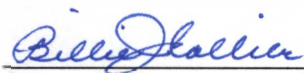


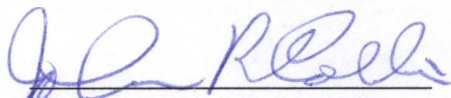
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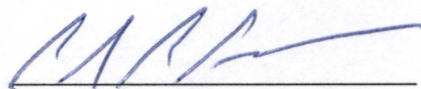


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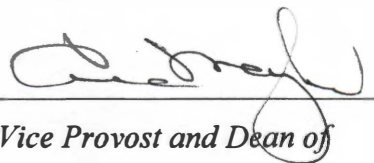


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Vice Provost and Dean of
Graduate Studies

Thesis
2003
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CORELATION BETWEEN PROCESS PARAMETERS AND DEMIQUE® NONWOVEN WEB PROPERTIES

**A THESIS PRESENTED FOR THE
MASTER OF SCIENCE
DEGREE**

THE UNIVERSITY OF TENNESSEE, KNOXVILLE

**ATUL DAHIYA
AUGUST 2003**

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The present study is an endeavor to understand Correlation Between Process Parameters and Demique® Nonwoven Web Properties. In this endeavor, I am indebted to my teachers, fellow researchers, colleagues, well wishers, friends, and others who helped me and encouraged me. It may not be possible to thank them all individually, but I would like to mention a few, without whom the study would not have been a reality.

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ABSTRACT

Polyetherester, a thermoplastic elastomer, characterized by high elongation and good mechanical properties, has been made into melt blown multi-layer nonwovens using a patented technology developed at Kimberly-Clark. The resulting fabric, Demique[®], was targeted for end-uses in the medical and athletic fields. Properties include high impact strength and minimum loss of flexibility at low temperatures, as well as the ability to perform well at elevated temperatures. The objective of this research is to investigate the effects of melt blowing process parameters on properties of single layer nonwoven webs, with the purpose of determining applications as bandaging materials.

The polyether ester Arnitel[®] EM400 was processed on a 20-inch melt blowing line into a nonwoven web. Processing conditions included: two die temperatures (249 and 260°C), two die-to-collector distances (DCD) (8 and 16 inches), two throughputs (0.4 and 0.6 grams/hole/minute), and two collector speeds (5 and 10 fpm). These parameters were selected based upon preliminary rheological experiments and processing trials, and represent the range of feasible parameters based on the polymer and the equipment available. Also, these parameters are the important processing variables controlling the end use properties of the nonwoven products made by melt blowing processes.

Air permeability was observed highest for high DCD, high collector speeds, low throughput and low die temperature. Tear strength along machine direction was observed highest for high DCD, low throughput and low die temperature, whereas along cross direction it was highest for high DCD and low collector speed. Peak elongation along machine direction was highest for high die temperature and low DCD, whereas along cross direction it was highest for high die temperature, high DCD and low throughput. Peak force along machine direction was highest for high throughput and low DCD, whereas along cross direction it was highest for high die temperature, low DCD and low collector speed.

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CHAPTER-1

INTRODUCTION

1.1 BACKGROUND

Melt blown (MB) nonwoven webs are known for their special properties such as softness, and high surface areas, which give good filtration and barrier properties. Demique® is one such MB thermoplastic elastic nonwoven characterized by high elasticity and good mechanical as well as barrier properties. It is a patented technology, developed by Kimberly-Clark Corporation, and given the trade name Demique®. It is made by melt blowing a polyether ester polymer resin. The nonwoven web has several potential applications and end uses, one of which is bandage applications for body joints (knee and elbow joints). An ideal bandage should stretch as needed and then recover without losing its shape and adhesion and should also serve as a barrier to foreign invaders to wounds, protecting from infection and keeping the wounds clean. Many of the existing commercial bandages lose their shape because of the regular movements and the force experienced as joints are bent. The main aim of this study was to develop a suitable material targeted for bandage application in the medical and athletic fields. The material should maintain its shape and strength while also offering minimum loss of flexibility at low temperature, as well as the ability to perform well at elevated temperatures. This research was also directed towards further optimizing the process for Demique®, correlating process parameters and properties, and rheologically characterizing polyether ester.

1.2 EARLIER RESEARCH

Earlier research reported by Kimberly-Clark Corporation in their patents, [1,2,3] focused on the properties and processability of different MB grade polyether ester polymers of different molecular weights and properties from different manufacturers. Nonwoven webs were formed from various polyether esters by extruding them through 1½ inch diameter Johnson extruder and then through a melt blowing die with 30 holes per linear inch for different processing conditions. The webs obtained were studied for properties such as strength, air permeability, and elongation.

At present for most of the commercial purposes, polyurethanes are the most common elastomers being used, and polyether ester offers an alternative because of several advantages offered over polyurethanes. Some of the physical properties of Kimberly-Clark Demique® copolyether ester MB webs were compared to Kanebo (hard) Espansione® polyurethane nonwovens [4]. Results were that Espansione® had better tensile properties and elastic modulus, slightly stiffer, generated fewer small lint particles (0.5 microns or smaller), and was more resistant to UV light, even after long exposures. Demique® had high peak and break elongations, higher bulk at equivalent weights, and better resistance to organic solvents.

Demique® can be melt spun and is therefore amenable to the MB process. Demique® webs are composed of elastic microfibers, making the fabric very breathable, both from the standpoint of overall porosity and moisture vapor transmission. Typically, the microfibers are 8-10 µm in diameter. Because it is truly a thermoplastic elastic, it resists embrittlement to well below -17.8°C (0°F), lower than other elastics. Demique® is tough, durable with good elastic recovery and shape retention. It is soft and breathable, yet capable of providing barrier properties. It exhibits ranges of elongation potential that are similar to spandex with high recovery.

CHAPTER – 2

LITERATURE REVIEW

2.1 THERMOPLASTIC ELASTOMERS

2.1.1 INTRODUCTION

Thermoplastic elastomers exhibit physical properties of elastomers, having good reversible extensibility, however, they can be processed as thermoplastics [5,6,7,8] at elevated temperatures in contrast to conventional elastomers (rubbers). Conventional elastomers are covalently crosslinked into a three dimensional network structure either via peroxide curing or sulfur vulcanization to provide useful physical properties [5,9], and behave as thermosetting materials which cannot be processed or reprocessed once they are crosslinked. Thermoplastic elastomers also have a three – dimensional network structure that prevents viscoelastic flow at room temperature. The physical forces of attraction forming the network can however be disrupted at high temperature making the polymer soft and flowable. The advantages of thermoplastic elastomers are that they can be processed by conventional thermoplastic methods such as injection molding, fiber and film extrusion, and blow molding.

Thermoplastic elastomers are multiphase copolymers composed of two or more thermodynamically incompatible covalently bonded chain segments or blocks. The phase separation of the incompatible segments results in physical, reversible crosslinking. The phases are composed of different blocks one of which is characterized by an accessible glass transition temperature or melting point that is above the useful temperature range of the thermoplastic elastomers; this phase is called the hard phase. A glass transition temperature that is well within the useful temperature range of the thermoplastic elastomers characterizes another block; this phase is referred to as the soft phase. The thermoplastic elastomers are block copolymers with an $(AB)_n$ type of structural unit where A is a polyether segment (soft) and B is the polyester segment (hard).

One family of thermoplastic elastomers with the segment block copolymer structure is based on polyester hard block segments [5]. The polyester blocks in these polymers generally have a regular structure that can phase separate into crystalline

domains that maximize the intermolecular forces of attraction between the segments. Even at temperatures approaching the melting temperature of the crystallites, these materials retain their integrity and will flow at higher temperatures under shear for thermoplastic processing. There are wide variety of segmented thermoplastic polyester structures possible, but commercially copolyether esters based on phthalate ester hard-phase segments and poly(ether) glycol soft segments are available. Brand names for primary commercial polymers are Hytrel produced by DuPont; Arnitel E. by Azko; Ecdel, by Eastman; Gafles, by GAF(Celanese); Lomod, by General Electric; and Pelprene by Toyobo [5,10,11].

The use of copolyether esters has grown considerably in recent years, because of their unique elastic behavior up to the melt temperature. Above the melt temperature, their flow is typical of non-Newtonian fluids, and therefore special rheological techniques are required for characterizing these materials.

2.1.2 STRUCTURE

The general structure of polyether ester thermoplastic elastomers is shown in Figure 2.1 [12].

2.1.3 POLYMER SYNTHESIS AND CHEMISTRY

2.1.3.1 GENERAL CHEMISTRY

These polymers contain no chemical cross-links and thus they can be processed as conventional thermoplastics, lowering production cost. The segmented block copolymers of continuous alternating hard and soft segments can be distinguished from long-block copolymers that are non-crystallizing such as Kraton[®]. The soft segment A (amorphous segment) has a low glass transition temperature and imparts the elastic behavior. It is derived from a hydroxyl-terminated polyether as shown in Figure 2.2 [5].

The hard segment B, which is a rigid high melting aromatic polyester, is responsible for producing intermolecular physical crosslinks to form a thermally reversible network and crystallization of the hard segment B is one of the mechanisms for intermolecular association. Hard segment, B, is derived from the transesterification producing components given in Figure 2.3 [13].

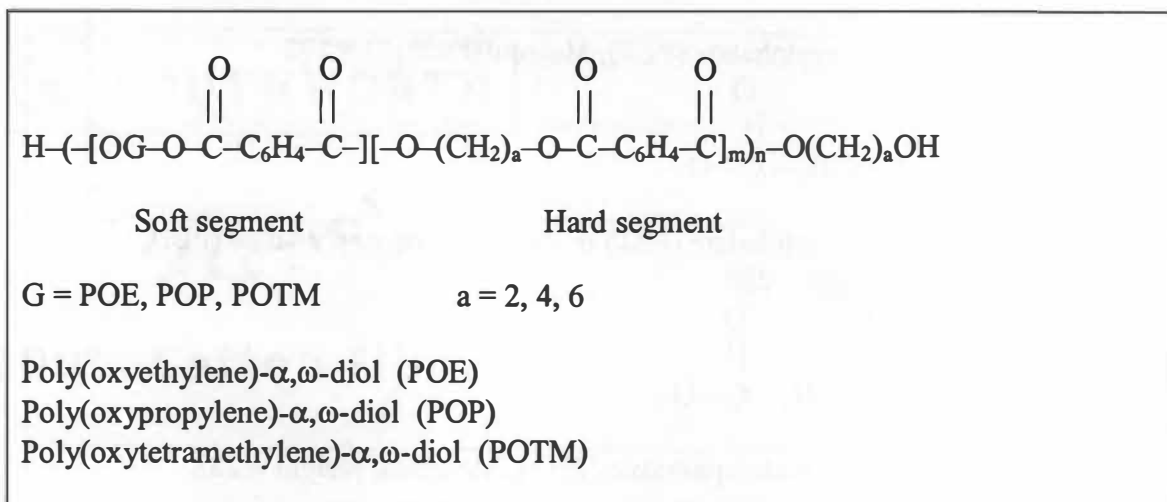


Figure 2.1. General structure of polyether ester

•	Polyethylene glycol (PEG), Molecular weight = 1,000 $\text{HO} - (\text{CH}_2\text{CH}_2\text{O})_x - \text{H}$
•	Polypropylene glycol (PPG), Molecular weight = 1,000 $\begin{array}{c} \text{CH}_3 \\ \\ \text{HO} - (\text{CH}_2\text{CH}_2\text{O})_x - \text{H} \end{array}$
•	Polytetramethylene glycol (PTMEG), Molecular weight = 1,000 or 2,000 $\text{HO} - (\text{CH}_2\text{CH}_2\text{CH}_2\text{CH}_2\text{O})_x - \text{H}$
•	Polypropylene glycol end-capped with polyethylene glycol (EOPPG) $\begin{array}{c} \text{CH}_3 \\ \\ \text{HO} - (\text{CH}_2\text{CH}_2\text{O})_x - (\text{CH}_2\text{CHO})_y - (\text{CH}_2\text{CH}_2\text{O})_z - \text{H} \end{array}$

Figure 2.2. Soft segments

•	Polyethylene terephthalate (PET), Molecular weight = 192 $\begin{array}{c} \text{O} \qquad \qquad \text{O} \\ \qquad \qquad \\ (\text{CH}_2)_2 \text{OC} - \text{C}_6\text{H}_4 - \text{C} - \text{O} - \end{array}$
•	Polybutylene terephthalate (PBT) or Polybutylene isophthalate (PBI), Molecular weight = 220 $\begin{array}{c} \text{O} \qquad \qquad \text{O} \\ \qquad \qquad \\ (\text{CH}_2)_4 - \text{OC} - \text{C}_6\text{H}_4 - \text{C} - \text{O} - \end{array}$
•	Polyhexamethylene terephthalate (PHT), Molecular weight = 233

Figure 2.3. Hard segments

The copolyether ester has a continuous two-phase structure in which the soft segments, A, because of their low glass transition temperatures are responsible for providing flexibility. The polyester segments, B, because of their strong, rapidly crystallizing structure provide physical cross-linking. With increase in the concentration of polyether, elongation increases and breaking strength reduces. Hardness and breaking strength are directly proportional to hard segment concentration. Replacing a portion of a polybutylene terephthalate (PBT) hard segment with polybutylene isophthalate (PBI) units results in an elastic polymer of lower modulus.

By varying the molecular weight of the polymeric glycol and using mixtures of phthalate isomers, a large number of products are possible. Most thermoplastic elastomers of this type are based on polytetramethylene glycol (PTMEG) and PBT. Increasing hard segment concentration increases polymer hardness along with increased melting point and softening point and the polymers become more crystalline, denser and stiffer. In addition tensile strength increases whereas elongation and resilience decrease. With decrease in temperature the polymer stiffens; however it does not embrittle down to the limit of the test. Good melt flow properties and melt stability as well as rapid crystallization rates are necessary for ease of processing and therefore these characteristics must be balanced against the hardness that contributes strength and stiffness.

Block frequency distribution is an important structural parameter that affects the properties of polyether ester block copolymers [5]. The average block sequence length can be calculated for these condensation polymers using a statistical method based on the mole fraction of each component [14]. The average block length not only depends on the composition but also on the molecular weight of the polyetherdiol. For example increasing the molecular weight of the polyetherdiol from 1000 to 2000 while holding other composition variables constant will increase the average tetramethylene terephthalate block length from 8 to 14 [15]. Crystallinity and modulus of the resulting thermoplastic elastomer are expected to increase with longer average sequence lengths for the hard-segment blocks.

Polyether esters have good resistance to different environmental conditions. The ether rich softer segments, A, are resistant to hot water whereas the ester rich harder segments B are less resistant to water but show higher resistance to chemicals compared to the soft segment [15]. Table 2.1 compares two different types of copolyether esters with similar hardness but from different manufacturers [5,16].

The vicat softening temperature is the temperature at which a flat-ended needle penetrates the specimen to the depth of 1 mm under a specific load. The temperature reflects the point of softening to be expected when a material is used in an elevated temperature application [ASTM Standard D1525].

2.1.3.2 POLYMER SYNTHESIS

The preparation of copolyether ester is based on an ester-interchange reaction, as is well known from the preparation of poly(ethylene terephthalate) and poly(butylene terephthalate) [12]. In the first reaction step, as shown in Figure 2.4, dimethyterephthalate is heated to 150-210 °C with an excess of ethylene glycol or butylene glycol in the presence of a catalyst. In the second step, as shown in Figure 2.5, the polycondensation reaction, the product of the first reaction together with a poly(oxyalkylene)- α,ω -diol is heated to 240 or 265 °C, depending on the use of butylene glycol or ethylene glycol in the first step. During the polycondensation reaction the pressure is continuously lowered to below 100 Pa to remove excess low molecular weight glycol and volatile by-products. The composition of the polymer is governed by the ratio of the starting monomers: as there is only a loss of ethylene glycol or butylene glycol, which must take place in order to complete the polycondensation, the weight percentage and the molecular weight of HO-G-OH determines the value of m.

2.1.3.3 SEGMNET CHARACTERISTICS AND PERFORMANCE CONTRIBUTION

2.1.3.3.1 SOFT BLOCK

Polyether Glycol (PEG):

PEG molecular weight affects the water absorption of its copolymers since it shows a high degree of volume swell in ambient temperature water. Partial crystallization

Table 2.1: Properties of Two Different Commercial Competitive Copolyether Esters

Properties	Hytrel-4056	Amitel EM 400
Shore D hardness	40	38
MFR, g/10 min 190°C 220°C	5.3 14.1	30
Vicat softening Point. , °C	108	130
Modulus, psi 10 % Strain 100 % Strain	530	537 1089
Tensile strength, psi	4050	2468
% Elongation at break	550	571
Melting point, °C	148	195
Specific gravity	1.16	1.12
% H ₂ O Absorption 24 hrs	0.6	0.3
Product description	General purpose extrusion grade. Soft segment – PTMEG (1000) Hard segment – a mixture of PBT and PBI. Contains combination non – discoloring Irganox® antioxidant package.	General purpose injection molding grade. Soft segment PTMEG (2000). Hard segment PBT. Contains combination non – discoloring phenolic antioxidant package.

Step 1, Ester interchange:

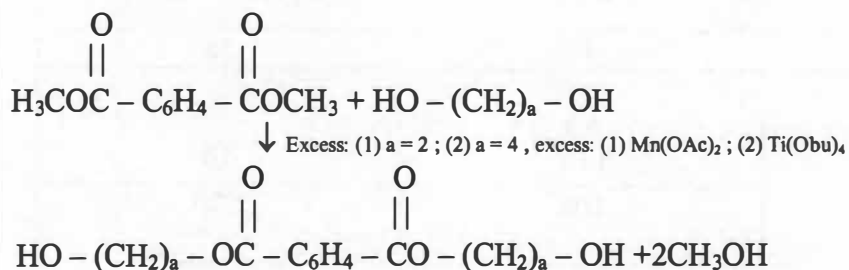


Figure 2.4. Step one - Ester interchange

Step 2, Polycondensation:

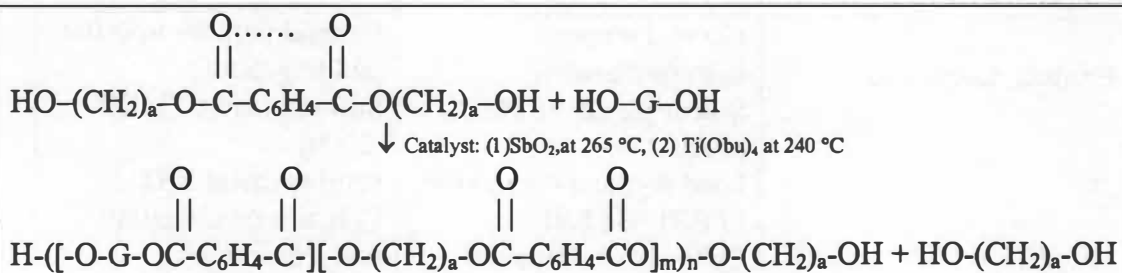


Figure 2.5. Step two – Polycondensation

of the soft segment occurs at molecular weights of 1000 and above, which increases overall copolymer crystallization. Because of the hydrophilic nature of PEG, PEG copolymers are highly susceptible to hydrolytic degradation. For an equivalent molecular weight and copolymer soft segment concentration, PEG systems exhibit 10 times greater volume swell and twice the hydrolysis rate of PPG or PTMEG based polymers in water. Wet strength is poor which is a function of molecular weight; i.e. the higher the molecular weight, the better the wet strength [13,14,17].

Polypropylene Glycol (PPG):

For PPG, phase separation occurs at lower molecular weights than PEG and PTMEG. It has a high melt viscosity, which retards the copolymer formation such that at any given temperature during polymer preparation, the inherent viscosities are low. The rate of thermal degradation is fast resulting in a copolymer of inferior properties. Because of the above properties with PPG, the copolymer is harder to synthesize.

Polytetramethylene Glycol (PTMEG):

It is easier to synthesize copolymers with PTMEG and this material offers the best overall combination of properties. PTMEG segments with molecular weight above 2000 contain crystalline regions. With PTMEG with a molecular weight of 1000, the block copolymer exhibits stress induced orientation and strain induced crystallization when stretched 100 % or more at room temperature.

2.1.3.3.2 HARD BLOCK

Polybutylene Terephthalate (PBT):

PBT offers some advantages over other hard segment materials such as ease of synthesis, high melting point, rapid crystallization rate, and good tensile performance in the resulting copolymer. Set properties depend on ester chain length and the polymer is very sensitive to this variable to the extent that an improvement in elastic recovery means significant physical property loss. The biggest performance sacrifice lies in elastic recovery capabilities [13,14,17].

Polyethylene Terephthalate (PET):

PET very closely resembles PBT allowing formation of copolymers exhibiting excellent performance characteristics. A significant drawback however is that it crystallizes very slowly.

Polybutylene Isophthalate (PBI):

Copolymers with PBI have a very slow rate of crystallization as well, but are stronger. Melting temperatures are considerably lower than PBT. PBI is generally used as a coester to enhance some of the failure properties.

Poly (1,4 – Cyclohexylenedimethylene) Terephthalate:

This polymer has a tendency to phase separate during melt copolymerization resulting in a copolymer with inferior properties in contrast to PBT. However it has excellent tensile set performance.

Transition temperatures for different segment components are given in Table 2.2 [16].

2.1.4 PROPERTIES**2.1.4.1 MECHANICAL PROPERTIES****Hardness:**

Polymer hardness depends on the proportion of hard segment. For polyether ester a practically linear relationship exists between hardness and the proportion of hard segment, independent of the polyether segment composition and regardless of whether the soft segment is incorporated by direct polymerization or by melt-blending. With increase in hard segment concentration, crystallinity, density, tensile strength and stiffness of the polymer increase [18].

c) Dynamic Mechanical Properties:

Dynamic modulus measurements are a very useful tool in establishing the temperature range in which the elastomers can be used. The modulus temperature behavior, hysteresis, set properties and low and high temperature behavior all depend on the degree of phase separation between soft and hard segments [12].

Table 2.2: Homopolymer Transitions of Segment Components

Segment	Molecular weight	Tg (°C)	Tm (°C)
PEG	44.05	- 67	69
PPG	58.00	- 69	75
PTMEG	72.01	- 85	23
PET	192.16	81	270
PBT	219.00	45	232
PBI	220.00	--	153

2.1.4.2 THERMAL PROPERTIES

A comparative study of thermal properties was done using differential scanning calorimetry on different grades of polyether ester [16]. Glass transition temperature (T_g) and melting temperature (T_m) for the soft segment and copolymer T_m of selected copolyether esters was determined. T_g for the hard segment was indistinguishable. It was reported in the earlier work [13,19], that T_g of the soft segment block increases with increasing hard segment content, supported by the fact that there is greater phase mixing of the two segments causing reinforcement of the amorphous (soft) portion. Copolymer T_m mainly depends on hard segment structure and concentration, which increases with increase in crystallinity [14]. T_m is independent of copolyether structure, but increases with increasing molecular weight. It is generally accepted that the softening temperatures of the copolymers lie between the T_g and T_m of the copolymer hard segment. One study determined that the enthalpy of fusion increased simultaneously with the weight % of the hard segment.

The glass transition range of the soft segment governs low temperature brittleness of an elastomer. Shorter polyether segments lower the glass transition temperature. This effect is counteracted, however, by coupling the soft segments to the hard segments, resulting in reduced mobility of the soft segments. A further reduction of soft segment mobility is brought about by incomplete phase separation, leading to increased obstruction of free movement of the soft segments. There is a decline in the mechanical properties at higher temperatures, which mainly depends on the behavior of the hard segment domains and additional chemical crosslinks. The transition temperature values for some of the commercially available copolyether esters are given in Table 2.3 [16].

2.1.4.3 CHEMICAL PROPERTIES

a) Environmental Resistance:

i) Oxidative Degradation:

Copolyether esters are generally stabilized with a single antioxidant for stability in both processing and use. Extensive experiments with a number of commercial

Table 2.3: Transition Temperatures of Copolyether Esters

Polymer				
Hytre 4056		T_g (°C) (a)	T_m (°C) (b)	Melting Range
	Soft Segment	- 60	--	--
	Hard Segment	--	70,148	106 – 172
Hytre 4059FG				
	Soft Segment	- 74	0	- 25 – 12
	Hard Segment	--	130,190	169 – 214
Arnitel EM 400				
	Soft Segment	- 75	0	- 26 - 11
	Hard Segment	--	144,197	172 - 210

(a) Midpoint temperature

(b) Peak temperature

antioxidants led to the conclusion that the addition of 0.5% of a hindered phenolic antioxidant during polymerization resulted in satisfactory stabilization for normal use [12]. For high temperature use (up to 150°C), however, the addition of a thiodipropionate based co-antioxidant is necessary to maintain prolonged service life.

ii) Resistance to Ultra-Violet Radiation:

The polyether segments are susceptible to UV radiation induced oxidation affecting the color and mechanical properties. Stability against UV-initiated degradation improved by incorporating a suitable UV stabilizer.

2.1.4.4 CHEMICAL RESISTANCE

Polyether ester block copolymers are insoluble below their melting point in most solvents [18]. So these polyether esters are unusually resistant to oils and solvents, and this characteristic increases with increasing crystalline content [20]. The classes of solvents to which these thermoplastic elastomers are resistant include aromatic and aliphatic hydrocarbons, phosphate esters, and chlorinated hydraulic fluids, as well as polar solvents such as alcohols, ketones, esters, amines and nitromethane. It has been reported in one of the works [21] that although this group of polymers has excellent resistance to nonpolar material such as oils and hydraulic fluids at elevated temperatures, their resistance to polar fluids is poor at temperatures of 70 °C or above.

2.1.4.5 BLENDING

A segmented elastomer can be blended with a polymer that is compatible with one of its segments. As long as the physical crosslinking remains, the blends will continue to exhibit elastomeric behavior. Plasticizers can be added in order to reduce the hardness and modulus of the copolyether ester. Glass fiber reinforcement can be used to raise the flexural moduli of the elastomeric copolymers to the level of those of non-reinforced thermoplastic polyesters and polyamides. The heat distortion temperature is also increased dramatically. However, the glass fiber reinforced elastomers show considerable decrease in impact strength and a severe loss of elongation [5].

2.2 INTRODUCTION TO MELTBLOWING PROCESS

MB is a one-step process for producing fibrous webs directly from thermoplastic polymers by extruding the polymer melt through a die having several holes, producing fibers that are attenuated by high velocity hot air. The fibers are then collected on a moving belt or a collector drum because of the high velocity air forming a self bonded nonwoven web structure. The fibers formed during the process range from 1-5 μm in diameter. Schematic for MB process is shown in Figure 2.6.

2.2.1 ELEMENTS OF MELT BLOWING PROCESS

A typical MB process consists of the following elements: extruder, metering pump, die assembly, web formation, and winding.

2.2.1.1 EXTRUDER

The extruder is one of the important elements in all polymer processing. It consists of a heated barrel with a rotating screw inside. Its main function is to melt the polymer pellets or granules and feed them to the next step/element. The forward movement of the pellets in the extruder is along the hot walls of the barrel between the flights of the screw. The melting of the pellets in the extruder is due to the heat and friction of the viscous flow and the mechanical action between the screw and the walls of the barrel. There are four different heaters in the extruder, which are set in incremental order. The extruder is divided into three different zones [22]:

i) Feed Zone: In the feed zone the polymer pellets are preheated and pushed to the next zone.

ii) Transition Zone: The transition zone has a decreasing depth channel in order to compress and homogenize the melted polymer.

iii) Metering Zone: This is the last zone in the extruder whose main purpose is to generate maximum pressure in order to pump the molten polymer in the forward direction. At this point the breaker plate controls the pressure generated with a screen pack placed near to the screw discharge. The breaker plate also filters out any impurities such as dirt, foreign particle metal particles and melted polymer lumps.

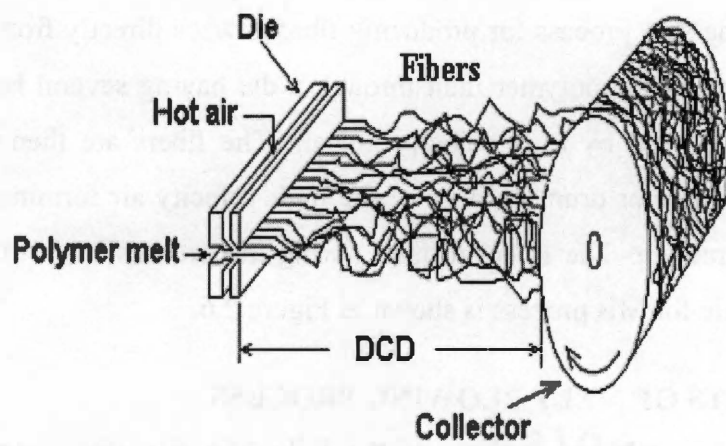


Figure 2.6. Schematic for MB process

2.2.1.2 METERING PUMP

The pump is a set of two intermeshing, positively driven and counter rotating toothed gears. It provides a constant volume of melted polymer to the die assembly for uniform delivery under various operating conditions.

2.2.1.3 DIE ASSEMBLY

The die assembly has four different components:

- i) Polymer Feed Distribution:** This component uses a coathanger shaped feed distribution to provide even polymer flow and residence time across the full width of the die.
- ii) Die Nosepiece:** It is a tapered piece of metal having several hundred holes in a row across its width through which the polymer melt is extruded in order to make filament strands. These are subsequently attenuated by hot air to make fibers as shown in Figure 2.7 [22].
- iii) Air Manifolds:** The function of the manifold is to supply high velocity hot air through the slots on each side of the die nosepiece.
- iv) Air Knives:** These are die components that can be moved to control the air gap on each side of the die. This in turn determines the volume of air that flows concurrently with the extruded fibers.

2.2.1.4 WEB FORMING

The filament strands are attenuated to microfibers when they exit the die holes by means of high velocity hot air and are laid randomly on the surface of the collector in the form of a nonwoven web. The nonwoven web formed is a physically bonded structure containing entangled and partially fused fibers. The cooling and solidification of the fibers are achieved with the help of surrounding cold air. The web can be formed in two ways depending on the type of collector: horizontal or vertical collector. In the case of horizontal collectors, the fibers are laid in horizontal direction on to the collector whereas for vertical collectors the fibers are laid in vertical direction.

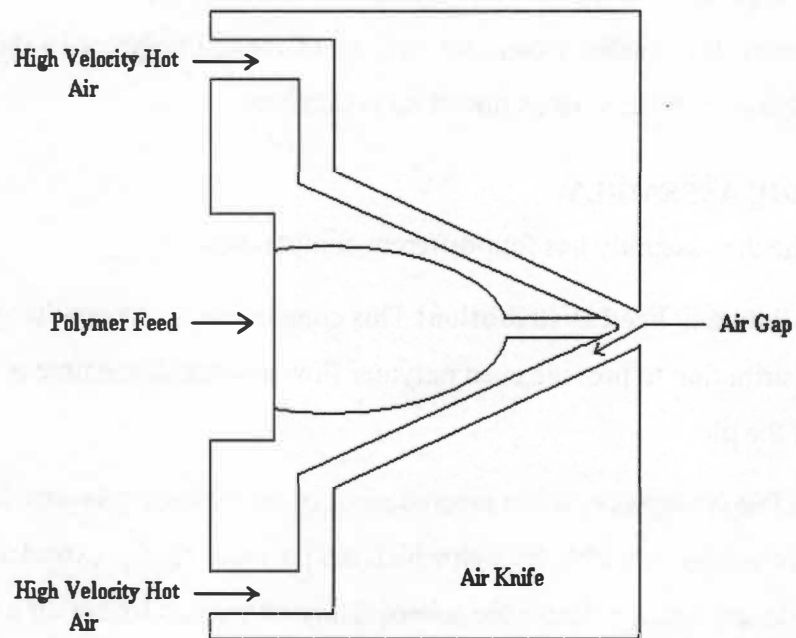


Figure 2.7. Schematic showing the air flow through the die assembly.

2.2.1.5 WINDING

Winding, the last element of the MB system, consists of a positively driven mechanism serving the purpose of collecting the web produced.

2.2.2 PROCESS VARIABLES

Process variables can be divided into three groups: machine/operational variables, off-line variables and material variables.

2.2.2.1 MACHINE VARIABLES

Machine variables, also called operational variables, are related to the machine and can be changed while the equipment is being operated. These variables include air temperature, polymer/die temperature, die to collector distance (DCD), collector speed, polymer throughput and air throughput. All of these affect the final properties of the nonwoven web.

a) Polymer Throughput and Air Flow: both polymer throughput and air flow rate control the final fiber diameter, fiber entanglement, basis weight and the attenuating zone.

b) Polymer/Die and Air Temperature: These variables combined with air flow rate affect the uniformity, shot formation (large globules of nonfibrous polymer larger in diameter than fibers in webs), rope and fly formation, fabric appearance and feel (soft or stiff).

c) Die to Collector Distance: This affects the openness of the fabric, thermal bonding among the fibers and basis weight.

2.2.2.2 OFF-LINE VARIABLES

Off-line variables are fixed during a process run and can only be changed when the machine is not in operation. These variables are air gap, air angle, die setback, and die hole size.

a) Die Hole Size: Die hole size along with die set back affects the fiber size.

b) Air Gap: It affects the degree of fiber breakage by controlling the air exit pressure.

c) Air Angle: It controls the nature of air flow, i.e. as the air angle approaches 90° it results in a high degree of fiber separation or turbulence that leads to random fiber distribution. At an angle of 30° , roped or parallel fibers deposited as loosely coiled bundles of fibers are generated. This structure is undesirable. At angles greater than 30° , attenuation as well as breakage of fibers occurs.

2.2.2.3 MATERIAL VARIABLES

Material variables include polymer type, molecular weight, molecular weight distribution, melt viscosity, polymer additives, and polymer pellet size (powdered or granular). The MB process is amenable to a wide range of polymers in terms of viscosities and blends.

2.3 RHEOLOGY

Rheology is the study of the flow and deformation of materials. It includes all aspects of the deformation of matter under the influence of imposed stress. Rheology gives information about how a polymer behaves internally under different conditions of force, temperature, and other influences. The rheological behavior of a polymer is influenced by temperature, rate of deformation, molecular weight, structure of the polymer, and various additives and fillers [23].

Rheology is an important parameter from the polymer processing point of view because it gives an idea about the stress levels a polymer goes through in operations such as extrusion, fiber spinning, and film blowing. Rheological behavior influences the mechanical behavior of the polymeric material. Two types of flow exist in a flowing polymeric material: shear flow and elongational flow. Measurements such as shear and elongational viscosity, storage modulus and loss modulus obtained during rheological study help in examining and understanding the interactions of different constituents in a multiphase mixture and their influence on the flow and other properties of such polymeric materials.

2.3.1 SHEAR FLOW

When a polymeric fluid is confined between two flat plates of area A separated by a distance D , in a shear flow all the motions are along one coordinate direction, x_1 , the velocity varies along coordinate x_2 and the third direction is neutral as shown in Figure 2.8 [23]. One of the instruments used for measuring shear viscosity is the Advanced Rheometric Expansion System (ARES) produced by TA instruments. It measures viscosity in torsional flow between a stationary and a rotating disk and can operate in a rotational or oscillatory mode as shown in Figure 2.9. Some of the variables involved in shear flow are [24]:

Shear Strain (γ)

When the upper plate is moved in the x_1 direction relative to the lower plate, the polymeric liquid is sheared with the amount of shear strain that is defined as:

$$\gamma = \tan \theta = \frac{S}{D}$$

where: S = Shear displacement

D = Distance between shearing surfaces

Shear Rate/Velocity Gradient ($\dot{\gamma}$)

$$\dot{\gamma} = \frac{\text{Relative Velocity}}{D}$$

Shear Stress (τ)

$$\tau = \frac{F}{A}$$

where: F = Shear force ; A = Area

For a Newtonian fluid, shear stress is directly proportional to the shear rate where the constant of proportionality is viscosity, η . The rate of deformation is directly proportional to the applied stress. In general, with an increase in shear rate, shear viscosity of the polymer decreases, exhibiting the behavior known as shear thinning. For

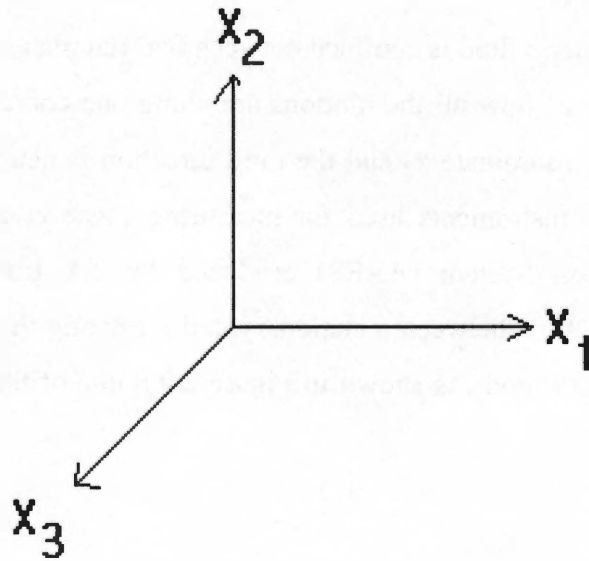


Figure 2.8. Schematic diagram for the measurement of shear viscosity

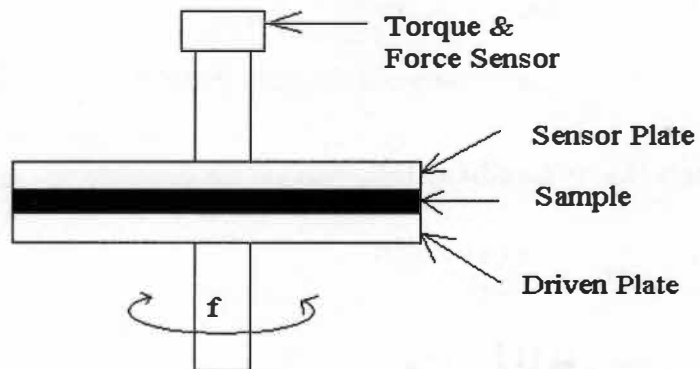


Figure 2.9. Parallel plate geometry

a fluid in motion, either shear stresses are present or normal forces are unequal. For a Newtonian fluid, normal stresses are equal to each other, resulting in the direct relationship between shear stress and shear rate. Unequal normal stress causes motion and deformation of a polymeric fluid and non-Newtonian behavior.

2.3.2 ELONGATIONAL FLOW

When polymeric materials flow in channels or tubes with decreasing cross sectional areas (as in the case of fiber spinnerets) elongational viscosity comes into play. Elongational flow is the dominant mode of flow compared to shear flow when there is a sudden change of shape in a process like fiber spinning. In case of Newtonian liquids, the elongational viscosity is three times the shear viscosity.

The Advanced Capillary Extrusion Rheometer (ACER) is one of the instruments used for measuring the elongational viscosity of polymeric materials. The ACER calculates an apparent viscosity that is derived from the sample by means of capillary extrusion. A ram, operating at constant velocity is pushed through a uniform bored cylinder filled with the polymer sample. The polymer is forced through a die of known diameter and length. The volume of sample extruded per unit is expressed as [25]:

$$Q = \pi R^2 v$$

where: Q = volume of sample extruded

R = internal radius of cylinder

v = liner velocity of ram

The apparent shear rate along the wall of the die is given by:

$$\lambda_a = \frac{4Q}{\pi r^3}$$

where: λ_a = apparent shear rate

r = radius of the die

So for purely Newtonian behavior:

$$\gamma_a = \frac{4R^2v}{r^3}$$

A pressure transducer is located just above the die entrance to measure the pressure. At a constant sample velocity through the die, the apparent shear stress at the wall of the die is given as:

$$\sigma = \frac{Pr}{2L}$$

where: P = pressure

L = length of the die

With a change in the ram speed the resultant equilibrium pressure changes, which give a flow curve of apparent shear stress versus apparent shear rate. The apparent viscosity is given as:

$$\eta_a = \frac{\sigma_a}{\gamma_a}$$

where: η_a = apparent viscosity

Another method was suggested for elongationally characterizing the polymer melts using the hyperbolic dies on ACER [26]. When capillary dies are replaced by hyperbolic dies, the effective elongation viscosity (η_{ef}) can be obtained by the following equation:

$$\dot{\epsilon} = (v_0/L_0)(\exp \epsilon_h - 1)$$

$$\eta_{ef} = \frac{\Delta P}{\dot{\epsilon} \epsilon_h}$$

where $\dot{\epsilon}$ = Elongational strain rate ; ϵ_h = Hencky strain

ΔP = Pressure difference

CHAPTER-3

EXPERIMENTAL DESIGN AND PROCEDURE

This experimental study was carried out in three different phases:

1. Polymer characterization
2. Meltblowing of the polymer
3. Melt blown nonwoven web characterization

3.1 POLYMER CHARACTERIZATION

Arnitel EM400, the copolyether ester used for this study, was provided by DSM Engineering Plastics Inc. The polymer was supplied in pellet form. Polymer characteristics are given in the Table 2.1. Polymer characterization was done by measuring the shear and elongational rheology of the polymer using the ARES and ACER instruments.

For shear rheology, experiments were carried out at four temperatures (200°C, 225°C, 250°C, 275°C) and for elongational rheology experiments were performed at three temperatures (225°C, 250°C, 275°C) for three die profiles (Hencky 5, 6, 7). Different testing temperatures were decided based upon the melting temperature of the polymer and preliminary testing done on the rheological apparatus.

3.1.1 RHEOLOGICAL MEASUREMENT

3.1.1.1 SHEAR VISCOSITY

The polyether ester pellets were melted at 200°C and pressed into 1-2 mm thick sheets using a hot press. These sheets were cut in small circular section and were placed in a desiccator for 5-6 days to avoid the moisture absorption. Since polyether ester is sensitive to moisture, while testing the samples on ARES, a nitrogen (N₂) jacket was placed around the sample to improve the accuracy of results. Before carrying out the viscosity measurements a strain sweep test was done at all the temperatures in order to determine the linear viscoelastic range of the polymer that was two in this case. Once the linear region was decided, dynamic frequency sweep test was performed for each

temperature, three runs were made so as to check the repeatability and minimize the measurement errors.

3.1.1.2 ELONGATIONAL VISCOSITY

For measuring the elongational viscosity the polyether ester pellets were dried in an oven for 5 hours at 80°C and later were sealed in different plastic bags. The first experimental run was done for the Hencky 7 die. Results this small exit die were used to determine the range of the pressure transducer to be used. Elongational viscosities were measured using Hencky 5, 6, and 7 dies.

3.2 MELT BLOWING

There are various operating variables that can be studied in a meltblowing process. The main focus of this research was to study the effect of die temperature, polymer throughput, collector speed and die to collector distance. For each of the four above-mentioned process parameters two extreme values were selected, based on experimental runs done previously at Kimberly-Clark Cooperation and the Textiles and Nonwovens Development Center (TANDEC). Pilot runs at TANDEC provided information on appropriate processing conditions.

In total there were 16 MB nonwoven samples made for different combinations of the process conditions on a 20 inch Accuweb MB pilot line at TANDEC at The University of Tennessee [Table 3.1]. Since the polymer used (Arnitel EM400) is moisture sensitive, a jacket of argon (Ar) gas was provided in the hopper so as to keep the polymer dry.

For each of the trial runs all other operating conditions (air temperature, air velocity) were kept constant. All samples were made using a 55% valve opening of the compressor corresponding to an air pressure of 7.1 psi. The die configuration was:

Nozzle Diameter = 0.0145 inch	Air gap = 0.030 inch
Set back = 0.030 inch	Number of holes = 401

Different settings were used for the different extruder temperature and die temperature as shown in Table 3.2 and Table 3.3.

Table 3.1. Different Combinations of the Processing Parameters

Sample No.	Die Temperature (°C)	DCD (inch)	Throughput (ghm*)	Collector Speed (fpm**)
1	249	8	0.4	5
2	249	16	0.4	5
3	249	16	0.4	10
4	249	8	0.4	10
5	249	8	0.6	5
6	249	16	0.6	5
7	249	16	0.6	10
8	249	8	0.6	10
9	260	8	0.6	10
10	260	16	0.6	10
11	260	16	0.6	5
12	260	8	0.6	5
13	260	8	0.4	5
14	260	16	0.4	5
15	260	16	0.4	10
16	260	8	0.4	10

*ghm = Grams/hole/minute

**fpm = feet/minute

Table 3.2: Extruder Temperature:

For Die Temperature of 249°C	For Die Temperature of 260°C
• Barrel Zone #1: 177°C • Barrel Zone #2: 249°C • Barrel Zone #3: 249°C • Barrel Zone #4: 249°C	• Barrel Zone #1: 177°C • Barrel Zone #2: 260°C • Barrel Zone #3: 260°C • Barrel Zone #4: 260°C

Table 3.3: Air Temperature

For Die Temperature of 249°C	For Die Temperature of 260°C
• Furnace Exit Pipe #1: 177°C • Furnace Exit Pipe #2: 289°C • Furnace Exit Pipe #3: 289°C	• Furnace Exit Pipe #1: 177°C • Furnace Exit Pipe #2: 316°C • Furnace Exit Pipe #3: 316°C

The manner in which the samples were collected was based on the ease of changing the processing conditions. The collector speed was easiest to change and the die temperature was most difficult. The polymer throughput rate was adjusted by weighing the amount of polymer extruded in the form of fibers collected on a plate in a minute.

3.3 MELTBLOWN NONWOVEN WEB CHARACTERIZATION

This phase consisted of physical testing of the nonwoven webs. Tests based on standard methods were performed on the webs for different properties. The nonwoven web samples were preconditioned in standard lab conditions of 65 ± 2 % RH (relative humidity) and 21 ± 1 °C temperature for more than 24 hours before the tests were performed on them.

3.3.1 WEB PROPERTIES

3.3.1.1 AIR PERMEABILITY

Air permeability is the rate of airflow perpendicular through a known area under a prescribed air pressure differential between the two surfaces of a material. It is expressed as ft³/min (cfm). This test was performed according to ASTM Standard D737 [27]. Ten different areas were selected at random over a length of 1m of the nonwoven fabric sample as shown in Figure 3.1. The area of the specimen tested by the test head was approximately 38.3 cm².

3.3.1.2 BASIS WEIGHT

This test gives the mass per unit area of the nonwoven fabric. It is expressed as grams per square meter (g/m²), gsm. This test was performed according to ASTM Standard D3776 [28]. Ten different areas were selected at random over a length of 1m of the nonwoven fabric sample as shown in Figure 3.2. The area of the specimen cut to measure the weight was approximately 100 cm².

3.3.1.3 TEAR STRENGTH

This test measures the average force in grams (g) required to propagate a single-rip tear starting from a cut in a nonwoven fabric using a falling pendulum apparatus (Elmendorf apparatus). This test was performed according to ASTM Standard D5734

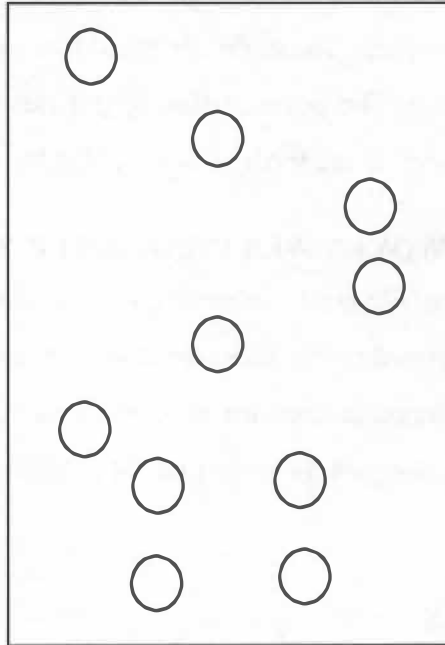


Figure 3.1. Schematic showing the manner in which specimens were obtained for air permeability

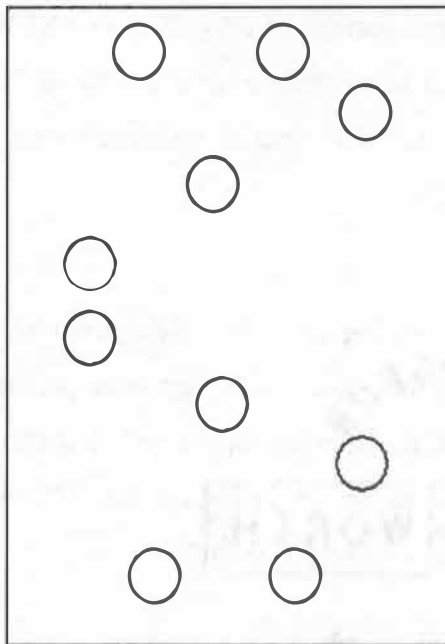


Figure 3.2. Schematic showing the manner in which specimens were obtained for basis weight

[28]. Five specimens each for MD and CD were cut from randomly selected area as shown in Figure 3.3. The area of the specimen tested is 4 inch $\times$ 2.5 inch.

3.3.1.4 TENSILE STRENGTH

This test measures two properties at the same time. It gives the peak breaking force (in lbs), which is maximum force applied to a material before it breaks or ruptures. Secondly it gives the peak elongation, which is the ratio of the maximum extension of the material to the original length of the material (expressed as a percent). This test was performed according to ASTM Standard D5035 [28]. Five specimens each for MD and CD were cut from randomly selected area as shown in Figure 3.4. The area of the specimen tested was 1 inch $\times$ 8 inch.

3.3.1.5 THICKNESS

Thickness of all the samples was measured in mm at a specified pressure of 4.14 ± 0.21 kPa. This test was performed according to ASTM Standard D5729 [28]. Ten spots were measure from randomly selected areas as shown in Figure 3.5. The dimension of the circular presser foot is 25.4 ± 0.02 mm diameter and that of anvil is 38 mm.

3.3.1.6 HYDROSTATIC HEAD

This test measures the resistance (in mbar) of nonwoven fabrics to the penetration of water under low hydrostatic pressure. Tests were performed according to INDA Standard IST 80.6 [29]. Four spots of areas 100 cm^2 were selected at random as shown in Figure 3.6.

3.3.2 WEB STRUCTURE

Any web property is a combination of fiber properties and web structure. Web structures such as basis weight uniformity, fiber bundle size fiber orientation, and pore size. were measured using test methods developed at The University of Tennessee. The instrument (WebPro) consists of a personal computer (386sx), frame grabber, system monitor, video camera, video monitor, microscope and illumination device [30].

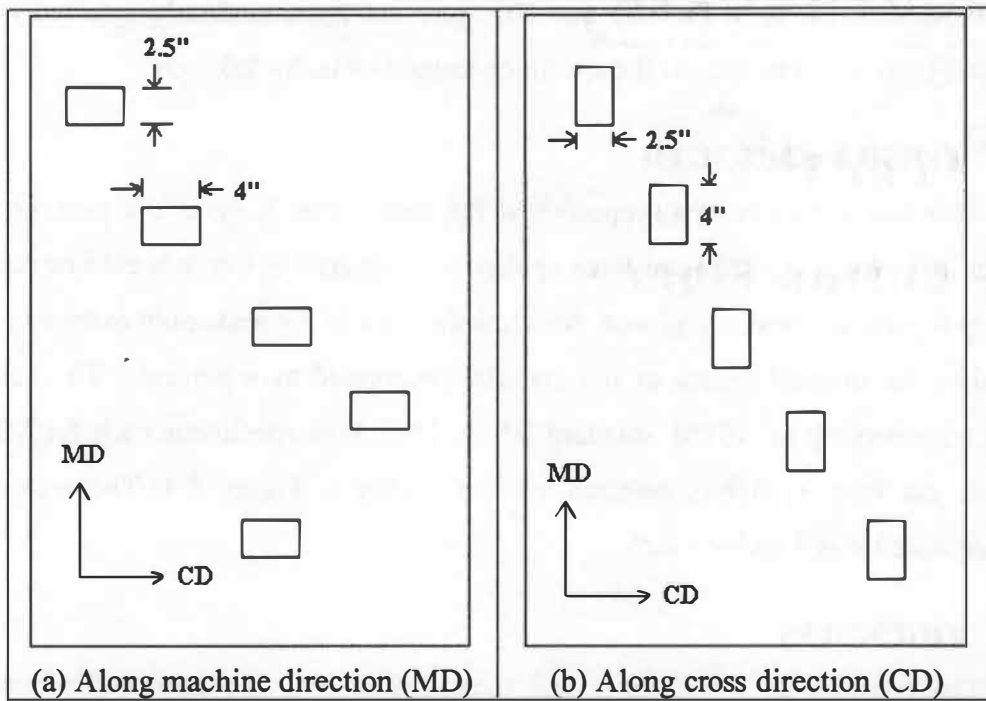


Figure 3.3. Schematic showing the manner in which specimens were obtained for tear strength

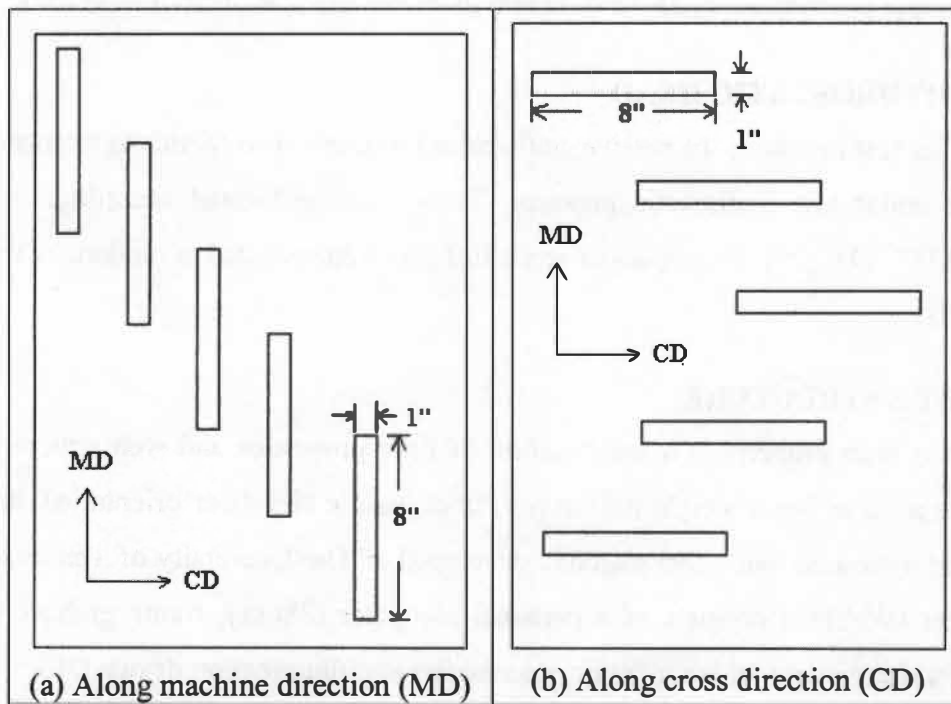


Figure 3.4. Schematic showing the manner in which specimens were obtained for tensile strength

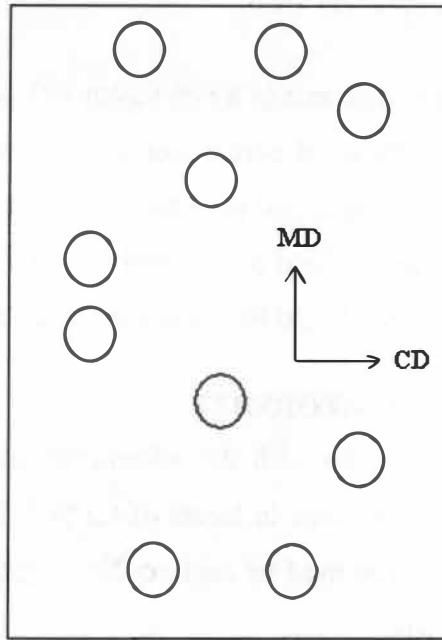


Figure 3.5. Schematic showing the manner in which specimens were obtained for thickness

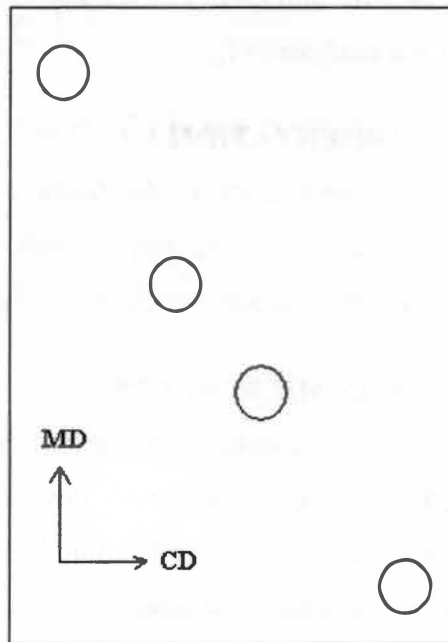


Figure 3.6 Schematic showing the manner in which specimens were obtained for hydrostatic head

3.3.2.1 PORE SIZE

Pore is defined as a void area in a nonwoven web surrounded by fibers [30]. Pore analysis provides results in terms of pore diameter, pore number/unit area (N/mm^2), pore cover ratio, pore orientation angle, and pore aspect ratio (pore shape). Pores in a web are brighter than fibers when bright-field transmitted illumination is used. Objective lens A4 was used. Sample size of 20 inch $\times$ 20 inch was cut for the analysis.

3.3.2.2 BASIS WEIGHT UNIFORMITY

This analysis provides us with the information about the how consistent is the basis weight of the nonwoven web in terms of CV% [31]. A camera, Navitor 1x with minimum zoom objective was used to capture the images. Sample size of 20 inch $\times$ 20 inch was cut for the analysis.

3.3.2.3 FIBER BUNDLE DIAMETER

This analysis gives the average size of the fiber bundles (in μm) present in the web. A camera, Navitor 1x with minimum zoom objective was used. Sample size of 20 inch $\times$ 20 inch was cut for the analysis [32].

3.3.2.4 FIBER BUNDLE ORIENTATION

This analysis gives the orientation of the fibers across MD and CD for a given nonwoven web sample [33]. A camera, Navitor 1x with minimum zoom objective was used. Sample size of 20 inch $\times$ 20 inch was cut for the analysis.

3.4 SCANNING ELECTRON MICROSCOPE

SEM images of the fabrics and the samples from tensile tests were taken using a electron microscope. Back-scattered images, under low gas pressure, were taken in order to minimize problems due to static charge generation. Some cross sectional micrographs were also obtained using a Leica confocal laser microscope by microtoming the sample in epoxide.

3.5 STATISTICAL ANALYSIS

As mentioned earlier the samples were collected based on the ease of changing the processing conditions. Since temperature was most difficult to change so first eight

samples were collected at lower temperature (249°C) for two different throughputs, two different die to collector speed and two different die to collector distance. The design of experiment is given in Figure 3.7.

The analysis was done to study the relation between process parameters and web properties; web properties and web structure and web structure and process parameters. While analyzing the data process parameters were treated as independent variables and physical properties were treated as dependent variables. The different combinations of the process parameters were designed in a full factorial design. Factorial designs are used when an experiment involves several factors and it is necessary to study the joint effect of the factors on a response [34]. Two levels were selected for each factor i.e. low and high based up the preliminary runs. Statistical analysis was done using JMP software. Analysis was done for the mean and the standard deviation of the data obtained for the web properties measured by plotting variability charts, effect tests and least square mean plots. In total four web properties were statistically analyzed air permeability, tear strength, peak elongation and peak force because of their importance in the end use fabric.

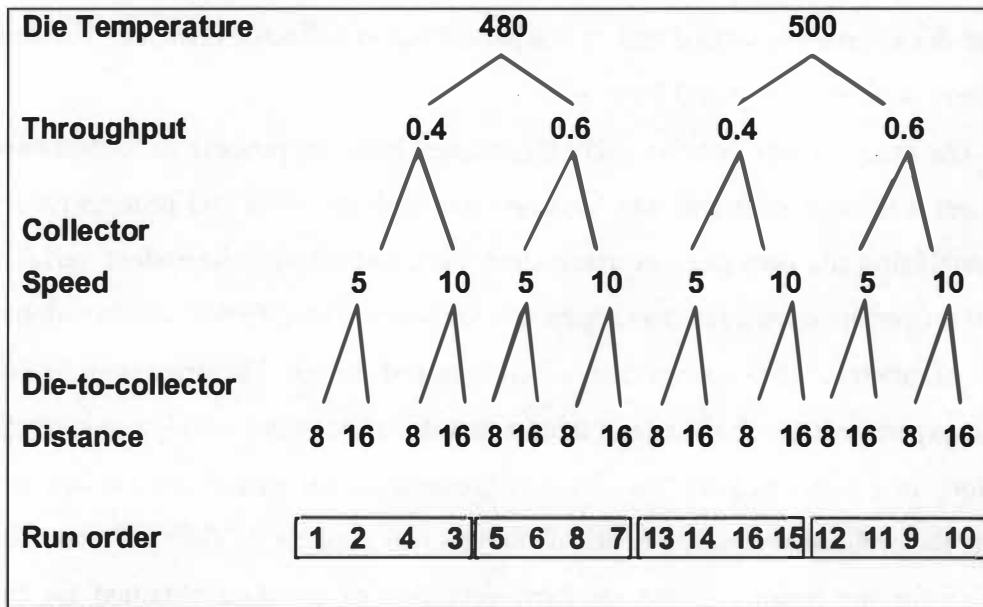


Figure 3.7: Design of experiment

CHAPTER-4

RESULTS AND DISSCUSSION

4.1 RHEOLOGY

4.1.1 SHEAR RHEOLOGY

The shear rheology of Arnitel EM400 was determined on the ARES instrument at four different temperatures. Complex viscosities at different temperatures are presented in Figure 4.1 and storage and loss moduli are shown in Figure 4.2.

As can be seen from the graph, viscosity appears to be constant at 225°C, 250°C, and 275°C temperatures with increase in angular frequency, except for 275°C where the viscosity decreases with increase in the angular frequency (which might be due to polymer degradation at this temperature). This indicates that, except at low temperature the polymer fluid is behaving more like a Newtonian fluid. Moreover viscosity is decreasing with increase in temperature, which is another characteristic of Newtonian fluids. However, at 200°C viscosity follows a different trend compared to rest of the temperatures, which suggests that 200°C is not sufficient to melt the polymer.

The storage modulus (G') at 200°C is higher than the loss modulus (G'') whereas the reverse is true for the other temperatures. This indicates that the polymer behaves more like an elastic solid at 200°C and a viscous fluid at 225°C, 250°C, and 275°C. Again at 275°C the plot shows polymer degradation since G'' is not following the regular trend.

Although 195°C is the melting temperature for the resin, the resin did not melt fully at 200°C, which indicates that the polymer should be processed at temperature higher than 200°C. It was highly viscous, whereas at around 225°C the resin was in a fluid state indicating that the appropriate processing temperature for the resin is around 20-25°C higher than the melting temperature.

4.1.2 ELONGATIONAL RHEOLOGY

The elongational rheology of Arnitel EM400 was determined using the ACER instrument at different temperatures, and Hencky strains [Figures 4.3 - 4.5].

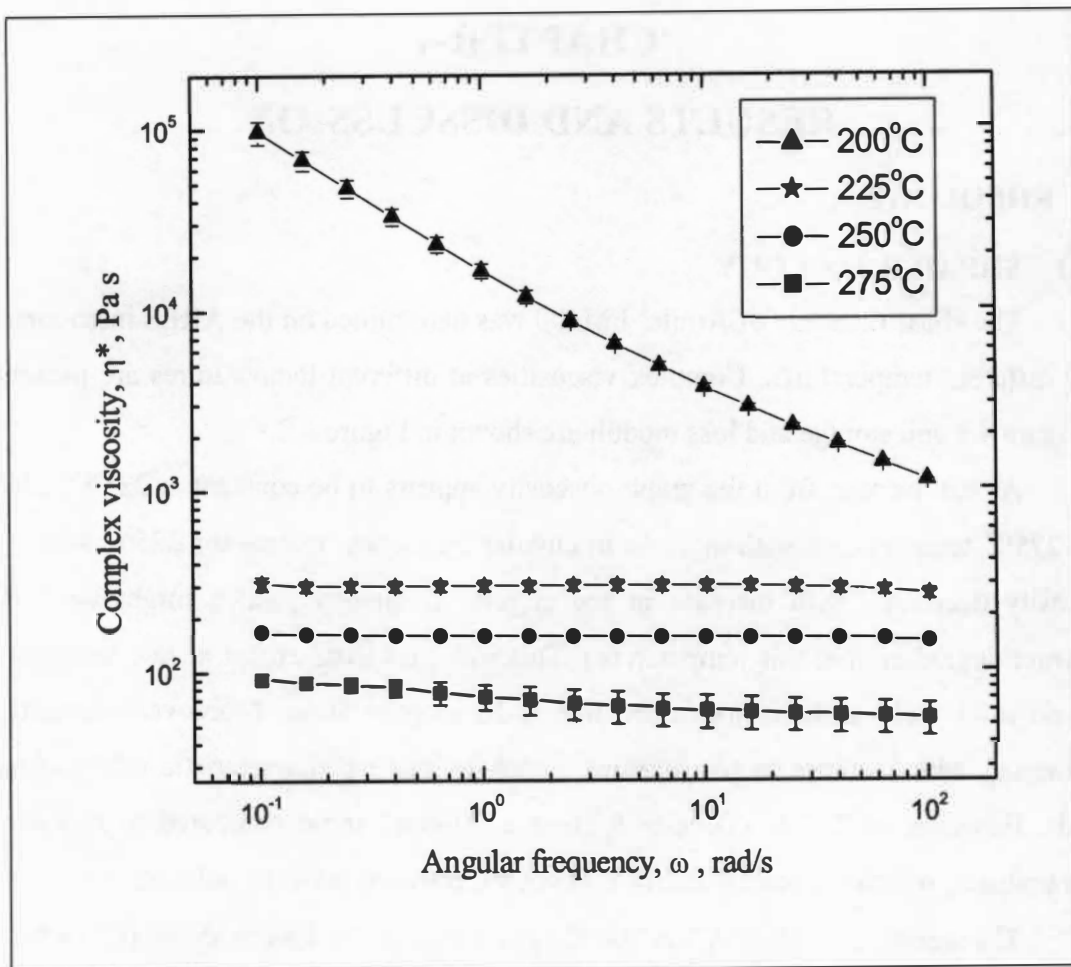


Figure 4.1. Complex viscosity vs. Angular frequency

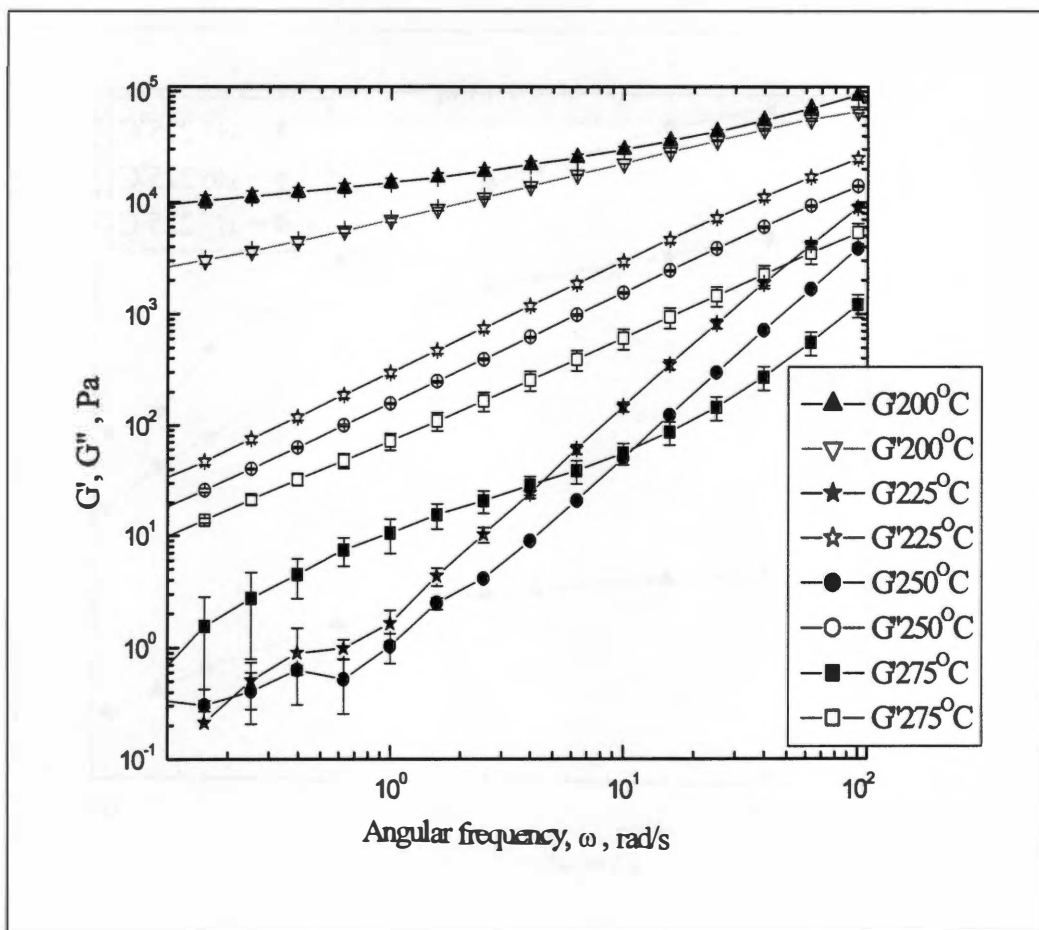


Figure 4.2. G' and G'' vs. Angular frequency

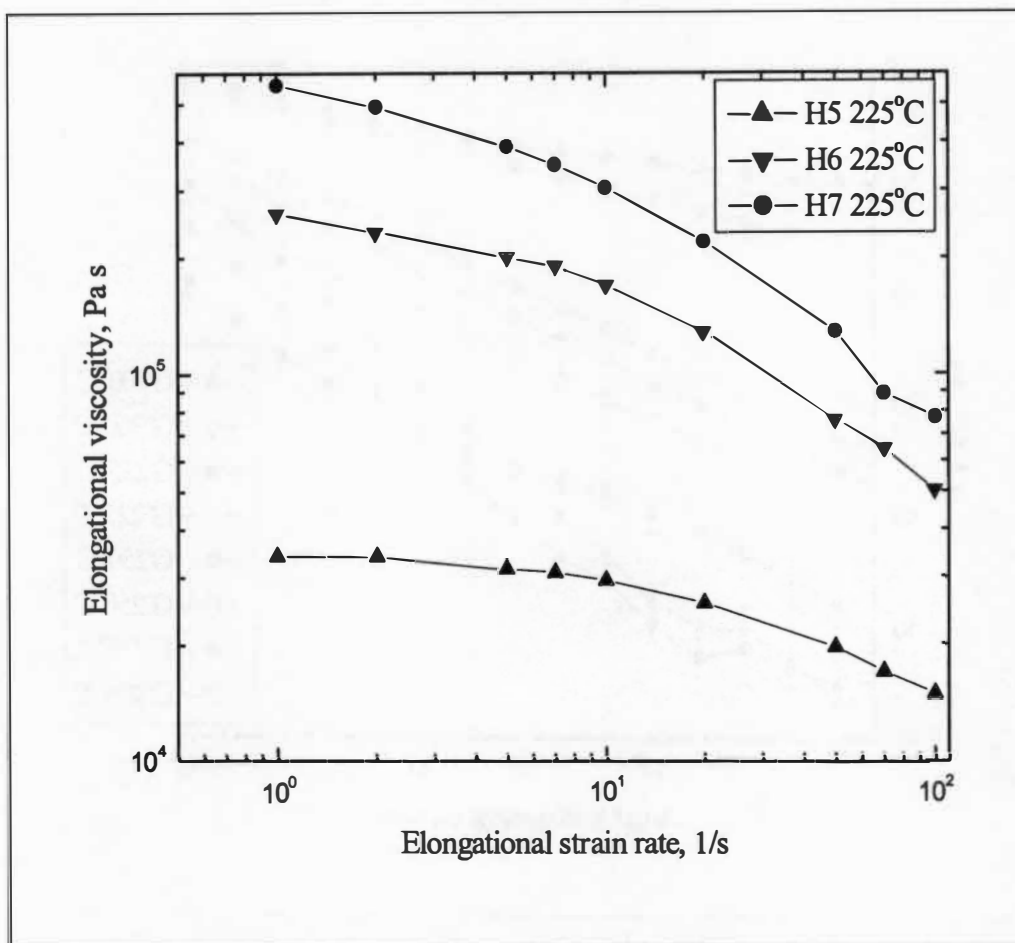


Figure 4.3. Elongational viscosity vs. Elongational strain rate at 225°C for different hencky strains

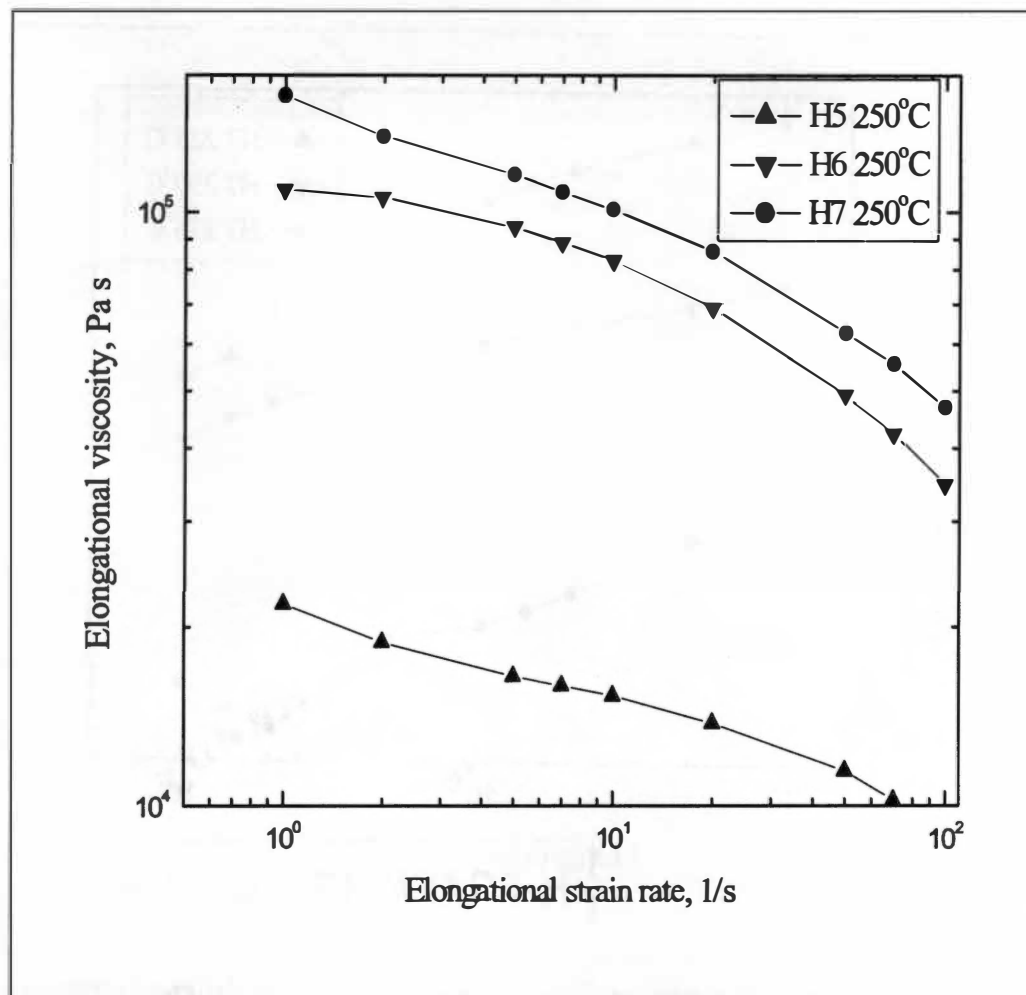


Figure 4.4. Elongational viscosity vs. Elongational strain rate at 250°C for different hencky strains

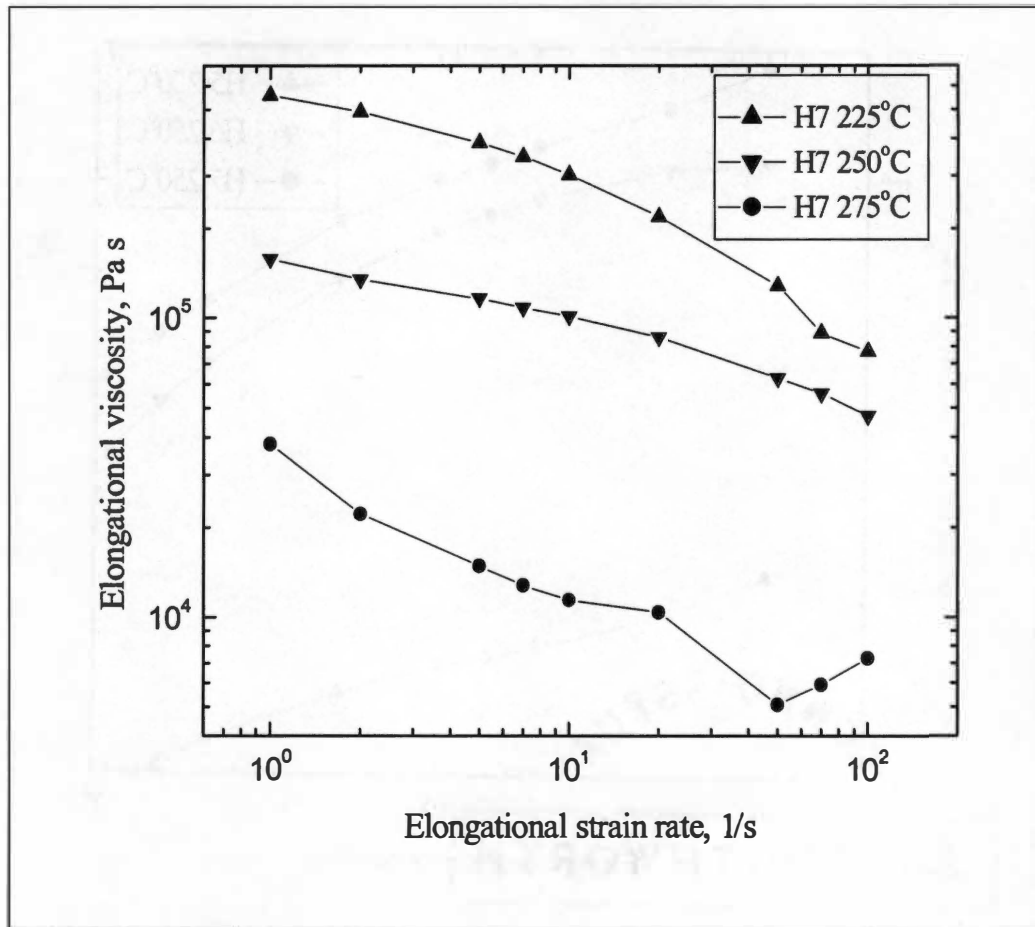


Figure 4.5. Elongational viscosity vs. Elongational strain rate for different temperatures

The higher the Hencky strain, the higher is the elongational viscosity the polymer experiences, which is a characteristic of strain hardening. With an increase in Hencky strain the viscosity goes up and with increase in elongational strain rate the elongational viscosity decreases, which is characteristic strain rate thinning of polymer melts.

The polymer degradation is again indicated at 275°C in Figure 4.5. This gives information about the range of temperatures at which the polymer can be processed without getting degraded.

At a temperature of 275°C dense white fumes were observed coming out of the instrument. This could indicate two things. Either this temperature is too high for the polymer resulting in polymer degradation. Alternatively there might be some amount of moisture present in the polymer which should be removed completely to obtain accurate measurement. The extruded polymer collected at 275°C had a wax like feeling and was a mixture of brown and white material whereas at other temperatures this was not observed. And also the polymer extruded out of the die in form of fiber was hot at 275°C whereas for 225°C and 250°C the fiber extruded was cold. All this indicates that 275°C is too high for the polymer and is resulting in polymer degradation.

At lower strain rates the extruded fiber was cold and more like a fiber whereas at higher strain rates resin was extruded out in hot liquid form in form of lumps. This indicates the recoiling of the polymer which means at higher strain rates polymer is contracting in itself because of its elastomeric nature.

4.2 MELT BLOWING

During the melt blowing of the resin on the 20-inch Accuweb pilot line it was observed that the web had a tendency to stick on the collecting drum which indicates some heat retention in the fibers. This was more apparent at the high throughput of 1.0 g/h/m, where the fabric was sticking badly to the collecting drum and the fibers were still in a semi molten state when they contacted the collector. These webs were very harsh and stiff. This behavior of the polymer suggests the necessity to cool the collecting drum simultaneously as the nonwoven web is collected or use a higher DCD.

SEM images were acquired, as shown in Figure 4.6 for one of the samples in order to study the surface morphology of the nonwoven web.

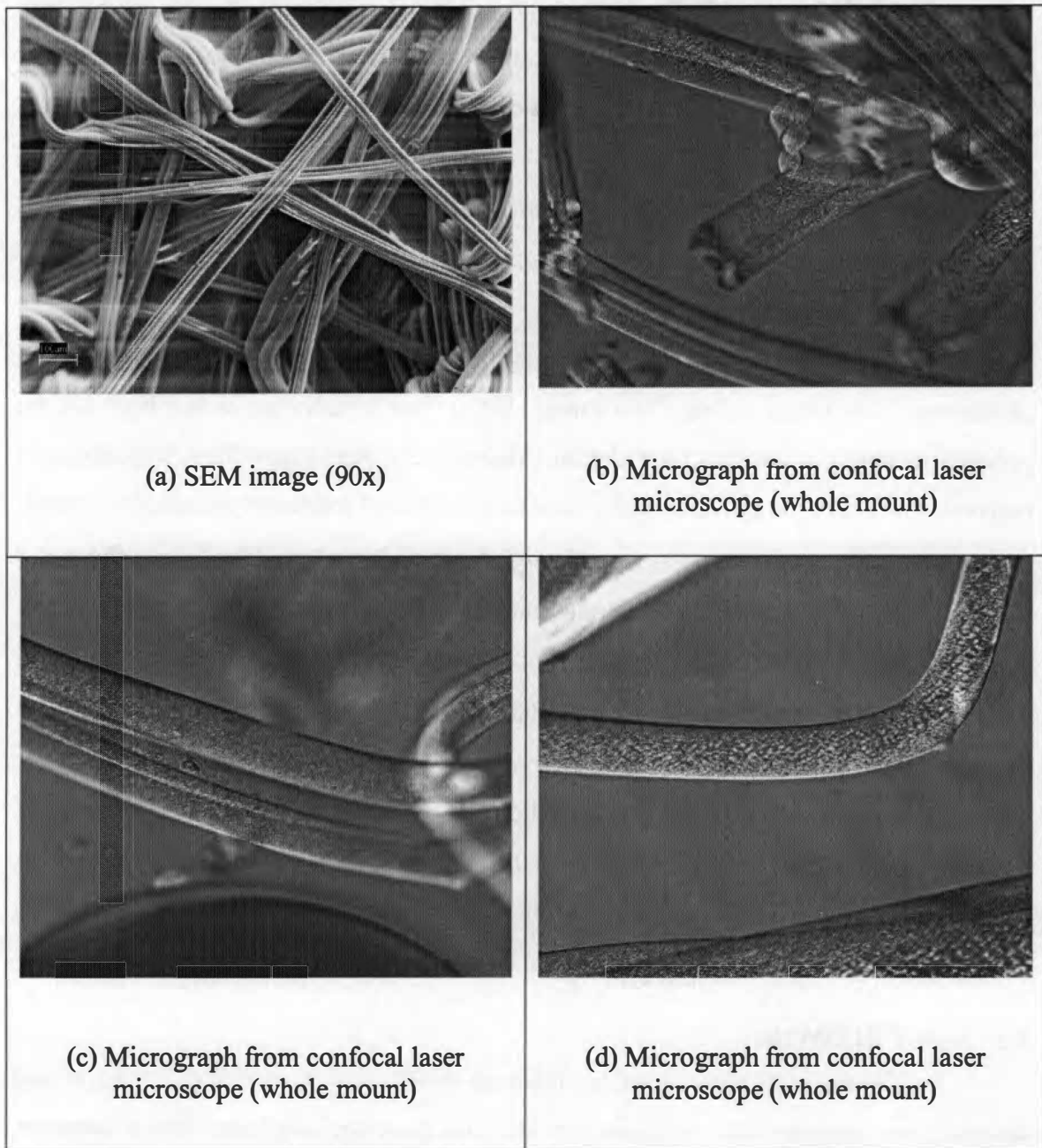


Figure 4.6. Micrographs of the nonwoven web

From the SEM image as shown in Figure 4.6 (a), it appears that the most of the fibers in the web are in bundles and are fused with each other. Individual fibers are very few and hard to locate. Also the fiber distribution in the web is isotropic however the fibers in bundles are parallel to each other over a long distance. This might be due to the fact that fibers contact each other near to the die and are very hot, fusing together before becoming entangled. The fusion among the fibers was confirmed by obtaining cross-sectional images of the fibers by microtoming the web and observing them under a confocal laser microscope as shown in Figure 4.7. The fibers in the nonwoven web are somewhere between the multilobed single fiber and fused fibers typical of spandex.

Another observation made from these micrographs is that pitting can be observed in the cross section micrographs, which might be an image artifact or it can be a structural defect on the surface. Some whole mount slides were prepared by taking out some fibers from the web and observing them under the confocal laser microscope in order to study the surface of the fibers [Figure 4.6 (b),(c),(d)]. It was observed that even the surface of the fibers had similar pitted structures as observed in the cross section of the fiber. This confirmed that these pitted structures are not image artifacts but structural defects/characteristics of the fibers.

4.3 MELTBLOWN NONWOVEN WEB CHARACTERIZATION

The webs were characterized to determine how the process variables affected nonwoven web properties. The process variables examined were: die temperature, throughput, collector speed, and die to collector distance. Properties measured were air permeability, tear strength, peak elongation and peak force. The information provided by this experiment might help in setting the machine and process parameters to get the required end use properties. Results obtained are given in Tables 4.1 - 4.2.

4.3.1 AIR PERMEABILITY

4.3.1.1 MEAN AIR PERMEABILITY

In order to study the effect of all the four parameters on air permeability and their interaction among themselves, a variability chart was plotted shown in Figure 4.8.

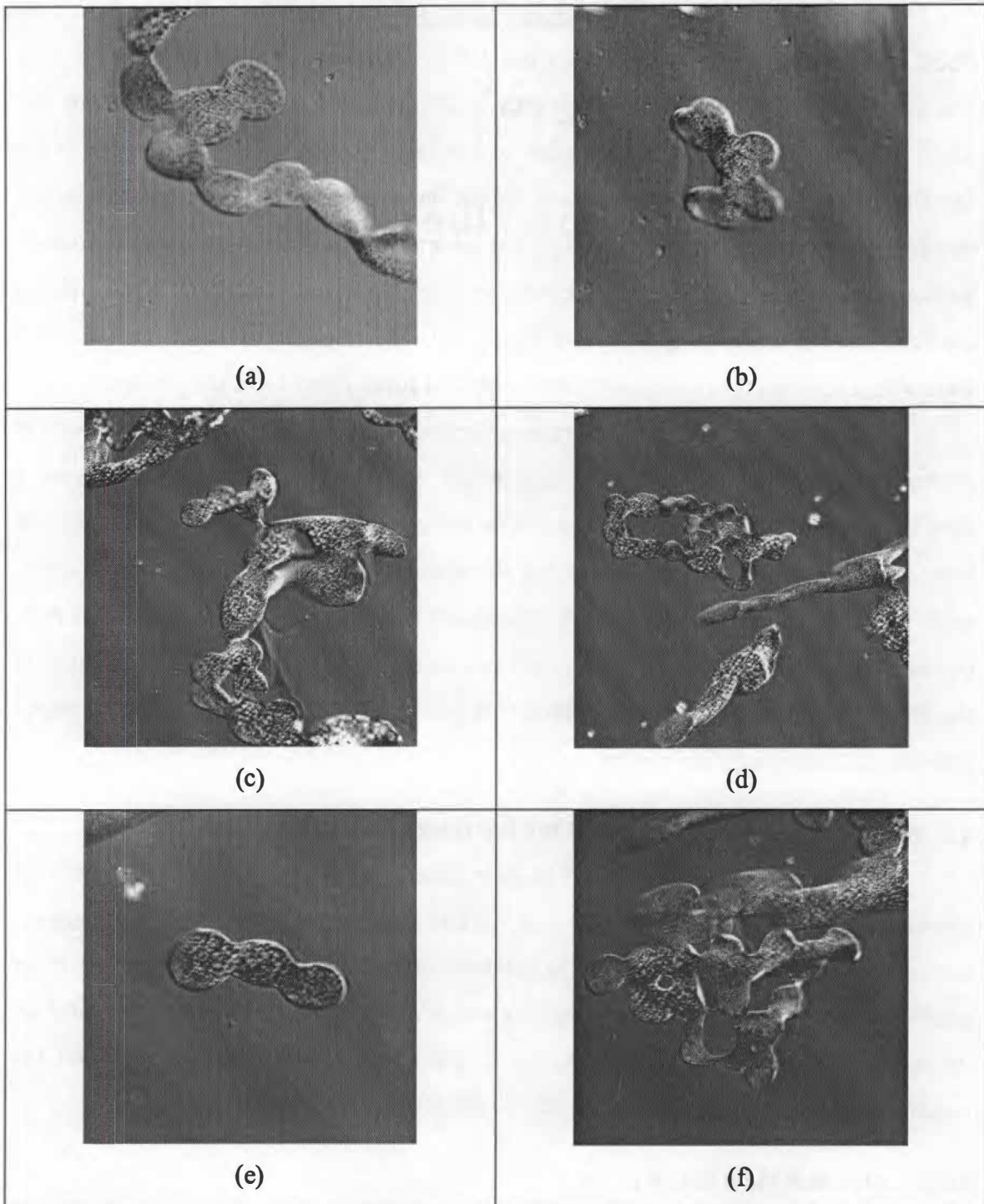


Figure 4.7. Cross-sectional image of the fibers in the nonwoven web obtained from confocal laser microscope

Table 4.1: Web Properties Test Results

Sample Number	Basis Weight (gsm)	Thickness (mm)	Air Permeability (cfm)	Hydrohead (mbar)	Tear Strength (g)	
					MD	CD
1	248.2	1.0002	156.3	7.33	471	823.6
2	256.8	1.3622	232.6	7.33	1378	1576
3	166.4	1.112	433.2	5.17	1736	1664
4	164.2	1.1435	326.6	6.5	453.2	762.2
5	495.8	1.4166	98.65	7.5	703	1470
6	421.4	1.7694	185.8	6.83	1141.4	2230
7	260.2	1.4335	311.4	6.33	1298	1574
8	257.4	1.0179	226.9	6.33	494.4	1200.2
9	257.4	0.967	184.1	6.33	438.4	751.8
10	255.6	1.3729	262.5	6	808.2	1313
11	542.2	2 +	115.5	7.5	1013	1632
12	549.4	1.3247	57.94	8	678	1424
13	353	1.0871	68.63	8.33	407.4	837.2
14	362.2	1.5277	131.2	7.5	1264	2110
15	167.8	1.041	291.1	5.83	1115.2	1550
16	162.6	0.7566	187	7.33	259.6	535.4

Table 4.1. Continued

Sample Number	Peak Elongation (%)		Peak Force (Lbs)		Modulus (lbs/inch)	
	MD	CD	MD	CD	MD	CD
1	471	823.6	389.504	386.43	7.99	7.03
2	1378	1576	220.916	355.78	4.58	4.58
3	1736	1664	190.75	368.11	2.28	2
4	453.2	762.2	284.89	326.58	3.35	3.87
5	703	1470	335.8	336.73	15.46	13.82
6	1141.4	2230	273.63	315.89	10.98	6.42
7	1298	1574	253.19	291.31	4.89	4.24
8	494.4	1200.2	365.01	303.17	8.6	6.12
9	438.4	751.8	342.39	275.32	8.96	6.72
10	808.2	1313	292.79	283.72	5.58	4.71
11	1013	1632	300.42	291.21	12.5	12.3
12	678	1424	480.89	331.63	26.67	19.44
13	407.4	837.2	401.89	344.5	12.68	10.44
14	1264	2110	286.69	493.86	6.37	6.66
15	1115.2	1550	412.69	455.17	3.82	2.7
16	259.6	535.4	337.45	321.63	4.78	4.07

Table 4.2: Web Structure Test Results

Sample Number	Fiber Bundle Orientation (MD/CD)	Mean Fiber Bundle Diameter (μm)	Pore Diameter Distribution (Cover %)	Gray Level (Average Basis Wt. Inverse, gsm)	Basis Wt. Web Uniformity	
					Minimum CV%	Maximum CV%
1	1.4	49.5	0.39	71.77	3.7	20.8
2	1.1	55	0.77	74.5	8.2	30.5
3	1.2	76.3	3.8	89.67	7.2	31.1
4	1.4	59.9	1.4	87.8	4.8	22.9
5	1.6	64	0.2	65.1	2.6	17.4
6	2.2	57.3	0.23	56.87	5.7	25.3
7	1.3	55.5	1.8	79.7	8.8	32
8	1.8	56.3	1.1	91.5	3.7	21.7
9	1.6	53.1	1	91.6	3	19
10	1.3	58.8	0.97	81.63	6.5	27.7
11	1.5	70.2	0.21	50.8	4.2	23.1
12	1.4	63.4	0.63	80.27	6.3	15.4
13	1.4	64.1	0.56	65.83	6.9	16.5
14	1.4	64	0.57	49.67	5.9	23.9
15	1.2	67.2	1.8	81.87	6.9	27.9
16	1.2	53.3	1.2	84.33	5.5	20.6

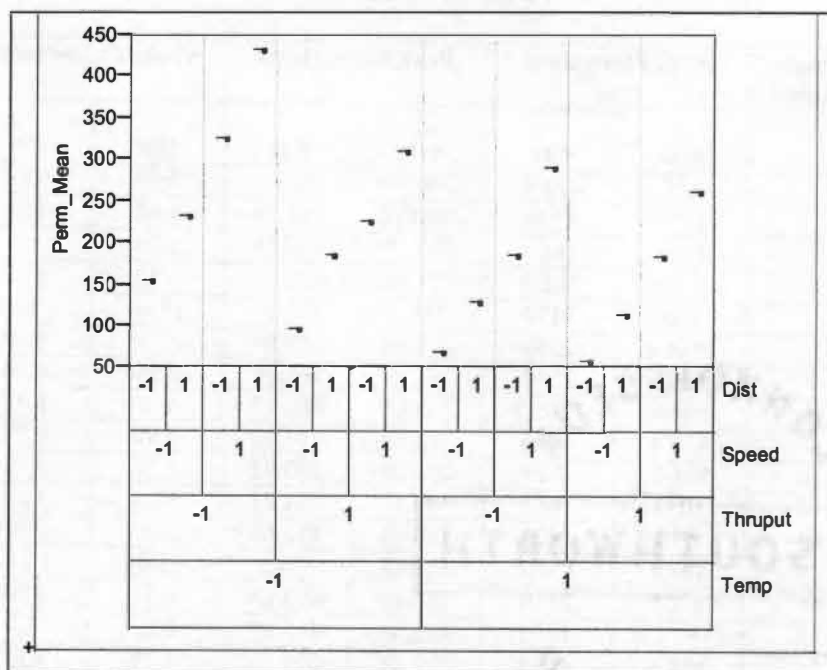


Figure 4.8. Variability chart for mean air permeability

The effect of throughput is not apparent at higher die temperature but for lower die temperature, lower throughput results in higher air permeability. Fitting a full model JMP resulted in seven significant terms (based on the normal plot) including all main effects, throughput*die temperature; throughput*collector speed; throughput* collector speed *die temperature. The output of the model fitted with these terms is given in Figure 4.9.

The interaction of throughput and collector speed and the three-way interaction temperature, throughput and collector speed were not significant at 95% confidence level. Their sums of square are much smaller compared to the other terms. These terms were dropped and the full model contained all main effects and the temperature*throughput interaction term. The full model is given in Figure 4.10.

Increase in the DCD, increases the air permeability. The effect of collector speed is also quite visible from the chart; increasing collector speed results in higher air permeability [Figure 4.11]. With increase in DCD and collector speed the web gets thinner, which results in increase in air permeability. Also with increase in DCD fibers have to travel longer distance and so get more time to entangle among themselves which results in more randomly distributed fibers because of change in air flow pattern resulting in lower air permeability. Air permeability is also related to the fiber diameter and the pore cover ratio (cover%), which is defined as total pore area divided by the total web image area defined as a void area, at the web structure level. Based on the web structure results given in Table 4.2 some graphs were obtained as shown in Figures 4.12 – 4.17 in order to study the effect of various interactions. With increase in DCD the mean fiber bundle diameter increases by approximately 9% [Figure 4.12] (while averaging over other factors) because of which the cover increases by approximately by 62% [Figure 4.13]. This explains the increase of air permeability with DCD.

All main effects are significant. The effect of speed is the largest, followed by die temperature and DCD. An increase in temperature is expected to give more fiber attenuation, which should increase the air permeability, but here the air permeability decreased. With increase in throughput however web gets thicker thereby reducing the air permeability. Increase in collector speed or DCD decreases web thickness (averaging

Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Temp	1	1	28348.457	160.9316	<.0001
Thruput	1	1	9208.322	52.2748	<.0001
Temp*Thruput	1	1	4491.010	25.4951	0.0010
Speed	1	1	86462.462	490.8396	<.0001
Thruput*Speed	1	1	932.692	5.2948	0.0504
Dist	1	1	26992.847	153.2360	<.0001
Temp*Thruput*Speed	1	1	783.160	4.4459	0.0680

Figure 4.9. First model for mean air permeability

Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Temp	1	1	28348.457	90.7131	<.0001
Thruput	1	1	9208.322	29.4660	0.0003
Temp*Thruput	1	1	4491.010	14.3709	0.0035
Speed	1	1	86462.462	276.6738	<.0001
Dist	1	1	26992.847	86.3752	<.0001

Figure 4.10. Final model for mean air permeability

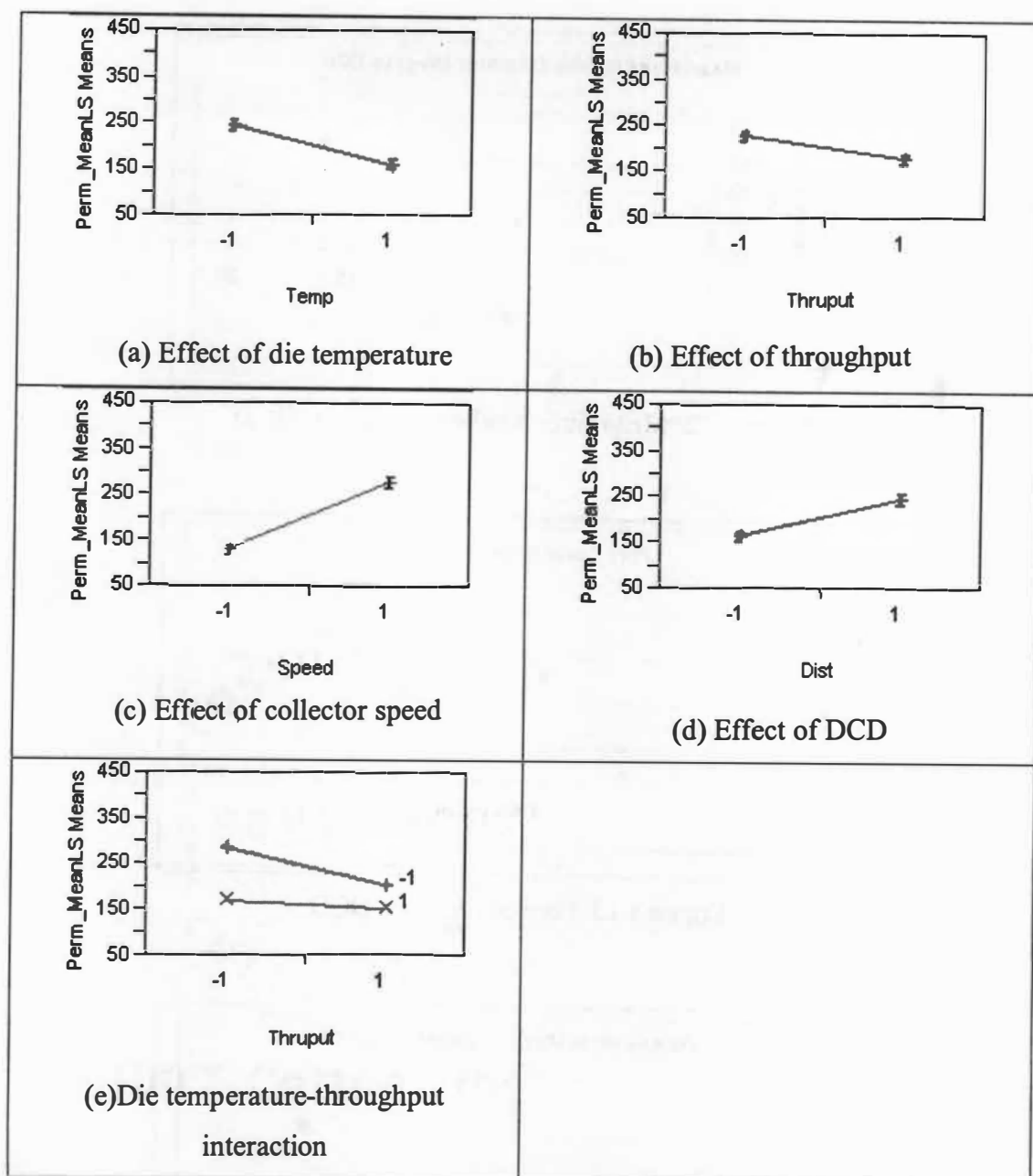


Figure 4.11. LS means plot for significant effects in mean air permeability

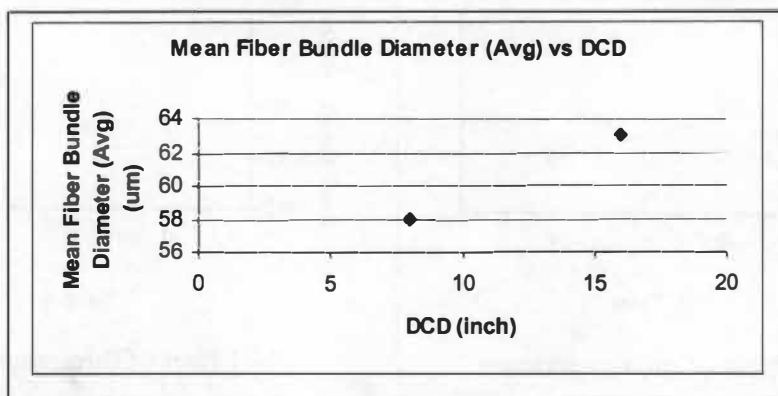


Figure 4.12. Mean fiber bundle diameter vs. DCD

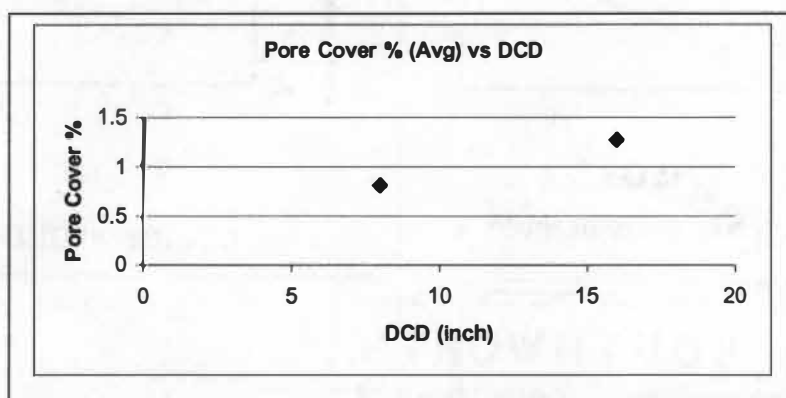


Figure 4.13. Pore cover % vs. DCD

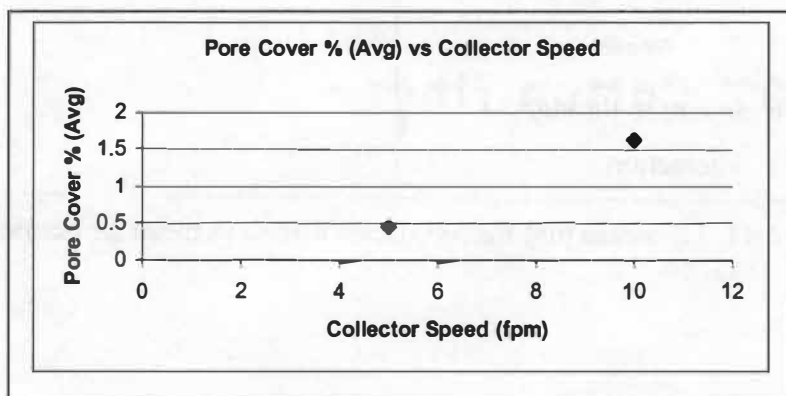


Figure 4.14. Pore cover % vs. Collector speed

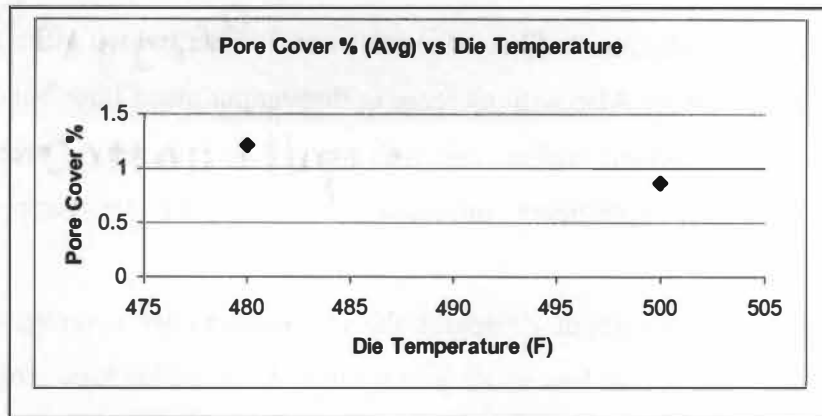


Figure 4.15. Pore cover % vs. Die temperature

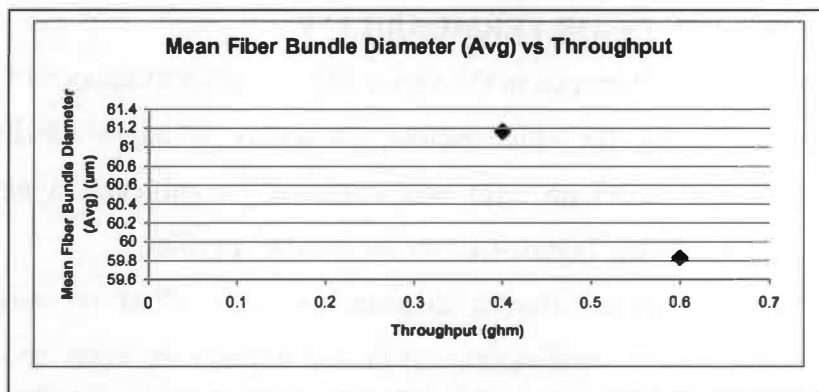


Figure 4.16. Mean fiber bundle diameter % vs. Throughput

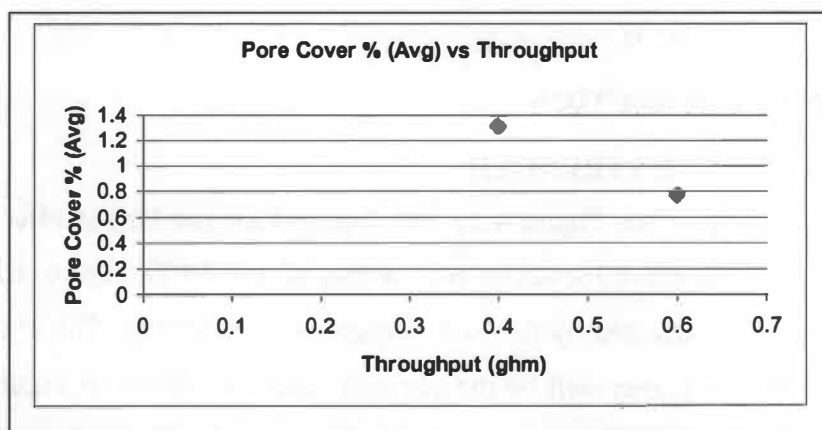


Figure 4.17. Pore cover % vs. Throughput

over other factors) and also limits fiber adhesion to each other, which affects the overall air permeability of the web. Also with increase in throughput mean fiber bundle diameter reduces [Figure 4.16] which makes the web very dense thereby lowering the air permeability. The only significant interaction was that of die temperature with throughput.

Increasing the throughput decreases the air permeability (averaged over other factors). However the relative loss in air permeability is small for high temperature but considerable for the lower temperature. In order to maximize air permeability the machine should be run at low temperature, low throughput, high collector speed and high DCD distance.

4.3.1.2 VARIABILITY IN AIR PERMEABILITY

There is no clear difference in the variability for different temperatures as shown in Figure 4.18. Adjusting for other factors, variability is larger for higher speed. However, on fitting a model no term was statistically significant in explaining the variability in air permeability. Figure 4.19 shows the JMP profiler.

It is clear that die-to-collector distance has little effect on variability. The variability is low for higher temperature and throughput and for lower speed. However none of these effects were statistically significant. There is no statistical evidence that some factors or their combinations are important in accounting for the variability in air permeability.

4.3.2 TEAR STRENGTH

4.3.2.1 MACHINE DIRECTION

4.3.2.1.1 MEAN TEAR STRENGTH

As can be seen from Figure 4.20 and Figure 4.21, the largest effect is of DCD with greater tear strength achieved at high value of the DCD Figure 4.22. The tear strength is very much affected by the basis weight web uniformity. The higher the basis weight uniformity the higher will be the strength, which is shown in Figure 4.23. Web structures that might affect the tear strength are basis weight, fiber orientation and basis weight web uniformity. With an increase in DCD fibers are less divergent giving higher

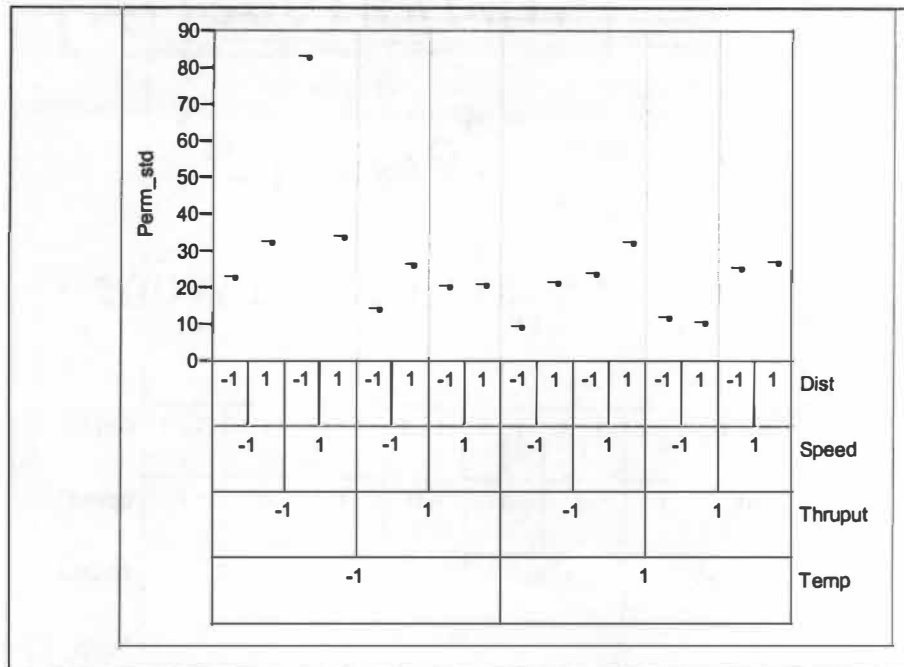


Figure 4.18. Variability chart for air permeability standard deviation

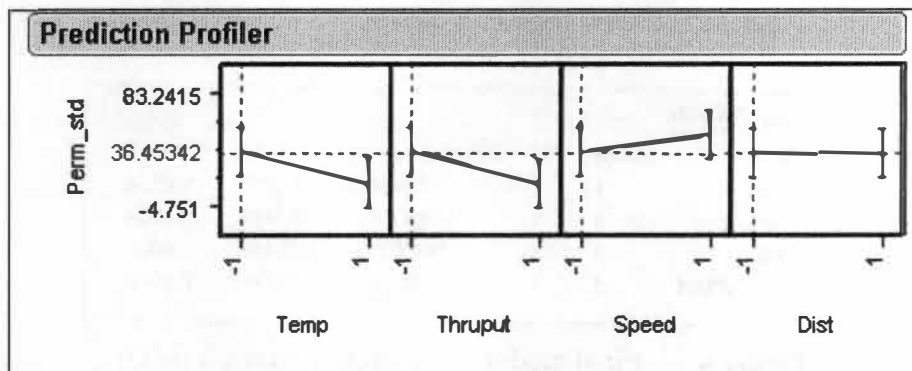


Figure 4.19. Prediction profiler for variability in air permeability

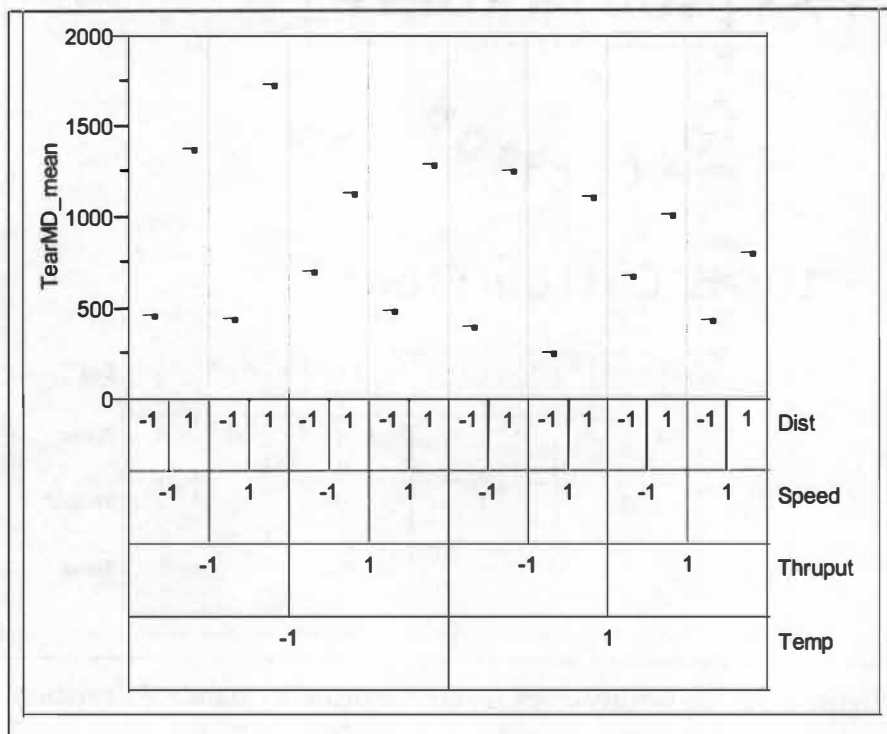


Figure 4.20. Variability chart for mean tear strength (MD)

Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Temp	1	1	178759.8	8.1975	0.0154
Thruput	1	1	16256.2	0.7455	0.4063
Dist	1	1	2138028.8	98.0453	<.0001
Thruput*Dist	1	1	238925.4	10.9566	0.0070

Figure 4.21. Final model for mean tear strength (MD)

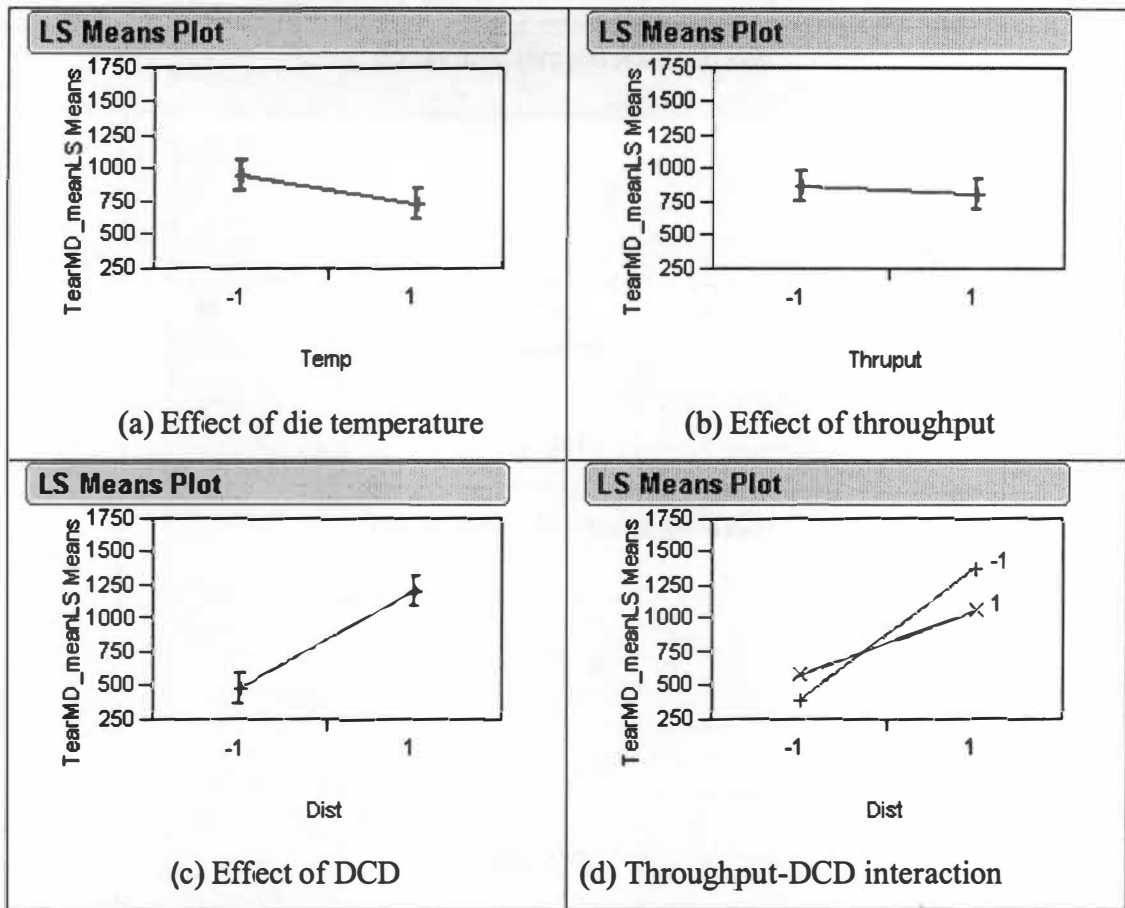


Figure 4.22. LS means plot for significant effects in mean tear strength (MD)

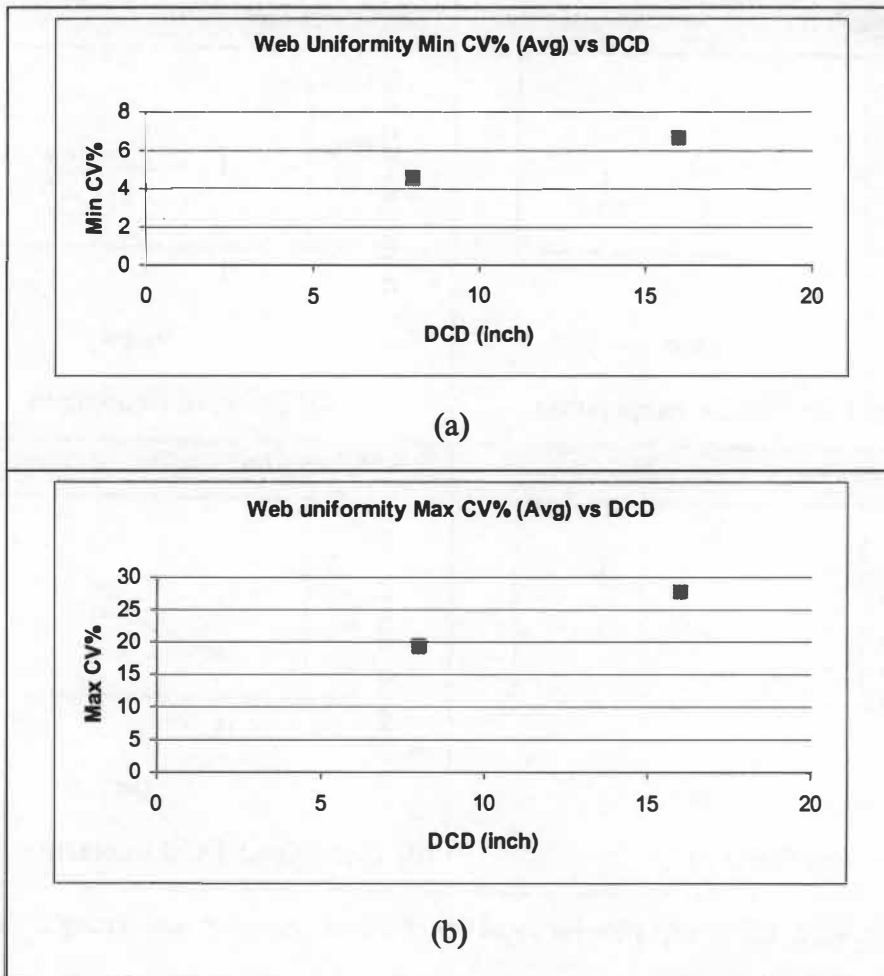


Figure 4.23. Basis weight web uniformity vs. DCD

web uniformity resulting and an increased value of tear strength. To some extent tear strength is also affected by the mean bundle strength and size. With increase in DCD the mean fiber bundle diameter increases [Figure 4.12] as fibers have more time to entangle with each other. Also with increase in mean fiber bundle diameter tear strength seems to be increasing as shown in Figure 4.24. However, tear strength for a web is more of a material property i.e. tear strength depends on the basic strength of the polymer material used and is least affected by any other parameter it also depends on the structure of the web e.g. entanglement.

Increasing the throughput increases the tear strength at high temperature whereas no clear pattern emerges for the low temperature case. This behavior might be due to increased fiber bundle orientation resulting from increase in throughput at higher die temperature as indicated in Figure 4.25. On fitting a model, JMP suggested three terms (based on the normal plot) including die temperature, DCD, and throughput*DCD interaction. The output of the model fitted with these terms is shown in Figure 4.21.

Increasing the die temperature decreases the tear strength whereas increasing the DCD increases it (while averaging over other factors). The effect of throughput is small and statistically insignificant. The only significant interaction is that of distance with throughput, as shown in Figure 4.22 (d). Increasing the DCD increases the tear strength. However, the relative increase is considerably greater for high throughput. In order to maximize the tear strength the machine should be run at low temperature and high DCD.

4.3.2.1.2 VARIABILITY IN TEAR STRENGTH

The coefficient of variation ranges from 7% to as high as 75.6%. Thus, the variability is very high. There is no clear difference in the variability for different temperatures as shown in Figure 4.26. Adjusting for other factors, the variability is larger for higher DCD as shown in Figure 4.27. No other clear patterns are present.

The variability is higher for high temperature and high DCD. The effect of speed is barely noticeable. Variability appears to decrease with throughput.

Based on the normal plot, JMP suggests DCD, throughput, and the following interactions: collector speed*DCD, die temperature*collector speed* DCD and die temperature*.throughput*collector speed* DCD. On fitting a model with DCD,

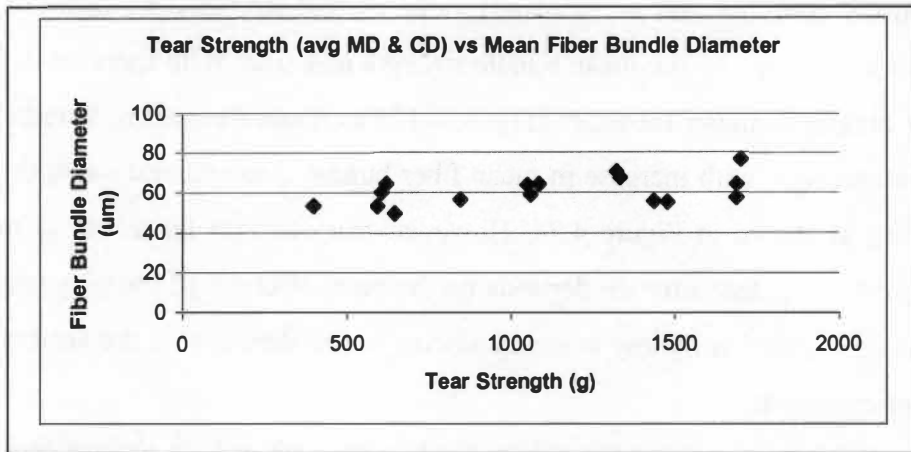


Figure 4.24. Tear strength (average MD & CD) vs. Mean fiber bundle diameter

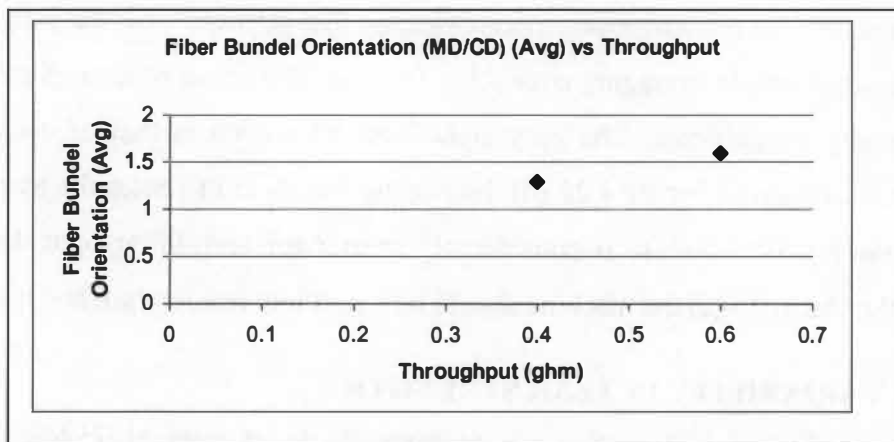


Figure 4.25. Fiber bundle orientation vs. Throughput

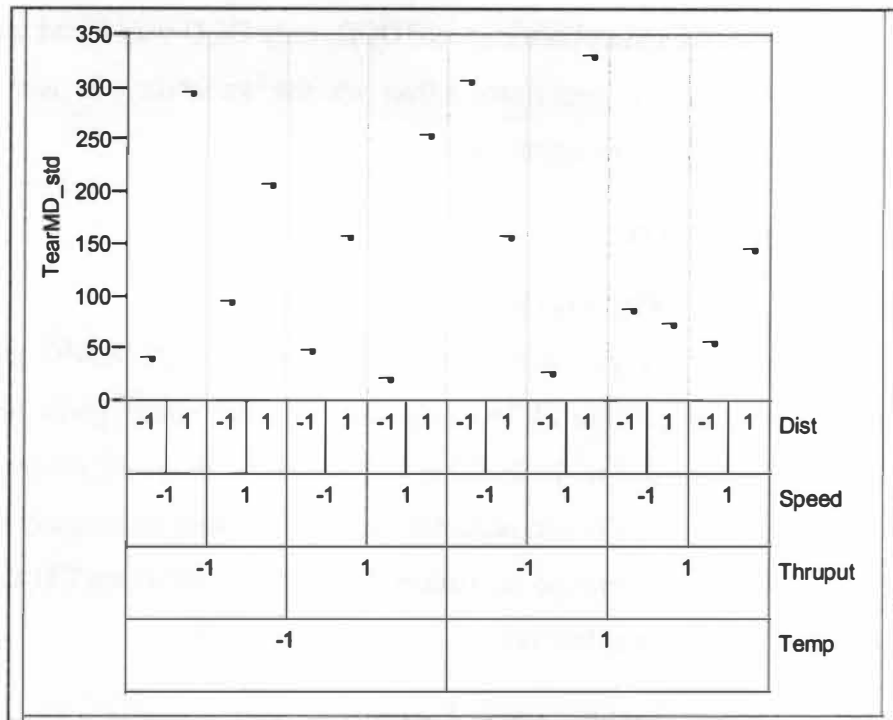


Figure 4.26. Variability chart for tear strength standard deviation (MD)

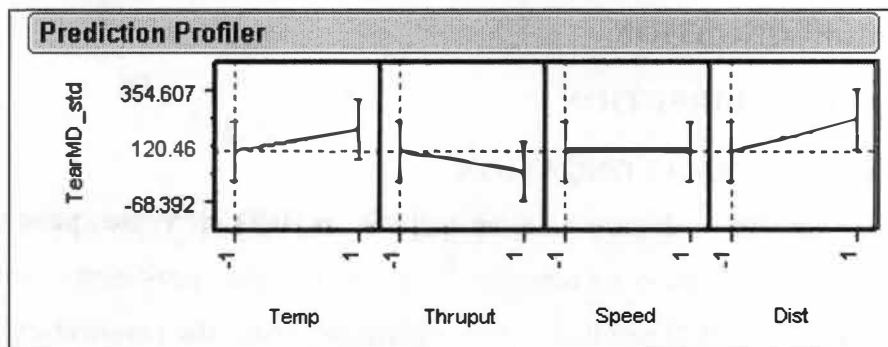


Figure 4.27. Prediction profiler for tear strength standard deviation (MD)

throughput, collector speed and collector speed*DCD, only DCD was found statistically significant. Only DCD has a significant effect on the variability in tear strength. Increasing the DCD decreases the variability.

4.3.2.2 CROSS DIRECTION

4.3.2.2.1 MEAN TEAR STRENGTH

As can be seen from Figure 4.28, the largest effect is of DCD, with greater tear strength achieved at higher value of DCD. Lower collector speed gives higher tear strength along CD, which is due to the fact that at lower collector speed, thicker webs are obtained. On fitting a model, DCD and collector speed were found statistically significant as shown in Table 4.3. So in order to maximize the tear strength along CD the process should be run at higher DCD and low collector speed Figure 4.29.

4.3.2.2.2 VARIABILITY IN TEAR STRENGTH

As can be seen from Figure 4.30 there does not seem to be any pattern for the variability in tear strength along CD. On fitting a model no effect was found statistically significant.

4.3.3 PEAK ELONGATION

4.3.3.1 MACHINE DIRECTION

4.3.3.1.1 MEAN PEAK ELONGATION

As can be seen in Figure 4.31, an increase in DCD, decreases peak elongation along MD and an increase in die temperature results in higher peak elongation. Fitting a full model JMP [Table 4.4] resulted in two significant terms: die temperature and DCD. The effect of DCD is the largest followed by die temperature.

During processing of the polymer on pilot line it was observed that at high temperature and low DCD the web was sticking on the collector, the fibers were in semi molten state, which might be the reason for the insufficient orientation of the fibers resulting in high elongation. Increasing die temperature increases the mean fiber diameter [Figure 4.32] and decreases the fiber bundle orientation [Figure 4.33], thereby increasing the peak elongation as shown in. So in order to maximize peak elongation along MD the

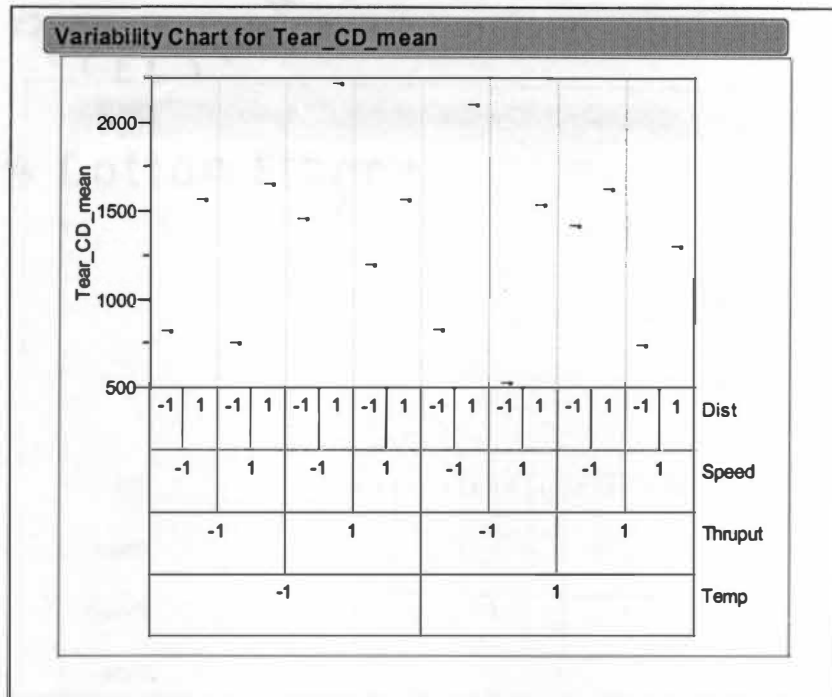


Figure 4.28 Variability chart for mean tear strength (CD)

Table 4.3: Final Model for Mean Tear Strength (CD)

Effect Tests				
Source	Nparm	Sum of Squares	F Ratio	Prob > F
Speed	1	473412.8	6.0794	0.0284
Dist	1	2134959.3	27.4165	0.0002

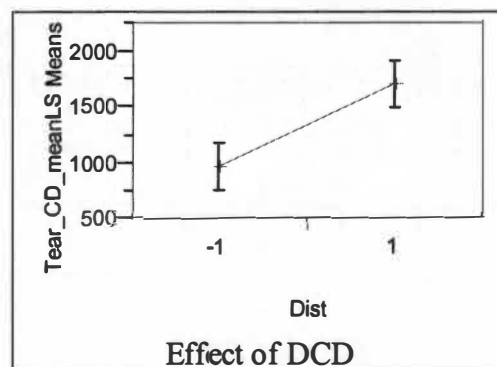


Figure 4.29: LS means plot for significant effects in mean tear strength (CD)

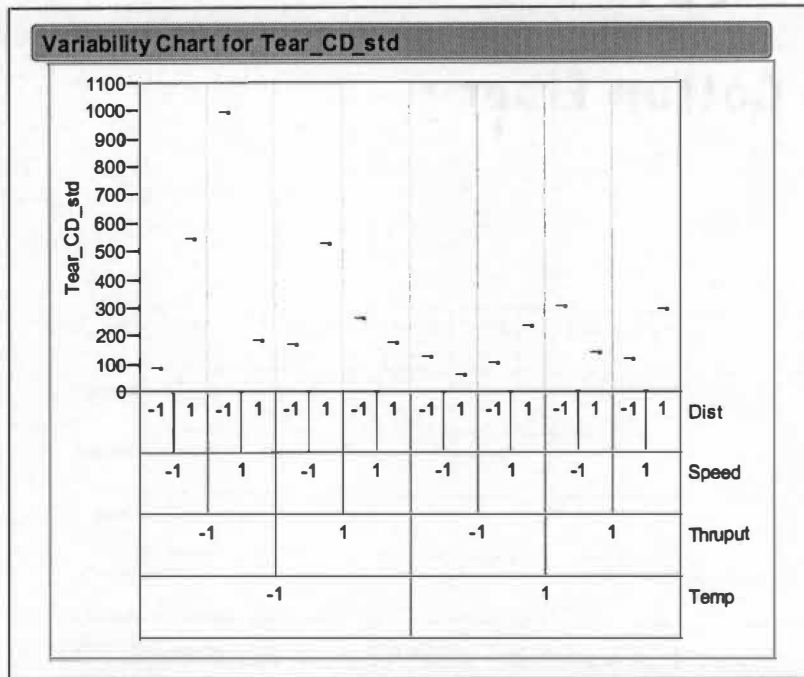


Figure 4.30. Variability chart for tear strength standard deviation (CD)

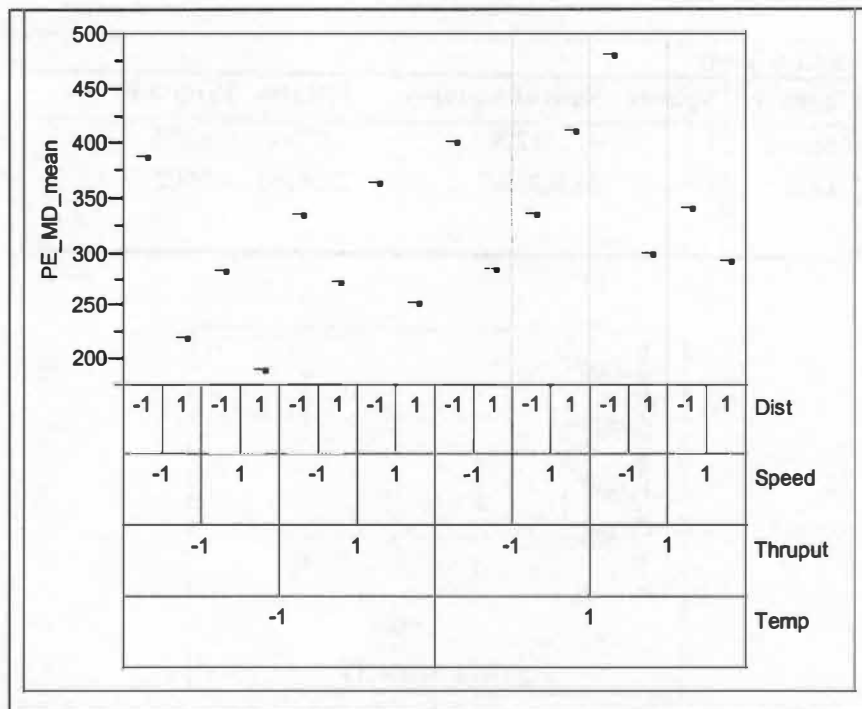


Figure 4.31. Variability chart for mean peak elongation (MD)

Table 4.4 Final Model for Mean Peak Elongation (MD)

Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Temp	1	1	18327.744	6.6179	0.0232
Dist	1	1	31218.296	11.2724	0.0051

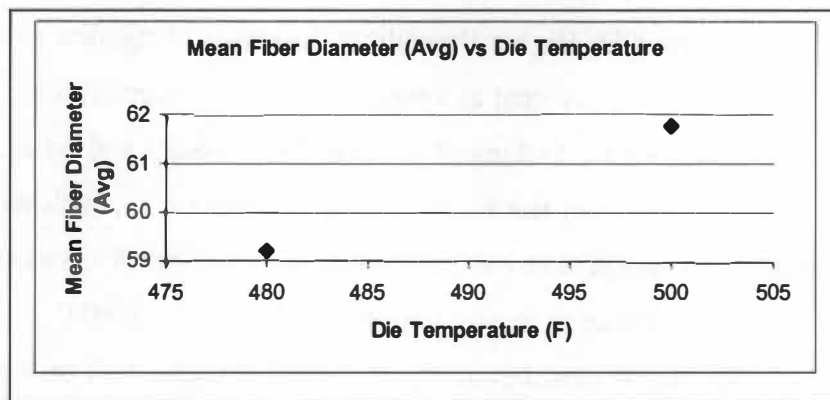


Figure 4.32. Mean fiber diameter vs. Die temperature

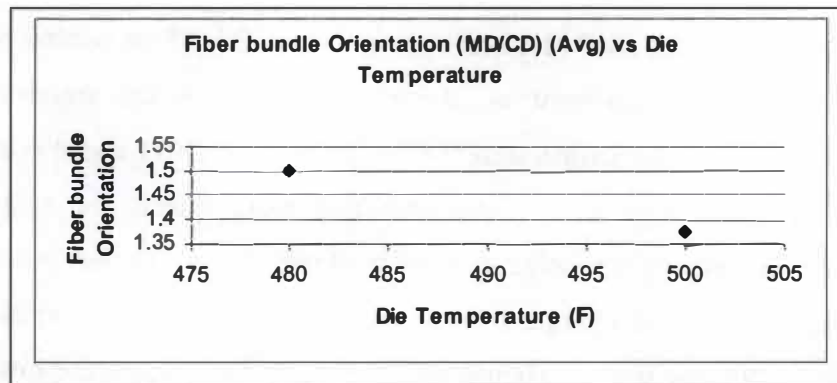


Figure 4.33. Fiber bundle orientation vs. Die temperature

process should be run at high die temperature and low DCD Figure 4.34.

4.3.3.1.2 VARIABILITY IN PEAK ELONGATION

There was no clear pattern observed in the variability for different process parameters as shown in Figure 4.35. When fit a model no effect was found statistically significant.

4.3.3.2 CROSS DIRECTION

4.3.3.2.1 MEAN PEAK ELONGATION

As can be seen from the variability chart [Figure 4.36], throughput has the largest effect on elongation along CD. Higher throughput decreases elongation along CD. The effect of throughput is more consistent at lower value of die temperatures. The effect of throughput can be explained by looking at average basis weight and basis weight web uniformity. As can be seen from the Figure 4.37 and Figure 4.38, with an increase in throughput average basis weight and web uniformity decrease thereby lowering the value for peak elongation as explained as in case of peak elongation along MD.

In case of fiber bundle orientation, lower the value, higher will be the elongation, as more fibers will try to orient themselves in the direction of the applied force. With an increase in DCD, fiber bundle orientation decreases resulting an increase in mean peak elongation.

Fitting a full model JMP resulted in seven terms (based on normal plots) out of which only five were significant as shown in Table 4.5 the interaction of die temperature*throughput, die temperature*DCD, throughput*DCD and die temperature*throughput*DCD were significant along with two main effects throughput and die temperature. So in order to maximize elongation along CD the process should be run at lower throughput and high die temperature as shown in Figure 4.39. As per the prediction profiler [Figure 4.40], the process should be run at high die temperature low throughput and high DCD so as to maximize the elongation.

4.3.3.2.2 VARIABILITY IN PEAK ELONGATION

Adjusting for the other factors variability is larger for throughput and DCD as shown in Figure 4.41. On fitting a model throughput, DCD, throughput*DCD and die

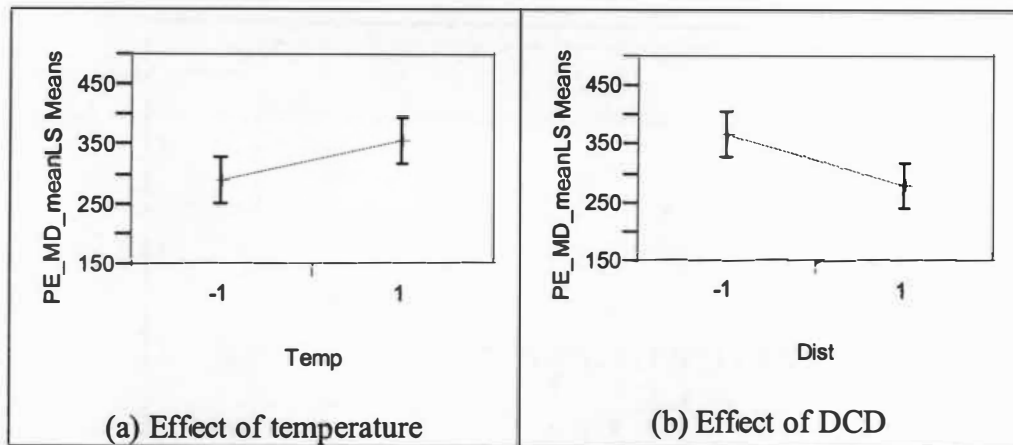


Figure 4.34. LS means plot for significant effects in mean peak elongation (MD)

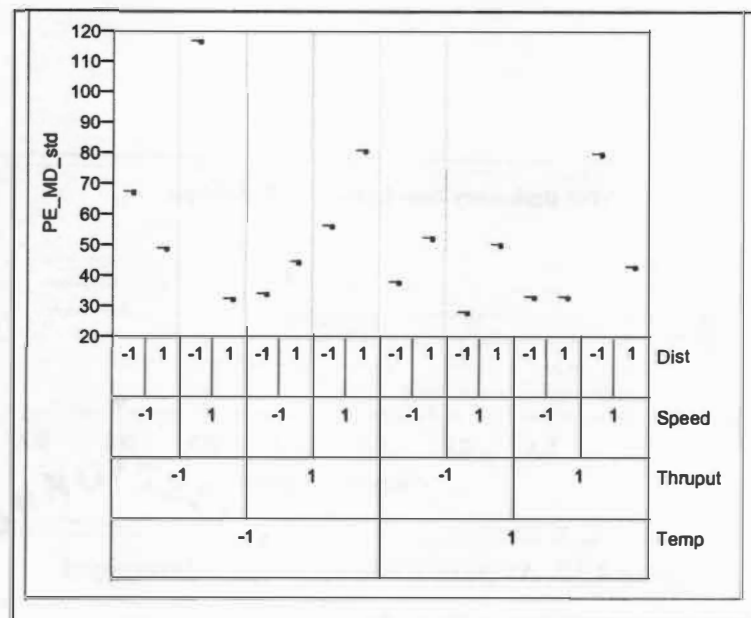


Figure 4.35. Variability chart for peak elongation standard deviation (MD)

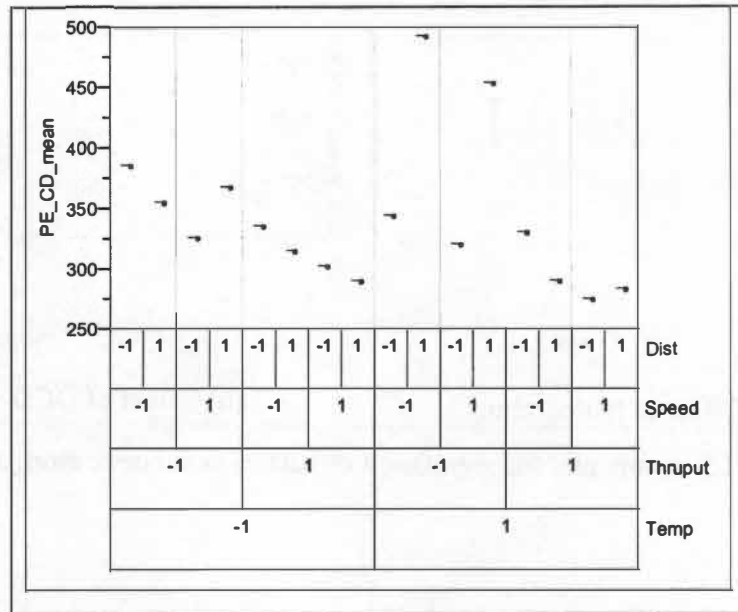


Figure 4.36. Variability chart for mean peak elongation (CD)

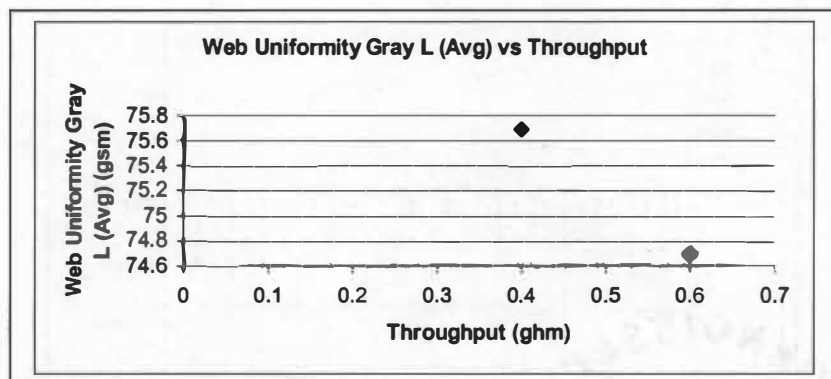


Figure 4.37. Average basis weight vs. Throughput

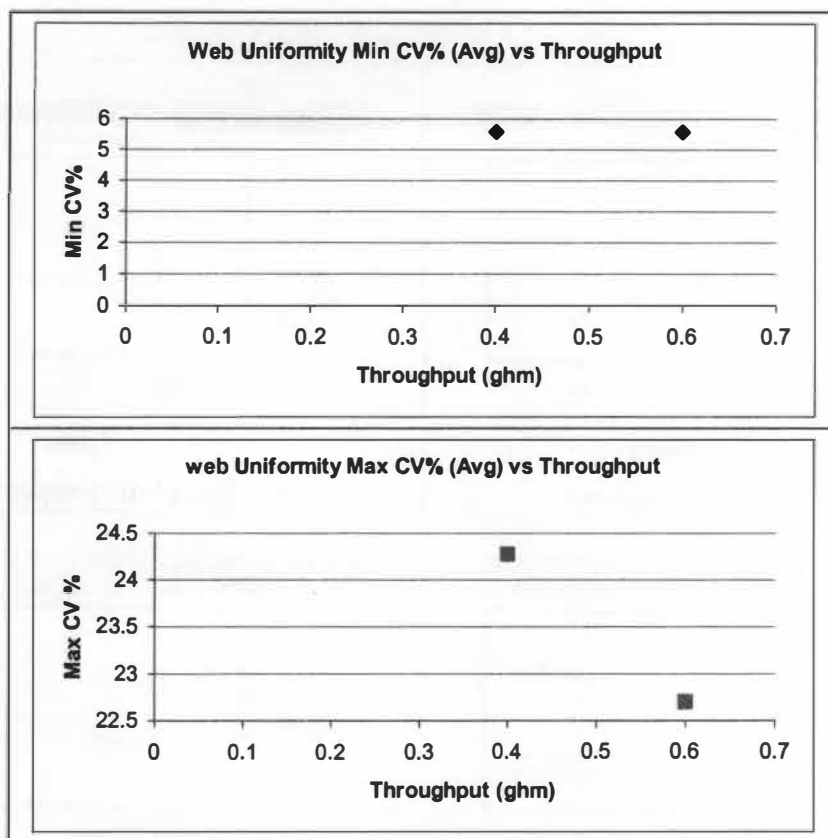


Figure 4.38. Basis weight web uniformity vs. Throughput

Table 4.5: Final Model for Mean Peak Elongation (CD)

Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Temp	1	1	798.628	1.1929	0.3065
Thruput	1	1	24264.293	36.2445	0.0003
Dist	1	1	3279.280	4.8984	0.0578
Temp*Thruput	1	1	3705.157	5.5345	0.0465
Temp*Dist	1	1	4647.831	6.9426	0.0299
Thruput*Dist	1	1	8032.641	11.9987	0.0085
Temp*Thruput*Dist	1	1	4601.587	6.8736	0.0306

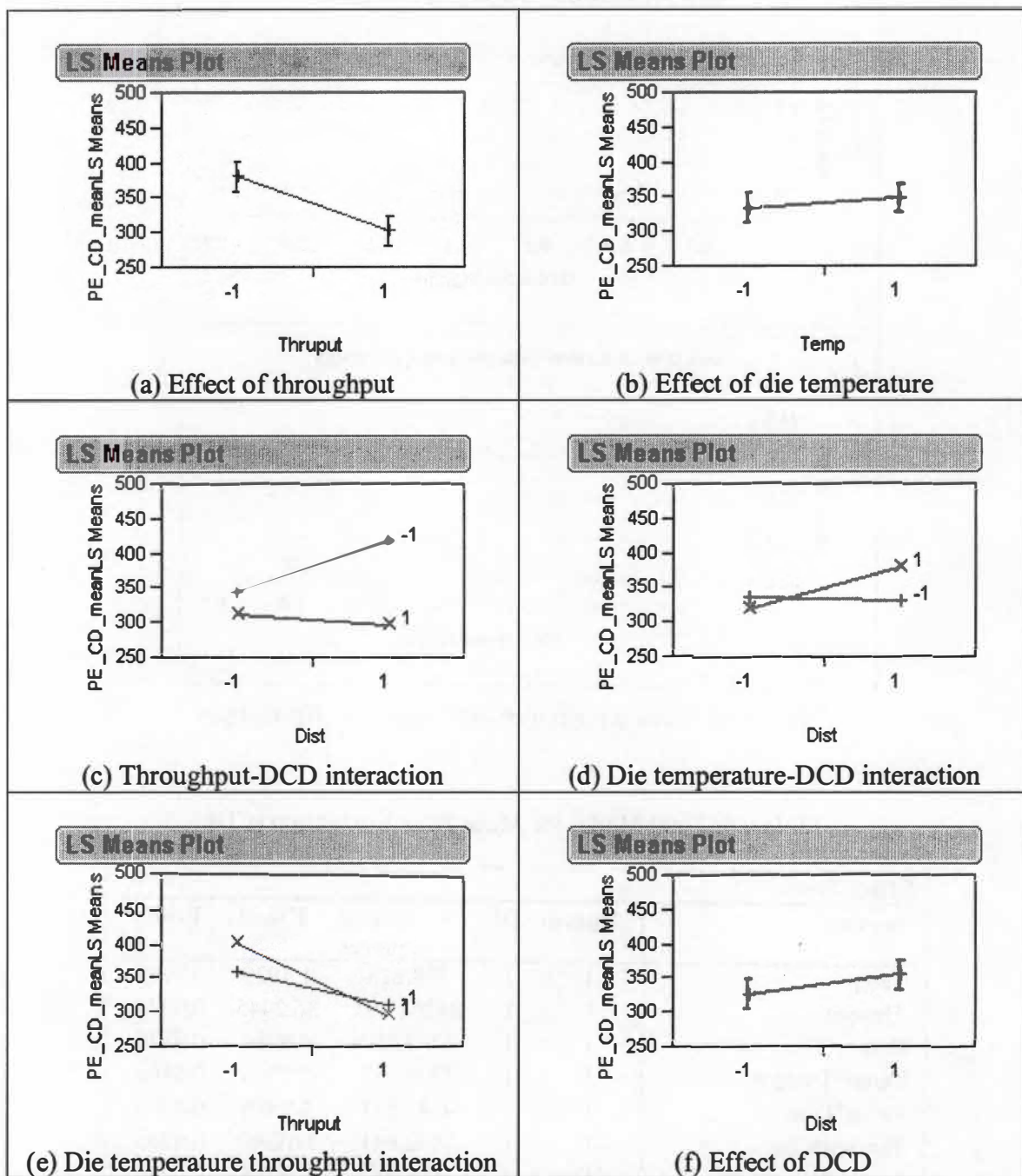


Figure 4.39. LS means plot for significant effects in mean peak elongation (CD)

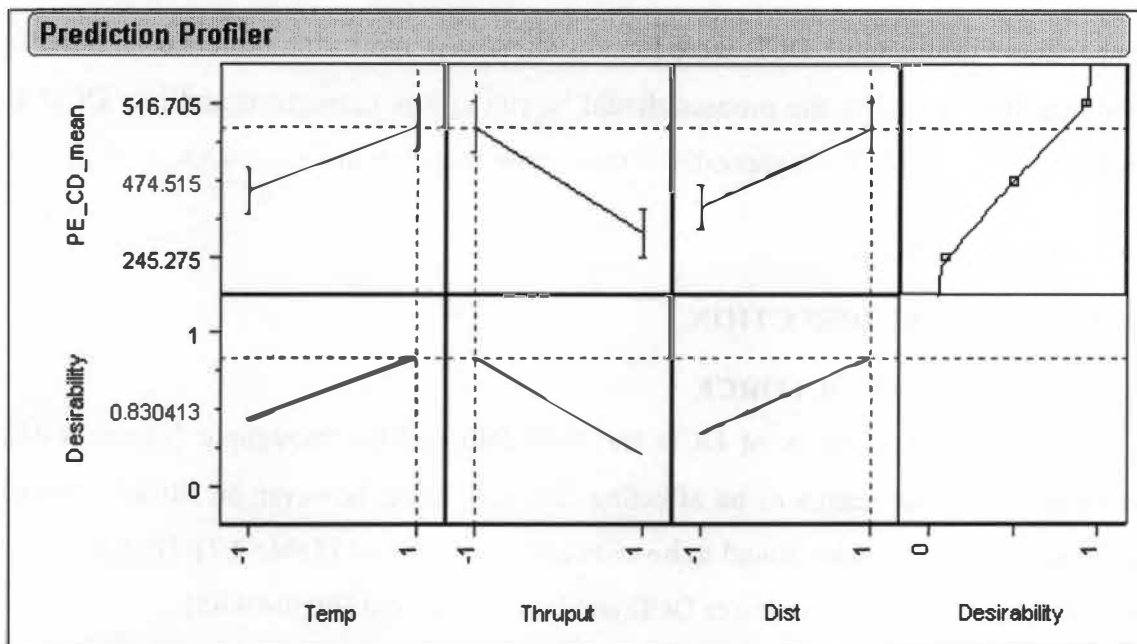


Figure 4.40. Prediction profiler for mean peak elongation (CD)

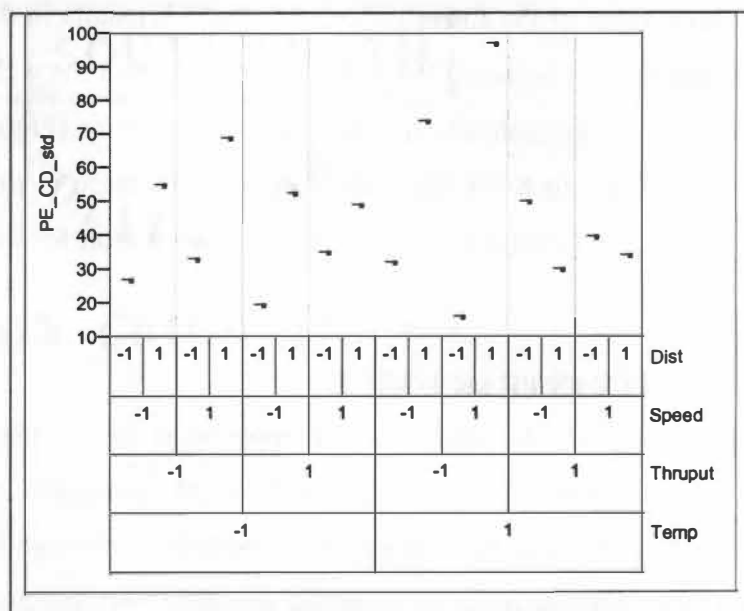


Figure 4.41. Variability chart for mean peak elongation standard deviation (CD)

temperature* throughput* DCD were found statistically significant Table 4.6. In order to minimize the variability the process should be run at low throughput and low DCD as shown in Figure 4.42. Throughput-DCD interaction is shown in Figure 4.43.

4.3.4 PEAK FORCE

4.3.4.1 MACHINE DIRECTION

4.3.4.1.1 MEAN PEAK FORCE

The largest effect is of DCD and then followed by throughput [Figure 4.44], collector speed also seems to be affecting the peak force, however on fitting a model DCD and throughput were found to be statistically significant [Table 4.7]. Higher values of peak force are obtained at lower DCD and high throughput [Figure 4.45].

The web structure properties that might affect the peak force are bundle size, average basis weight, basis weight uniformity and fiber orientation. With increase in DCD the web becomes thinner, which means it needs lesser force to break the fibers in the web [Figure 4.46]. For higher DCD the fibers have to travel for longer distance during which the movement of the fibers gets chaotic, which results in disoriented fiber laying on the collector thereby reducing the force required to break the web [Figure 4.47]. Where as with increase in throughput the fabric becomes heavier [Figure 4.37] which means it needs higher force to break the web. Also with increase in throughput, fiber bundle orientation increases [Figure 4.25], which is another reason for the peak force to increase.

4.3.4.1.2 VARIABILITY IN PEAK FORCE

From Figure 4.48 all the main factors appears to be having an effect the variability for peak force however on fitting a JMP model throughput, collector speed, DCD and throughput*DCD interaction were found to be statistically significant as shown in Table 4.8 and Figure 4.49. In order to minimize the variability the process should be run at low throughput, low collector speed and low DCD as shown in Figure 4.50.

Table 4.6: Final Model for Peak Elongation Variability (CD)

Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Temp	1	1	70.2244	0.8133	0.3935
Thruput	1	1	550.1370	6.3712	0.0356
Dist	1	1	2733.7212	31.6595	0.0005
Temp*Thruput	1	1	94.2841	1.0919	0.3266
Temp*Dist	1	1	12.8881	0.1493	0.7093
Thruput*Dist	1	1	1698.6762	19.6725	0.0022
Temp*Thruput*Dist	1	1	1092.9636	12.6577	0.0074

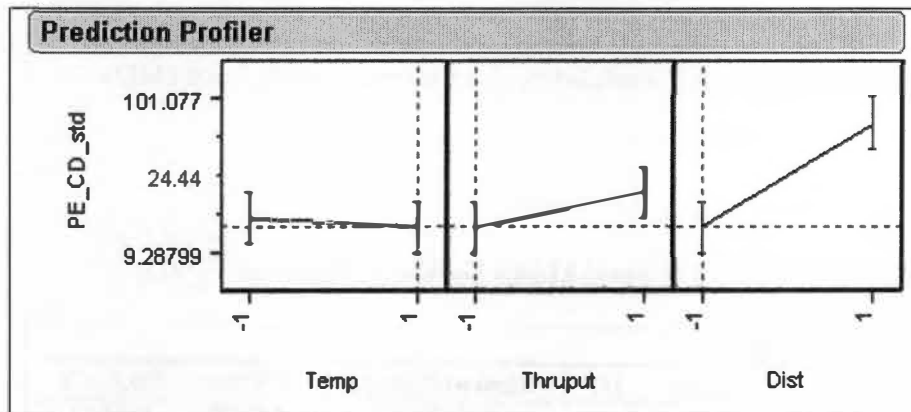


Figure 4.42. Prediction profiler for peak elongation standard deviation (CD)

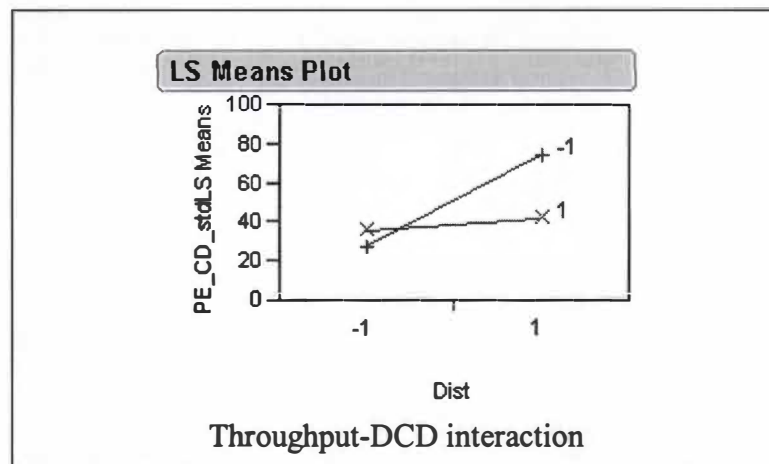


Figure 4.43. LS means plot for peak elongation standard deviation (CD)

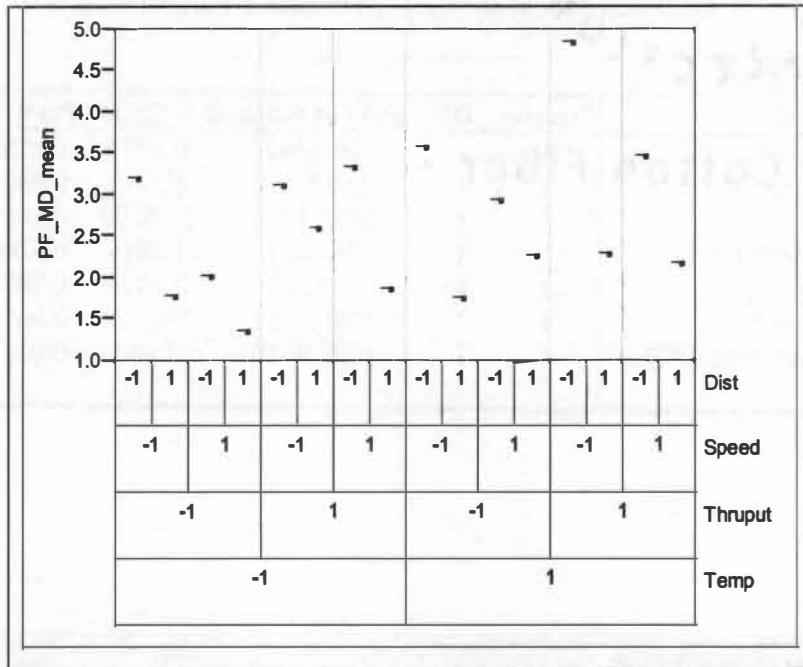


Figure 4.44. Variability chart for mean peak force (MD)

Table 4.7: Final Model for Mean Peak Force (MD)

Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Thruput	1	1	1.4328227	4.7297	0.0487
Dist	1	1	6.7905503	22.4153	0.0004

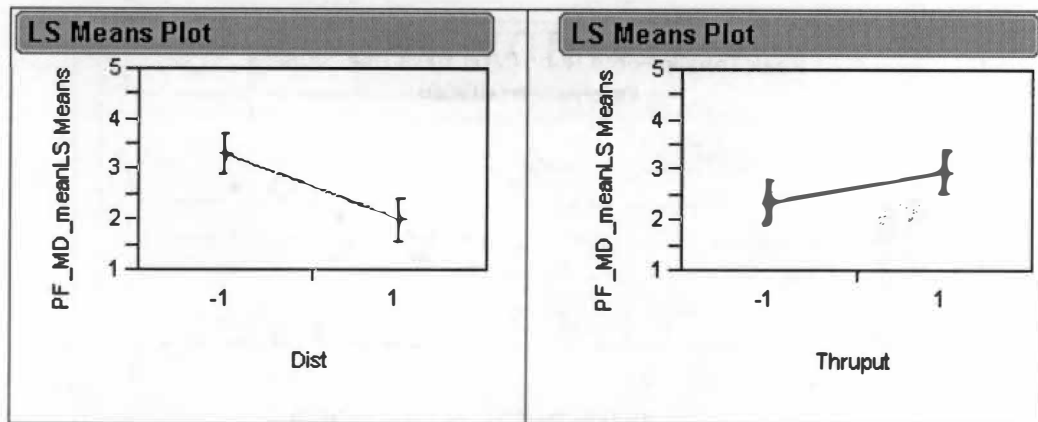


Figure 4.45: LS means plot for significant effects in mean peak force (MD)

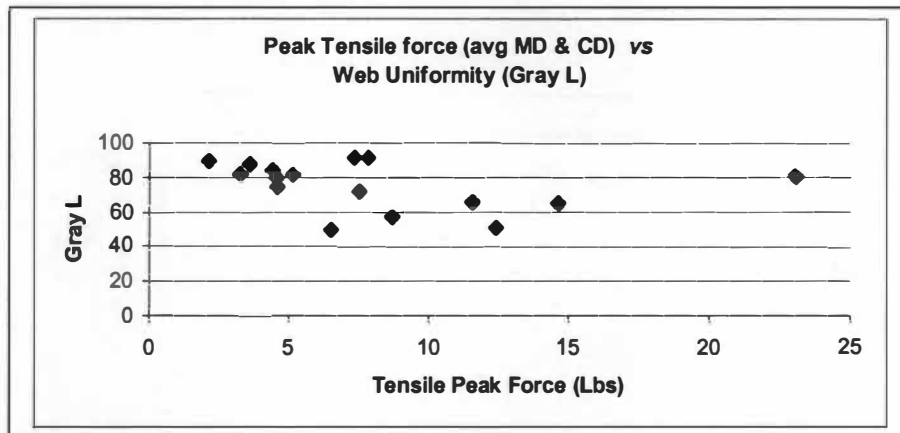


Figure 4.46. Peak tensile force vs. Average basis weight

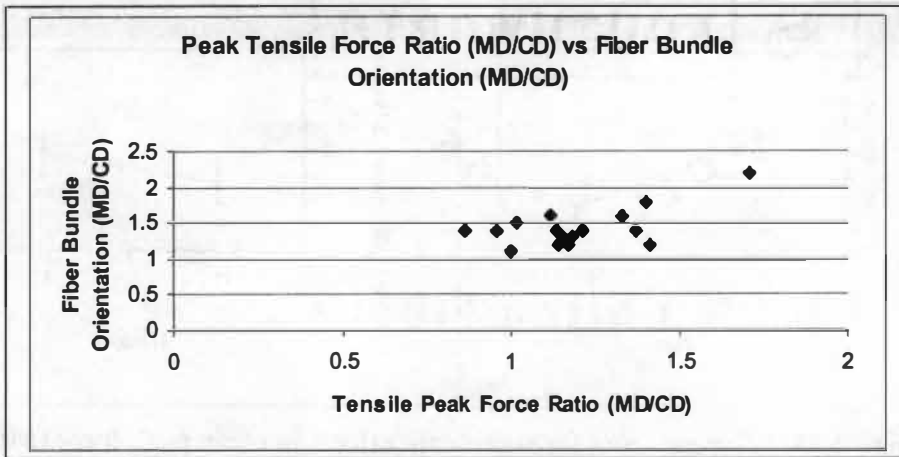


Figure 4.47. Peak tensile force ratio vs. Fiber bundle orientation

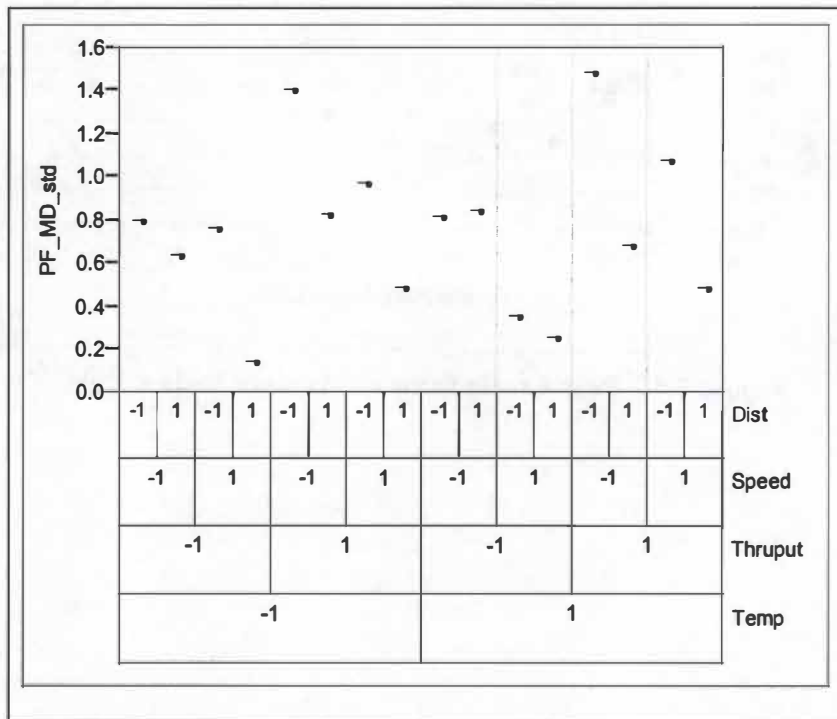


Figure 4.48. Variability chart for peak force standard deviation (MD)

Table 4.8: Final model for mean peak force standard deviation (MD)

Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Thruput	1	1	0.49000000	28.5261	0.0002
Speed	1	1	0.54760000	31.8793	0.0001
Dist	1	1	0.68062500	39.6236	<.0001
Thruput*Dist	1	1	0.16000000	9.3146	0.0110

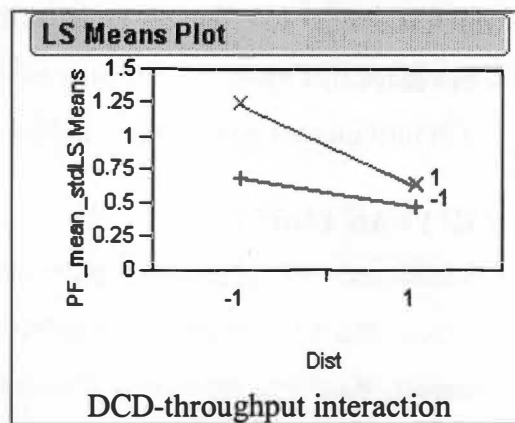


Figure 4.49. LS means plot for peak force standard deviation (MD)

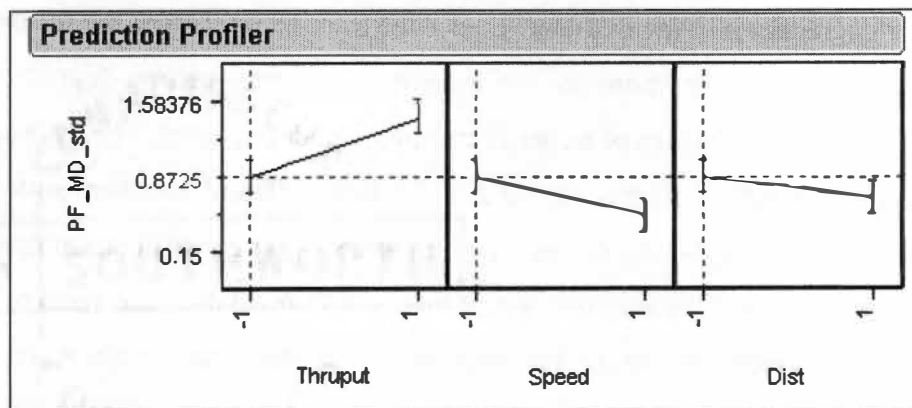


Figure 4.50. Prediction profiler for peak force standard deviation (MD)

4.3.4.2 CROSS DIRECTION

4.3.4.2.1 MEAN PEAK FORCE

From the Figure 4.51 as can be seen all the main factors seems to affecting the mean peak force, however on fitting a JMP model three main factors were found statistically significant, die temperature, DCD and collector speed [Table 4.9]. Peak force increases with increase in temperature, decrease in DCD and collector speed as shown in Figure 4.52. The basis for the explanation for increase in force with decrease in DCD throughput is the same as explained in 4.3.4.1.1. At higher values of collector speed thinner webs are obtained which is similar to effect observed at high DCD. At higher die temperature, the peak force increases that might be because of increase in mean bundle diameter [Figure 4.32], which in turn increases the force required to break the web.

4.3.4.2.2 VARIABILITY IN PEAK FORCE

Among all the main factors and their interactions only collector speed is affecting the variability where as for others there is not any clear pattern observed as shown in Figure 4.53. Also when fit a model speed was the only term found statistically significant [Table 4.10]. Variability is higher at lower speed as shown in Figure 4.54.

4.4 POLYMER DEGRADATION

Change in throughput rate and die temperature is expected to have some effect on the polymer degradation in the extruder. Lower the throughput, higher the residence time of polymer in the extruder, more are the chances pf polymer getting degraded. And at higher temperature the chances of polymer getting degraded is more. This was confirmed measuring the complex viscosity on ARES for four different samples with different combinations of throughput and die temperature at 255°C at constant strain rate in order to study the correlation between them. From Figure 4.55 there does not seem to be much difference in the viscosities of all the samples. Since three runs were made for each sample, to check the repeatability, the errors are with in the statistical limits. So it is hard to comment on the polymer degradation behavior by measuring the viscosities of the nonwoven samples for different die temperature and throughput conditions.

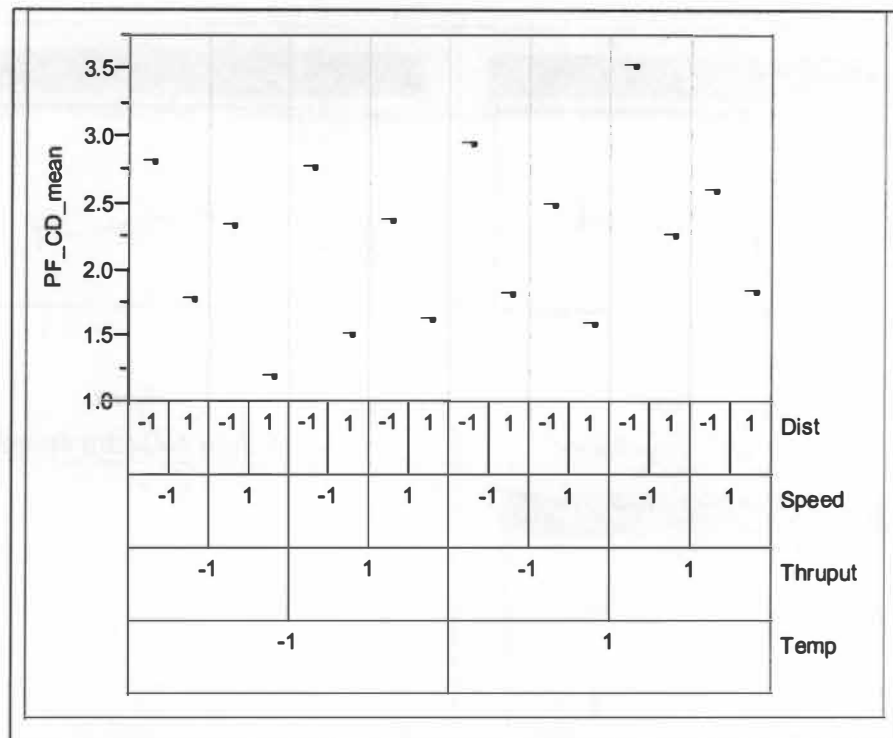


Figure 4.51. Variability chart for mean peak force (CD)

Table 4.9: Final Model for Mean Peak Force (CD)

Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Temp	1	1	0.4475803	9.9846	0.0082
Speed	1	1	0.7218537	16.1030	0.0017
Dist	1	1	4.2709604	95.2762	<.0001

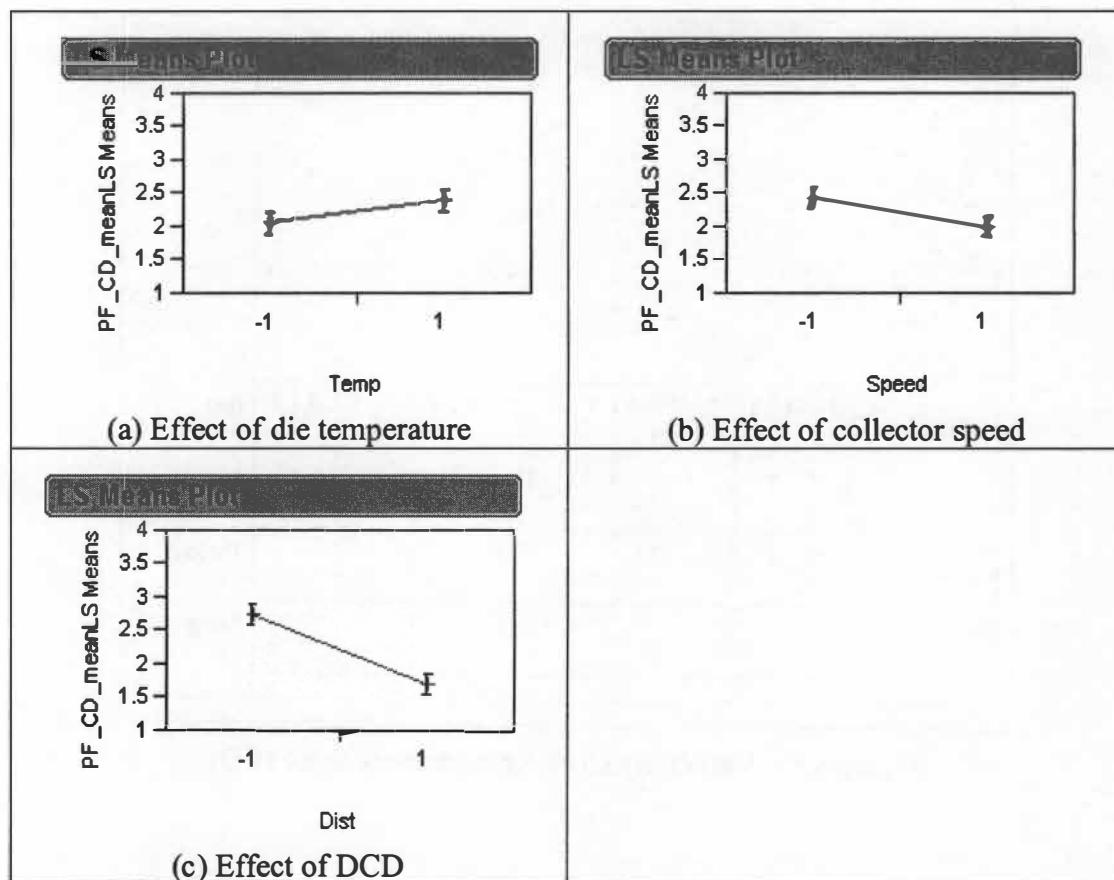


Figure 4.52. LS means plot for mean peak force (CD)

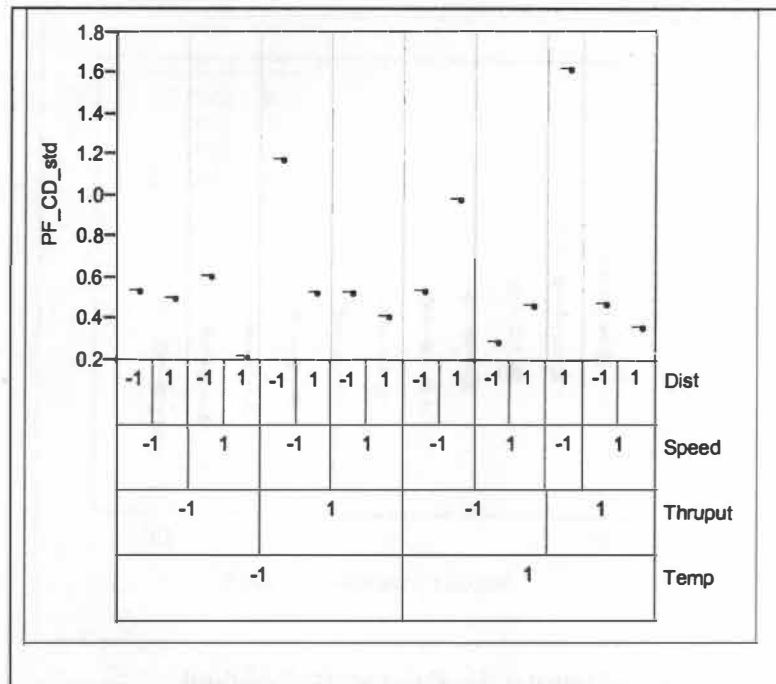


Figure 4.53. Variability chart for peak force standard deviation (CD)

Table 4.10: Final model for peak force standard deviation (CD)

Effect Tests					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Speed	1	1	0.66867857	6.8897	0.0210

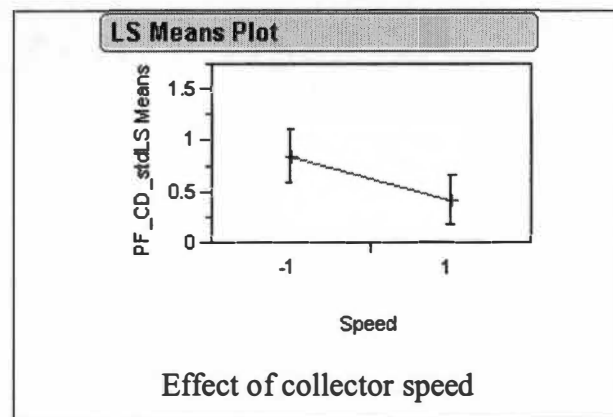


Figure 4.54. LS means plot peak force standard deviation (CD)

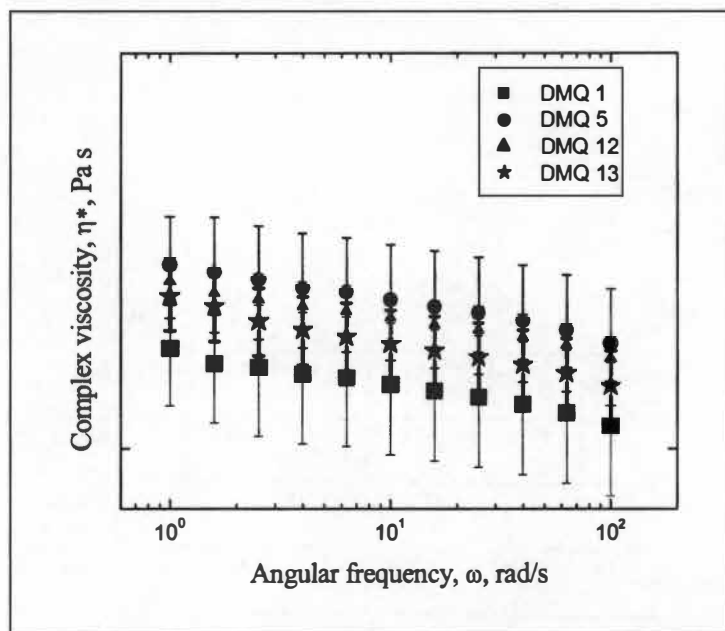


Figure 4.55. Polymer degradation

CHAPTER-5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

This experiment was helpful in giving information about three different aspects of the Demique® nowwoven webs. The part gives some of the basic rheological properties and processing temperatures for polyether ester. Second part gives information about the fiber structure and the manner in which these are laid on the collector and how it varies with different processing conditions. And the last part gives information the correlation between the processing conditions and the web properties. Different conclusions obtained from this experiment are as follows:

1. Except at the low temperature this polymer behaves like a Newtonian fluid.
2. The processing range of the polymer is above 225°C and below 275°C.
3. The fibers in the web are in fused form and are multilobed in structure due to fusion.
4. The surface of the fibers is not smooth, pitting on the surface could be seen which is a structural characteristics of the fibers.
5. The correlation between the processing conditions and the web properties is given Table 5.1. All of the correlations given below in the table are statistically significant for obtaining higher values of four mentioned nonwoven web properties.
6. Peak tensile force increases with increase in basis weight web uniformity, increase in basis weight and increase in fiber bundle orientation.
7. Basis weight web uniformity increases with increase in mean fiber bundle diameter.
8. Pore cover % increases with increase in mean fiber bundle diameter.

5.2 RECOMMENDATIONS

Based on this research and results obtained, following work is suggested for future studies:

1. Study of polymer degradation in Demique® nonwoven webs in relation to different throughput and die temperature.
2. Optimization of fiber structure.
3. Meltblowing of additional new polymer and optimizing the process and web properties along with rheological characterization of the polymer.

Table 5.1: Correlation Between Process Parameters and Web Properties

Property		Die Temperature	Throughput	DCD	Collector Speed	Interactions
Air permeability		Low	Low	High	High	L.T.&L.DT.
Tear Strength	MD	Low	Low	High	No Effect	H.DCD&L.T.
	CD	No Effect	No Effect	High	Low	-
Peak Elongation	MD	High	No Effect	Low	No Effect	-
	CD	High	Low	High	No Effect	H.DCD&L. T. H.DCD&H.DT. L.T.&H.DT
Peak Force	MD	No Effect	High	Low	No Effect	-
	CD	High	No Effect	Low	Low	-

L.T. = Low Throughput

L. DT. = Low Die Temperature

H. DCD. = High Die to Collector Distance

H. DT. = High Die Temperature

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