direction and wale direction derived from the regression equations are presented Figure 8.5.



(a) (b)

Figure 8.5 : Estimated thermal shrinkages in the (a) wale direction and (b) course direction derived from the regression equations

The regression equation represent the thermal shrinkage in the wale direction shows a strong relationship (R-squared is 80.89%) with the initial stitch length and over feed than the regression equation which represent the thermal shrinkage in the course direction (R-squared is 70.82%).

As per the estimated regression values, as initial stitch length increases the thermal shrinkage in the wale direction increases and as percentage of over feed increases the thermal shrinkage in the wale direction decreases. As the initial stitch length increases, the thermal shrinkage in the course direction decreases and the thermal shrinkage in the wale direction increases [Figure 8.5 (a)]. Considering the strcural

parameter of the heat-set fabric and heat-cured fabric samples thermal shrinkage behavior of heat-cured fabrics can be analyzed.

As the percentage of over feed increases, CPI rises in the amount of heat-set fabrics (Table 8.2). The thermal shrinkage in the wale direction has decreased as the amount of over feed increases. Higher stitch density resulted in higher thermal shrinkage of the wale direction.

Two parameters of the knitted loop may determine the the thermal deformation of plain knitted fabrics. One is dimensional change due to loop shape change without significant change in loop length and the other is dimensional change due to loop length change (Choi & Lo, 2003). The ANOVA results revealed that the initial stitch lengths of heat-cured fabrics are significantly different. The contraction in the height of the knitted loop will reach a value that may increase the width of the knitted loop as the length of the yarn in the knitted loop does not change substantially. This condition can result in more thermal shrinkage in the wale direction than thermal shrinkage in the course direction as seen in this study (Ucar & Ertugrul, 2002).

During knitting, the spacing of the wale depends largely on the needle spacing on the machine as the yarn has to pass through the needles. The fabric take-down roller tends to pull and take the extra yarn in the direction of the length of the fabric when the length of the loop increases while the spacing of the wale remains more or less the same as the spacing of the machine. This extra length in the direction of the length causes the CPI in the fabric to be reduced in the length of the stitch. The knitted stitch tends to retain its minimum energy level without constraints during recovery and has resulted in the structure of the fabric to include the freedom for the loop to bend out of the fabric panel and result in a wavy loop as described by Choi (2003). The increased course spacing in fabrics with larger initial stitch lengths facilitates this process. However, increasing over feed in the heat-set fabric has led to an increase in the CPI and a reduction in the course spacing in the fabric with higher percentages of over feed. Increased spacing of the course allows the fabric to shrink and increase the thermal shrinkage in the wale direction. If the spacing of the course decreases, the thermal shrinkage of the wale direction may decrease. Therefore, decreasing thermal shrinkage in the wale direction will lead to a given

initial stitch length as the percentage of overfeed increases. As the initial stitch length increases, the increased course spacing with increased initial stitch length cause the thermal shrinkage of the wale direction to increase.

Choi (2006) showed that the loops are shorter and wider in shape in wet-relaxed condition compared to dry-relaxed condition. Knitted fabrics are also subjected to relaxation process during heat-curing treatment by reducing the stress and strains incurred in previous heat treatments (Bhatt & Bell, 1976; Trznadel, Pakuła, & Kryszewski, 1988). There is a strong negative correlation between increasing initial stitch length and CPI. The CPI of heat-set fabric decreases as initial stitch length increases. This increases the spacing of the course and increases the thermal shrinkage in the wale direction. Thermal shrinkage of the wale direction causes the stitch to be shorter and wider (Choi & Lo, 2006). This can cause the thermal shrinkage in the course direction to decrease as the length of the stitch increases. Increased percentage of over feeds caused the CPI to increase and the spacing between courses to be decreased. This behavior is revealed as the percentage of overfeed increases thermal shrinkage in the wale direction decreases. This may result in increased thermal shrinkage in the course direction as the percentage of over feed increases.

Table 8.18 : Bivariate correlation analysis between stitch density of heat-set fabric, thermal shrinkage in the course direction and the thermal shrinkage in the wale direction

Source		course direction thermal shrinkage	Wale direction thermal shrinkage
Stitch density (heat-set)	Pearson correlation	0.771	-0.653
	Significance	0.000**	0.000**

**. Correlation is significant at the 0.01 level (2-tailed).

As shown in Table 8.18, when comparing the correlations between thermal shrinkage of heat-cured and stitch density of heat-set fabrics, the thermal shrinkage in course direction of heat-cured fabric has a strong positive correlation with stitch density of heat-set fabrics. Correlation analysis also shows that the correlation between the percentages of over feeds and the thermal shrinkage in the course direction is weak

positive. These results show that, as stitch density of heat-set fabric increases, thermal shrinkage in the course direction decreases. The thermal shrinkage in the wale direction has a moderate negative correlation with the stitch densities of the heat-cured fabrics. It indicates that the thermal shrinkage in the wale direction during subsequent heat treatments increases as the stitch density of the heat-set fabric increases.

8.8 Summary

This study was conducted to investigate the influence of the percentage of over feed during heat-setting towards the thermal shrinkage behavior of heat-set fabrics when they were exposed to post heat treatment processes. Three polyester plain knitted fabrics with different initial stitch lengths were subjected to 15%, 20%, 25% and 30% over feed during heat-setting at 130°C. These fabrics were exposed to heat-curing at 140°C (which is the heat curing temperature use by the garment industry) and thermal shrinkage values and structural analysis were done and the data was statistically analysed. The results revealed that percentage of over feed has strong positive correlation with the courses per inch of the heat-set fabrics and there is no significant correlation between the wale per inch and the initial stitch length of the heat-set fabrics.

From the multiple linear regression equations, the initial stitch length and the over feed are identified as the two significant variables to predict the thermal shrinkages in the course direction and wale direction due to curing. The decreasing stitch density and increasing initial stitch length increase the thermal shrinkage in the course direction while reduce the thermal shrinkage in the wale direction. Results also revealed that the thermal shrinkage in the course direction and the thermal shrinkage in the wale direction are negatively correlated at 95% significant level.

9 THERMAL SHRINKAGE BEHAVIOR OF POLYESTER /ELASTOMERIC PLAIN KNITTED FABRICS

9.1 Introduction

The use of co-knitting of elastomeric yarns such as Spandex and other natural or synthetic yarns are increasing due to the excellent stretch and recovery properties delivered by the elastomeric yarns. Before the dyeing process, polyester/spandex knitted fabrics are usually subjected to pre-heat-setting treatment for uniform stabilization of the spandex yarn across the fabric. The dyed polyester / spandex fabric are then subjected to the final heat-setting process to achieve the width and weight measurement requested by the customer.

In the previous chapters from 4 to 8, the thermal shrinkage behavior of 100% polyester plain knitted fabrics with varying heat-setting and heat-curing parameters was analyzed. As the thermal shrinkage behavior of the 100% polyester plain knitted fabric has been studied so far, this study will determine the effect of spandex on thermal shrinkage behavior of polyester/spandex plain knitted fabrics. Hence the study presented in this chapter was conducted to analyze the thermal shrinkage behavior of polyester / spandex plain knitted fabrics when they were subjected to heat treatment process subsequent to heat-setting.

9.2 Materials and Experiments

9.2.1 Knitting process

Using 75 denier yarns with 72 filaments and 40 denier spandex yarns, polyester/spandex blended fabrics with 80% polyester and 20% spandex were produced on a circular knitting machine. Table 9.1 and Table 9.2 present the yarn specifications and stitch lengths of polyester/spandex plain knitted fabrics and respective knitting machine parameters.

Table 9.1: Yarn specifications and stitch lengths of polyester/spandex knitted fabrics

Fabric code	Stitch length	Composition (poly/spandex)	Yarn count	
			Polyester	Spandex
P/S1	2.7mm	80% Poly , 20% Spandex	75D/72F polyester	40D Spandex
P/S2	3.0mm	80% Poly , 20% Spandex	75D/72F polyester	40D Spandex
P/S3	3.1mm	80% Poly , 20% Spandex	75D/72F polyester	40D Spandex

Table 9.2 : Knitting machine parameters

Fabric code	Knitting machine setting				
	No of feeders	Gauge	Diameter (Inches)	No of needles	Speed (ms^{-1})
P/S1	90	28	30	2640	20
P/S2	90	28	30	2640	20
P/S3	90	28	30	2640	20

9.2.2 Pre-heat-setting and dyeing process

The conditions used for pre-heat-setting and dyeing processes are presented in Table 9. 3. For the fabric P/S1, 40% over feed was provided during pre-heat-setting while the others were kept at 0% overfeed. The width of the stenter main frame for fabric P/S3 was maintained at 175 cm and the width of the stenter main frame width was maintained at 130 cm and 133 cm for the fabrics P/S1 and P/S2. The fabrics were dispersed dyed using similar dyeing conditions after the pre-heat-setting process.

Table 9.3 : Pre-heat-setting and dispersed dyeing conditions

Fabric code	Conditions of pre-heat-setting				Conditions of disperse dyeing		
	Temperature (°C)	Speed (ms^{-1})	Overfeed (%)	Mainframe width (cm)	Dwell time (min)	Holding time (min)	Temperature (°C)
P/S1	198	25	40	130	45	15	130
P/S2	198	25	0	133	45	15	130
P/S3	198	26	0	175	45	15	130

9.2.3 Final-heat-setting process

Using the conditions given in Table 9.4, the final-heat-setting of the fabrics was performed after the dyeing process. Exception of the mainframe width of the fabric P/S3, all final-heat-setting parameters were maintained the same for the three fabrics.

Table 9.4 : Final-heat-setting conditions

Fabric code	Conditions of final-heat-setting				
	Temperature, °C	Speed, ms^{-1}	Overfeed, %	Underfeed, %	Mainframe width, cm
P/S1	140	20	25	-5	128
P/S2	140	20	25	-5	133
P/S3	140	20	25	-5	160

9.2.4 Post-heat-treatment (Heat-curing treatment)

The heat-set polyester/spandex fabrics were subjected to heat-curing process in order to analyze the thermal shrinkage behavior of heat-set polyester/spandex plain knitted fabrics. Thermal shrinkages in the course direction and the wale direction due to heat-curing were measured on fabric samples with the dimensions 30 X 30 cm^2. Test specimens were cut with their grainlines parallel to wales and the shrinkage measurements were taken as described in Chapter 5. The temperatures 130°C, 140°C, 150°C, 160°C, 170°C, 180°C 190° C and 200°C were selected for the heat-curing process. Five specimens from each heat-set fabric were subjected to each heat-curing temperature for five cycles of 90 seconds in an industrial drying machine as described in Chapter 4. The numbers of curing cycles were selected as five, considering the maximum number of different adornments that requiring heat-curing treatment, though this number may vary from 1 to 5 generally in actual industrial practice. Five specimens were subjected to each heat-curing temperature and the average shrinkage of the five specimens was reported. After heat-setting and heat-curing treatments, fabrics were held flat for 24 hours at 21°C ± 1°C and 65% ± 2% relative humidity for standard conditioning of the specimens before taking any measurement.

9.2.4.1 Thermal shrinkage (S_T)

The thermal shrinkages (S_T) in the course direction and the wale direction of fabric specimens due to heat-curing were calculated using the equation 9.1.

$$S_T = \frac{l_i - l_a}{l_i} \times 100\ \% \qquad (9.1)$$

Here l_i is the length between data lines marked in particular direction before thermal application and l_a is the length between the same data lines after the thermal application. The (+) values indicate the thermal shrinkage and (-) values indicate the thermal expansion.

9.3 Thermal Shrinkage Values of Heat-Cured Polyester/Spandex Fabric Specimens

The thermal shrinkage in the course direction and wale direction of heat-cured fabric specimens are presented in Table 9.5.

Table 9.5 : Mean and standard deviations of thermal shrinkage in the course and wale directions of heat-cured polyester/spandex fabrics

Fabric code	Heat-curing temperature, °C	Thermal shrinkage (course direction),%		Thermal shrinkage (wale direction), %	
		Mean	Std. Deviation	Mean	Std. Deviation
P/S1	130	1.26	0.28	0.91	0.14
	140	1.26	0.37	1.40	0.27
	150	1.44	0.56	1.66	0.25
	160	1.96	0.62	1.90	0.21
	170	2.12	0.43	2.63	0.22
	180	2.38	0.28	3.16	0.30
	190	2.99	0.32	3.62	0.19
	200	2.76	0.32	3.22	0.15
P/S2	130	1.37	0.50	3.43	0.37
	140	1.71	0.37	4.08	0.27
	150	2.36	0.35	5.00	0.22
	160	2.44	0.31	5.74	0.30
	170	2.70	0.34	6.51	0.38
	180	2.56	0.38	6.67	0.32
	190	2.60	0.31	6.92	0.23
	200	3.60	0.49	8.07	0.22
P/S3	130	2.40	0.37	3.50	0.30
	140	2.74	0.43	3.98	0.28
	150	3.27	0.37	4.11	0.28
	160	3.76	0.24	4.16	0.40
	170	3.81	0.34	4.99	0.45
	180	4.72	0.32	5.34	0.25
	190	4.99	0.28	5.75	0.25
	200	6.40	0.48	6.72	0.22

Thermal shrinkage values revealed that as the heat-curing temperature increase from 130°C to 200°C in 10°C interval, thermal shrinkage values in the course direction

and the wale direction are increasing. In order to investigate whether there is significant different among the thermal shrinkage values resulted from heat-curing at different temperature analysis of variance test was performed. The statistical analysis tests are described in the section 9.4.

9.4 Statistical analysis of the effect of heat-curing temperature on the thermal shrinkage of the course and wale directions of polyester/spandex fabrics

9.4.1 Analysis of variance to evaluate the effect of heat-curing temperature on the thermal shrinkage in the course direction of polyester/spandex fabrics

Figure 9.1 demonstrates the distribution of standard thermal shrinkage residues in the course direction due to heat curing. The significance of thermal curing temperature in the course direction is analyzed by ANOVA.

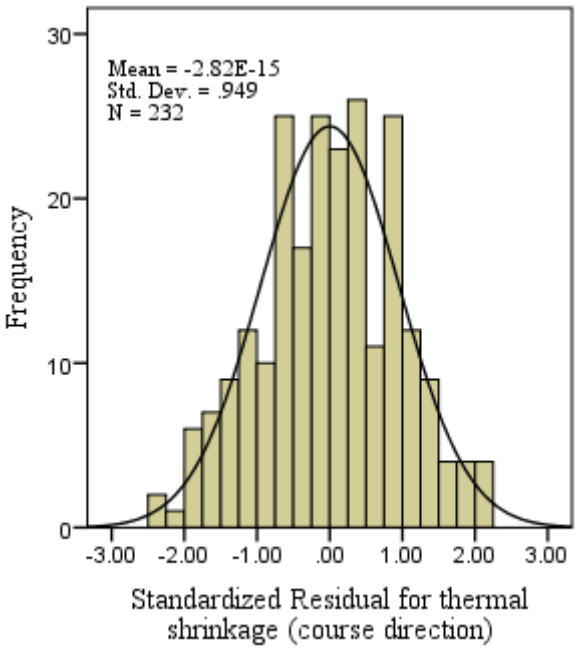


Figure 9.1: Standardized residual for thermal shrinkage (course direction)

The Levene's test and standard residual error plot was evaluated to verify ANOVA assumptions. Levene's test results show that F (23,208)= 1,114, p>0,05 was achieved with the hypothesis of variance of homogeneity. The residual values showed

estimated normality with a mean value of close to zero and a standard deviation of approximately 1.

9.4.1.1 Analysis of variation (ANOVA) of thermal shrinkage in the course direction

Hypothesis test 9.1 was conducted to test the significance effect of heat-curing temperatures on the thermal shrinkage of the course direction. The ANOVA results are presented in Table 9.6.

Hypothesis test 9.1*: H_o: There is no significant difference between thermal shrinkage values in the course direction due to heat curing at different temperatures*

Vs *H_1: There is significant difference between at least two thermal shrinkage values in the course direction due to heat curing at different temperatures*

Significance level α=0.05

Table 9.6 : The ANOVA results to determine the overall impacts of heat-curing temperatures on thermal shrinkage in the course direction

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	345.387[a]	23	15.017	104.405	.000
Intercept	1696.533	1	1696.533	11795.275	.000
Fabric type	160.199	2	80.099	556.897	.000
Heat-curing temperature	151.943	7	21.706	150.914	.000
Fabric type X Heat-curing temperature	29.791	14	2.128	14.795	.000
Error	29.917	208	.144		
Total	2123.781	232			
Corrected Total	375.303	231			

a. R Squared = .920 (Adjusted R Squared = .911)

The effect of heat-curing temperature on the thermal shrinkage of the course direction is statistically significant at 0.05 significance level (p-value is less than 0.05). Therefore, the alternative hypothesis (H_1) is accepted. There is a significance difference between the thermal shrinkage in the course direction of the fabric samples heat-cured at different temperatures.

9.4.2 Analysis of variance to evaluate the effect of heat-curing temperature on the thermal shrinkage in the wale direction

In order to verify the assumptions of ANOVA, the Levene's test and standard residual error plot were evaluated. Results of Levene's test verified that the hypothesis of homogeneity of variance reached $F(23,201) = 1.556$, $p > 0.05$. The residual values displayed estimated normality with a mean value close to zero and a standard deviation close to 1. The distribution of standardized residues of thermal shrinkage in wale direction due to heat-curing is presented in Figure 9.2. The significance of heat-curing temperature on the thermal shrinkage in the wale direction is analyzed using ANOVA.

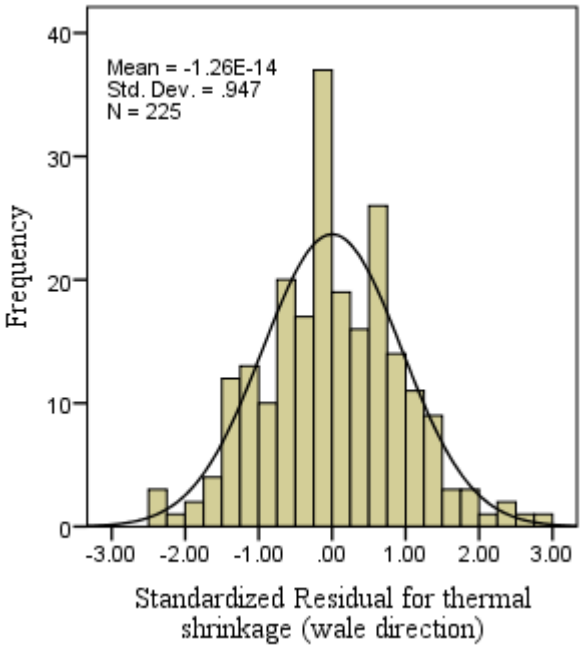


Figure 9.2 : Standardized residual for thermal shrinkage (wale direction)

9.4.2.1 Analysis of variation (ANOVA) of thermal shrinkage in the wale direction

Hypothesis test 9.2 was conducted to test the significance effect of heat-curing temperatures on thermal shrinkage in the wale direction of fabric specimen. The ANOVA results are presented in Table 9.7.

Hypothesis test 9.2*: H_o: There is no significant difference between thermal shrinkage values in the wale direction due to heat curing at different temperatures*

Vs *H_1: There is significant difference between at least two thermal shrinkage values in the wale direction due to heat curing at different temperatures*

Significance level α=0.05

Table 9.7 : The ANOVA results to determine the overall impacts of heat-curing temperatures on thermal shrinkage in the wale direction

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	345.387[a]	23	15.017	104.405	.000
Intercept	1696.533	1	1696.533	11795.275	.000
Fabric type	160.199	2	80.099	556.897	.000
Heat-curing temperature	151.943	7	21.706	150.914	.000
Fabric type X Heat-curing temperature	29.791	14	2.128	14.795	.000
Error	29.917	208	.144		
Total	2123.781	232			
Corrected Total	375.303	231			

a. R Squared = .920 (Adjusted R Squared = .911)

The effect of heat-curing temperature on the thermal shrinkage in the wale direction is statistically significant at 95% confidence level. Therefore, the alternative hypothesis (H_1) is accepted. There is a significance difference between the thermal shrinkage in the wale direction of the fabric samples heat cured at different temperatures.

9.5 Student-Newman-keuls test for comparison of thermal shrinkage in the course direction and wale direction of polyester/spandex knitted fabrics

The Student – Newman – Keuls (SNK) method is a step-by-step process of multiple comparisons used to identify sample means that significantly different from each other.

The SNK test comparison presented in Table 9.8 revealed that thermal shrinkage in course direction and wale direction increases as curing temperature increases (Table 9.8).

Table 9.8 : Student–Newman–Keuls ranking at 5% significant level of thermal shrinkages in the course direction and wale direction of fabrics P/S1, P/S2 and P/S3of ANOVA model

Curing temperature, °C	Fabric P/S1		Fabric P/S2		Fabric P/S3	
	Mean thermal shrinkage, %		Mean thermal shrinkage, %		Mean thermal shrinkage, %	
	Course direction	Wale direction	Course direction	Wale direction	Course direction	Wale direction
130	1.26 (1)	0.91 (1)	1.37 (1)	3.43 (1)	2.40 (1)	0.30 (1)
140	1.26 (1)	1.40 (2)	1.71 (1)	4.08 (2)	2.74 (2)	0.28 (2)
150	1.44 (1)	1.66 (3)	2.36 (2)	5.00 (3)	3.27 (3)	0.28 (2)
160	1.96 (2)	1.90 (4)	2.44 (2)	5.74 (4)	3.76 (4)	0.40 (2)
170	2.12 (2)	2.63 (5)	2.70 (2)	6.51 (5)	3.81 (4)	0.45 (3)
180	2.38 (2)	3.16 (6)	2.56 (2)	6.67 (5) (6)	4.72 (5)	0.25 (4)
190	2.99 (3)	3.62 (7)	2.60 (2)	6.92 (6)	4.99 (5)	0.25 (5)
200	2.76 (3)	3.22 (6)	3.60 (3)	8.07 (7)	6.40 (6)	6.72 (6)

Note:

1. Mean values calculated from a minimum of fifteen measurements.
2. The values 1,2,3 in parentheses denote the effect of curing temperature on the thermal shrinkages in the course direction and wale direction of fabric P/S1,P/S2 and P/S3 (highest value denotes the highest rank and lowest value the lowest rank)

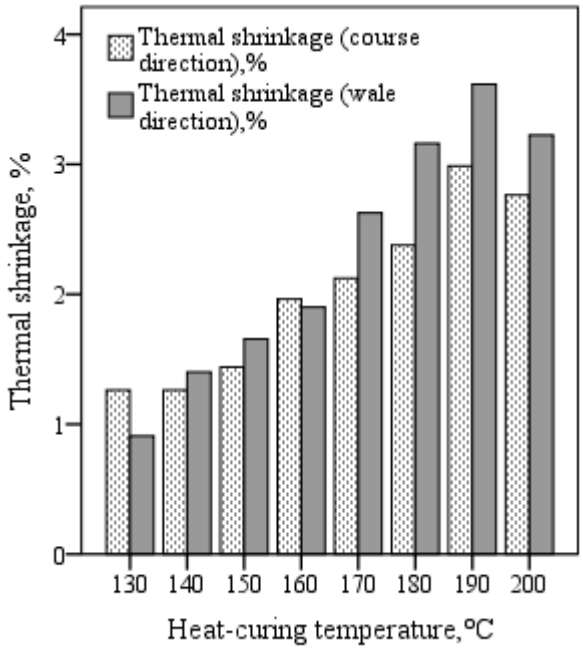


Figure 9.3 : Mean thermal shrinkage in the course and wale direction of fabric P/S1

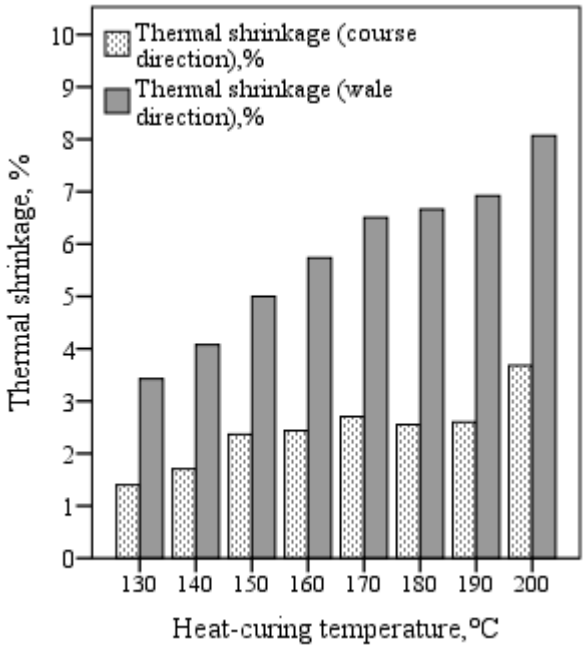


Figure 9.4 : Mean thermal shrinkage in the course and wale direction of fabric P/S2

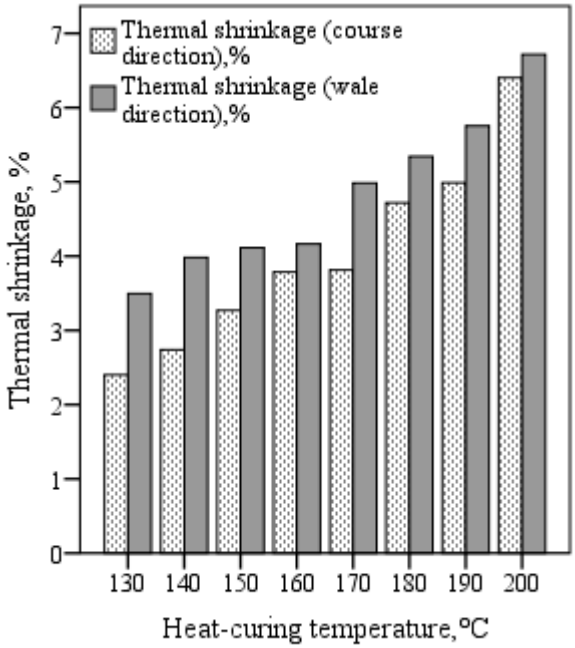


Figure 9.5 : Mean thermal shrinkage in the course and wale direction of fabric P/S3

The lowest thermal shrinkage in both course direction and wale direction for all three fabrics resulted when the heat-set fabric specimens were subjected to 130°C. The highest thermal shrinkages were resulted for both wale direction and course direction for the heat-set specimens when subjected to heat-curing at 190°Cor 200°C. There

is gradual increase in the thermal shrinkage in both the course direction and wale direction with the increase in heat-curing temperature.

As the curing temperature increases from 130°C to 200°C, the thermal shrinkages in the direction of the course and wale of all three fabrics have increased. In chapter 7, for the 100% polyester plain knitted fabrics heat-set at 190°C and 200°C and when specimens were subjected to heat-curing treatment at lower temperatures, the similar gradually increasing thermal shrinkage behavior was observed. Pre-heat-setting at 198°C and final-heat-setting at 200° have made the polyester / elastomeric fabrics dimensionally stable and ultimately led to a gradual increase in thermal shrinkages as the curing temperature increases.

Among the three P/S1, P/S2 and P/S3 fabrics, the fabric P/S1 showed lowest thermal shrinkage in course direction and wale direction. This may resulted due to the higher over feed percentage (40%) and lower width extension applied during the pre-heat-setting treatment. Wu, Cuculo and Yoshida (1998) suggested that the external tension applied during heat treatment to a polyester fibre would determine the internal tension caused by the molecules during subsequent heating. If chain refolding is permitted during the annealing process, the potential for subsequent shrinkage and the amount of internal shrinkage tension will be lowered and higher temperatures will be required to produce further shrinkage. Due to pre-setting with high width extension, the P/S3 fabric resulted in the highest thermal shrinkage in the course direction.

9.6 Summary

The introduction of elastomeric yarns into polyester plain knitted fabrics has caused the heat-setting process to take place at higher temperatures (above 190°C) to stabilize the elastomeric yarn uniformly though out the fabric.

The results revealed that thermal shrinkage behavior of heat-set polyester / spandex plain knitted fabric and 100% polyester fabrics are comparable if the heat-setting treatment was performed above 190°C and subjected to subsequent heat treatment. Gradually increasing thermal shrinkage behavior was observed for the heat-set

polyester/spandex fabrics as the subsequent heat-curing temperature increases from 130°C to 200°C.

10 DISCUSSION

The aim of this study is to analyze the thermal shrinking behavior of polyester and polyester/elastomeric plain knitted fabrics that undergo thermal setting processes and to provide recommendations to minimize thermal shrinking during garment processing. The series of experiments were performed in order to analyse the thermal shrinkage behavior of polyester/elastomeric weft knitted fabrics. As the first step, the thermal shrinkage behavior of 100% polyester plain knitted fabrics were analysed and then the combination effect of polyester/elastomeric plain knitted fabrics were analysed. In each chapter the significant results were discussed and the key findings of the series of experiments are discussed in this chapter 10.

All the fabrics which were used for this study were knitted using circular knitting machine, scoured, bleached and dispersed dyed on a jet dyeing machine (Model: Salavos) at 130°C. Heat-setting was performed varying process parameters in a hot air pin stenter. The fabrics and fabric specimens were conditioned as standard in accordance with ASTM D1776 before any measurement was taken. Thermal shrinkage was measured after subjecting fabric specimens to post-heat treatment processes.

As the first step, the significance of thermal shrinkages of 100% polyester plain knitted fabrics due to post-heat treatment processes were analysed. The thermal shrinkage in the course direction and the wale direction of fabric specimens were measured for the analysis. For this study, four post-heat treatment processes which are commonly practiced in garment production were selected as the heat treatment processes subsequent to heat-setting. The post-heat treatment process results the highest thermal shrinkage due to the application of heat and the process which shrinks the fabric panel the highest was selected for further studies of this research. It was also investigated whether the thermal shrinkages of test specimens subjected to heat treatment processes are similar to the commercially accepted norms of tolerances or accepted levels of shrinkage.

The findings of the initial study (Chapter 4) revealed that post-heat treatment process conditions; temperature, time and pressure have significant impact over the thermal

shrinkage behavior of the 100% polyester fabric. Disregard the free-end annealing or taut-end annealing, if the subsequent heat-treatment temperature is high, higher thermal shrinkages were observed. Thermal expansion was observed for the specimens that were post-heat treated under applied pressure. Thermal expansion can be attributed to the pressure on the fabric plane which inhibited thermal shrinkage and facilitated thermal expansion. The results of wash shrinkage test revealed that laundering caused fabric panels to shrink. The findings also revealed that agitation and the three-dimensional movement during drying caused considerable change in knitted fabric structure.

Rubber print curing led to the most significant thermal shrinkage in the course direction and the second highest thermal shrinkage in the wale direction among rubber print curing, sublimation printing, heat transfer printing and bonding treatment processes. The thermal shrinkage in course direction even exceeds the accepted thermal shrinkage limits in the garment industry. Thus, the rubber print curing method was chosen as the post-heat treatment process for the rest of the studies of this research. The findings of first study revealed that significant change in the thermal shrinkage of wale direction and course direction of the fabric panel subjected to various post-heat treatment processes. This revealed that the thermal shrinkage allowance has to be adjusted depending on which post- heat treatment process the fabric panels are subjected to.

The next sets of experiments were performed in order to investigate the effects of panel parameters and heat-setting temperature on thermal shrinkage. Standard test method to carry out thermal shrinkages is currently not in existence and therefore all tests carried out during the research have to be standardized for all the experiments of this research. Dimensions of the fabric panels to be used in experiments and the orientation or the panel layout are established by carrying out several experiments. Though the dimensions for fabrics after dyeing and heat-setting are not restricted, the dimensions of the fabric panel for post-heat treatment are restricted by the bed of the heat-curing machine. The other factors considered in finalizing the standard size were the maximum possible thermal deformations when polyester fabrics are

exposed to thermal treatments, compatibility with the available heat treatment machines settings and easy repeatability of the test.

In order to investigate the dimensions of the fabric panels and the orientation or the panel layout for the standard test method, experiments were performed varying the fabric specimen size, the layout of the panels and the heat-setting temperature of the fabrics. The correlation test results showed that thermal shrinkage in the course direction is predominantly determined by heat-setting temperatures and by the specimen size. The thermal shrinkage in the wale direction is mainly determined by the heat-setting temperatures. The layout of the specimen has an insignificant impact on thermal shrinkage in course direction and the thermal shrinkage in the wale direction. The findings also revealed that the insignificance of the effect of measuring position over thermal shrinkages in the wale direction and the thermal shrinkage in course direction. Therefore the mean thermal shrinkage of panel in the wale direction and course direction can be represented by the average of the three measurements of thermal shrinkage in the wale direction and the thermal shrinkage in the course direction respectively.

Since the heat-setting temperature, specimen size and thermal shrinkage in the course direction demonstrated strong correlations; a multiple linear regression test was performed. Estimated regression coefficients (β) were shown to decrease thermal shrinkage in the course direction for a given heat-setting temperature as the specimen size increases. The regression analysis further showed that the cut panel layout has an insignificant effect on thermal shrinkage in the course direction. Furthermore, compliance with the existing thermal treatment system settings and the easy repeatability of the experiment are considered for finalizing the standard specimen size. The cut panel layout which has the grainline parallel to wales was chosen as the cut panel layout. After considering the key criteria for standard specimen size, the specimen size 30 X 30 cm^2 was chosen for further thermal shrinkage testing.

In order to investigate the thermal behavior of polyester plain knitted fabrics when heat-set and after a post-heat treatment process, the thermal shrinkage behavior of heat-set polyester knitted fabrics is studied using the results of Differential Scanning Calorimetric (DSC) and measuring the shrinkage values after a post-heat treatment

(heat-curing) process. The thermal behavior of polyester fabrics after heat-setting and after heat-curing is investigated using DSC analysis and the fabric shrinkage. Analysis was carried out on fabrics knitted using 100% polyester yarns and found that the primary effect of the heat-setting is the change in effective temperature of the heat treatment. No significant difference between effective temperatures is observed in low heat-setting temperatures, while the effective temperature of fabrics heat-set at temperatures higher than 160°C increases with the increasing heat-setting temperature. The study on the percentage of shrinkage of yarns due to curing at different temperatures confirmed this behavior. The variance analysis of the percentage of shrinkage caused on yarns in the cured fabrics at different temperatures endorsed this behavior.

There are key finding of the DSC and thermal shrinkage analysis of the yarns of heat-set and heat-cured at various temperatures. The shrinkage of yarns on heat-set fabrics due to post-heat treatments (heat-curing) at temperatures below or equal to 140°C was not significant, while the shrinkage of yarns of cured fabrics at higher temperatures is significant. Thus, it can be recommended that when subject to heat-based processes, the effective temperature of the polyester fabrics is the major determinant of the observed thermal shrinkage. The DSC analysis was performed for the second set of fabrics and the similar change of effective temperature was observed. Hence it is evidence that the temperature is the main factor. The change of effective temperature with the heat-setting temperature is Heat treatments cause the structure to significantly change, when the applied heat is more than the effective temperature. The structure remains stable so long the applied heat is less than the effective temperature. The effective temperatures are changed due to post-heat treatments. This reveals that the effects of heat on polyester depend on the thermal history and hence the fabrics procured by garment manufacturers may rarely have the thermal history of the polyester fabrics. Furthermore, heat-setting at higher temperatures converts the polyester structure into a more crystalline state and makes the structure to be more thermally stable. Heat-setting even at very high temperatures causes no change to the crystallinity percentage of the polyester structure. The analysis carried out on a fabric (fabric A) was repeated for a second

fabric (fabric B) in order to establish and accept the observed behavior of polyester fabric A is common to all polyester fabrics manufactured under using similar yarns and similar conditions. Fabric B delivered similar results from the DSC analysis and the thermal shrinkage.

The results of the above experiments revealed that heat treatment processes have caused thermal deformations in 100% polyester knitted fabrics. Heat-based processes on thermoplastic fibre materials are well known to cause the materials to shrink (Wilson, 1974). However, it is yet to be investigated that, whether the contribution of the yarn itself or the knitted fabric structure has more significant impact on the thermal deformation when the knitted fabrics are subjected to heat treatments. Because of the thermal shrinkage of the constituent yarns in the fabric and the change in the loop shape, knitted fabrics can change their dimensions. The next set of experiments were performed in order to analyse the extent to which the thermal shrinkage of polyester yarn affects the thermal shrinkage behavior of polyester knitted fabrics and the effect of heat on fabric parameters. After dyeing, heat-setting and subsequent heat-curing processes, the thermal shrinkage behavior of polyester yarn and the plain knitted fabric made of the same yarns were analysed. The thermal effects were investigated on yarns, yarns in fabrics, and densities of wale and course of the fabrics. Comparison was made of yarn in hank form and yarn in the knitted stitch. The thermal effects on other parameters of knitted fabric were also analysed. The results revealed that thermal shrinkage in course direction is highly associated with the width-wise extension applied during heat-setting and the thermal shrinkage in the wale direction is highly correlated with the yarn shrinkage behavior in hank form.

A significant change in polyester thermal behavior at 160°C was observed. There is a clear difference in the thermal behavior of polyester below and above its effective temperature (160°C). Although thermal shrinkage is expected after heat-setting, thermal expansions are also observed at temperatures below 160°C in the knitted stitches. Yarns in the fabric extend at low heat-setting temperatures due to the external forces applied to the stenter, while yarns shrink at high heat-setting

temperatures. However, there is a clear difference between shrinkage of the yarn in the hank and shrinkage of the yarn in the fabric at the same heat-setting temperature.

Heat-setting causes the fabric to decrease the wales density with increasing temperature, while the effect on course is to increase the course density. At low curing temperatures (below 160°C) the shrinkage observed is unpredictable however is very low and thermal shrinkage in wale direction is directly correlated to the yarn shrinkage. Thermal shrinkage in the course direction due to curing is mainly due to the width-wise tension exerted at the preceding heat-setting process. In order to validate the results of the yarn (yarn A) and the fabric (fabric A), same experiments were performed for a second yarn (yarn B) and fabric (fabric B). The result of the second yarn and fabric also confirms the finding of the first yarn and the fabric.

The effects of heat-setting temperature and heat-curing temperature on the behavior of thermal shrinkage have been discussed in initial experiments. During heat-setting, temperature is one parameter to adjust and the other two important parameters are the extension of width and overfeed during heat-setting. Width extension and overfeed of fabric is performed during heat-setting to achieve the required width measurement and to prevent extraordinary fabric deformation due respectively to width extension. Since overfeeding is an important heat-setting parameter, the influence of the percentage of overfeed during heat-setting on the thermal shrinkage behavior of heat-set fabrics has also been analyzed when exposed to post-heat treatment processes.

Plain knitted fabrics with different initial stitch lengths were subjected to varying percentage of overfeed during heat-setting treatment. These fabrics were exposed to heat-curing at 140°C. The results revealed that overfeed percentage has a strong positive correlation with courses per inch of the heat-set fabric and there is no significant correlation between the wale per inch and initial stitch length of heat-set fabrics.

The initial stitch length and overfeed are identified from the multiple linear regression equations as the two significant variables to predict thermal shrinkages in the course direction and the wale direction due to curing. The decreasing stitch

density and the increasing initial stitch length increase the thermal shrinkage in the course direction while reducing the shrinkage in the wale direction. Results also revealed a negative correlation between the thermal shrinkage in the course direction and the thermal shrinkage in the wale direction at a significant level of 95 percent.

The thermal shrinkage behavior of heat-set polyester/ spandex plain knitted fabrics when subjected to heat-curing treatments were analysed. The lowest thermal shrinkage in both course direction and wale direction due to heat-curing treatment was observed for the fabrics heat-set at 130°C. When subjecting to heat-curing at 190°C and 200°C, the highest thermal shrinkages were obtained for the both course direction and the wale direction for the heat-set specimens. With the increase in heat-curing temperature, there is a gradual increase and a trend in thermal shrinkage in both course direction and the wale direction. The DSC analysis and thermal shrinkage behavior of heat-set 100% polyester plain knitted fabrics revealed that when heat-set at 190°C and above the yarns in the fabric more structurally stable thus resulting in very low thermal deformation. Pre-heating at 198°C and final heat-setting at 200°C made the polyester / elastomeric fabrics dimensionally stable and ultimately led to a gradual increase in thermal shrinkages as the curing temperature rises. Due to pre-heat-setting at 190°C, the permanent stabilization of spandex yarns at lower denier stabilized the 100% polyester yarns under pre-heat-setting conditions.

The results revealed that heat-set polyester / spandex plain knitted fabric thermal shrinkage behavior and 100% polyester fabrics show similar trends when the heat-setting treatment was performed above 190°C and subjected to subsequent heat treatment. As the subsequent heat-curing temperature increases from 130°C to 200°C, gradually increasing thermal shrinkage behavior was observed for the heat-set polyester / spandex fabrics.

Considering the results of the research study, it can be recommended that although the heat-setting was performed to stabilize the dimensions of heat-set polyester / elastomeric plain knitted fabrics, thermal shrinkage still occurs in varying amounts depending on the post-heat-treatment process conditions. The results of the DSC analysis and thermal shrinkage values revealed that due to subsequent heat treatments, thermal history of the fabric has a significant effect on the behavior of

thermal shrinkage. Analyzing the results of DSC and the thermal shrinkage behavior of 100% polyester yarn in hank form and yarn in fabrics revealed that 160°C is a significant temperature at which heat-setting can be carried out. The shrinkage due to heat-curing depends entirely on the temperature of heat-setting, particularly at temperatures above 160°C; the predictability becomes low below 160°C. This shows the importance of the thermal history of the material. The thermal behavior of polyester demonstrates trends after 160°C, below this temperature the predictability is less, and thermal expansion too can happen instead of thermal shrinkages.

11 CONCLUSION

This research investigated the thermal shrinkage behavior of heat-set polyester/elastomeric weft knitted fabrics. The study was organized on five specific objectives as identified in the Introduction section (Chapter 1). Chapters 4 to 9 of this thesis address these objectives. The key findings corresponding to these specific objectives are given below.

The first objective was to investigate the thermal shrinkage behavior of commercially used polyester/elastomeric plain knitted fabrics subjected to heat treatment processes subsequent to heat-setting. From the results of the Chapter 4 and 5, It was found that the heat-setting temperature as the significant factor which affect the thermal shrinkage behavior in course direction and wale direction of the post-heat treated (heat-cured) fabric panels. The results also reveal that post-heat treatment caused significant thermal shrinkage in polyester/elastomeric plain knitted fabrics. Low (below 160°C) heat-setting temperatures caused thermal expansion in subsequent heat treatments. The results also revealed those temperatures of pre-heat-setting, final-heat-setting and heat-curing has significant effect over thermal shrinkage behavior of polyester/spandex plain knitted fabrics.

The garment industry currently does not practice standard testing procedure for measuring the thermal shrinkage. Therefore all tests carried out during the research have to be standardized for all the experiments. After a series of experiments and considering the dimensions of the beds of heat curing machines, the sample size for thermal shrinkage testing was established as 30cm X30cm. It was found through the experiments that there is no statistically significant difference whether the sample is cut parallel to wales or parallel to courses. This is due to the fact that the shrinkage in wale and course directions has different behaviors and the courses are not normally perpendicular to wales in weft knitted fabrics, therefore, the optimum sample size and orientation for thermal shrinkage testing was established as 30cm X 30cm.

The third objective was to investigate thermal shrinkage behavior of single jersey plain knitted polyester/elastomeric fabrics of different tightness factors. The results

of Chapters 6, 7 and 8 revealed that thermal shrinkage was evidence of a change in the structural parameters of knitted material. Structural changes are mainly due to the change of shape of the loop and/or thermal shrinkage of the stitch length.

Under the fourth objective empirical relationships to predict the thermal shrinkage of polyester/elastomeric plain knitted fabrics were identified. Results given in Chapter 6 and 7 showed that heat-setting temperature is the primary determinant of the thermal stability of a fabric under post-heat treatment processes (indicated by the changing effective temperature). Low heat-setting temperatures (less than 160°C) resulted in higher subsequent thermal shrinkage (ie. no significant difference between effective temperatures). Chapter 7 results showed that the shrinkage in course direction is highly correlated with the width-wise extension applied during heat-setting and wale direction shrinkage is highly correlated with the shrinkage behavior of the yarn. Chapter 9 results showed that polyester/spandex fabrics showed better thermal stability and predictability of thermal shrinkage behavior.

Final objective of research was to provide recommendations to minimize thermal shrinkage upon heat treatment subsequent to heat-setting process. Based on the results and analyses given in Chapters 4 to 9 following key recommendations were formulated.

1. Heat-setting at higher temperatures is recommended for obtaining higher thermal stability of fabrics subjected to frequent and intensive post-heat treatment processes
2. The common industry practice of extensively stretching the fabric during heat-setting actually causes excessive shrinkage in the post-heat setting processes. Therefore moderate width extension is recommended.
3. Percentage of over feed has strong positive correlation with the courses per inch of the heat-set fabrics. Therefore moderate percentage of overfeed is recommended to reduce wale-wise thermal shrinkage
4. The thermal history of polyester or polyester/spandex fabrics has an effect on shrinkages due to post heat treatments. Therefore it is recommended for garment manufacturers to obtain the records of thermal history of yarns and the fabric from the suppliers wherever possible.

5. It is also recommended to conduct post-heat treatment processes (eg. Rubber print curing, sublimation printing) at low temperatures (below 160°C) where possible
6. When a garment manufacturing plant receives a fabric causing large variations of shrinkage and possibly variations at different places within the same roll and difficult to manger, it can be recommend that the fabric roll be reprocessed at a temperature above 160°C.

The scope of this research did not cover the effect of time duration of heat-setting and heat-curing process on thermal shrinkage behavior of polyester/elastomeric fabrics. Therefore it is recommended for future research to further study and elaborates on these aspects.

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Appendices

Appendix A1: Mean thermal shrinkages of three pairs of data point of fabric specimens

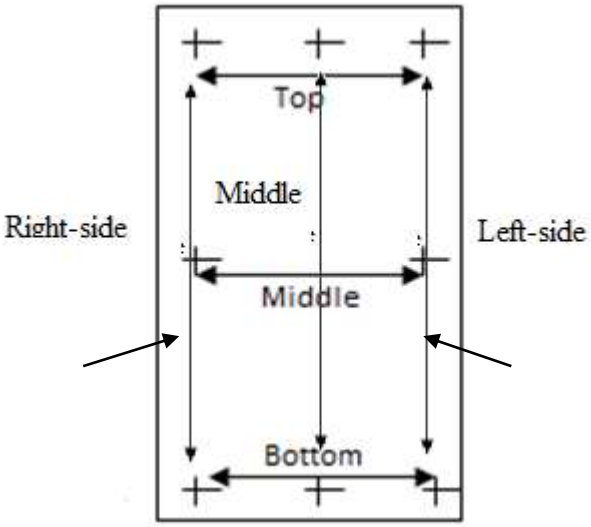

Figure A.11.1: Three pairs of data lines

The mean thermal shrinkage in the wale direction at three pairs of data points (left, middle and right) for each sample size for cut panel layout 1 and 2 of fabric heat set at temperature 140°C, 160°C and 180°C are shown in Table A1.1 , Table A1.2 and Table A1.3 respectively.

Table A1.11.1: The mean thermal shrinkage in the wale direction at three pairs of data points (left, middle and right) for each sample size for cut panel layout 1 and 2 of fabric heat set at temperature 140°C

Size	Measuring point	Cut-panel layout 1			Cut-panel layout 2		
		Number of data	Thermal shrinkage in the wale-direction	Standard deviation	Number of data	Thermal shrinkage in the wale-direction	Standard deviation
3	Left	5	2.94	0.51	5	2.87	0.51
	Middle	5	2.81	0.38	5	3.00	0.30
	Right	5	2.91	0.62	5	2.90	0.28
6	Left	5	2.80	0.45	5	3.02	0.23
	Middle	5	2.71	0.24	5	3.04	0.24
	Right	5	2.81	0.27	5	2.88	0.15
10	Left	5	2.74	0.47	5	2.92	0.74
	Middle	5	2.69	0.24	5	3.31	0.56
	Right	5	2.96	0.36	5	3.49	0.37
15	Left	5	2.75	0.22	4	3.04	1.50
	Middle	5	3.01	0.41	5	2.72	0.38
	Right	5	3.27	0.23	4	1.90	1.42
21	Left	5	3.02	0.17	5	3.03	0.92
	Middle	5	3.36	0.24	4	3.84	0.42
	Right	5	3.21	0.37	4	3.82	1.10
28	Left	5	2.82	0.22	4	1.90	0.34
	Middle	5	2.85	0.17	5	2.21	0.17
	Right	5	3.36	0.35	5	2.20	0.72
35	Left	5	3.25	0.45	5	3.70	1.03
	Middle	5	2.89	0.38	5	4.06	0.14
	Right	5	2.81	0.55	5	4.27	0.46
45	Left	5	1.74	0.52	5	2.23	0.55
	Middle	5	2.72	0.64	4	1.79	0.84
	Right	5	2.24	0.67	5	2.16	0.71
50	Left	4	1.93	0.88	5	2.66	1.10
	Middle	5	2.46	0.66	3	1.94	0.10
	Right	5	2.06	0.46	5	1.62	0.13

Table A1.11.2 : The mean thermal shrinkage in the wale direction at three pairs of data points (left, middle and right) for each sample size for cut panel layout 1 and 2 of fabric heat set at temperature 160°C

Size	Measuring point	Cut-panel layout 1			Cut-panel layout 2		
		Number of data	Thermal shrinkage in the wale-direction	Standard deviation	Number of data	Thermal shrinkage in the wale-direction	Standard deviation
3	Left	5	3.46	0.86	4	3.47	0.23
	Middle	5	3.14	0.30	4	2.48	1.33
	Right	5	3.27	0.27	3	3.37	0.44
6	Left	5	2.56	0.18	3	3.74	0.28
	Middle	5	2.67	0.11	2	3.53	0.24
	Right	5	2.66	0.23	3	3.27	0.35
10	Left	5	2.79	0.47	3	3.86	0.09
	Middle	5	2.73	0.36	3	3.81	0.11
	Right	5	2.94	0.77	3	3.39	0.58
15	Left	5	2.70	0.61	3	3.23	0.28
	Middle	5	2.88	0.84	3	3.22	0.18
	Right	5	3.18	0.72	3	3.24	0.09
21	Left	5	3.24	0.02	4	3.04	0.70
	Middle	5	3.35	0.33	4	3.15	0.56
	Right	5	3.05	0.16	3	3.05	0.20
28	Left	5	3.06	0.45	2	3.31	0.97
	Middle	5	3.68	0.01	2	3.25	0.22
	Right	5	3.40	0.75	2	3.21	0.11
35	Left	5	2.82	0.71	2	3.44	0.17
	Middle	5	2.79	0.22	3	3.63	0.20
	Right	5	2.71	0.44	2	3.21	0.14
45	Left	5	1.68	0.53	5	1.09	0.99
	Middle	4	2.19	0.38	5	1.91	0.86
	Right	5	1.68	0.10	5	1.66	0.29
50	Left	5	1.83	0.36	5	2.60	0.40
	Middle	5	2.19	0.69	4	1.80	0.38
	Right	5	1.56	0.11	5	2.10	0.16

Table A1.11.3 : The mean thermal shrinkage in the wale direction at three pairs of data points (left, middle and right) for each sample size for cut panel layout 1 and 2 of fabric heat set at temperature 180°C

Size	Measuring point	Cut-panel layout 1			Cut-panel layout 2		
		Number of data	Thermal shrinkage in the wale-direction	Standard deviation	Number of data	Thermal shrinkage in the wale-direction	Standard deviation
3	Left	5	3.46	0.86	4	3.47	0.23
	Middle	5	3.14	0.30	4	2.48	1.33
	Right	5	3.27	0.27	3	3.37	0.44
6	Left	5	2.56	0.18	3	3.74	0.28
	Middle	5	2.67	0.11	2	3.53	0.24
	Right	5	2.66	0.23	3	3.27	0.35
10	Left	5	2.79	0.47	3	3.86	0.09
	Middle	5	2.73	0.36	3	3.81	0.11
	Right	5	2.94	0.77	3	3.39	0.58
15	Left	5	2.70	0.61	3	3.23	0.28
	Middle	5	2.88	0.84	3	3.22	0.18
	Right	5	3.18	0.72	3	3.24	0.09
21	Left	5	3.24	0.02	4	3.04	0.70
	Middle	5	3.35	0.33	4	3.15	0.56
	Right	5	3.05	0.16	3	3.05	0.20
28	Left	5	3.06	0.45	2	3.31	0.97
	Middle	5	3.68	0.01	2	3.25	0.22
	Right	5	3.40	0.75	2	3.21	0.11
35	Left	5	2.82	0.71	2	3.44	0.17
	Middle	5	2.79	0.22	3	3.63	0.20
	Right	5	2.71	0.44	2	3.21	0.14
45	Left	5	1.68	0.53	5	1.09	0.99
	Middle	4	2.19	0.38	5	1.91	0.86
	Right	5	1.68	0.10	5	1.66	0.29
50	Left	5	1.83	0.36	5	2.60	0.40
	Middle	5	2.19	0.69	4	1.80	0.38
	Right	5	1.56	0.11	5	2.10	0.16

The mean thermal shrinkage in the course directions at three pairs of data points (top, middle and bottom) for each sample size for cut panel layout 1 and 2 of fabric heat set at temperature 140°C, 160°C and 180°C are shown in Table A1.4 , Table A1.5 and Table A1.6 respectively.

Table A1.11.4 : The mean thermal shrinkage in the course directions at three pairs of data points (top, middle and bottom) for each sample size for cut panel layout 1 and 2 of fabric heat set at temperature 140°C

Size	Measuring point	Cut-panel layout 1			Cut-panel layout 2		
		Number of data	Thermal shrinkage in the course direction	Standard deviation	Number of data	Thermal shrinkage in the course direction	Standard deviation
3	Bottom	3	6.33	0.31	4	6.72	0.12
	Middle	5	6.38	0.35	4	6.72	0.12
	Top	3	6.40	0.44	4	6.29	0.75
6	Bottom	5	5.31	0.65	5	6.51	0.90
	Middle	5	5.15	0.79	4	6.30	0.81
	Top	5	5.86	0.96	5	6.15	1.18
10	Bottom	5	6.05	0.31	5	5.47	0.68
	Middle	5	5.54	0.66	5	5.99	0.35
	Top	5	5.50	0.37	4	5.41	0.49
15	Bottom	5	4.79	0.41	5	5.65	0.57
	Middle	5	5.17	0.26	5	5.67	0.48
	Top	4	5.04	0.45	5	5.97	0.59
21	Bottom	5	5.19	0.26	5	4.82	0.34
	Middle	5	5.23	0.55	5	6.28	1.11
	Top	5	4.92	0.50	5	6.41	1.29
28	Bottom	5	4.76	0.47	5	5.73	0.45
	Middle	5	5.39	0.16	5	5.82	0.53
	Top	5	5.11	0.73	5	5.78	0.36
35	Bottom	5	4.70	0.83	5	5.37	0.36
	Middle	5	5.60	0.69	5	5.56	0.49
	Top	5	4.93	0.51	5	5.24	0.94
45	Bottom	5	3.87	0.28	5	4.41	0.28
	Middle	5	4.03	0.46	5	4.69	0.44
	Top	5	4.44	0.36	5	4.16	0.53
50	Bottom	5	4.13	0.58	4	4.10	0.45
	Middle	5	4.28	0.45	5	4.16	0.56
	Top	4	4.14	0.93	4	4.15	0.67

Table A1.11.5: The mean thermal shrinkage in the course directions at three pairs of data points (top, middle and bottom) for each sample size for cut panel layout 1 and 2 of fabric heat set at temperature 160°C

Size	Measuring point	Cut-panel layout 1			Cut-panel layout 2		
		Number of data	Thermal shrinkage in the course direction	Standard deviation	Number of data	Thermal shrinkage in the course direction	Standard deviation
3	Bottom	5	6.16	0.65	4	5.45	1.55
	Middle	5	6.03	0.95	5	5.10	1.70
	Top	5	6.45	0.00	5	5.38	1.76
6	Bottom	4	5.85	1.34	5	5.07	1.05
	Middle	5	5.65	0.93	5	5.51	0.47
	Top	5	6.31	0.66	3	5.45	1.39
10	Bottom	2	5.25	0.44	5	4.93	0.84
	Middle	4	4.93	0.03	5	5.50	0.72
	Top	5	6.01	0.53	5	5.37	0.18
15	Bottom	5	5.03	0.44	5	4.61	0.63
	Middle	5	5.50	0.30	5	5.22	0.30
	Top	5	5.28	0.36	5	4.83	0.26
21	Bottom	5	4.92	0.17	5	4.43	0.83
	Middle	5	4.96	0.25	5	4.87	0.47
	Top	5	4.46	0.45	5	4.38	0.62
28	Bottom	5	4.40	0.48	5	4.64	0.75
	Middle	5	4.74	0.16	5	4.88	0.30
	Top	5	4.40	0.50	5	4.56	0.67
35	Bottom	5	4.75	0.74	5	4.60	0.27
	Middle	5	4.46	0.17	5	4.58	0.22
	Top	5	4.06	0.47	5	4.38	0.70
45	Bottom	5	4.26	0.12	5	4.14	0.35
	Middle	5	4.24	0.43	5	3.86	0.17
	Top	5	4.20	0.85	5	3.92	0.37
50	Bottom	5	3.20	0.63	5	4.23	0.54
	Middle	5	3.79	0.33	5	4.20	0.89
	Top	5	3.06	0.53	5	4.18	0.85

Table A1.11.6: The mean thermal shrinkage in the course directions at three pairs of data points (top, middle and bottom) for each sample size for cut panel layout 1 and 2 of fabric heat set at temperature 180°C

Size	Measuring point	Cut-panel layout 1			Cut-panel layout 2		
		Number of data	Thermal shrinkage in the course direction	Standard deviation	Number of data	Thermal shrinkage in the course direction	Standard deviation
3	Bottom	3	3.26	0.06	5	2.65	0.90
	Middle	4	3.25	0.05	5	2.98	0.75
	Top	3	3.23	0.00	5	2.35	0.81
6	Bottom	4	2.88	0.02	5	3.23	0.82
	Middle	5	2.82	0.73	5	2.36	0.92
	Top	3	2.83	0.05	5	2.95	0.56
10	Bottom	5	2.60	0.27	5	2.89	1.06
	Middle	5	2.55	0.41	5	2.91	0.71
	Top	5	2.48	0.64	4	2.42	0.32
15	Bottom	5	2.65	0.78	5	2.39	0.28
	Middle	5	2.76	0.32	5	2.97	1.01
	Top	5	2.00	0.44	5	2.14	0.61
21	Bottom	5	2.52	0.30	5	2.26	0.23
	Middle	5	2.55	0.25	5	2.36	0.35
	Top	5	2.25	0.24	5	2.41	0.38
28	Bottom	5	1.89	0.29	5	2.08	0.31
	Middle	5	2.42	0.52	5	2.31	0.20
	Top	5	2.61	0.89	5	1.92	0.24
35	Bottom	4	2.25	0.27	5	2.30	0.57
	Middle	5	2.11	0.26	4	2.19	0.37
	Top	5	1.91	1.22	5	1.80	0.35
45	Bottom	5	1.82	0.69	5	2.17	0.51
	Middle	5	1.85	0.11	5	1.74	0.16
	Top	5	1.60	0.39	5	1.54	0.58
50	Bottom	5	0.84	0.36	5	1.40	0.17
	Middle	5	1.57	0.22	5	1.63	0.16
	Top	5	1.43	0.70	5	1.06	0.62

Appendix A2: Results of Levene's test of yarn in hank and yarn in fabric of fabric A at 200°C

The results of Leven's Test of equality of error variances of yarn in hank and wale direction thermal shrinkage of fabrics subjected to heat curing at 200°C.

Heat setting temperature 130°C	F (1, 24) =3.054, p=0.093>0.05
Heat setting temperature 140°C	F (1, 23) =3.920, p=0.060>0.05
Heat setting temperature 150°C	F (1, 19) =3.925, p=0.062>0.05
Heat setting temperature 160°C	F (1, 20) =1.001, p=0.329>0.05
Heat setting temperature 170°C	F (1, 23) =2.150, p=0.156>0.05
Heat setting temperature 180°C	F (1, 24) =0.463, p=0.504>0.05
Heat setting temperature 190°C	F (1, 20) =0.981, p=0.334>0.05
Heat setting temperature 200°C	F (1, 21) =0.099, p=0.756>0.05